

# Collaboration of results from industry round-robin on engineering critical assessment evaluations

Prepared by **Serco Assurance**  
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**Serco Assurance**  
Thomson House  
Birchwood Park  
Risley  
Warrington  
Cheshire WA3 6GA

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This report collates the results and discusses the magnitude of variation between the respective Participants’ answers to the benchmark questions, and presents the answers from the face-to-face discussions. The information presented within this report will allow HSE to gain a better appreciation of how practising engineers undertake ECA evaluations and, if appropriate, provide recommendations for improved general guidance on such evaluations.

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# Executive Summary

Assessing the significance of flaws or defects, which have been found during inspection, is performed using “Engineering Critical Assessment (ECA)” techniques, also sometimes referred to as “Fitness for Service” or “Fitness for Purpose” techniques. The implications of an incorrect ECA can be highly damaging; both to personnel Health and Safety and to the finances of the operating company.

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This report collates the results and discusses the magnitude of variation between the respective Participants’ answers to the benchmark questions, and presents the answers from the face-to-face discussions. The information presented within this report will allow HSE to gain a better appreciation of how practising engineers undertake ECA evaluations and, if appropriate, provide recommendations for improved general guidance on such evaluations.

Through obtaining the results and reviewing the procedures used within the reports for the Round-Robin exercises, a series of conclusions can be drawn into how ECA’s are performed within industry. Further to these conclusions are a number of recommendations. Both the conclusions and the recommendations can be found below:

In general the CRACKWISE solutions are similar to those performed by hand (i.e. within a spreadsheet) or on similar self-developed software

Human error was apparent in a number of cases, some of which would have major influences on the evaluated limiting crack size.

A large number of methods have been used to evaluate a non-stress-relieved weld. Amongst these assuming a residual stress profile is possibly the most non-conservative. Two other main types of method are used for the non-stress-relieved case, (a) to use a stress profile (Equation Q.4.b of BS7910) or (b) to use a constant yield stress of either the weld or parent material.

The validity of using a stress profile for a given heat input and weld type within Example 2 is unclear as the heat input contradicts with what is said to be valid for all the contents of Annex Q. To accentuate this, two Participants provide two solutions; one using Equation Q.4.b and one using a constant residual stress.

The interpretation of the stress profile provided by equation Q.4b is also seen to change between participants.

Where a constant yield stress is used for the secondary membrane term, there is no guidance as to use the parent or weld yield stress.

Where a remaining lifetime is found within Exercise 3, either no advice for continued inspection is provided, or it is flawed.

The findings from the work carried out within this project have shown that when carrying out an ECA evaluation using BS7910 (or similar procedure/software), there is the potential to produce a relatively wide range of results. This range of results stems from the different assumptions

made and the interpretations of the practitioner in relation to the contents and the guidance provided within the procedure.

The exercises presented to the participating organisations were relatively simple problems and it was evident that only a small complexity needed to be added to the problems for there to be a concerning diversity in results. It is anticipated that as a problem becomes more complicated, the diversity in the results will become greater.

There was a marked difference in some of the results submitted as part of this exercise, primarily due to different levels of 'conservatism' being assumed. As long as a practitioner applies any assumptions made in a conservative manner, then an acceptable answer should be obtained. Any assumptions being made outside the guidance within the assessment procedure must be fully justified. Although calculations of this kind are usually correct based on any assumptions made, the reasoning behind those assumptions is not always given and this very often makes it difficult to evaluate the credibility of the conclusions drawn.

This work highlighted that while simple problems assessed by ECAs gave similar results, any additional complexity resulted in a variety of answers.

With ECAs increasingly being used in Risk Based Inspection and for plant life extension, the HSE and industry should have considerable concerns regarding the accuracy of the ECAs submitted to them.

As a result of these findings, the Steering Committee has highlighted some specific areas which may be regarded as 'recommended practice' and must be given careful consideration when undertaking an ECA, in order to produce suitably conservative information on the significance of flaws under a particular set of circumstances.

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# 1 Introduction

Assessing the significance of flaws or defects, which have been found during inspection, is performed using “Engineering Critical Assessment (ECA)” techniques, also sometimes referred to as “Fitness for Service” or “Fitness for Purpose” techniques. The implications of an incorrect ECA can be highly damaging; both to personnel Health and Safety and to the finances of the operating company.

The Health and Safety Executive (HSE) contracted Serco Assurance to lead a project comprising a Round-Robin exercise such that a better appreciation can be gained of how practising engineers undertake ECA evaluations. Participants from appropriate industrial companies and supporting organisations were contacted, and supplied three benchmark questions as an exercise. Following initial interpretation of the results, a small team of Serco Assurance staff conducted face-to-face discussions to further investigate the methods used to solve the exercises, and how they might cope with more complex issues.

The project follows on from work commissioned by the HSE (2004) (Reference 1 and 2) that evaluated differences between the various ECA methodologies (and associated software packages) available to UK industry.

This report collates the results and discusses the magnitude of variation between the respective Participants’ answers to the benchmark questions, and presents the answers from the face-to-face discussions. The information presented within this report will allow HSE to gain a better appreciation of how practising engineers undertake ECA evaluations and, if appropriate, provide recommendations for improved general guidance on such evaluations.

# 2 ECA ‘Recommended Practice’ Guidelines

As a result of the findings of this work, the Steering Committee has highlighted some specific areas which may be regarded as ‘recommended practice’ and must be given careful consideration when undertaking an ECA, in order to produce suitably conservative information on the significance of flaws under a particular set of circumstances.

- ❑ Ensure that the person undertaking the ECA is suitably qualified and has sufficient knowledge and understanding of the subject area, and ensure that the work is fully verified by a suitably qualified person
- ❑ Before undertaking any ECA work the code/software/standard should be checked to warrant that the most up-to-date version is available and used.
- ❑ Any deviation from the code/software/standard or any assumptions being implemented by the practitioner must be fully justified and the reasoning behind these deviations must be provided as part of the reporting procedure.
- ❑ Obtain as much information as possible regarding the component being assessed in relation to the material, the operating conditions and the operating environment.
- ❑ If no or limited material properties are available then suitable options are:
  - use default material properties,
  - obtain the relevant data sheets for the component being assessed,
  - undertake laboratory testing using material for the required test specimen.
- ❑ Carry out suitable sensitivity studies on particular issues which can be provided to the client (i.e. the use of different geometry solutions within BS7910)

- ❑ It is beneficial to both client and the person undertaking the ECA if the whole process of the assessment is carried out in an iterative manner.
- ❑ When calculating the limiting crack size it is generally assumed that the surface and deepest points of the crack are the two extreme situations. It is good practice as part of the assessment not to hold the a/c ratio constant.
- ❑ Care should be taken on which value of yield stress,  $\sigma_y$  ( $\sigma_{0.2}$ ) to use for the calculation of  $L_r$  and the membrane stress. Guidance is provided for a Level 1 assessment and this must be adhered to for a Level 2 assessment also (although it is not stated here explicitly).
- ❑ When allowing for the effect of residual stresses in an assessment the guidance in BS7910 should be carefully followed. Deviation from the guidance must be justified. The level of conservatism must be known by both the practitioner and the client.

### 3 Background

The current project follows on from work commissioned by the HSE (2004) (Reference 1 and 2) that evaluated differences between the various ECA methodologies (and associated software packages) available to UK industry. Within Reference 2, the recommendations section highlights the need for a Round-Robin exercise to be undertaken. The work covered within this report is a direct result of that recommendation.

HSE contracted Serco Assurance to lead the project. The study was undertaken through a combination of benchmark questions and detailed discussion with representatives from the participating companies. There were five companies, in addition to HSE and Serco Assurance, who participated.

The benchmark question structure has been defined by a Steering Committee of experts. The questions were to contain both basic (e.g. pressure loading only, homogeneous material etc.) and more complex (e.g. pressure plus other types of loading, residual stresses, weld features etc.) cases.

Particular areas of interest for the initial benchmark exercises are:

- How the information presented, regarding the benchmark exercises, is interpreted and subsequently used by the Participant.
- How the assessment methodologies/procedures used are interpreted by the Participant.
- How the assessment methodologies/procedures have been applied by the Participant.

The Steering Committee, made up of recognised experts in the field of fracture mechanics, overseeing the project is detailed below:

Bob Andrews	Advantica
Harry Bainbridge	Health and Safety Executive
Adam Bannister	Corus Group
Bill Geary	Health and Safety Laboratory
Neil Henry	ABB
Henryk Pisarski	TWI
John Sharples	Serco Assurance
Alan Smith	Det Norske Veritas
Keith Wright	Rolls Royce/Structural Integrity Assessments Ltd.
John Yates	The University of Sheffield

## 4 Methodology

To investigate how different companies implement ECA techniques within their own work, three exercise questions were delivered to the participants (see Section 4.1). Each Participant was to answer these exercises to the best of their ability, using their preferred methodology, which in all cases was based on BS 7910 (Reference 3). The method adopted between each Participant could vary depending on what was normally used, be it hand (written) calculations, spreadsheet analysis or specialist software (e.g. CRACKWISE).

Each Participant was to return a report detailing their answers to, and the methodology adopted in, each exercise. Requesting this style of reporting allows any discrepancies between the answers to be highlighted and subsequently understood.

Following the initial collation of the reports, a selection of questions to further investigate the methods used by all the participants was compiled. The questions were then put to all of the participants within face-to-face discussions by members of Serco Assurance staff.

These discussions help to obtain an understanding of how the participants conduct their analysis, how they would obtain their material data and where they might encounter problems. The information obtained through the discussions will be crucial in determining if more information could be included within the guidance material (e.g. BS 7910, R6).

The Participant's individual details are not to be provided within this report. This is to ensure that ambiguity is maintained and that confidence between companies is not broken. Therefore, each Participant is allocated a letter (A through to G) so that individual results can be referred to whilst maintaining ambiguity.

Note that where conservatism is mentioned below, the following definitions are implied:

- Conservative – The calculated limiting crack depth is less than that which would cause failure in a real-life component. *This is generally beneficial, but over-conservatism might lead to replacing components too frequently or unnecessary closure.*
- Non-conservatism – The calculated limiting crack depth is more than that which would cause failure in a real-life component. *This can obviously be very serious if it leads to a component, with a known defect, being left in an environment where it is likely to fail.*

### 4.1 Benchmark Exercises

The benchmark questions, sent to all of the participants to be answered, can be found below:

#### General

Ferritic Steel Cylindrical Pressure Vessel operating at Room Temperature (20°C).

Outer Diameter = 525 mm

Wall Thickness = 25 mm

Length = 800 mm

Young's modulus = 200 GPa

Poisson's ratio = 0.3

Yield Strength (0.2%) = 300 MPa

Ultimate Tensile Strength = 430 MPa

Fracture Toughness = 50 MPa√m

Operating Pressure = 100 bar

### Exercise 1

Evaluate limiting flaw depth for an internal surface axial and internal surface circumferential flaw of  $a/c = 0.2$  and  $a/c = 1.0$  where  $a$  is flaw depth and  $2c$  is flaw length (i.e. four cases in total).

### Exercise 2

Assume now that the internal circumferential surface flaw lies in the centre of a circumferential butt weld (i.e. in the centre of the weld material).

The electrical heat input of the welding technique is 2.5 KJ/mm.

The material properties for the parent material are as in Exercise 1.

The material properties for the weld are as follows:

Young's modulus = 200 GPa

Poisson's ratio = 0.3

Yield Strength (0.2%) = 400 MPa

Ultimate Tensile Strength = 570 MPa

Fracture Toughness = 50 MPa $\sqrt{m}$

Evaluate limiting flaw depth for the internal circumferential surface flaw of  $a/c = 0.2$  assuming the weld to be (i) stress relieved, and, (ii) Non-stress relieved (i.e. two cases in total).

### Exercise 3

An internal circumferential surface flaw has been detected in the centre of the circumferential weld (assumed to be non-stress relieved). The maximum depth of the flaw is reported to be 4.5 mm and the length is reported to be 45 mm. The sizing error margin for the NDT technique used is considered to be  $\pm 1$  mm for the length measurement and  $\pm 2$  mm for the depth measurement.

The crack growth (Paris Law) relationship for the weld material is:

$$da / dN = 7.43 \times 10^{-9} (\Delta K)^{3.8}$$

where  $da / dN$  is in mm/cycle

and  $\Delta K$  is in MPa $\sqrt{m}$

The threshold value of range of stress intensity factor range,  $\Delta K_{TH}$  is 4 MPa $\sqrt{m}$ .

