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**A NEW LIMIT STATE FUNCTION
FOR THE INSTANTANEOUS
FAILURE OF A DENT CONTAINING
A GOUGE IN A PRESSURISED
PIPELINE**

Confidential

Restricted to UKOPA & Advantica

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Executive Summary

It has been recognised for many years that third party interference is the most likely cause of pipeline failure, and this is highlighted in historical data. For example, damage induced by excavating equipment, can pose a serious threat to the structural integrity of high pressure onshore pipelines. The most onerous scenario possible is an impact resulting in damage of sufficient severity to cause a full-bore rupture of the pressurised pipeline. This would lead to the rapid release of a large quantity of gas, which if ignited could pose a very significant safety hazard to anyone in the vicinity of the release.

In recognition of this, comprehensive integrity and risk management procedures are customarily adopted by pipeline operators. A key component of these procedures is management of structural integrity and this requires a limit function describing the failure mechanisms.

The current limit state function, addressing mechanical damage, and used by Transco (and indeed many other operators), was developed around 1980 and is considerably less up-to-date than other aspects of the risk and integrity management process. This does not mean that the existing limit state function is 'unsafe' (there has not been a full bore rupture within the UK in over 500,000 kilometre years of operation). However, there are four important issues to be considered;

- Fracture mechanics methods, on which the limit state function is based, have improved considerably over the past 25 years
- The Health and Safety Executive (HSE) adopt a different (more up-to-date) method
- Some pipelines in the UK are being operated more onerously than previously (uprating)
- The model is a major component of Transco's risk and land use planning methodology.

In view of the above, the United Kingdom Onshore Pipeline Operators Association (UKOPA) has commissioned Advantica to undertake a theoretical study to update the current limit state function. The study has the objectives of;

- achieving alignment with contemporary fracture mechanics methods
- achieving alignment with the HSE method

The limit state approach, as opposed to alternative approaches using historical data, permits pipeline operators to understand how varying the pipeline design parameters can affect the likelihood of pipeline failure.

This report describes the general two parameter fracture mechanics approach that is to be adopted and identifies the relationship between this approach and the original model. It then goes on to derive the new model, incorporating a number of new features, and illustrates the fit of the new model to the original test data. This work has therefore developed a new limit state function for UKOPA that builds on the work previously carried out by British Gas and the HSE.

Conclusions

A new limit state function has been developed which aligns the methodologies used by Transco and HSE, in order to provide a better fit to the existing test data.

This is based on the two parameter approach to elastic-plastic fracture mechanics for assessing the significance of mechanical damage, taking account of enhancements to the methodology that have been introduced since the time that the original Transco model was developed. In addition, the new model includes the effects of residual stress and the presence of a micro-crack.

This new model should provide a consistent approach in predicting mechanical damage failure rates when carrying out pipeline risk assessment in the UK.

Recommendations

The new model developed in this project should be applied to all methodologies where the frequency of external interference is required (i.e. land use planning, risk assessments, uprating)

Further refinement of the model, building on the findings of this work and supported by more detailed testing may provide additional improvements in the understanding of the controlling parameters and the accuracy of the failure prediction.

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1 INTRODUCTION

It has been recognised for many years that third party interference is the most likely cause of pipeline failure, and this is highlighted in historical data. For example, damage induced by excavating equipment, can pose a serious threat to the structural integrity of high pressure onshore pipelines. The most onerous scenario possible is an impact resulting in damage of sufficient severity to cause a full-bore rupture of the pressurised pipeline. This would lead to the rapid release of a large quantity of gas, which if ignited could pose a very significant safety hazard to anyone in the vicinity of the release.

In recognition of this, comprehensive integrity and risk management procedures are customarily adopted by pipeline operators. These procedures comprise a number of mitigating measures that generally include:

- management of the likelihood of impact
 - surveys and surveillance
 - burial depth
- management of the likelihood of rupture if impact occurs
 - maximum design factor
 - minimum wall thickness
- management of the safety hazard if a rupture occurs
 - minimum separation distance between the pipeline and occupied buildings
 - allowable population density

Thus, in basic terms, the probability of occurrence of a safety hazard, $p(S)$, can be expressed as

$$p(S) = p(S | R)p(R | I)p(I) \quad (1)$$

where $p(S | R)$ is the probability of a safety hazard given that a rupture has occurred, $p(R | I)$ is the probability of a rupture given that an impact has occurred and $p(I)$ is the probability of occurrence of an impact.

Although simplistic, the above expression serves to illustrate that the risk management procedure comprises three basic elements and consequently that due consideration should be given to each of these.

Over recent years extensive experimental and theoretical research work has been undertaken within the UK to construct sophisticated models for determining the quantity $p(S | R)$ and these models form the 'hub' of the risk assessment software PIPESAFE^[1] as described in Transco's Hazard Assessment Methodology Manual^[2].

Statistically significant data have been collected over many years to quantify the likelihood of impact, $p(I)$; the majority of impacts do not result in failure.

On the other hand the quantity $p(R|I)$ is based on fracture mechanics formulations that were developed around 1980 and is therefore 'behind the times' of its two counterparts in equation (1). This does not mean that the existing formulation is 'unsafe' (there has not been a full bore rupture within the UK in over 500,000 kilometre years of operation), however, there are four important issues to be considered. These are:

- Fracture mechanics methods have improved considerably over the past 25 years
- The Health and Safety Executive adopt a different (more up-to-date) method^[3]
- Some pipelines in the UK are being operated more onerously than previously (uprating)
- The model is a major component of Transco's risk and land use planning methodology

In view of the above, the United Kingdom Onshore Pipelines Association (UKOPA) have commissioned Advantica to undertake a theoretical study to update the current fracture mechanics formulation (limit state function), on which $p(R|I)$ is based. The study has the objectives of,

- achieving alignment with contemporary fracture mechanics methods
- achieving alignment with the HSE method

Understanding how the design of the pipeline, in terms of wall thickness, material strength, fracture toughness, etc. affects behaviour in light of third party damage is key to effective pipeline safety management. The limit state approach, as opposed to alternative approaches using historical data, permits pipeline operators to understand how varying these parameters can affect the likelihood of pipeline failure.

As with all theoretical work of this nature, there is a requirement for some experimental work for the purpose of validation. For the present purpose the approach adopted is to use to the original test data that were obtained in support of the original limit state function^[4].