If the pressure vessel is cycled from a pressure of 0 to 100 bar approximately twice a day, evaluate its remaining life.

## 5 Results

The interpretation of the results can be found below. Details of the actual results can be found tabulated in Section 9, and in graphical form in Section 10. The graphs in Section 10 are frequency plots of the results. This section is separated into subsections that deal with the different areas of the project. These subsections range from the method used to derive the primary stress (axial and hoop stresses), the exercises and the issues arising from the face-to-face discussions.

## 5.1 Interpretation of Primary Stresses

### 5.1.1 Hoop Stress

A varied amount of complexity was seen in the way that the axial and hoop stresses were calculated. A simple histogram of the range of values can be seen in Figure 1. The exact values are contained in Table 1. It can be seen that the derived stress is concentrated around 100 MPa, with 100 MPa being the derived hoop stress from the simplest calculation (see Equation 1 below).

$$\sigma_h = Pr/t$$

**Equation 1 – Hoop Stress 1**

Where P is the pressure, r is the pipe radius and t is the wall thickness. Some of the values have been found by using the radius as the inner pipe radius (those at 95 MPa), others with the mean pipe radius (those at 100 MPa) and another with the outer pipe radius. Where the stress was 105 MPa the pipes outer radius was used, as this was considered to be the worst case scenario (i.e. it provided a higher primary stress).

Participant B derived a bending stress, to be present in all calculations, from the difference in the internal and external hoop stresses. In this case the general hoop stress was taken as the average from the internal to external (using Equation 2 below). The approximated bending stress (5 MPa) was therefore the difference of the average hoop stress to the maximum and minimum hoop stress.

$$\sigma_h = \frac{Pb^2(a^2 + r^2)}{r^2(a^2 - b^2)}$$

**Equation 2 – Hoop Stress 2**

Where P is the pressure, b is the inner radius, a is the outer radius and r is the radius that the stress is applied.

Equation 2 is of course the thick walled, and Equation 1 is the thin walled, cylinder hoop stress equation. Both of these equations correspond to those provided within Roark (Reference 4). Some guidance is provided for when to use them within Roark, which states that the thin walled solutions can be used if “*the walls are less than approximately one tenth of the principle axis of curvature*”. If the principle axis of curvature is taken from the mean pipe radius, the wall thickness is exactly one tenth the pipes radius, meaning both methods are equally valid.

Although the presented values of hoop stress are derived in a number of ways, the range of values is minimal and can be encompassed by  $\sigma_h = 100 \text{ MPa} \pm 5\%$ . The differences associated in the final limiting crack depth are generally not going to be significant for a variation of 5%, but might have more substantial effects when the defect size is small (for example Exercise 2b and 3).

Of all the methods of deriving the hoop stresses, the one that could potentially have the greatest effect on the method of assessing the limiting crack size is the one that approximates a bending stress from the difference in the internal and external hoop stresses. However, the results that include the bending stress are not seen to differ drastically from other results. This is because the bending stress used is negligible compared to the primary membrane stress.

### 5.1.2 Axial Stress

In the vast majority of cases, the axial stress was taken as half the hoop stress (thin walled axial stress solution). The values can be seen in Table 1. This meant that, in most cases, the axial stress was covered by the relation  $\sigma_l$  50 MPa  $\pm$ 5%. However, Participant B found the axial stress to be 45 MPa, derived from the thick wall solution within Roark (Reference 4), shown in Equation 3 below:

$$\sigma_l = \frac{Pb^2}{a^2 - b^2}$$

**Equation 3 – Axial Stress**

Again the variation seen in the axial stress has not affected the results significantly. As the hoop and axial stresses are related, the reason for the observed differences is the choice of the variables (i.e. the what radii was taken) and if the pipe is assumed to be thick or thin walled.

## 5.2 Exercise 1

Exercise 1 covered the cases where the limiting crack depth (a) had to be assessed for a possible circumferential crack and a possible axial crack, both with two assumed a/c ratios of 0.2 and 1.0. The results for these can be seen in Table 2 and graphically interpreted within Figure 2 and Figure 3. Figure 2 represents the axial crack with an a/c ratio of 0.2 and Figure 3, as the results are all above 20 mm, represents the remaining axial defect a/c ratio of 1.0 and both of the circumferential defects.

The results for the axial crack, with an a/c ratio of 0.2, are seen to have quite a large range; from a minimum value of 12 mm to a maximum value of 17.2 mm. Moreover, there would appear to be a grouping of the results that used CRACKWISE in their analysis. The results from CRACKWISE are seen to have a limiting crack depth of approximately 14 mm. Of those that did not use CRACKWISE, one was at approximately 17 mm and the other near 14 mm. This might be a result of the CRACKWISE software deriving the  $M_m$  and  $M_b$  components specifically. Of the cases where CRACKWISE was not used, it appears that the magnification factors found in M.4.3.3.1 of BS 7910 were used with no bending stresses present, or that the magnification factors from M.3.2.2.2 (membrane) and M.3.2.3 (for bending although not used) were used. The second of these is seen to agree with the CRACKWISE solutions. This would indicate that CRACKWISE is based on the magnification factors found in M.3.2.2.2 and not the cylinder specific solution in M.4.3.3.1. This would lead to the conclusion that there is an additional level of conservatism inherent to the curved plate solution in CRACKWISE compared to the geometry specific cylinder solution. It is possible that this added level of conservatism is a result of the bulging factor, M, where in Section M.4.3.3.1 for the cylinder specific solution, M is set to 1, but in Section M.4.2.1, M is governed by Equation M.21 for axial defects. Equation M.21 allows the bulging factor to exceed 1 and therefore increases the level of conservatism.

The effect of including bending within the solution has little effect on the limiting crack depth as some of the CRACKWISE solutions include bending and others do not, whereas all the CRACKWISE solutions are similar. This is because where bending is included, the magnitude of the bending stress is insignificant compared to the membrane stress.

It is not clear within most participants reporting at what position upon the crack the assessment is being performed (within all exercises). It is generally assumed that the surface and the deepest point of the crack are the two extreme situations which determine the limiting crack size. The exercises studied here show that the crack depth determines the limiting crack size. It may be recommended in the future, if a further Round-Robin comparison is considered, that an example where the surface point of the crack is the worst position to be used. This would

show if the participants are looking at different positions around the crack, not just the deepest point.

Increasing the  $a/c$  ratio to 1.0 increases the limiting crack length so that it is approaching the thickness of the pipe. The magnification factors provided within M.4.3.3.1 are seen to only apply up to an  $a/c$  ratio of 0.8 (where  $a/t$  is the crack depth over the pipe thickness). Although the magnification factors can be extrapolated beyond  $a/t = 0.8$ , this is strictly wrong unless there is a good well documented reason for doing this. Some analytical work may be performed to provide strength to the extrapolation justification. In the results, where the limiting crack depth is presented as  $>20$  mm, the magnification factors have not been extrapolated and the solution limited by  $a/t = 0.8$ . Some participants have shown the limiting crack depth as 25 mm, meaning that even a through wall crack would not be critical. The Crackwise software does not allow any extrapolation beyond  $a/t = 0.8$  and in cases where this limit is reached, warnings are displayed in order to inform the user.

All the limiting crack lengths are in agreement for an  $a/c$  ratio of 1.0, as they are all above 20 mm or stated as  $>20$  mm. It is worth noting that Participant D initially submitted the answers with an  $a/c$  ratio of 0.1. The affected results from Participant D were later re-submitted using the stated  $a/c$  value of 1.0. Although the calculations were correctly performed with an  $a/c$  ratio of 0.1, this still represents the issue of human error, where the Participant misinterpreted the values being used.

The results presented for both aspect ratios for the circumferential defect in Table 2 show that all the solutions are above 20 mm or reported as  $>20$  mm. This indicates that the question was solved in the same method by all participants, or that the difference in the methods is not observable as the limiting crack depth was outside the validity range defined by the magnification factors.

It is considered likely that the method used to derive the limiting crack depth by all participants is valid, but the questions do not allow any subtle differences to be noticed in the results. To investigate the possibility of differences in the methodology, it might be useful to present another exercise, designed to have a smaller limiting crack depth. This would be most beneficial if similar uncertainties are encountered in the results from Exercise 2 and Exercise 3 below.

Generally through Exercise 1, all participants appeared to obtain approximately the same answers. Where there are differences, this can be explained through the solution method chosen (in some of the hand calculated results) and that adopted within CRACKWISE. Possible reasons for this may be that the CRACKWISE calculations use a curved plate solution or that there is an influence from the inclusion of bulging factors when using a flat plate solution. It should be noted that Crackwise does allow the user the freedom to apply whichever solution they feel is most appropriate. It is evident that the hand calculated solutions have adopted the flaw specific cylinder solutions within Annex M of BS 7910. Adopting the flaw specific cylinder solutions might reduce some of the conservatism found in using a curved plate solution to model a pipe.

### **5.3 Exercise 2**

Exercise 2 was split into two sections. The first was to assess the limiting crack depth for a flaw within a butt weld (no specified geometry) after a stress relieving process (was generally assumed to be PWHT, but was not stated within the exercise) and the second was to assess the limiting crack depth when the pipe has not been stress relieved. The results from the different participants can be seen in Table 3, as well as in Figure 4 and Figure 5.

### 5.3.1 Stress Relieved

The limiting crack depth results for the stress relieved case appear to be localised around 18.5 to 20 mm, indicating that the method adopted by most participants was comparative. One result was seen to be substantially lower, at 15 mm.

Most participants used the residual stress component as 20% of the lower yield stress of the different materials (i.e. 60 MPa), but, the Participant who obtained a limiting crack length of 15 mm used a residual stress of 20% of the weld material (i.e. 80 MPa). The use of 20% of the weld material is unclear as the Participant quotes section 7.2.4.2 of BS 7910 as a reference, but section 7.2.4.2 clearly states that the lower yield stress should be used. This highlights a point that even though an appropriate section was found within BS 7910, the statement was incorrectly implemented, either through human error or BS 7910 not being easily interpreted.

Participant D provides two limiting crack depths, depending on what yield stress is used to determine the  $L_r$  parameter in the analysis. Advice is provided, by the Participant, to use the pipe yield stress under the circumstances that the answers are significantly different. Similar advice could not be found within BS 7910 for use in determining the  $L_r$  for specific crack geometry (note that some advice is provided for obtaining a material specific FAD).

How the residual stress is treated within the methodology of Participant C is unclear as a secondary stress of 300 MPa is quoted, but with a comment saying that it is in the “post weld heat treatment condition”. The comment (and the result) indicates that the residual stress has been taken as 20% of the lowest value, but this is not explicitly stated.

Generally most participants followed the same procedure and the results were found to correlate well. Where a result was found to be outside this correlation, it is considered to be a result of the residual stress value used.

### 5.3.2 Non-Stress Relieved

The limiting crack depths for the non-stressed relieved case show that the results from the participants range from 2 to 11 mm. Excluding Participant A (2 and 8 mm) and Participant G (11 mm) from the results narrows the limiting crack depth range from 3.8 to 6 mm. Both of these ranges show a large amount of variation.

The procedure followed is seen to vary between different participants. A list of the different procedures used can be found below:

- Section Q.3.2 (equation Q.4b) used to gain a residual stress profile.
  - Some then linearized the whole residual stress profile.
  - Some then linearized the profile to the crack tip.
  - Some then used the equation to provide a singular stress value at each crack tip which they then took as a membrane stress.
- Assumed a linear residual stress distribution (shown in Equation 4).
- A constant residual stress of the parent material.
- A constant residual stress of the weld material.

The results are separated into the ones that use the different methods, which can be seen in Table 4. The results show that when a method is used, the results are generally in agreement. The problem arises in determining what method is the most applicable to the situation.

Table 4 shows that assuming a residual stress distribution as shown in Equation 4 (which gives a linear relationship) may lead to a highly over-predicted estimate for the limiting crack depth, but assuming the worst case constant residual stress distribution may be too conservative. It is therefore likely that these methods should not be used. For Participant G, the assumed residual

stress distribution can be seen in Equation 4, where  $\sigma_R$  is the secondary stress,  $\sigma'_y$  is the minimum of the two yield stresses present,  $a$  is the crack depth and  $B$  is the wall thickness.

$$\sigma_R = \sigma'_y \left( \frac{a}{B} \right)$$

#### Equation 4 – Assumed Secondary Membrane Stress Distribution

It is not clear within the work presented from Participant G how Equation 4 was implemented within the analysis. However, it is clear that additional stresses have been included in the analysis from the difference in the stress-relieved and non-stress-relieved solutions.

Of the methods adopted, it is considered that the most suitable would be to predict a residual stress profile for the given weld, and if this is not available, use a constant residual stress distribution as detailed in section 7.3.4.2. It should be noted that this section does not provide guidance explicitly on what yield stress to use if more than one is present. However, guidance is provided earlier for a Level 1 assessment in Section 7.1.3, in that the material yield strength should be taken as either the lower yield or the 0.2% proof strength depending on the material type. This information should be reiterated in the sections relevant to a Level 2 assessment. In attempting to model the residual stress, Annex Q of BS 7910 is used to provide a residual stress distribution.

Table Q.1 (within BS 7910) shows the range of weld values that are covered in the residual stress profiles within Annex Q. The quoted electrical heat input of 2.5 KJ/mm in Exercise 2 is seen to be outside the values in Table Q.1. Therefore, some of the participants have not used a distribution from Annex Q and, as such, assumed that a constant residual stress (as described in 7.3.4.2) is present.

Disregarding Table Q.1, a weld specific solution for the residual stress profile can be found within Annex Q, which allows for a heat input of 2.5 KJ/mm (through the E/B ratio). Participant B performed two methods and Participant D performed three methods of modelling the residual stress in order to observe the sensitivity on the result. This could be done as part of this work in order to observe the effect but could potentially be a problem when having to make a decision on which to use when relating this to a real problem for a client. Therefore, where a profile was used to model the residual stress distribution, Equation Q.4b was used.

The interpretation of the residual stress profile provided by equation Q.4b is also seen to change between participants. Three methods were adopted, firstly to linearize the entire residual stress through the thickness, secondly to linearize the stress to the crack tip and thirdly to take the membrane stress directly from the crack depth without linearizing. The first two methods produce an additional membrane term as well as a bending term (which is not present in the cases where a constant residual stress is assumed). The third method just produces a membrane term and also shows signs of possible non-conservatism through the results (as bending has not been included).

The methods adopted to find the limiting crack depth for a non-stress relieved pipe are seen to be varied. They highlight a lack of clarity and guidance within the procedures. Examples of some extra necessary guidance that have arisen in the Exercise 2b are:

- Should Equation Q.4b be used despite Table Q.1?
- Should the yield stress used as a uniform residual stress (Section 7.3.4.2 of BS 7910) be the weld or parent materials? Guidance is provided for a Level 1 assessment but this information needs to be reiterated in the relevant sections for a Level 2 assessment.

The question has also highlighted some areas that might result in some non-conservatism, such as:

- Linearizing the residual stress through the method shown in Figure 1 of Reference 3.
- Linearizing the residual stress over the material thickness, not the crack length.
- Assuming a residual stress profile.

It is recommended that the comments bulleted above be addressed, and possibly another Round-Robin exercise to test how any changes are implemented.

## 5.4 Exercise 3

Exercise 3 investigates the remaining lifetime on a component containing a detected crack, with a known error on the measured dimensions present. A crack growth law is provided given that the internal pressure build up occurs twice a day. The results can be seen in Table 5 and Figure 6.

All Participants used the worst case sizing for the crack, with a postulated crack depth of 6.5 mm. All but three participants therefore state that, either through repeating the calculation or because Exercise 2b has a limiting crack depth below 6.5 mm, there is no remaining life. Of the three that have predicted some remaining life, both Participant A and Participant G had previously predicted a limiting crack depth of 8 mm and 11 mm respectively. The result from Participant D also shows remaining life, which initially appears to contradict their answer to Exercise 2b. This is consistent with their previous answer because the deepest and shallowest points of the crack are grown at different rates, thus changing the  $a/c$  ratio. As the crack grows deeper faster than it grows wider, the crack can reach a larger depth before becoming critical, whereas in Exercise 2b the  $a/c$  ratio was held constant.

Participant A, within their analysis, re-calculates a limiting crack depth of about 9 mm for the same structure, but advises that, given the previous result in Exercise 2b, the crack is re-measured at 57000 cycles (which corresponds to the previous limiting crack depth of 8 mm). Assuming that the method used is applicable (which is discussed in Section 4.3), the re-measurement guideline should be questioned as the crack could quite feasibly become critical around 8 mm (given the previous results) and the crack growth could be underestimated, both meaning that the crack could become critical before the next inspection. Any inspection procedure should have an inherent safety margin, so that a crack can be re-observed to gain a better understanding of the growth rate within further ECA.

Participant G was seen to have the highest predicted lifetime for the defect, but this is not surprising given that the limiting crack depth to exercise 2 – non-stress-relieved, was also the highest. The results from Participant G must be questioned as the limiting crack depth for the growing crack is seen to be 13.9 mm, but the solution to the previous exercise was 11 mm. However, Participant G states that proprietary software based on BS 7910:2005 was used on all but exercise 3, where software based on BS PD 6493:1991 was used; which might explain the differences. A consequence of this that should be highlighted is the likelihood of errors arising from using possibly out-of-date software or guidelines. No guidance was provided by Participant G as to continued inspection or inspection frequency (most likely as remaining life predicted by Participant G was approximately infinite).

A slight difference in procedure was observed in the level of complexity used to calculate the crack growth with some of the other possible crack dimensions. In these cases, some participants held the  $a/c$  ratio as a constant whilst changing the crack depth over time whilst other people changed the crack depth and crack length independently, thus continually changing the  $a/c$  ratio. The difference in remaining lifetime was not large between the two methods, but this might significantly alter the remaining lifetime within different scenarios.

Participant C performs a short investigation into the effects of changing the crack depth on the remaining lifetime. Within this investigation, they appear to have misread the data and assume

that the pipe reaches its pressure twice a year, not twice a day! This obviously has a significant effect on the number of years some of the other crack depths can survive. The effects of misreading the cycle time could have significant effects if the crack was not already critical.

Generally, the participants predict that there is no remaining life in the pipe. One of the predictions of remaining life is human error, either in interpretation or reporting, despite the results showing zero life. Where some remaining life is shown, the limiting crack depth may not be correct, and the re-inspection plan of the crack does not take possible errors and crack growth accelerations into account.

## **5.5 Face to Face Discussions**

Following the submission of the benchmark exercises, individual discussions were held with all seven of the organisations that participated in the round-robin exercise. A selection of questions was asked and specific subject areas discussed in order to further investigate the interpretation and application of the assessment methodologies/procedures employed by each of the participants. The notes taken from each of the individual discussions are tabulated in Appendix 1, Table A1. The comments presented are those of the particular individual(s) participating in this exercise and consequently do not necessarily reflect the views of the organisation as a whole.

The following sections provide an overview of the main elements of these discussions.

### **5.5.1 Organisation Details**

The participating organisations ranged in size from individual consultants contracted to larger companies, to large industry specific organisations with a few hundred members of staff. Of the number of staff overall within any one organisation, generally only 10-20 employees are directly involved in the field of structural integrity. Two companies had 70-80 employees directly involved. From these numbers of employees, there were generally less than 3 ECA experts amongst 5 or 6 regular practitioners.

All of the participants have similar roles, in that they provide engineering services and advice to clients, primarily within their organisation or industry sector, but occasionally to outside clients. The frequency of ECA work ranged from being carried out on a daily basis, and it being the main area of activity, to being carried out very infrequently.

### **5.5.2 Training and Experience**

The general level of experience was considered to be an engineering degree qualification (or similar), and some of the organisations have a number of members of staff who have Masters and/or PhD qualifications. The main avenue for training staff and increasing their level of competency was from on-the-job training, and where possible, with assistance from experts. The amount of on-the-job training provided is heavily dependent on the frequency of this kind of work being undertaken by the organisation. In general, staff from all of the participating organisations would attend related training courses (mainly Sheffield Fracture Training, TWI BS7910 and Crackwise) at some stage.

Some of the organisations had some personal/company involvement in the working groups/networks, which have been formed in this subject area (i.e. BS WEE/37 Committee, FIT-NET European Network).

In relation to experience and competency levels required in order to carry out ECA's, it was evident that due to the lack of any formal guidance on this, it was an organisational decision to ensure that the person undertaking the work was suitably qualified and experienced.

One of the organisations mentioned that there were a large number of HNC/HND level employees within their particular industry sector. Concerns were raised that their level of knowledge and understanding of the subject may not be sufficient enough to perform an ECA to the required standard without additional training.

### 5.5.3 Assessment Methods/Codes Used

The British Standard Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures, BS 7910:2005 was used by all participating organisations. The TWI CRACKWISE Version 4 software package was used by more than half of the participants. This software is an automation of the BS7910 assessment procedure. On occasions API 579, Recommended Practice for Fitness-For-Service and Continued Operation of Equipment, was used for particular areas and situations such as stress intensity factor solutions, reference stress solutions, residual stress profiles, mixed mode loading, volumetric defects in welds. It was suggested that only experienced personnel should go out-with BS7910 where required as they will be able to fully justify the reasons why.

Some of the participants had formulated their own methods within MATHCAD and EXCEL software packages, originally based upon the content of PD6493 (the predecessor to BS7910) and have evolved to include updates in line with BS7910. These independent formulations tended to be verified with CRACKWISE.

One of the participating organisations tend to use the R6 Procedure for the 'Assessment of the Integrity of Structures Containing Defects, Revision 4' for a large amount of the plant specific assessments which they undertake on a regular basis.

Version and copy control of BS7910 was generally the responsibility of the technical individual/team who are actively using the standard. Three of the companies had a well-established library system, which was responsible for the control of BS7910. Concerns were raised that if this type of work was being carried out in-frequently then there may be the potential for updates to be overlooked. Out of date versions that were used the last time this type of work was carried out may be returned to and used. It should be noted though that in some cases there may be legitimate requirements to use an old version.

In most of the organisations that participated, a Level 2A assessment was carried out as a minimum when undertaking ECA's. Some of the participants had never conducted a Level 1 assessment and suggested that Level 1 should be removed. Others felt that it was beneficial to be able to refer to it if only minimum data were available. There was a comment made that the Level 1 assessment and a Level 2 assessment were developed differently and that there was an inconsistency between the two, which may be confusing to the practitioner.

Finite element analysis and the BEASY boundary integral method software have been used by some but not all of the participating organisations. Finite element analysis has been used extensively by one or two of the participants in order to calculate residual stress profiles, stress intensity factors and reference stress for complex geometries. Such analyses have sometimes been used to evaluate elastic-plastic J as an alternative to using an ECA procedure like BS7910.

All work involved in carrying out an ECA will go through a formal checking/approval system, which is employed as standard by each of the participating organisations. Self-checking will be carried out by the person performing the ECA and in some cases sensitivity of input parameters may be observed. It was not usual for all organisations to carry out independent calculations

but the assessment is checked and approved before being delivered to the client. One of the organisations does carry out independent calculations in order to fully verify the results when undertaking this type of work for a specific client.

The assessment methods/codes detailed above and used by the participating organisations in this exercise are generally applied to work in the areas of fracture and fatigue. One organisation carries out work based on high temperature creep and fatigue crack growth. SCC and corrosion fatigue work is also considered on occasions. Specific parts of the assessment document may be referred to for advice, rather than carrying out a full assessment involving these aspects.

Most of the work being undertaken by each of the organisations is of a deterministic nature, with only one or two being involved in probabilistic studies. Where probabilistic work is being carried out it is normally related to research and development programmes.

#### **5.5.4 Links with NDE**

This aspect of an assessment was varied in that some organisations have a close link with NDE personnel and others do not. In one case all NDE inspection targets are derived from ECA assessments. It was common for inspection information to be supplied to the structural analysts in order to perform an assessment and occasionally some sensitivity analyses. It was agreed by all of the participating organisations that better guidance should be incorporated into the BS7910 on NDE aspects. The extent to which work is carried out in an iterative manner with the customer seemed to vary depending on the problem. Most of the organisations would generally have close communication throughout the work.

#### **5.5.5 Materials**

Obtaining tensile and fracture toughness material properties data can sometimes be the most difficult aspect of conducting an ECA. Depending on the industry, and also the material in question, there can be well-characterised material properties available, knowledge of previous similar materials may be drawn upon or, if material is available, then properties can be measured in-house in some companies.

Fracture toughness data are seldom available and some organisations have to depend on Charpy data, although some do not use Charpy data at all. As noted above, some organisations do have testing facilities to enable them to evaluate such material properties themselves. It was very industry specific as to whether it was general practice for Charpy data to be available/used and as to whether fracture toughness data were readily available.