This report describes the general two parameter fracture mechanics approach that is to be adopted and identifies the relationship between this approach and the original model. It then goes on to derive the new model, incorporating a number of new features, and illustrates the fit of the new model to the original test data. This work has therefore developed a new limit state function for UKOPA that builds on the work previously carried out by British Gas and the HSE.

2 THE TWO PARAMETER FRACTURE MECHANICS METHODOLOGY

The methodology to be adopted recognises that a steel structure, containing a defect, can generally fail due to a combination of plastic collapse and brittle fracture. The salient features of this methodology are described below and are also documented in published standards^{[5], [6]} for further reference.

2.1 Brittle Fracture

Failure due to brittle fracture is predicted to occur if the inequality,

$$K_r \geq 1 \quad (2)$$

is satisfied, where the parameter K_r is defined as

$$K_r = \frac{(K_m^p + K_m^s + K_b^p + K_b^s)}{K_{IC}} + \rho. \quad (3)$$

In the above, the parameter ρ is known as the plasticity correction factor and K_m^p , K_m^s , K_b^p and K_b^s are measures of the stress singularity that occurs at the sharp front of a crack-like defect, in a loaded structure due to various categories of stress. They are known as the primary membrane, primary bending, secondary membrane and secondary bending stress intensity factors, respectively.

The parameter, K_{IC} , is a material property, known as the fracture toughness and is a measure of the material resistance to brittle fracture. In the pipeline industry it is not common to measure the fracture toughness directly but rather to determine it using a correlation with the more commonly measured Charpy energy, C_v . In general the correlation can be expressed as

$$K_{IC} = AC_v^\alpha + B \quad (4)$$

where A , B and α are empirical constants. The above formulations are discussed in more detail later.

2.2 Plastic Collapse

Failure due to plastic collapse is predicted to occur if the inequality,

$$S_r \geq 1, \quad (5)$$

is satisfied, where the parameter S_r is defined by

$$S_r = \frac{\sigma_{ref}}{\sigma_f} . \quad (6)$$

In the above σ_{ref} is a measure of the stress state in the ligament ahead of the defect and is known as the reference stress. The parameter σ_f is a material property known as the flow stress and is a measure of the resistance of the material to plastic collapse.

A general definition of flow stress is given by

$$\sigma_f = \lambda\sigma_y + (1 - \lambda)\sigma_u \quad (7)$$

where σ_y is the yield strength, σ_u the ultimate tensile strength and λ is a dimensionless scalar quantity lying within the range zero to unity. Each of the above terms is discussed in more detail later.

2.3 Elastic-Plastic Fracture

In general, the failure of steel structures containing defects will occur due to a combination of brittle fracture and plastic collapse. In recognition of this, the above two inequalities are combined and expressed in the form

$$K_r \geq F(S_r) \quad , \quad S_r \leq 1, \quad (8)$$

where F is a function that decreases monotonically from unity to zero as S_r increases from zero to unity. The failure mechanism governed by the above inequality is known as elastic-plastic fracture and the curve described by the function F is known as the failure assessment line.

The value of K_r is irrelevant for $S_r > 1$ since failure will necessarily occur due to plastic collapse as described by inequality (5).

2.4 Overview

Based on the above, it is noted that the limit state function comprises the following items:

- the failure assessment line, $F(S_r)$
- the reference stress, σ_{ref}
- the stress intensity factors, K_m^p , K_m^s , K_b^p and K_b^s
- the plasticity correction term, ρ
- the flow stress, σ_f
- the correlation between fracture toughness, K_{IC} and Charpy energy, C_v

In Section 3 the specific details of each of the above items that are relevant to the existing limit state function, used by Transco, are described.

In Section 4 the changes to a number of the formulations are introduced in order to produce a new limit state function (based on contemporary fracture mechanics methods) that is aligned to the current limit state function used by HSE^[3].

3 THE EXISTING TRANSCO MODEL

A brief description of the salient features of a generalized fracture mechanics approach to assessing the significance of defects in loaded structures has been provided in Section 2. The specific formulations of each of the key elements of the approach that are relevant to the model currently used by Transco^[4] are described in this section.

3.1 The Damage

It is assumed that external interference causes a dent containing a gouge in the wall of the pipe.

The limit state function, described in this section, is thus used to determine the conditions for failure of a gouge of depth a and length L located in a dent of depth D that is present in the a pipeline having radius R , wall thickness w , yield strength σ_y , ultimate tensile strength, σ_u , Charpy toughness C_v , and subject to internal pressure P .

3.2 The Failure Assessment Line

The functional form of F was based on the Dugdale^[7] strip yield model and is given by

$$F = S_r \left[\frac{8}{\pi^2} \ln \sec \left(\frac{\pi}{2} S_r \right) \right]^{-\frac{1}{2}}. \quad (9)$$

A plot of the function described by equation (9) is shown in Figure 1.

3.3 Plasticity Correction Term

No residual stresses were included and no plasticity correction term was used, hence $\rho = 0$.

3.4 The Stress State

In order to determine the reference stress, and stress intensity factors, it is first necessary to determine the stress field that would exist in the pipe at the location of

the defect, if the defect was not present. This is referred to here as the undisturbed stress field.

3.4.1 The Undisturbed Stress Field

The section of pipeline containing the defect (dent/gouge) is considered to be straight and only subject to internal pressure loading. The two significant (principal) stress components are thus the hoop stress, σ_H and the axial stress, σ_A which are given by

$$\sigma_H = \frac{PR}{w} \quad (10)$$

and

$$\sigma_A = \frac{\nu PR}{w}. \quad (11)$$

Since Poison's Ratio, $\nu (= 0.3)$, is less than unity, the maximum (principal) stress is equal to the hoop stress. Furthermore, assuming that the hoop stress acts uniformly across the pipewall, the maximum principal stress state, assuming that the defect is not present, can be expressed as

$$\sigma_m = \sigma_H \quad (12)$$

and

$$\sigma_b = 0, \quad (13)$$

where σ_m and σ_b are known as the membrane and bending components of the maximum principal stress state, respectively.

3.4.2 Effect of the Dent

The effect of the change in curvature due to the presence of the dent leads to a modification of the stress state and this is described by

$$\sigma_m = \sigma_H \left(1 - 1.8 \frac{D}{2R} \right) \quad (14)$$

and

$$\sigma_b = 10.2 \sigma_H \frac{R}{w} \frac{D}{2R}. \quad (15)$$

The dent was assumed not to cause any residual stress field.