The derivation of properties for sub-critical crack growth (e.g. fatigue, SCC, corrosion-fatigue etc.) are not often available and the guidance within BS7910 would generally be followed. Depending on the industry sector, weld mis-match and dissimilar metal welds are either never considered (i.e. lowest properties assumed), previous knowledge is relied upon, or evaluation of the properties will be carried out. Where mis-match is considered, finite element analysis is normally undertaken and in some cases the mis-match limit load solutions in R6 are applied.

#### **5.5.6 Stresses**

More informative guidance is required in relation to stress classification. Currently most organisations will follow the guidance within BS7910 or apply engineering judgement. Residual stress formulations ranged from using the membrane yield or distributed profiles recommended within BS7910 to using own justified methods. Best estimate values developed by some organisations by carrying out detailed or more simplistic finite element analysis.

Most participants used the simplest form for the derivation of the additive term  $\rho$ , in the calculation of the stress intensity factor for a residual stress field. Only one of the organisations used the  $\psi$  and  $\phi$  tables as standard in performing an assessment, although in the case of the benchmark exercise they did not. The use of the simplest form of  $\rho$  is conservative for the majority of situations. However, it can lead to non-conservatism when elastic follow-up is a possibility. In this situation, and when the secondary stress is much larger than the primary stress, or when the primary stress is not present, it is best to use the  $\psi$  and  $\phi$  tables to obtain  $\rho$ . The level of conservatism when using the  $\psi$  and  $\phi$  tables is reduced compared to the simple method, but is still larger than if explicit FE modelling was performed for the structure.

Given that there are circumstances where the simple method should not be used, where the more complex method of using the  $\psi$  and  $\phi$  tables is the suggested method, it is perhaps surprising that the simple method is generally used by most of the participants. This is likely to be a result of the added complexity of using the  $\psi$  and  $\phi$  tables, and that the method does not lend itself easily to repetitive calculations. It would therefore be beneficial to find a simple way of calculating  $\rho$  that is equivalent to that obtained from the  $\psi$  and  $\phi$  tables. It may be noted that there is development work in hand aimed at simplifying procedures for dealing with combined primary and secondary stresses in ECA calculations. It is intended that this will eventually lead to a major revision of annex R of BS7910.

Generally the stresses are evaluated by classical means but sometimes finite element analysis or boundary integral method are employed in order to evaluate these if assessment involves particularly complex geometries.

#### **5.5.7 Flaw and Geometry**

Information on geometries of structures being assessed is generally well characterised and carefully controlled. Information is generally readily available from the client. The most conservative assumptions were generally applied with respect to the tolerances of a component.

For one particular organisation, aspects such as corrosion tolerances and misalignment information were frequently taken into consideration in an assessment.

There were no major issues with BS7910 in relation to the characterisation of multiple flaws, but it was agreed that better guidance would be beneficial. Two of the organisations have been involved in research and development activities related to the characterisation of multiple flaws.

All participating organisations consider error margins in an assessment when dealing with NDE results.

#### **5.5.8 Assessment Methodology**

The extent to which higher level analyses are used by the participating organisations varied from never being used to all aspects of higher level analyses being considered.

Cases where higher-level analyses have been carried out included leak-before-break, constraint, J-estimation evaluations and strain/displacement-based methodologies. It should be noted that some industries would rather replace a flawed component rather than invest in undertaking any higher-level analysis.

Finite element analysis and the boundary integral method (using BEASY software package) are employed by most of the organisations in order to calculate stress intensity factor and limit load solutions for complex geometries.

Normally, as standard, plate or cylinder solutions from BS7910 are used although, as highlighted by some of the organisations, this is an area where more informative guidance is required. The sequencing of fatigue cycles was another area where it was agreed more informative guidance was required within BS7910. Normally some kind of sensitivity analysis should be performed in order to observe the worst-case sequencing.

Mixed mode loading had only been considered in limited cases where advice had been taken from out with BS7910, or detailed finite element analysis calculations were undertaken.

### **5.5.9 Assessment Output**

It was evident from the discussions that safety margins are rarely considered in an assessment but, depending on the particular application and client, there may be the need to consider them. There was one organisation where a safety factor of 20% would generally be added to the values of stress. Others will ensure that the worst-case estimates of input parameters are considered in the assessment.

Generally sensitivity studies are carried out, to some extent, within an assessment and tend to follow the guidance of the assessment document being used. Only one of the participating organisations did not generally have the requirement to undertake any sensitivity studies in their line of work. In this case, conservative input data were considered and factors were applied later by the client for the required applications.

The layout and detail incorporated into the submitted reports of the benchmark exercise has been of a high standard in the benchmark and has followed the normal output format of work done for external customers. In no way did any of the participants treat this exercise differently from that of a piece of work specifically for a client, in respect to the level of detail of the work undertaken and the deliverable.

Normally providing some level of guidance on future inspection strategies is part of the scope of the work for most of the organisations that participated. In some of the industries, due to economic reasons there tends to be a requirement to repair rather than carry out any further inspection after a relatively short period of time. Here work required is more from a materials qualification perspective.

On occasions the inspection data are used as the input in fatigue crack growth calculations. Some of the work is primarily aimed at removing the need to undertake any in service inspection.

### **5.5.10 General Issues**

Issues raised regarding areas of BS7910 where more informative guidance was felt to be required were:

- The treatment of volumetric defects (e.g. pores, etc.)
- The sequencing of fatigue cycles
- How to deal with mixed mode loading
- The use of local and global reference stress solutions
- K and reference stress solutions for embedded defects
- NDE guidance
- Multi-material components
- More simplified use of  $\rho$  factor (or alternative approach)
- Residual stress profiles

An additional issue raised was of re-familiarisation problems for in-frequent users of the standards/procedures used in carrying out an ECA. As most of the organisations depend quite heavily on on-the-job training as their main avenue for increasing competencies in this area of work, it was raised as a concern that if an organisation was not carrying out this type of assessment on a regular basis, a practitioner could potentially overlook some important issues which he/she may not have been made aware of since the last time they were involved in using the standard/procedure in an assessment. This would affect the level of competency of the practitioner and it is important that this issue is addressed.

It is recommended that some further advice is provided within BS7910, to help when deciding to:

- Use some of the solutions within Annex Q (namely Q.4.b), despite the values provided within Table Q.1 for the Annex.
- Use either the parent or weld material yield stress for both calculating  $L_r$  and for use as the secondary membrane stress in a non-stress-relieved weld.

Practitioners should be encouraged, within submitted reports, to provide full justification and reasoning behind any assumptions they have made, which fall outside the guidance in BS7910.

### 5.5.11 Suggested Improvements

It was suggested by many of the participating organisations that the layout of BS7910 tended to be somewhat cumbersome. Those who were familiar with FITNET commented that it was much more user friendly. An improvement to BS7910 would be to make the layout more like that of FITNET and the participants generally welcomed the views that the Wee/37 committee was seriously considering incorporating the relevant state-of-the-art developments from FITNET.

The stress intensity factor and reference stress solutions within BS7910 should be more prescriptive, or more defined guidance should be provided, rather than providing options for the user to choose between a cylinder and a curved plate solution.

Although there were areas where improvement, by means of better guidance, was required within BS7910, there were concerns raised over making the standard too simplified. This may encourage less experienced/knowledgeable practitioners to just follow the assessment process within BS7910 to produce an answer without fully understanding what is being done throughout the assessment process. In no way should good engineering practice be prohibited, as in some particular cases, it may be beneficial to perform some kind of higher level assessment.

A further suggestion was to provide some detailed guidance on the background and theory involved in the derivation of some of the information provided (e.g. residual stress profiles) within BS7910.

## 6 Conclusions

Through obtaining the results and reviewing the procedures used within the reports for the Round-Robin exercises, a series of conclusions can be drawn into how ECA's are performed within industry. These are as follows:

A large percentage of Participants used the crack evaluation software CRACKWISE to perform the calculations. In general the CRACKWISE solutions are similar to those performed by hand (i.e. within a spreadsheet) or on similar self developed software. The answers to Exercise 1, axial crack with an  $a/c$  ratio of 0.2, show that there might be a difference between the CRACKWISE solutions and some of those performed by hand. This is believed to be a result of

the magnification factors used, where those used in the hand calculations were found from the axial defect, geometry specific cylinder solutions in BS7910:2005 section M.4.3.3.1 and those used in CRACWISE are for a curved plate.

Human error was apparent in a number of cases, some of which would have major influences on the evaluated limiting crack size. Some of the human error was apparent in either interpreting or implementing BS7910, which might indicate that BS7910 can be hard to use.

Where multiple materials are present (i.e. weld), advice is given within BS7910 Section 7.1.3 that the tensile properties of the lower of the parent, weld metal or HAZ should be used in calculating  $L_r$ . This is for a Level 1 assessment. For a Level 2 assessment this is not stated explicitly and reference back to Section 7.1.3 should be made. This also goes for advice on yield strength in relation to residual stresses.

A large number of methods have been used to evaluate a non-stress-relieved weld. Amongst these assuming a residual stress profile is possibly the most non-conservative. Two other main types of method are used for the non-stress-relieved case, (a) to use a stress profile (Equation Q.4.b of BS7910) or (b) to use a constant yield stress of either the weld or parent material.

The validity of using a stress profile for a given heat input and weld type within Example 2 is unclear as the heat input contradicts with what is said to be valid for all the contents of Annex Q. Two Participants provided more than one solution in order to observe the sensitivity of the different residual stress profiles on the result obtained.

The interpretation of the stress profile provided by equation Q.4b is also seen to change between participants. Three methods were adopted, firstly to linearize the entire stress through the thickness, secondly to linearize the stress to the crack tip and thirdly to take the membrane stress directly from the crack depth without linearizing. Linearizing the entire stress through the whole thickness, as in Figure 1 of BS7910 produces a conservative result, whereas only linearizing the stress to the crack tip gives a slightly more conservative result. Taking the membrane stress at discrete points from the crack depth without linearizing gives a non-conservative result.

The results from linearizing the stress over the crack length and at discrete points show signs of over-conservatism compared to taking the stress over the entire thickness

Where a constant yield stress is used for the secondary membrane term, there is no guidance as to use the parent or weld yield stress in carrying out a Level 2 assessment. Guidance is provided in carrying out a Level 1 assessment and this needs to be reiterated in the relevant Sections of BS7910. Changing between the two is observed to have a large effect on the limiting crack depth.

Where a remaining lifetime is found within Exercise 3, either no advice for continued inspection is provided, or it is flawed.

Some solutions to Exercise 3 contradict similar solutions found earlier by the Participants.

In general, this work highlighted that while simple problems assessed by ECAs gave similar results, any additional complexity resulted in a variety of answers.

If the calculations had been for real cases, the inaccuracies in the calculations would have resulted in the following safety concerns:

- In practice, the NDT technique, the NDT acceptance criteria and the margin to the unsafe condition would all be based upon the limiting crack size evaluation. If the inaccurate calculation provided a larger (non-conservative) limiting crack size than the correct calculation, then the vessel could have been deemed as 'fit for service' when the actual

margin for safe continued operation was reduced, with the potential to operate the vessel in an unsafe condition.

- In the case of the calculations on remaining fatigue life, three organisations specified a remaining fatigue life, when in fact the remaining correctly calculated fatigue life was zero. If this had been a real situation, then allowing further fatigue usage would have been extremely dangerous, leading to the potential catastrophic failure of the vessel.

With ECAs increasingly being used in Risk Based Inspection and for plant life extension, the HSE and industry should have considerable concerns regarding the accuracy of the ECAs submitted to them.

## 7 Recommendations

It would be beneficial if a further Round-Robin exercise could be undertaken, so that the sections below can be incorporated:

- The critical location around the crack should not always be the deepest point.
  - To investigate if this is being taken into account by all participants.
- A question similar to Exercise 1 with limiting crack depths below the a/t ratio of 0.8.
- Another remaining lifetime question that has a remaining lifetime of approximately 6-10 years so that the repeated inspection schedule can be discussed.
- Another non-stress-relieved weld question to investigate how any changes are implemented and interpreted.
- Generally open this exercise out to several industry sectors in order to establish how different industries deal with structural integrity issues in general and ECA evaluations in particular.

## 8 References

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2. Hobbs J W, Sharples J K, Wilkes M A and Hayes J P, Comparison of Fracture Mechanics Methods – Phase II Summary Report, MM/04/09, March 2004.
3. British Standard – Guide to methods for assessing the acceptability of flaws in metallic structures, BS7910:2005
4. Roark's Formulas for Stress and Strain, Seventh Edition, W. Young and R. Budynas, Mc Graw Hill, 2002.