3.4.3 Stress Categorisation

In order to determine the effect of the stress state on the structural integrity it is necessary to categorise the stresses as primary or secondary.

In general, primary stresses are load controlled stresses that can cause failure by both plastic collapse and brittle fracture. Secondary stresses are displacement

controlled (constrained) stresses that can cause failure by brittle fracture but cannot cause plastic collapse.

In view of the above the membrane stress is categorised as primary and the bending stress is categorised as secondary. The complete stress state is thus represented by

$$\sigma_m^p = \sigma_H \left(1 - 1.8 \frac{D}{2R} \right), \quad (16)$$

$$\sigma_m^s = 0, \quad (17)$$

$$\sigma_b^p = 0 \quad (18)$$

and

$$\sigma_b^s = 10.2 \sigma_H \frac{R}{w} \frac{D}{2R}, \quad (19)$$

where superscripts 'p' and 's' denote primary and secondary respectively. The above stress components are used to determine the reference stress and the stress intensity factor in the following sections.

3.5 Reference Stress

The gouge is considered to lie in a plane that is normal to the direction of the maximum principal stress (i.e. along the axial direction of the pipe). The presence of the gouge causes a localised reduction in wall thickness. Based on a consideration of equilibrium of forces, it follows that there will be a localised increase in maximum principal stress. It is this localised increase in stress that may lead to failure due to plastic collapse. Since only primary stresses can cause plastic collapse, the reference stress is a function of the primary membrane stress and local geometry, and can be expressed in the form

$$\sigma_{ref} = \frac{\sigma_m^p (1 - a / Mw)}{(1 - a / w)}. \quad (20)$$

The factor, M , is known as the Folias factor, given by

$$M = \left[1 + 0.26 \left(\frac{L}{\sqrt{Rw}} \right)^2 \right]^{\frac{1}{2}} \quad (21)$$

and takes account of the effect of the gouge length, L .

3.6 Stress Intensity Factor

The gouge is considered to be a rectangular ($a \times L$) sharp defect and only the gouge depth and not the gouge length determine the condition for brittle fracture.

Note that the length only determines whether the failure will occur as a leak or a rupture, the portion of the limit state function associated with this aspect of the failure is assumed not to change and hence the formulation that is currently used by Transco and HSE will be retained and is discussed no further here.

Both membrane and bending stresses can contribute to brittle fracture and hence the stress intensity factor may be expressed in the form,

$$K = (\sigma_m^p Y_m + \sigma_b^s Y_b) \sqrt{\pi a}, \quad (22)$$

where a is the gouge depth and $Y_m(a/w)$ and $Y_b(a/w)$ are normalised stress intensity compliance functions. For the present purpose, the functions $Y_m(a/w)$ and $Y_b(a/w)$ are given by the conservative expressions,

$$Y_m = 1.12 - 0.23(a/w) + 10.6(a/w)^2 - 21.7(a/w)^3 + 30.4(a/w)^4 \quad (23)$$

and

$$Y_b = 1.12 - 1.39(a/w) + 7.32(a/w)^2 - 13.1(a/w)^3 + 14.0(a/w)^4. \quad (24)$$

3.7 Flow Stress

With reference to equation (7), the flow stress is commonly obtained by assigning a value of 0.5 to λ . However, since for many steels the ratio σ_u / σ_y typically lies within the range (1.2 -1.3), the flow stress was defined as

$$\sigma_f = 1.15\sigma_y. \quad (25)$$

3.8 Fracture Toughness

With reference to equation (4) it was assumed that the constant B was equal to zero and linear regression analysis was used to determine the constants A and α using the 132 original test data that are given in Table 1. This resulted in

$$K_{IC} = 10.5C_v^{0.878} \text{ (MPa}\sqrt{\text{m)}), \quad (26)$$

where C_v is expressed in Joules.

4 THE PROPOSED NEW LIMIT STATE FUNCTION

The new model described in this section is based on that described in Section 3 but includes a number of modifications. The purpose of the modifications is: (i) to align the new limit state function to that currently used by the HSE where an improvement can be gained, and (ii) to take account of advances in fracture mechanics methodologies that have taken place since the original model was constructed.

4.1 The Damage

In addition to the dent and gouge, described in Section 3.1, it is further assumed here that a micro-crack is also introduced at the root of the gouge. Inclusion of this feature is more likely to be closer to the actual physical behaviour of the damage.

The limit state function, described in this section, is thus used to determine the conditions for failure of a micro-crack of depth δ at the root of a gouge of depth a and length L located in a dent of depth D that is present in a pipeline having radius R , wall thickness w , yield strength σ_y , ultimate tensile strength, σ_u , Charpy toughness C_v and subject to internal pressure P .

4.2 The Failure Assessment Line

In accordance with Reference [5], the proposed functional form for the failure assessment line, F is given by

$$\begin{aligned} F &= (1 + 0.5L_r^2)^{-1/2} (0.3 + 0.7 \exp(-0.6L_r^6)) \quad , \quad L_r \leq L_{r \max} \\ F &= 0 \quad , \quad L_r > L_{r \max} \end{aligned} \quad (27)$$

where L_r is defined by

$$L_r = S_r \frac{\sigma_f}{\sigma_y} \quad (28)$$

and $L_{r \max}$ is given by

$$L_{r \max} = \frac{\sigma_f}{\sigma_y} \quad (29)$$

The above modification to the failure assessment line takes account of work hardening properties of the steel.

4.3 The Plasticity Correction Term

The plasticity correction term ρ is given by

$$\begin{aligned} \rho &= \rho_1 \quad , \quad L_r \leq 0.8 \\ \rho &= 4\rho_1(1.05 - L_r) \quad , \quad 0.8 \leq L_r \leq 1.05 \\ \rho &= 0 \quad , \quad 1.05 \leq L_r \end{aligned} \quad (30)$$

In the above, ρ_1 is given by

$$\rho_1 = 0.1 \left(\frac{K^s}{K^p / L_r} \right)^{0.714} - 0.007 \left(\frac{K^s}{K^p / L_r} \right)^2 + 0.00003 \left(\frac{K^s}{K^p / L_r} \right)^5 \quad (31)$$

where the primary and secondary stress intensity factors, K^p and K^s , respectively, are given by

$$K^p = K_m^p + K_b^p \quad (32)$$

and

$$K^s = K_m^s + K_b^s .$$

4.4 The Stress State

4.4.1 The Undisturbed Stress Field

The stress field remote from the location of the dent and gouge is identical to that used in the original model and hence is described by equations (12) and (13).

4.4.2 Effect of the Dent

In addition to the effect of the change in curvature on the undisturbed stress field described above, it is also recognised here that the plastic deformation associated with the presence of the dent will result in a residual stress field. Using $D/2R$ as a simple measure of plastic deformation, and noting that the residual stresses are secondary, the following stress state is proposed;

$$\sigma_m^p = \sigma_H \left(1 - 1.8 \frac{D}{2R} \right), \quad (33)$$

$$\sigma_m^s = (1 - \xi) \Phi \left(\frac{D}{2R} \right) \sigma_y, \quad (34)$$

$$\sigma_b^p = 0 \quad (35)$$

and

$$\sigma_b^s = 10.2 \sigma_H \frac{R}{w} \frac{D}{2R} + \xi \Phi \left(\frac{D}{2R} \right) \sigma_y \quad (36)$$

In the above ξ is a constant to be determined within the range 0 to 1 and Φ is a function of $D/2R$ given by

$$\Phi = \frac{D}{2R} \quad , \quad \frac{D}{2R} < \zeta \quad (37)$$

and

$$\Phi = 1 \quad , \quad \frac{D}{2R} \geq \zeta ,$$

where ζ is a further constant to be determined.

4.5 Reference Stress

The effect of the micro-crack, on the susceptibility to plastic collapse, is to increase the effective depth of the gouge from a to $a + \delta$. The reference stress may thus be expressed as

$$\sigma_{ref} = \frac{\sigma_m^p [1 - (a + \delta) / Mw]}{[1 - (a + \delta) / w]}, \quad (38)$$

where σ_m^p is given by equation (33) and M is given by equation (21).

4.6 Stress Intensity Factor

In this case, the gouge is treated as blunt (not crack-like) and hence does not make a direct contribution to the stress intensity factor. However, there will be a localised increase in the stress at the root of the gouge (the location of the micro-crack) and this results in modification of the stress state, as described by:

$$\sigma_m^p = \sigma_H \left(1 - 1.8 \frac{D}{2R} \right) K_t, \quad (39)$$

$$\sigma_m^s = (1 - \xi) \Phi \left(\frac{D}{2R} \right) \sigma_y, \quad (40)$$

$$\sigma_b^p = 0 \quad (41)$$

and

$$\sigma_b^s = 10.2 \sigma_H \frac{R}{w} \frac{D}{2R} K_t + \xi \Phi \left(\frac{D}{2R} \right) \sigma_y, \quad (42)$$

where K_t is known as the notch factor and is given by

$$K_t = 1 + 2\sqrt{a/r}, \quad (43)$$

where r is the radius of the root of the gouge. The gouge radius is regarded as a further fit parameter here.

The stress intensity factor is then given by

$$K = [(\sigma_m^p + \sigma_m^s) Y_m (\delta / (w - a)) + \sigma_b^s Y_b (\delta / (w - a))] \sqrt{\pi \delta}, \quad (44)$$

where the relevant stress components are given by equation (39), (40) and (42) and the functions of Y_m and Y_b are given by equations (23) and (24) with the argument a/w replaced with $\delta / (w - a)$.

4.7 Flow Stress

The flow stress is taken to be the same as that used in the original (Transco) model and hence is given by equation (25).

4.8 Fracture Toughness

The basic correlation between fracture toughness and Charpy Energy given by equation (4) is assumed here and the constants A , B and α are determined (along with other parameters) in the following section.

5 QUANTIFICATION OF NEW LIMIT STATE FUNCTION PARAMETERS

In addition to the parameters, A, B, α, ξ and ζ identified above, it is also necessary to determine the depth of the micro-crack δ . Evidence of micro-cracking was not sought at the time of the original testing since this element of the model was not conceived at that time. Consequently, no physical measurements are currently available on which to base this quantity. It is therefore necessary to treat this quantity as a further 'fit' parameter.

Intuitively the depth of the micro-crack is likely to be dependent on the size of the remaining ligament and on the amount of plastic straining. Assuming that $D/2R$ is a simple measure of plastic strain, a relationship of the form,

$$\delta = C \left(\frac{a}{w} \right)^\gamma \left(\frac{D}{2R} \right)^\beta, \quad (45)$$

is postulated, where C, γ and β are constants.

Hence, in order to complete the definition of the new limit state function it is necessary to assign values to the parameters, $A, B, C, \alpha, \beta, \gamma, \xi, \zeta$, and r .

In principle, although cumbersome, it would be possible to determine values for the above nine parameters, that would represent the best fit using non-linear regression analysis. However, such an approach would involve a level of analysis that is not warranted for the present purpose. Consequently a pragmatic approach was adopted. This involved iteratively assigning values to each of the nine parameters and visually observing the 'goodness of fit' of the data to the failure assessment line. In addition to the 'visual information' a check on the parameter,

$$\sum_i (K_{ri} - F(L_{ri}))^2, \quad (46)$$

was made, where K_{ri} and L_{ri} are computed values for each of the i data.

It is important to note that 112 of the 132 tests were carried out on rings and only 20 were carried out on pressurised cylinders. The significance of this is that for the ring tests the length can be regarded as tending to infinity in which case, as seen from

equations (20) and (21), the effect of length is removed from the model. However, this is not considered to be a major limitation since length only appears in the reference stress formulation (21) and this aspect of the model is considered to be perfectly valid and will remain unchanged in the new model.

5.1 Fracture Toughness

A range of values for A , B and α were investigated and the contribution of A was clearly observed as the most sensitive parameter. The final outcome was $A = 3.2$, $B = 0$ and $\alpha = 1.1$. A graphical comparison of this model with the original model is shown in Figure 2. The fracture toughness has generally reduced by a factor of about 0.7 and is regarded as being more representative of pipeline steels than the original model.

5.2 Micro-crack

The depth of micro-cracking plays a significant role and the final outcome was $C = 0.023$, $\beta = 0.5$ and $\gamma = 1.5$. The application of these values to the 132 data resulted in a mean value for δ of 0.4mm and a standard deviation of 0.2mm.