## 9 Tables

**Table 1 – Derived Hoop and Axial Stresses**

Participant	Hoop Stress (MPa)	Axial Stress (MPa)
A	105	52.5
B	95 <sup>1</sup>	45 <sup>2</sup>
C	100	50
D	95	47.5
E	100	50
F	100	50
G	105	52.5

1 - Derived from Equation 2 and also incorporates a 5 MPa bending stress.

2 - Derived from Equation 3.

**Table 2 – Participants Limiting Crack Depth (mm) Solutions to Exercise 1**

Flaw Orientation	Axial (mm)		Circumferential (mm)		
	Participant	a/c = 0.2	a/c = 1.0	a/c = 0.2	a/c = 1.0
A	A	13.8	22.6	23	24
B	B	14.4	22.9	23.6	24.8
C	C	14.3	>20 <sup>4</sup>	>20 <sup>4</sup>	>20 <sup>4</sup>
D1	D1	12 <sup>3</sup> / 14.6	>20 <sup>2,4</sup>	>20 <sup>4</sup>	>20 <sup>2,4</sup>
E	E	17.2	>20 <sup>4</sup>	>20 <sup>4</sup>	>20 <sup>4</sup>
F	F	14	22	25 <sup>5</sup>	25 <sup>5</sup>
G	G	13.8	23.3	24.6	25 <sup>5</sup>

1 - Note that in some cases, two solutions were presented for different solution methods

2 - The initial a/c ratio used was 0.1, but was corrected after submission of the report.

3 - The size quoted is at the limit of the permitted geometry, but remains within the FAD.

4 - Note that where >20 is shown, no more definite answer is provided as 20 mm represents the upper limit a/t for the solutions shown within BS 7910.

5 - The critical flaw depth is limited by the wall thickness.

**Table 3 – Participants Limiting Crack Depth (mm) Solution to Exercise 2**

Participant	Stress Relieved (mm)	Non-Stress Relieved (mm)
A	15	2 / 8
B	19.4	4.57 / 4.95 <sup>3</sup>
C	18.9	4.5
D	19.2 <sup>1</sup> / 19.5 <sup>2</sup>	4.1 <sup>1</sup> / 4.2 <sup>2</sup> / 6 <sup>3</sup>
E	19	4.1
F	25 <sup>4</sup>	5.4
G	18.1	11

- 1 – The value for  $L_r$  was determined from the parent material tensile data.
- 2 – The value for  $L_r$  was determined from the weld material tensile data.
- 3 – The limiting crack depth was determined from equation Q.4b.
- 4 – The critical flaw depth is limited by the wall thickness.

**Table 4 – Participants Solutions to Exercise 2b with Method Employed**

Method used	Participant	Non-Stress Relieved (mm)
Residual stress constant at weld yield stress.	A	2
A residual stress distribution assumed	G	11 <sup>1</sup>
Residual stress constant at parent (lower) yield stress.	B	4.57
	C	4.5
	D	4.1 <sup>2</sup> / 4.2 <sup>3</sup>
	F	5.4
Equation Q.4b used. Linearized whole residual stress profile.	B	4.95
	D	6
Equation Q.4b used at specific points to gain a single value used as a membrane stress <sup>4</sup> .	A	8 <sup>5</sup>
Equation Q.4b used. Linearized residual stress profile to the crack tip.	E	4.1

- 1 – Residual stress profile for  $\sigma_R = \sigma_{Y(\text{Min})} * (a/B)$ .
- 2 –  $L_r$  was determined from the parent material tensile data.
- 3 –  $L_r$  was determined from the weld material tensile data.
- 4 – Secondary Membrane stress found at surface and at the deepest point;  $z = a$ .
- 5 – Limiting crack depth governed by crack interaction at the surface.

**Table 5 – Participants Limiting Crack Depth (mm) Solutions to Exercise 3**

<b>Participant</b>	<b>Remaining Cycles</b>
A	87000
B	0
C	0
D	51100
E	0
F	0
G	180658



## Figures

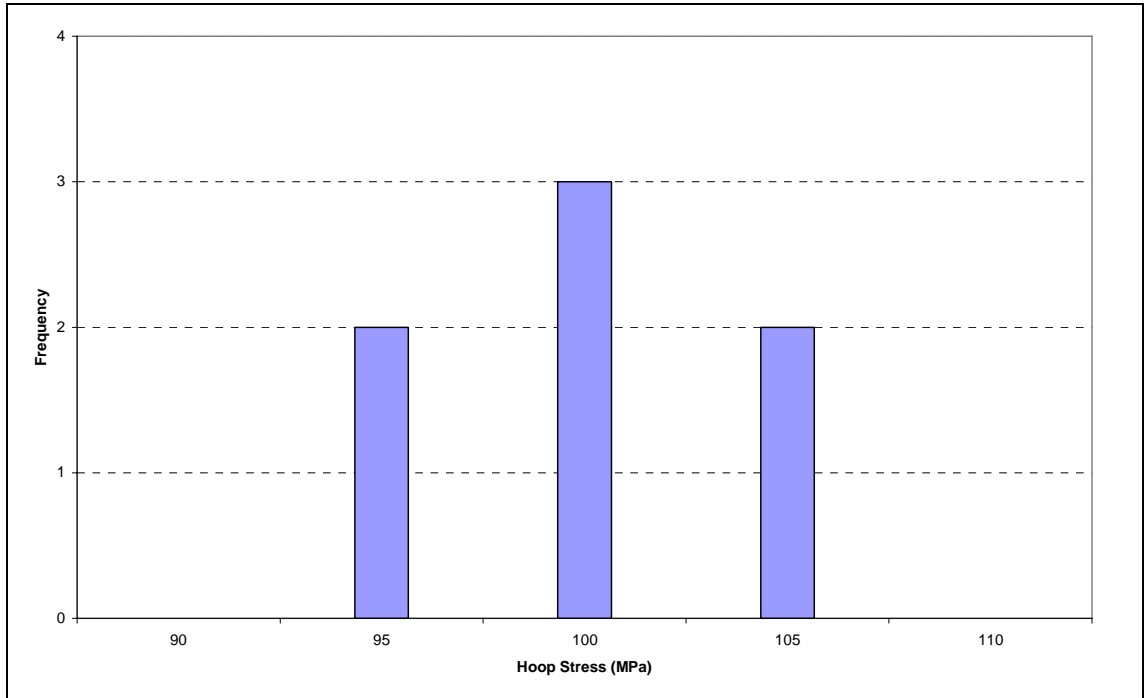


Figure 1 – Histogram of Derived Hoop Stresses

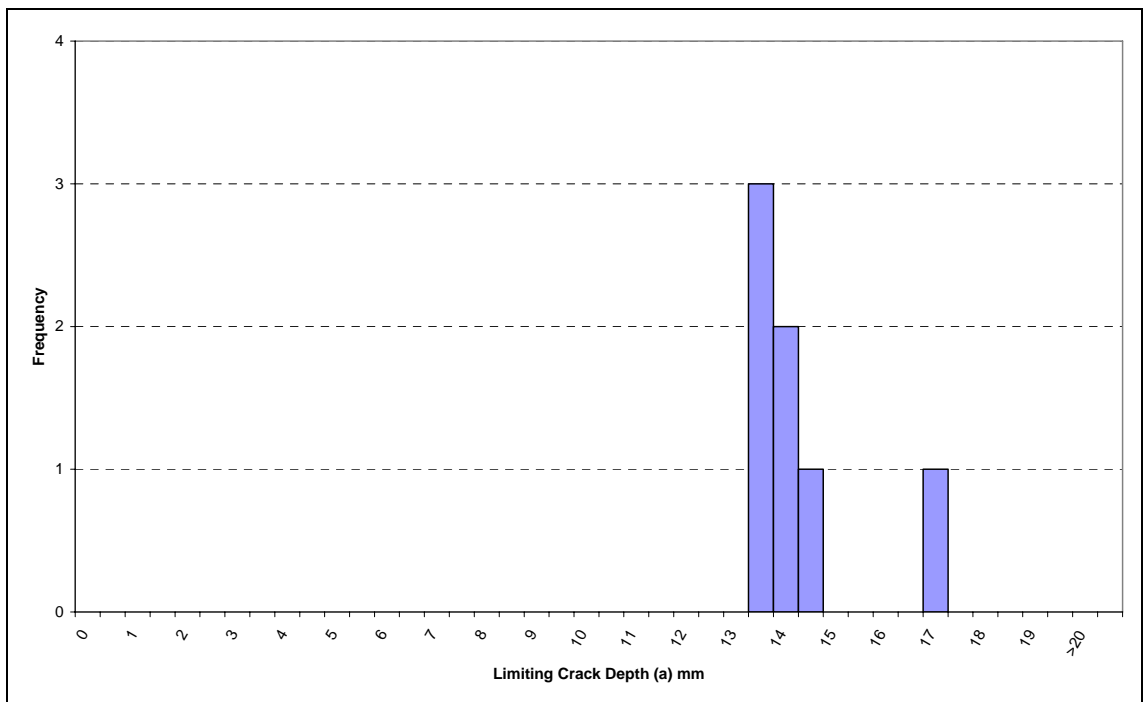
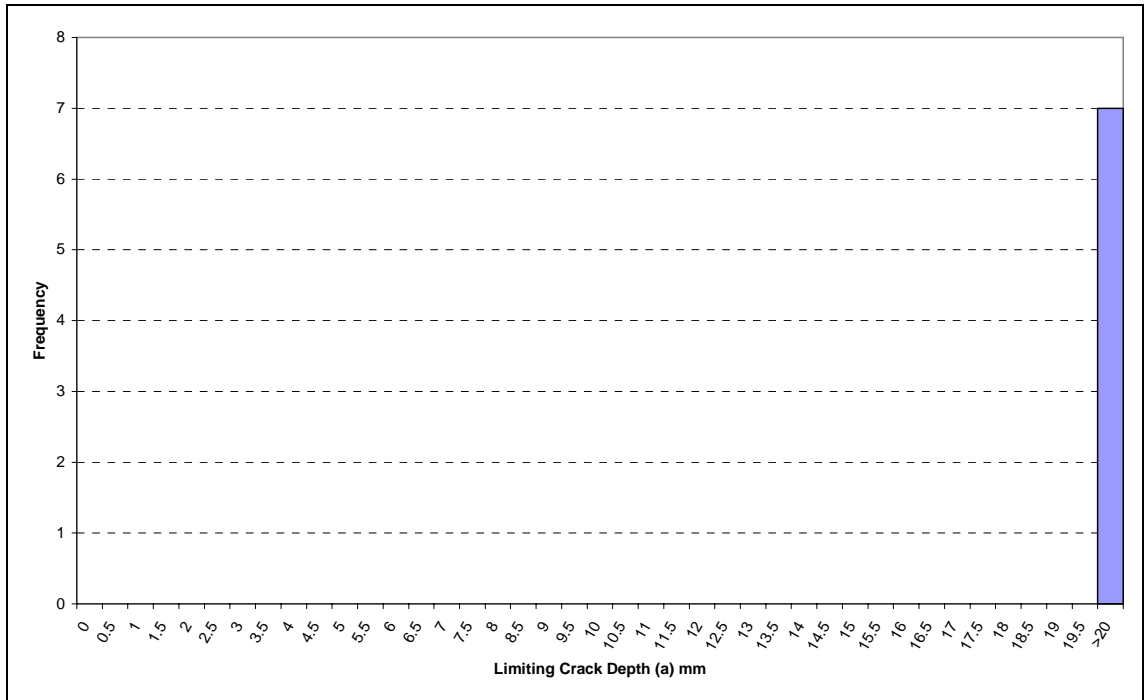
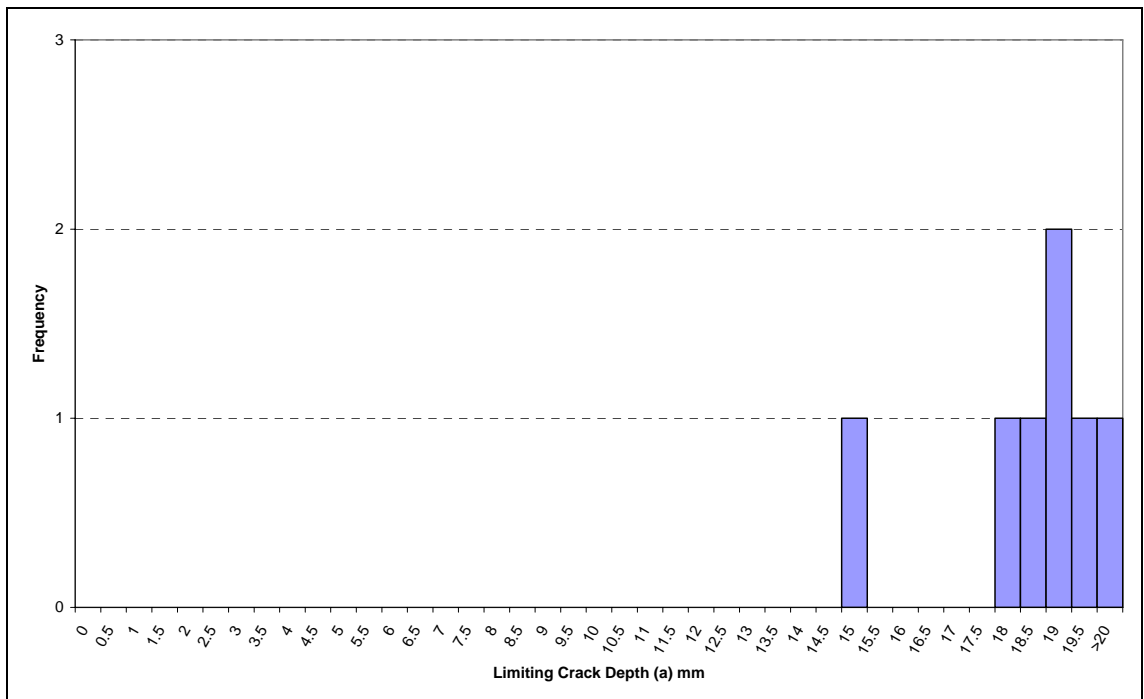


Figure 2 – Histogram of Exercise 1 – Axial Flaw with  $a/c = 0.2$



**Figure 3 – Histogram of Exercise 1 – Axial Flaw with  $a/c = 1.0$  – Circumferential Flaw with  $a/c = 0.2$  – Circumferential Flaw with  $a/c = 1.0$ .**



**Figure 4 – Histogram of Exercise 2 – Stress-Relieved**

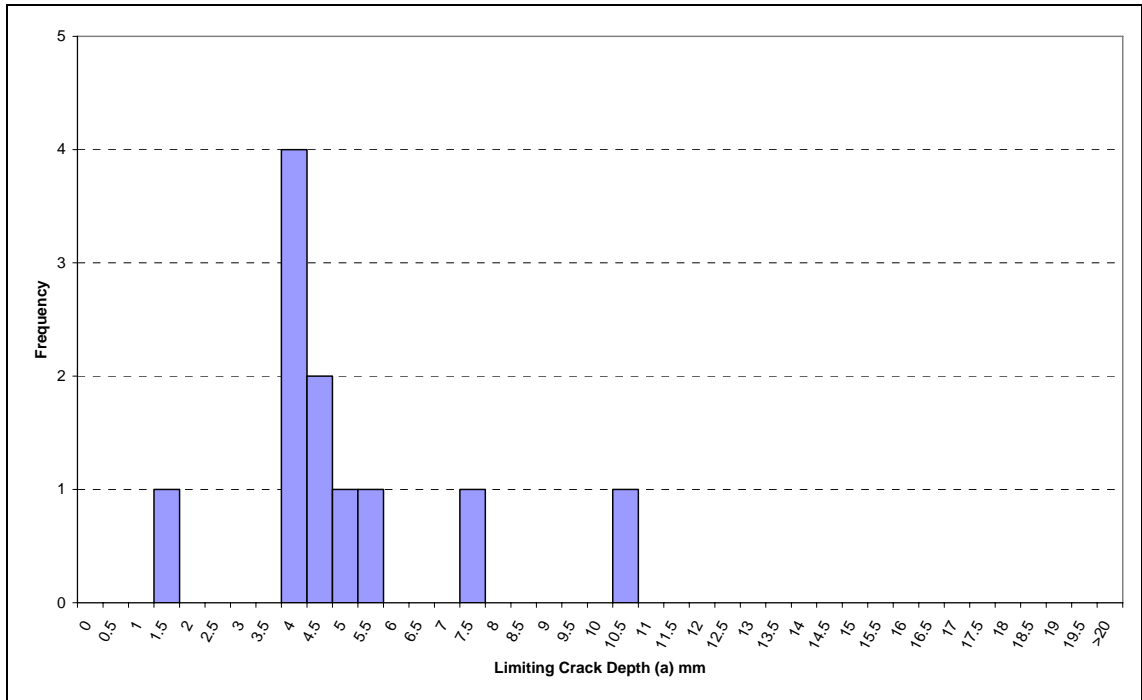


Figure 5 – Histogram of Exercise 2 – Non-Stress-Relieved

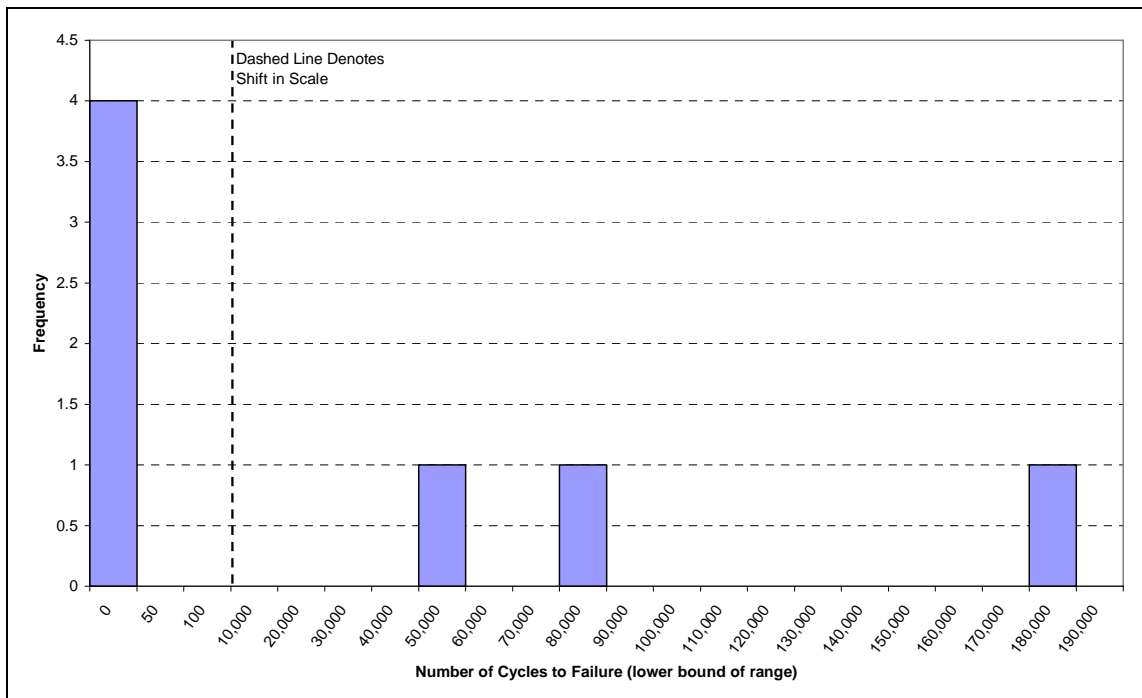


Figure 6 – Histogram of Exercise 3 – Remaining Lifetimes



# Appendices



## Contents

Appendix 1

Notes from Individual Discussions with Participating Organisations



# Appendix 1

## Notes from Individual Discussions with Participating Organisations



### Contents

Table A1	Notes from Individual Discussions with Participating Organisations
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This Appendix contains the responses of each participant to the Issues and Sub-Issues addressed in the Face to Face discussions.

## General

### **Size, type, role and sector of organisation and the number of people working in the structural integrity field.**

Organisations ranged in size from individual consultants contracted to larger companies, to large industry specific organisations with a few hundred members of staff. Of the number of staff overall within any one organisation, generally only 10-20 employees are directly involved in the field of structural integrity. Two companies had 70-80 employees directly involved. From these numbers of employees, there were generally less than 3 ECA experts amongst 5 or 6 regular practitioners.

### **Frequency of ECA work.**

Low frequency of this type of work carried out (10% or less of time).

Day-to-day business.

Daily. This is main area of activity.

4 to 6 jobs per year of varying complexity.

People involved frequently carry out this type of work, either within research projects or for 'safety cases'.

Very frequently for 1 person, virtually continuous work. Other people use parts of ECA procedures from time to time. Responsible for installing up to six pipelines/year, most of which require an ECA. Also provide this service within the company to worldwide location on an as-requested basis.

2 to 3 times a year.

### **Level of experience considered appropriate to undertake ECS work. Would this be different if it were a real job for a customer rather than a round robin exercise?**

All graduates + some masters and/or PhD's. Trained on-the-job, consulting with experts and associated BS7910 training. Line management decision on who has ability to undertake such work.

Degree or higher qualification, attending training courses (e.g Sheffield) and on-the-job training. Department decides who is fully competent.

High level of graduates, many of which have higher degrees. Mix of training (e.g. Sheffield FM course) and on-the-job experience.

Minimum requirement would be a Degree in Mechanical Engineering (or similar). This particular industry employs a lot of HNC/HND level staff. Concern raised regarding inexperienced people carrying out ECAs without any supervision due to the lack of expertise in this area.

More formal training is required in this area by the companies responsible for the assessment procedures, in order for users to obtain some kind of certificate to provide evidence of experience.

Contact with other industry sectors would also be very beneficial. Where not a lot of this type of work is carried out, it would help them keep abreast of current best practice and updates.

On-the-job training for appropriately qualified people. Background in structural analysis and/or training in fracture mechanics essential. Work done in consultation with welding and NDT specialists (to keep a reality check).

On-the-job training.

Combination of suitable training (e.g. Sheffield FM course) and experience (no formal route). Essentially, a company decision on level of competence.

### **Level of training (SQEPness).**

Difficulties in implementing on-the-job training due to the low frequency of this kind of work. Again concerns raised in keeping up-to-date with new developments in codes/procedures.

Heavily dependant on the frequency of this type of work being undertaken. See earlier Sub-Issue.

Addressed by some of the participants under previous Sub-Issue.

### **Extent of performing calculations and extent of developing safety justifications. Extent to awareness of the real risks and extent of ownership of these risks.**

Most of work involves providing high-level advice. Due to the high industry specific costs, much of the emphasis is on keeping plant operating, although more recently, because of the increasing costs, there has been the suggestion to implement more safety justifications in order to continue operation with existing defected components rather than the extra cost involved in replacing.

Provide inputs into safety justifications and usually aware of the safety implications.

Involved in developing safety justifications. Have thorough involvement throughout the process in relation to materials behaviour, assessment, post inspection (defect being found).

Most of work involves safety justifications with strong ownership.

Project lead owns project and will provide advice to clients.

Mixture, but largely supporting safety cases. Usually aware of risks. Take full ownership of own work but the client has ultimate responsibility for applying the results to the plant.

Main work is on setting inspection acceptance limits and criteria for girth welds during pipe laying.

### **Assessment methods and computer codes used (In-house developed, BS7910 etc.)**

BS7910 and API579. Own software formulation based upon BS7910. Have some experience of Crackwise and have used it to verify own formulation. API 579 sometime referred to for information such as fracture toughness values.

Primarily BS7910 used (API 579 used for corrosion). In-house software used to carry out calculations. This was initially based upon PD6493 but has been updated based upon BS7910.

BS7910, Crackwise software. Use MATHCAD sheets which are used mainly for verification. Have R6 documents for reference purposes.

BS7910, API579 (2000 version), Crackwise.

BS7910, Crackwise plus other codes from other countries.

BS7910, others on occasion e.g. R6, API579. Use Crackwise software package. Experienced personnel may go out with the BS7910 on occasion. User defined input allowed in Crackwise for simple cases.

R6, R5, BS7910, R.CODE, SACC. Numerous In-house developed spreadsheets and computer programmes.

### **Controlled copies of codes/standards, particularly in relation to updated versions.**

Copies controlled by technical individuals but no formal central system.

Tight control over copies of standards.

Controlled by technical individuals or Teams rather than a formal company/department system.

Well controlled by library system. Sometimes, it is required to use old codes so these are kept available.

Well controlled by Library system. Better communication required from the developers (BS/TWI).

Company has membership of BSI and regular checks for any updates are carried out. Associated with UCAS so must ensure up-to-date copies are in place.

Raised some concerns as to whether this is always suitably addressed. Because of the frequency of the work, this may not be given the required attention. Practitioner is a member of FIT-NET and does his best to keep up with developments in this work area through contact with experts in the field.