5.3 Residual Stress

The best fit was obtained for a very small value of ζ ($\rightarrow 0$) implying that a residual stress equal to the yield strength was appropriate to all situations. This is not too surprising since denting clearly introduces permanent plastic deformation. However, the fit was relatively insensitive to ξ indicating that treating the residual stress field as either membrane or bending makes little difference. In view of this a value of $\xi = 0$ (pure membrane) was arbitrarily chosen.

5.4 Gouge Radius

Many of the tests were conducted using flat-bottomed gouges. This would have resulted in an 'effective' gouge radius ($\rightarrow \infty$) that is greater than would be generally incurred in practice.

In practice, the gouge radius is likely to be determined by the size, shape and angle of incidence of the indenter and in general will be significantly greater than the gouge depth. For the present purpose the gouge radius was taken to be a fit parameter and a value of 0.2m was found to give a good fit. This 'large' value is consistent with the flat-bottomed nature of the test geometries and is considered to be representative of gouge radii that will be encountered in the field.

5.5 New Limit State Function

The new limit state function is fully described by equations (3), (27-32) and (37-42) and the values of the parameters given above. An illustration of the fit of the new function to the test data is illustrated in Figure 3.

It can be seen from this figure, that although there is some scatter in the new model, the general functional behaviour of the failure assessment line and the data are well aligned. The new model can therefore be considered to provide a firm basis for risk and integrity management. It should also be noted that this new limit state function takes the same functional form as that used by HSE^[3].

A further point to note is that 20 of the 132 tests were made on pressurised cylinders (vessels) and not rings, as mentioned above. In the case of vessels both gouge depth and gouge length need to be taken into account in accordance with equations (20) and (21). A significant effect of length will be a reduction in the value of L_r . The four points at the extreme right of Figure 3 represent the outcomes of three of the vessel tests and consequently, since, the length was implicitly assumed to be infinite, have erroneously high L_r values. In order to obtain a more valid indication of the fit, the 20 vessel tests were removed and the revised plot is shown in Figure 4. The most notable change is the removal of the four points to the extreme right of Figure 4; the effect on the other 17 points appears to be less remarkable. Also for completeness a vertical line has been included that represents the value of $L_{r\max}$ (see equation (29)).

Note that if measured defect length were known then the actual effect on the fit could be investigated. However, for the present purpose this level of detail is of no real significance.

Also, a more detailed treatment of the fit through the use of non-linear regression, for instance, may result in some refinement of the values of the parameters. However, noting that the data is 25 years old and subject to some uncertainty, such a refinement is not considered to be appropriate for the present purpose.

Overall, the analysis presented has identified a number of shortcomings of the original (Transco) model and has produced a revised model that is significantly more accurate. However, the semi-empirical nature of the model still remains. If further refinement was seen as necessary a more detailed theoretical study, building on the findings of this work and supported by more detailed testing could be undertaken in the future.

6 CONCLUSIONS

A new limit state function has been developed which aligns the methodologies used by Transco and HSE, in order to provide a better fit to the existing test data.

This is based on the two parameter approach to elastic-plastic fracture mechanics for assessing the significance of mechanical damage, taking account of enhancements to the methodology that have been introduced since the time that the original Transco model was developed. In addition, the new model includes the effects of residual stress and the presence of a micro-crack.

This new model should provide a consistent approach in predicting mechanical damage failure rates when carrying out pipeline risk assessment in the UK.

7 RECOMMENDATIONS

The new model developed in this project should be applied to all methodologies where the frequency of external interference is required (i.e. land use planning, risk assessments, uprating)

Further refinement of the model, building on the findings of this work and supported by more detailed testing may provide additional improvements in the understanding of the controlling parameters and the accuracy of the failure prediction.

8 REFERENCES

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TABLES

	Diameter (m)	Wall Thickness (m)	Dent Depth (m)	Gouge Depth (m)	Failure Stress (MPa)	SMYS (MPa)	Charpy Energy (J)
1	0.762	0.0127	0.023	0.0028	97.2	414	21
2	0.762	0.0127	0.036	0.0028	37.9	414	21
3	0.762	0.0127	0.009	0.0028	180.0	414	21
4	0.762	0.0127	0.013	0.0028	127.6	414	21
5	0.762	0.0127	0.028	0.0034	70.5	414	23
6	0.762	0.0127	0.046	0.0034	32.4	414	23
7	0.762	0.0127	0.025	0.0034	79.4	414	23
8	0.762	0.0127	0.016	0.0034	161.3	414	23
9	0.762	0.0127	0.053	0.0034	29.2	414	23
10	0.762	0.0127	0.010	0.0034	153.1	414	23
11	0.762	0.0127	0.013	0.0029	117.2	414	20
12	0.762	0.0127	0.014	0.0029	101.4	414	20
13	0.762	0.0127	0.012	0.0029	126.2	414	20
14	0.762	0.0127	0.011	0.0029	129.6	414	20
15	0.762	0.0127	0.014	0.0029	78.4	414	20
16	0.762	0.0127	0.010	0.0044	235.8	414	54
17	0.762	0.0127	0.012	0.0044	213.7	414	54
18	0.762	0.0127	0.014	0.0044	192.4	414	54
19	0.762	0.0127	0.011	0.0044	245.5	414	54
20	0.762	0.0127	0.012	0.0044	222.0	414	54
21	0.762	0.0127	0.019	0.0007	599.4	414	31
22	0.762	0.0127	0.015	0.0010	463.3	414	31
23	0.762	0.0127	0.018	0.0011	422.0	414	31
24	0.762	0.0127	0.019	0.0010	412.3	414	31
25	0.762	0.0127	0.018	0.0011	400.6	414	31
26	0.762	0.0127	0.018	0.0013	390.9	414	31
27	0.762	0.0127	0.019	0.0012	388.9	414	31
28	0.762	0.0127	0.021	0.0025	139.3	414	31
29	0.762	0.0127	0.053	0.0011	104.1	414	31
30	0.762	0.0127	0.053	0.0005	196.5	414	31
31	0.762	0.0127	0.053	0.0024	73.4	414	31
32	0.762	0.0127	0.058	0.0003	274.4	414	31
33	0.762	0.0127	0.058	0.0003	292.0	414	31
34	0.762	0.0127	0.067	0.0002	252.3	414	31
35	0.762	0.0127	0.011	0.0030	395.8	359	64
36	0.762	0.0127	0.015	0.0030	383.4	359	64
37	0.762	0.0127	0.018	0.0030	367.5	359	64
38	0.762	0.0127	0.020	0.0030	363.4	359	64
39	0.762	0.0127	0.025	0.0030	303.4	359	64
40	0.762	0.0127	0.013	0.0030	373.0	359	71
41	0.762	0.0127	0.021	0.0030	313.0	359	71
42	0.762	0.0127	0.017	0.0030	301.3	359	71
43	0.762	0.0127	0.018	0.0030	294.4	359	71
44	0.762	0.0127	0.020	0.0030	286.8	359	71
45	0.762	0.0127	0.024	0.0030	279.2	359	71

Table 1 Results from testing carried out circa 1980

	Diameter (m)	Wall Thickness (m)	Dent Depth (m)	Gouge Depth (m)	Failure Stress (MPa)	SMYS (MPa)	Charpy Energy (J)
46	0.762	0.0127	0.027	0.0030	264.1	359	71
47	0.762	0.0127	0.012	0.0030	295.1	359	31
48	0.762	0.0127	0.015	0.0030	268.9	359	31
49	0.762	0.0127	0.011	0.0030	264.8	359	31
50	0.762	0.0127	0.015	0.0030	260.6	359	31
51	0.762	0.0127	0.019	0.0030	242.0	359	31
52	0.762	0.0127	0.022	0.0030	234.4	359	31
53	0.762	0.0127	0.031	0.0030	199.3	359	31
54	0.762	0.0127	0.025	0.0030	187.5	359	31
55	0.762	0.0127	0.030	0.0030	184.1	359	31
56	0.762	0.0127	0.034	0.0030	149.6	359	31
57	0.762	0.0127	0.041	0.0030	126.9	359	31
58	0.610	0.0119	0.043	0.0018	44.1	317	20
59	0.610	0.0119	0.044	0.0015	53.1	317	20
60	0.610	0.0119	0.040	0.0017	65.5	317	20
61	0.610	0.0119	0.040	0.0019	109.6	317	20
62	0.610	0.0119	0.045	0.0025	57.2	317	20
63	0.610	0.0119	0.028	0.0013	182.0	317	20
64	0.610	0.0119	0.029	0.0015	89.6	317	20
65	0.610	0.0119	0.029	0.0013	110.3	317	20
66	0.610	0.0119	0.030	0.0012	226.1	317	20
67	0.610	0.0119	0.031	0.0012	227.5	317	20
68	0.610	0.0119	0.015	0.0033	183.4	317	20
69	0.610	0.0119	0.017	0.0044	122.7	317	20
70	0.610	0.0119	0.016	0.0033	109.6	317	20
71	0.610	0.0119	0.014	0.0031	197.9	317	20
72	0.762	0.0119	0.028	0.0021	117.2	359	27
73	0.762	0.0119	0.027	0.0023	113.8	359	27
74	0.762	0.0119	0.026	0.0025	162.0	359	27
75	0.762	0.0119	0.024	0.0025	170.3	359	27
76	0.914	0.0162	0.016	0.0024	443.3	448	38
77	0.914	0.0164	0.015	0.0031	353.7	448	38
78	0.914	0.0164	0.016	0.0026	424.0	448	38
79	0.914	0.0158	0.068	0.0042	88.3	448	38
80	0.914	0.0158	0.071	0.0046	142.7	448	38
81	0.914	0.0158	0.069	0.0052	124.8	448	38
82	0.914	0.0162	0.026	0.0019	275.8	448	38
83	0.914	0.0161	0.026	0.0016	307.5	448	38
84	0.914	0.0161	0.026	0.0018	302.0	448	38
85	1.067	0.0143	0.051	0.0030	162.0	414	46
86	1.067	0.0143	0.048	0.0033	167.5	414	46
87	1.067	0.0143	0.050	0.0029	170.3	414	46
88	1.067	0.0143	0.077	0.0017	133.8	414	46
89	1.067	0.0143	0.078	0.0016	170.3	414	46
90	0.762	0.0127	0.025	0.0035	80.7	414	20

Table 1 Results from testing carried out circa 1980 (continued)

	Diameter (m)	Wall Thickness (m)	Dent Depth (m)	Gouge Depth (m)	Failure Stress (MPa)	SMYS (MPa)	Charpy Energy (J)
91	0.762	0.0127	0.012	0.0061	137.9	414	20
92	1.067	0.0143	0.006	0.0028	455.7	414	46
93	1.067	0.0143	0.009	0.0029	458.5	414	46
94	0.325	0.0068	0.006	0.0007	408.2	359	18
95	0.325	0.0069	0.007	0.0008	386.8	359	18
96	0.325	0.0074	0.006	0.0010	405.4	359	18
97	0.325	0.0076	0.016	0.0015	98.6	359	18
98	0.325	0.0075	0.016	0.0015	81.4	359	18
99	0.325	0.0077	0.018	0.0012	115.1	359	18
100	0.325	0.0077	0.025	0.0023	44.1	359	18
101	0.325	0.0076	0.026	0.0021	48.3	359	18
102	0.325	0.0069	0.024	0.0023	46.2	359	18
103	0.457	0.0078	0.004	0.0027	247.5	290	27
104	0.457	0.0079	0.002	0.0027	268.9	290	27
105	0.457	0.0079	0.002	0.0027	267.5	290	27
106	0.457	0.0079	0.009	0.0013	375.8	290	27
107	0.457	0.0078	0.009	0.0012	370.3	290	27
108	0.457	0.0080	0.010	0.0012	368.2	290	27
109	0.457	0.0078	0.027	0.0009	310.3	290	27
110	0.457	0.0078	0.028	0.0008	355.1	290	27
111	0.457	0.0079	0.028	0.0007	371.6	290	27
112	0.762	0.0119	0.030	0.0031	144.1	359	31
113	0.762	0.0119	0.014	0.0030	460.6	359	64
114	0.762	0.0119	0.016	0.0030	355.1	359	64
115	0.762	0.0119	0.025	0.0030	310.3	359	71
116	0.762	0.0119	0.010	0.0030	276.8	359	31
117	0.762	0.0119	0.020	0.0030	144.1	359	31
118	0.762	0.0119	0.008	0.0030	380.6	359	35
119	0.762	0.0119	0.017	0.0030	247.5	359	35
120	0.762	0.0119	0.013	0.0030	220.6	359	35
121	0.762	0.0119	0.019	0.0030	208.2	359	35
122	0.762	0.0119	0.027	0.0030	153.8	359	35
123	0.762	0.0127	0.011	0.0036	111.7	414	16
124	0.762	0.0127	0.017	0.0036	133.1	414	16
125	0.762	0.0119	0.010	0.0031	444.7	359	64
126	0.762	0.0119	0.010	0.0031	457.5	359	64
127	0.762	0.0119	0.010	0.0032	453.7	359	64
128	0.762	0.0119	0.019	0.0033	368.2	359	71
129	0.762	0.0119	0.020	0.0033	344.9	359	71
130	0.762	0.0119	0.021	0.0031	326.1	359	64
131	0.762	0.0119	0.023	0.0033	308.9	359	71
132	0.762	0.0119	0.028	0.0033	236.8	359	71