### **Extent to which there are occasions/areas where slight deviation from the assessment code comes into play.**

Commonly resort to FE calculations (including crack modelling) when geometries are such that code solutions for K and reference stress are thought to be inadequate. FE also employed for multi-material components (clad pipes) and for strain/displacement controlled situations. SENT, as well as SENB fracture toughness data compiled in order to take benefit from low constraint in

pipework structure. Fracture toughness testing is usually part of the Welding Qualification (WPQ) Works for each pipeline project.

If using BS7910, might refer to API579 for stress intensity factor and reference stress solutions if borderline result. Might generate own K solutions using the Boundary Integral programme, BEASY.

Have gone to published material on occasions but tend to stay within BS7910.

Very seldom is there any deviation from the assessment code. Advice has been sought when required from referenced publications on particular issues (e.g. cycle blocking, cracks from notches, mixed mode loading).

Better stress intensity and reference stress solutions. Detailed modelling/exp work to evaluate best estimate residual stresses. Issues like mixed mode loading and volumetric defects in welds where guidance was inadequate (outside limits of code) and additional justification work had to be performed.

Fairly common for deviations to be made from assessment code, but this is mainly in R&D projects.

Experienced personnel may go out with the BS7910 on occasion.

### **General views/issues/problems encountered with assessment methods and areas where improvements should be made.**

Improvements could be made in the areas of:

- Cracks from notches
- Cycle blocking
- Fracture toughness values
- Stainless steel properties
- Stress classification
- Treatment of nozzles
- Weld profile clarity (inner/outer side of flaw)
- Linkage of NDE to aspects of ECA.

Layout of procedure could be improved (e.g. along the lines of FITNET and R6). Concerned about worked examples being used by inexperienced people without properly understanding the methodology.

Finds API579 easier to use in general, particularly in the handling of K solutions. API579 gives better guidance than BS7910 on how to proceed when outside the constraints (i.e. validity limits) of various aspects of the procedure (e.g. K solutions). However, there were some aspects where API579 was considered to be somewhat cumbersome to use.

BS7910 would benefit from major revision. Residual stress profiles require more informative guidance. Research required though in order to address some of the major issues. There are some grey areas, which require attention before a major revision. See earlier Sub-Issue also.

K solutions for polynomial residual stress solutions in BS7910. Better guidance on stress classification, better guidance on cycle sequencing in fatigue crack growth, better guidance on best limit load solutions to use (local and global collapse), guidance on difference between cylinder and curved plate solutions. Consistency in notation in a number of areas (e.g. distance  $z$  defined from inside and outside of cylinder wall). General layout is fairly cumbersome.

Addressed by some of the participants under later Sub-Issue.

Embedded defect solutions considered to be inadequate. Inadequate for assessments of multi-material components (clad pipes). Inadequate for strain/displacement loading. Better guidance on constraint issues would be beneficial.

### **Verification and QA of work (consideration of real work as opposed to round robin exercise).**

Independent review always performed. There are one or two contacts, through an informal network within the field, who can carry out independent checks when required. This is more often than not carried out. Exercise was treated as real work.

Thorough checks are carried out by the persons performing the work and reports are reviewed and authorised. Not unusual for calculations to be repeated several times.

Usually 1 person carrying out the assessment, 1 other person checking and another as approver. Numerical check with Crackwise on occasion.

Consultation with expert colleagues throughout the work. All work checked and approved but not by repeating the calculations in detail.

Crackwise inputs checked thoroughly. Normally, no independent checks of calcs are necessary if these are carried out using Crackwise (which is fully verified). Work checked and approved before going out.

For high integrity/loF component assessments, independent verification is undertaken using alternative software/tools and personnel. For other work, spot check verification is usually carried out. Reports are always checked and approved.

All calculations are carefully checked internally as per QC procedures. Approval/ authorisation of documentation is obtained by Clients, and/or their third parties and/or the project warranty surveyors.

### **Proportion of work based on fracture, fatigue, high temperature creep, corrosion wall-thinning, stress corrosion cracking and corrosion-fatigue.**

Mainly fracture and fatigue. Some corrosion wall-thinning using API579 and some corrosion-fatigue assessments have been performed in the past. Sometimes, only small parts of the assessment documents might be referred to rather than carrying out full assessments involving any of these aspects.

Mainly fracture and fatigue. Fatigue is weather related (short term) and on-bottom stability and operations (long term). Corrosion is allowed for in the design and so ECA calculations are not generally necessary.

Primarily fracture and fatigue, occasionally creep life assessments carried out but not from fracture mechanics perspective. Temperature info provided in the guidance is used for creep cases.

Mostly fracture, some fatigue. Have been involved in work based on creep and corrosion wall-thinning.

Over 95% in fatigue and fracture. The rest in SCC and corrosion-fatigue. Don't use high temperature creep procedures but have a strong interest in creep properties.

Mainly fracture and high temperature creep and also fatigue crack growth. SCC and corrosion-fatigue is mainly considered by corrosion experts and not people generally involved in ECA.

Fracture and fatigue – BS7910 (less than 10% of own time).  
Corrosion – API579 (a lot of this work is done).

### **Extent of deterministic and extent of probabilistic analyses.**

Deterministic.

Mostly deterministic analyses carried. Larger organisation are involved in some probabilistic analyses.

Mainly deterministic but work previously carried out on probabilistic studies on pipelines. Also involved in research projects on probabilistic aspects.

All deterministic.

All deterministic work except in exceptional circumstances.

Deterministic, some probabilistic work is done within other areas of department/company.

Mainly deterministic work. Probabilistic studies are undertaken in R&D programmes.

### **Linkage of NDE aspects to ECA (inspection technique based on knowledge of limiting crack sizes etc.).**

Not normally a link between inspection and ECA but information derived from ECA results would be provided to the customer in order to derive their own conclusions on inspection issues.

All NDE inspection targets are derived from ECA assessments based on BS7910.

Project dependent. Where inspection data are provided initially, correction factors are applied.

There has been linkage in several pieces of work over the past few years but this is an aspect that could usefully be strengthened.

Work closely together with NDE team within company . Aware of risk concerned in finding defects. Have been involved in writing “technique” sheets for specific defects.

In-house information on NDE available within some big companies that are dealt with, but more informative guidance required within BS7910.

Useful to work closely with the NDE group in order to develop the best inspection techniques to be implemented on a particular component and on inspection intervals.

It was suggested that the current 'limited' guidance in BS7910 be removed and reference made to other more detailed documents, or, the current guidance should be expanded.

Inspection information regularly supplied to structural analysts. Sensitivity analyses performed with inspection error margins.

## **Extent to which work is performed in an iterative manner with the customer. To what extent is there communication throughout the ECA process with regard to assumptions that were/could be made.**

Tends to be fairly strong iterative working when required depending on nature and importance of work. Iteration usually required satisfy needs of safety case.

Work usually performed in an iterative manner. This is more beneficial to the project, client and the person carrying out the work.

Can vary depending on problem. Perhaps there is more emphasis on just delivering the results of the work to the client (usually internal to the company) rather than keeping him/her informed throughout the work.

Details of link of ECA to pipe laying inspection process are agreed in early stages of each project. Iterative way of working is thus not generally required.

Always close communication with client (mainly in-house). Familiarity of issues resulted from long term relationship and continually increased awareness and knowledge.

Customer always kept informed throughout the duration of the work, but the extent of this does depend on the information provided by the customer from the offset of the work.

Work is almost always performed in an iterative manner. Good relationship with clients. Results usually interpreted and insurance then given to the client. Trepanning has been carried out for testing where required.

## **Materials**

### **Derivation of tensile properties**

All materials are well defined in terms of tensile and fracture properties. Parent company laboratories are available to provide any additional data required. These are generally part of the WPQ scope of work for each pipeline project. All weld metal testing carried out on all welding procedures for which there is to be ECA based acceptance criteria

Sometimes produced themselves and can be supplied by the client also.

Tensile properties are usually available from client and if required, in-house testing can be undertaken (subject to material availability). There can be problems though in obtaining properties for material representative of current plant conditions and life in service.

Material properties are usually the most difficult aspects of ECAs. In many cases have to rely on knowledge of similar components/materials. If material is available, then properties will often be measured. Hardness testing is also used.

Some are available but not always complete.

Usually some information provided. Assumptions made on fracture toughness.

All materials properties usually well characterised.

## **Derivation of fracture toughness (use of Master Curve, Charpy correlations, ductile tearing etc.)**

Not unusual for FT properties to be available. Further data can usually be made available when required.

Toughness data very seldom available. Usually have to rely on Charpy data, if available.

Charpy data is baseline data for fracture toughness and FT testing is always carried out. SENB or SENT testing is conducted on welding procedure tests for weld metal and HAZ. Metallurgical validation is carried out on HAZ specimens. All welding procedures for pipelay are qualified on project material and FT tested when acceptance criteria are ECA based.

Fracture toughness data obtained according to BS7448 or other procedures from own testing or supplied by client. Sometimes use Charpy correlations.

Addressed under previous Sub-Issue. Charpy data seldom used.

FT biggest issue. Sometimes Charpy information available and on occasions samples are taken for testing. Usually no fracture surface information. Helpful if there were some "lower bound" values in BS7910 which could be used.

There is seldom any fracture toughness data made available, but there may be Charpy data available.

## **Derivation of material properties for sub-critical crack growth (fatigue, SCC, corrosion-fatigue etc.)**

In-house experimental data obtained if required.

Use BS7910. Main client has some data which can be made available.

Produce material specific data out according to BS7910 or other procedures where data is not available. R-curves for tearing usually produced in-house.

Properties such as these are almost never available.

Never derived experimentally (upper bound data from codes are used).

Rely on information in BS7910 in first instance. Can obtain data experimentally if required.

Information in the standards/procedures would always be used (own data have never been obtained for these).

## **Weld strength mis-match**

All welds are even-matched or over-matched against linepipe SMYS and so worse case of using parent metal tensile properties are considered.

Follow advice in BS7910 and other standards (e.g. R6). Limited data availability.

This is usually considered by way of FE analysis and sometimes by using the mis-match limit load solutions in R6.

Would normally go to weld procedures where this information would be noted. Hardness testing has been carried out in the field and plate values have been used if no data available.

This was not really considered. The present guidance is to use the lowest properties of the two materials in question. However, this may be non-conservative for cases where residual stresses are present.

Usual to evaluate all properties (parent, weld, HAZ) but rarely apply any mis-match specific FAD methods.

Addressed under previous Sub-Issue (rely on previous knowledge of similar components/materials).

### **Dissimilar metal welds**

Not come across this.

Clad pipes are sometimes used and in these cases, detailed FE calculations are undertaken (see earlier Sub-Issue).

Sometimes work has involved this but not common.

This is usually considered by way of FE modelling.

Addressed by some of the participants under previous Sub-Issue.

## **Stresses**

### **Classification**

This is an area, which requires more informative guidance. There seems to be a lack of clarity in what is classed as a primary or secondary stress. Engineering judgement is currently applied. Thermal and residual stresses usually categorised as secondary

More informative guidance would be helpful. Usually though this is considered to be reasonably straight forward to resolve for type of work involved.

Follows information in procedures but agreed that better guidance would be useful.

Better guidance on this would be useful. Currently use engineering judgement along with current (limited) guidance).

Follow guidance in procedures but improvements in this would be useful.

Not considered to be an issue since stresses are usually considered to be Primary. When weld residual stresses need to be considered, they are usually taken as membrane yield in a conservative way.

More informative guidance required (primary vs. secondary). This is one of the grey areas, which requires some work.

## Residual Stresses (determination and treatment of profiles in relation to KI evaluation)

In the case of the round-robin exercise, own formulation had been used (with justification for this), which had been checked against BS7910. Used a linear response from 0 to  $y'$  instead of the upper bound distribution given in Annex Q, Fig. Q.1(b), Equation Q.4.b.

Own formulation increments residual stress, so there is a new residual as the crack grows.

Undertake detailed FE analyses to evaluate residual stresses. Then use maximum value as membrane stress for stress intensity factor evaluations. Would find polynomial K solutions useful (currently BS7910 allows the use of membrane and bending stress components only)-. Have experts to consult on residual stress measurements and FE modelling.

Provision of K solutions required within BS7910. FEA carried out and data fed back into ECA's. Weld tests carried out for FEA calibration.

Upper bound used in first instance. Best estimate values developed if required by detailed or more simplistic FE modelling. The  $\psi$  and  $\phi$  tables are usually the norm for evaluating the  $\rho$  factor for combined primary and secondary loading (but not in the benchmark calculations).

Err on the side of caution here. Beneficial if there was more informative guidance on the background and applicability of the profiles given. Rho difficult to use. Normally used in simplest form (with warning).