Table 1 Results from testing carried out circa 1980 (continued)

FIGURES

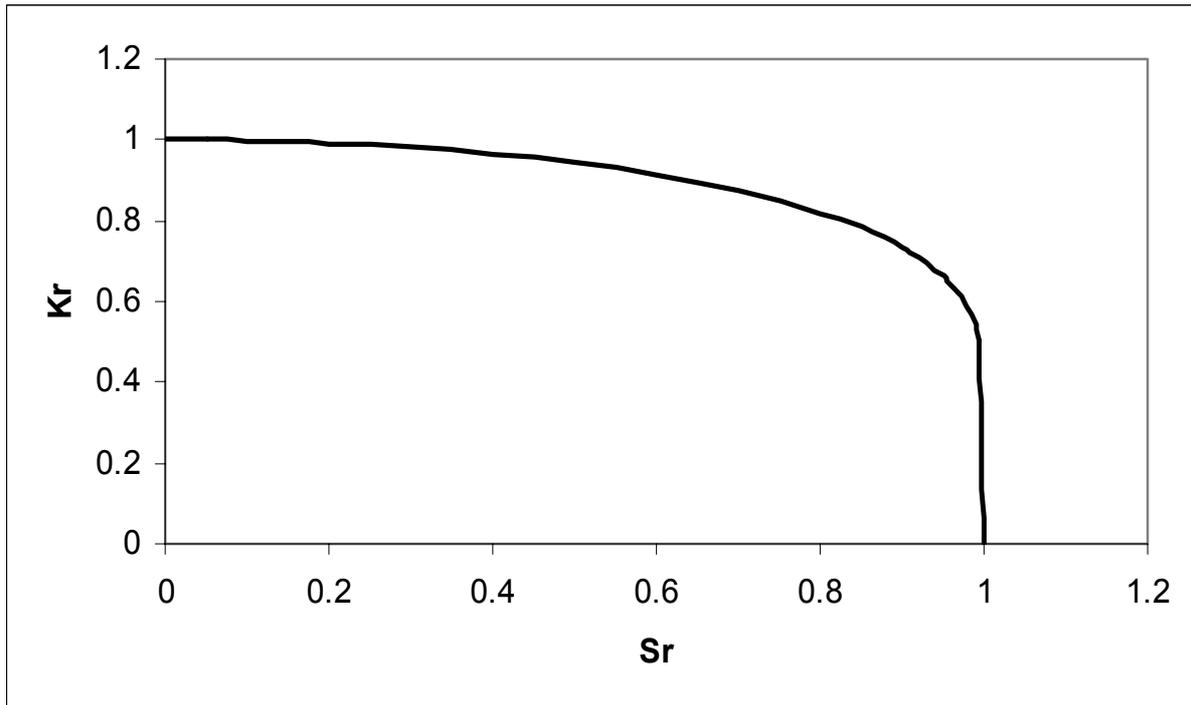


Figure 1. Failure assessment line based on the Dugdale strip yield model

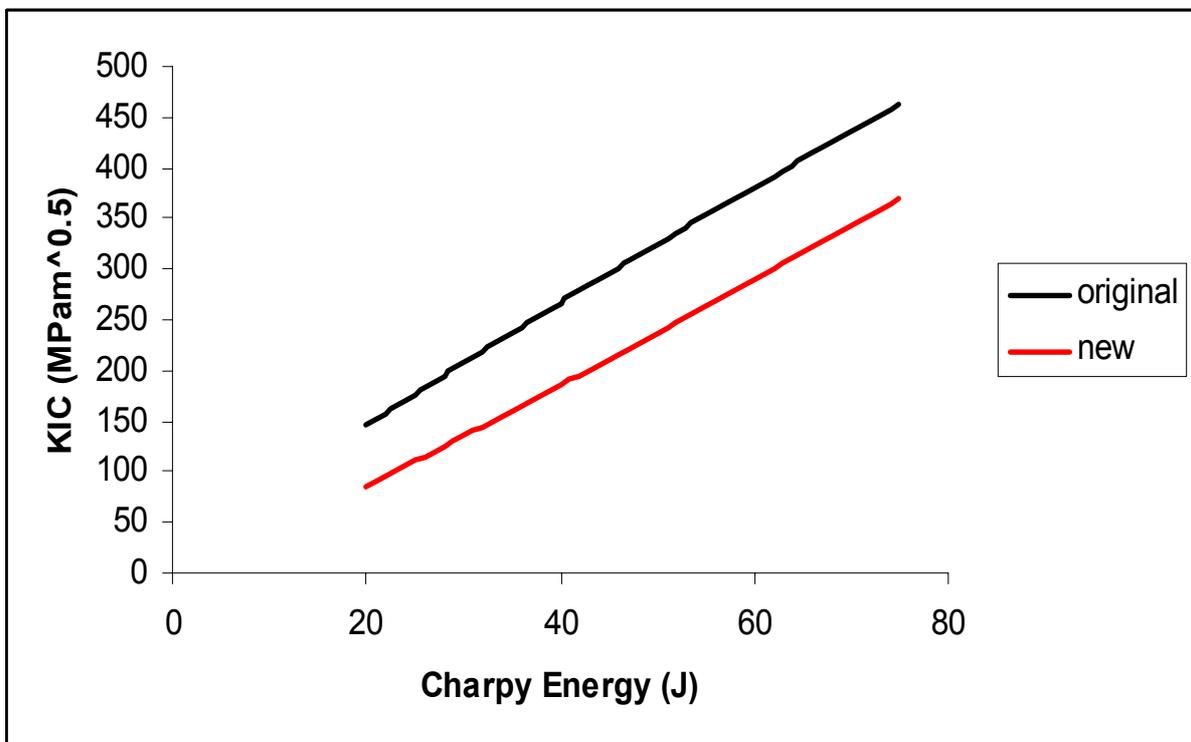


Figure 2. Correlations between Charpy impact energy and fracture toughness

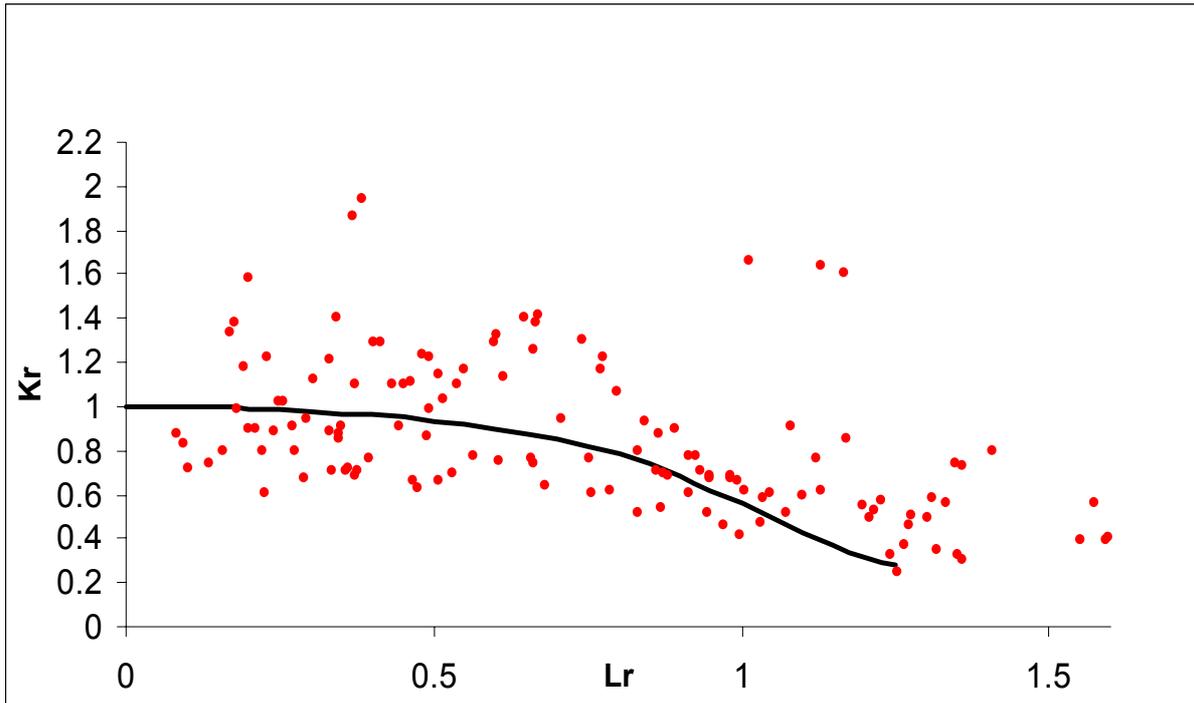


Figure 3. Fit of test data to R6 rev 4 failure assessment line

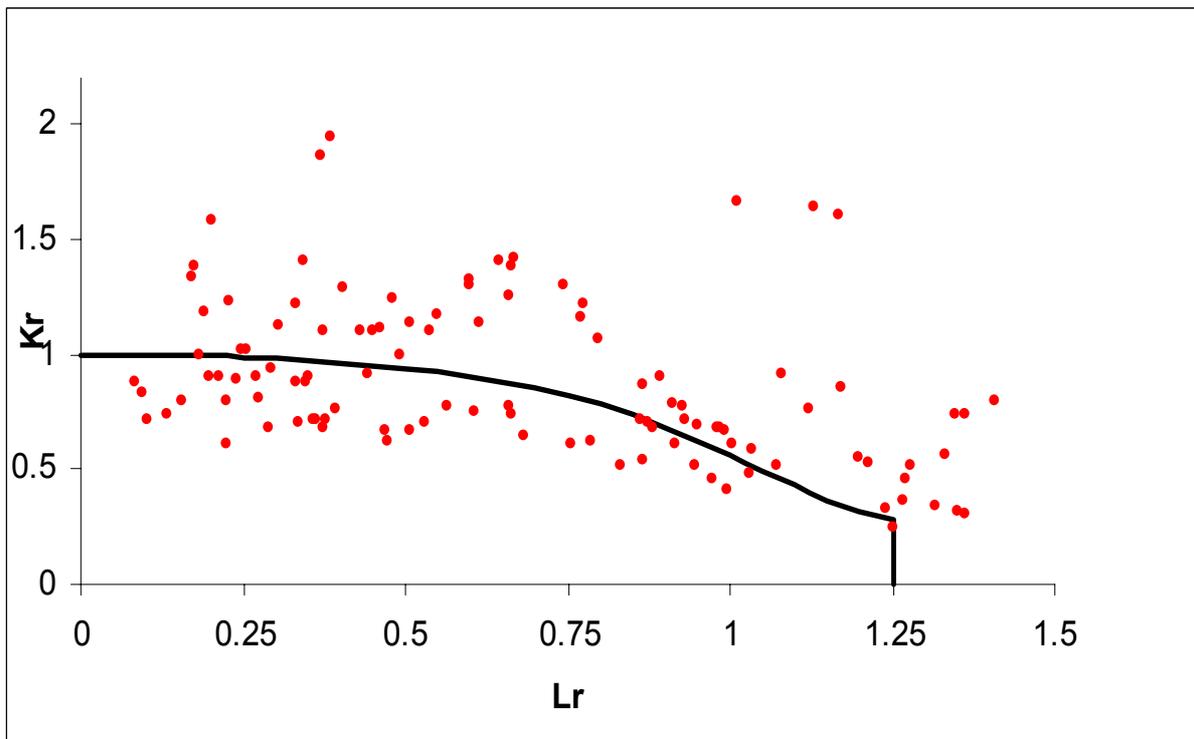


Figure 4. Fit of test data to R6 rev 4 failure assessment line (ring test data only)