Always uses profiles recommended and does not consider best estimate residual profiles of any kind. Derives  $\rho$  factor in the simplest form. Thinks that V-factor approach in API579 is more straight forward to process.

Addressed by some of the participants under previous Sub-Issue.

## Finite Element capabilities and extent of use

Extensive use of FE in residual stress modelling, elastic-plastic fracture mechanics modelling, high temperature creep. Also local approach micro-mechanistic modelling used (but mainly in R&D work).

Significant use of FEA without and with modelling of cracks. The use of FEA needs to be addressed within standard.

ABAQUS FE calculations are undertaken when necessary – see previous Sub-Issue.

Stresses are usually evaluated by classical means, but there have been occasions where there has been the requirement to commission some FE analysis. It seemed to be the case that if more investment is required to investigate a crack in more detail, the money would be better spent removing the crack.

For complex components where no assessment solution is available, FE analysis may be required and would be carried out.

Uses the 3-D Boundary Integral programme BEASY to evaluate elastic stresses and K values for complex geometries.

Use of elastic and elastic-plastic FE analyses to obtain input stresses to BS7910. Crack modelling to evaluate crack driving force in a research context.

Don't have the capabilities at the moment but are seeking to obtain some in-house. Have gone external for this in the past and the resultant stresses have been fed into an assessment. Not really concerned with complex structures although it would be nice to have the capabilities to do FE if required.

## Flaw and Geometry

### The usual way of obtaining geometries and the handling of tolerances of components if they are not provided

Request this information from client regarding wall thickness tolerances and these are taken into consideration. Conservative assumption normally made.

Detailed drawings are usually available but tolerances are sometimes difficult to ascertain.

Usually take conservative manufacturing tolerances (i.e. maximum). Would go to vessel codes for further guidance (BS5500, ASMEVIII).

This depends on the application. There may be drawings and further information held or provided by the client. Usually there is good information available.

Worst-case tolerances will be taken for assessment.

Usual to apply cylinder and plate geometries if component in question can be broken down into more simplistic shapes.

Geometry well characterised in general. Aspects such as corrosion tolerances and misalignment information frequently is taken into account.

Geometry information has always been available. Tolerances never an issue.

Geometries are carefully controlled and accurately taken into account in ECA work.

### Characterisation of multiple flaws

Has used re-characterisation rules in the past. These rules should only be applied when defects touch (detailed in BS7910).

Never been a significant problem but substantial R&D activities have been performed on this. Have also had to deal with this in the past for a particular component.

Not encountered work involving multiple flaws.

Procedures in BS7910 used. Surface defect results are conservatively used for embedded defects. Flaw Interaction rules apply in the derivation of flaw acceptance criteria where appropriate.

Follow BS7910. Most of the guidance provided is related to single flaws. Better guidance required on treatment of multiple flaws. Interaction rules in PD6493 more conservative. Concern with rules from a brittle fracture viewpoint.

Use BS7910. Experienced problems with multiple flaws in SCC.

Multiple flaws a current issue. Consider that BS7910 guidance should be revised along the lines of the FITNET guidance. Currently undertaking research type work on this issue.

### **NDE results (error margins etc.)**

Interprets these results himself and would go back to NDE analysts for further information if required. Will take expert guidance on safety factors where required.

Taken into account.

These are generally considered by liaising with expert NDE colleagues.

Usually involve NDE and error margins are applied.

These would always be considered appropriately. Acceptance criteria are defined from the ECA taking account of statistical qualifications of NDT system for probability of detection and defect sizing accuracy. Carry out full qualifications of the system to quantify these values. The frequency is determined by project requirements and system changes, but our NDT company, are generally carrying out a detailed qualification each year, and hence have a lot of accumulated data and statistical analysis.

Would consider NDE error margins and would usually work on the most conservative case.

Addressed by some of the participants under previous Sub-Issue.

### **General characterisation (parallel to free surface etc.)**

Not an issue since assumed to be parallel to the free surface for girth welds.

Follow BS7910. Better advice would be useful.

Never been a significant problem but better guidance might be useful.

A factor for pitting from, for example, photos, would be helpful in the guidance.

This usually assumed. More informative guidance required in this area.

No issues.

Never considered to be an issue.

## **Assessment Methodology**

### **Usual base-level used (BS7910 Levels 1 and 2 etc.)**

Level 2a of BS7910.

BS7910 Level 2A, R6 Option 1.

Level 2 base level. Rarely use Level 1 as it was developed differently from Level 2.

Level 2B is base level.

Level 2a is base level. Didn't really see need for Level 1 to still be included but recognised that it might be useful if only minimal data were available.

Level 2A assessment usually carried out as a minimum.

For old equipment, with no/limited data, Level 1. Usually Level 2a.

### **Extent to which higher level analyses are used (FADs, weld strength mismatch, LBB, constraint, J estimation scheme etc., FE analysis in general.)**

Not really required in the work undertaken. Have used higher level FADs (tearing behaviour) and constraint on limited occasions.

High level analyses never used. The industry would rather replace the component than invest in higher level analyses. However, opinions are changing.

Best estimate residual stresses (see earlier Sub-Issue). Fracture Toughness data is sometimes obtained from SENT specimens, allowing for constraint in the fracture toughness test rather than the FAD. Strain-based ECA is needed for components if subjected to large strains but methods not yet generally available.  $\rho$  factor is always evaluated in the simplest form (as implemented in Crackwise).

LBB procedure has been used but no other higher level analyses.

Higher levels are used when required, mainly based on results of FE calculations. These include use of constraint and J-estimation evaluations.

FEA or Level 3 frequently applied. Sometimes SENT, constraint taken into consideration. Involved in local approach research.

All aspects of higher level analyses have been considered at various times. The higher level analyses form the basis of much of the R&D activities.

### **Stress intensity factor and limit load (reference stress) solutions for complex geometries (nozzles, T-joints, pipe bends etc.)**

Complex geometries generally not required to be assessed.

Nozzle to shell solutions would be helpful for example.

Normally use cylinder or plate solutions. More informative guidance required in this area.

FEA used for complex geometries, then results have been fed into analysis. Have researched J (from FEA) in relation to limit loads.

Plate or cylinder solutions mainly used but FE evaluations are made on some occasions.

BEASY used for these cases.

Tend to resort to FE evaluations – see earlier Sub-Issue.

## Sequencing of fatigue cycles

Aspect never been considered.

Fatigue is not really a big issue. When it is considered, cycles are applied in order of occurrence.

Follow BS7910 (requires updating). Sensitivity normally carried out. Can be applied in any order within Crackwise.

Sensitivity studies are performed. Better guidance would be useful.

Usually applied in their real order. There are facilities within software formulation to change sequencing.

Some guidance is given in PD550 and has been used in the past for the sequencing of fatigue cycles. More informative guidance required in this area in BS7910.

Better guidance required.

## Mixed mode loading

Aspect never been considered.

Rarely being an issue.

Follow BS7910. Normally assumed Mode 1. Guidance requires revision to reflect recent findings including those concerning fracture toughness.

Work has been undertaken in the past, mainly on R&D programmes.

Not much involvement regarding this. Have had to resolve stresses around nozzles in the past. Not handled too well in BS7910 and more informative guidance is required.

Has had some experience with mixed mode loading on the same geometry. Has referenced outside publications on this subject.

Previous work contained a mixed mode loading issue that required a more detailed study to be undertaken since it fell outside the limits of the guidance in BS7910.

## General issues relating to methods such as BS7910

As the document is worked through it would be helpful if solutions were stated again, where appropriate, rather than always jumping around the document. An active PDF document with links included would be extremely beneficial.

The treatment of volumetric defects such as those resulting from lack of penetration in welds requires better guidance so that they don't have to be treated as crack-like flaws.

Re-familiarisation problems for in-frequent users of procedures.

K and reference stress solutions need some attention.

Addressed by some of the participants under previous Sub-Issue.

## **Suggested improvements for methods like BS7910**

Revision is required to reflect recent developments including R6, API579 and FITNET.

More information on the justification of what is included in the standard. A theory manual to go a bit deeper into specific aspects (perhaps status notes like in R6).

Requested clarification in certain areas (mentioned in earlier Sub-Issue) but did not want the code to become too simplified, to a large extent, so that inexperienced people could use the code without fully understanding it.

Should incorporate all relevant state-of-the-art developments in FITNET. Better guidance on use of local and global reference stress solutions (for 3D cracks).

See earlier Sub-Issue plus solutions such as K and reference stress should be more prescriptive rather than providing options for the user to choose.

Addressed by some of the participants under previous Sub-Issue.

## **Assessment Output**

### **Safety margin considerations (partial safety factors etc.)**

Rarely use partial safety factors. Use worst case estimates of every input parameter and follow the guidance within BS7910.

These are practically never considered in the calculations but they may be taken into account by the client when developing the safety justification based on our ECAs.

These are used. Likelihood of failure fraught with uncertainties from operators.

Safety margins are used and are dependent on the particular application and the client. Will generally add own safety factor on stress of ~20%.

Safety margins generally not used. Noted that there was further work being undertaken by Rolls-Royce on partial safety factors that should be incorporated into BS7910 in the future.

Safety margins generally not considered.

The results of the ECA calculations are handled in a conservative way (and the ECA calculations themselves) when using them to set the NDE acceptance limits.

### **Sensitivity studies**

Always done where possible by flexing the input parameters.

Sensitivity studies are carried out in tune with assessment document being used.

These are always considered in ECAs, particularly to highlight to Client (usually within company) which data to focus on improving the quality of.

Such studies are occasionally used.

Don't generally have the need to undertake sensitivity studies. However, toughness, strength and misalignment inputs are investigated if required.

Frequently carried out to establish most influential parameters. Reliability also a consideration.

Sensitivity studies generally performed according to procedure recommendations.

## **Detail and lay-out of reporting**

Important for report to contain significant detail (from a QA viewpoint).

Calculational sheets or computer outputs are generally not included unless the client requires them. Reports are usually detailed with additional information contained in Appendices. Reports are checked and verified and drafts are usually sent to the clients prior to issuing the final version. Reports always contain sufficient information to enable independent replication of the analyses.

Not usual to give calculation sheets. Normally produce a summary report and then go and talk to the client face-to-face and present the results and how they affect them.

Reports are usually self-contained. Output from software used is also included in the report. The software that has been used here produces very concise information and is well laid out.

Didn't usually include all Crackwise outputs in report but otherwise quite detailed reports are produced. Summary at the front very informative and concise.

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Detailed report produced with Crackwise output and other sheets attached as Appendices.

## **Future inspection strategy**

Regularly asked to re-visit calculations following further inspections. Was particularly interested in receiving feedback on his work, as this was good validation for his original calculations.

Work is aimed at removing the need for ISI. Company construct the pipelines to clients' designs which take account of their in-service inspection requirements. Generally modern pipelines are designed for intelligent pigging. Some pipelines are designed with internal corrosion resistant alloy layer where the fluids are known to be particularly aggressive.

Much of the outcome of the ECAs are linked to future inspection strategy.

A lot of work postulating flaws and justifying techniques around this. Sizing and findings an issue. Results are often revisited after next inspection has been carried out.

For real cases this is usually part of the scope of work.

Recently become more involved in advising on future inspection strategies. However, due to economic reasons, there tends to be a requirement to repair rather than carry out any further inspection in a fairly short time period. Work required is more from a materials perspective than an inspection aspect.

Limit of detectability crack sizes sometimes used as starting point in fatigue crack growth calculations to identify future inspection intervals.



# Collaboration of results from industry round-robin on engineering critical assessment evaluations

Assessing the significance of flaws or defects, which have been found during inspection, is performed using “Engineering Critical Assessment (ECA)” techniques, also sometimes referred to as “Fitness for Service” or “Fitness for Purpose” techniques. The implications of an incorrect ECA can be highly damaging; both to personnel Health and Safety and to the finances of the operating company.

The Health and Safety Executive (HSE) contracted Serco Assurance to lead a project comprising a Round-Robin exercise such that a better appreciation can be gained of how practising engineers undertake ECA evaluations. Participants from appropriate industrial companies and supporting organisations were contacted, and supplied three benchmark questions as an exercise. Following initial interpretation of the results, a small team of Serco Assurance staff conducted face-to-face discussions to further investigate the methods used to solve the exercises, and how they might cope with more complex issues.

This report collates the results and discusses the magnitude of variation between the respective Participants’ answers to the benchmark questions, and presents the answers from the face-to-face discussions. The information presented within this report will allow HSE to gain a better appreciation of how practising engineers undertake ECA evaluations and, if appropriate, provide recommendations for improved general guidance on such evaluations. This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.