

Good Practice Guide

Managing Pipeline Dents

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The guidance in this document identifies what is considered by UKOPA to represent current UK pipeline industry good practice within the defined scope of the document. All requirements should be considered guidance and should not be considered obligatory against the judgement of the Pipeline Owner/Operator. Where new and better techniques are developed and proved, they should be adopted without waiting for modifications to the guidance in this document.

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CONTENTS

1	INTRODUCTION	2
2	Scope and Application	2
2.1	Scope	2
2.2	Application	3
3	Definitions	3
4	Dent Assessment Process	4
5	Assessment of Dents	4
5.1	Data Gathering	4
5.2	Apply Dent Assessment Rules	5
5.3	Prioritisation of Dents	6
5.4	Action Required	10
5.5	Applying the Specified Prioritisation	11
6	Assessment of Weld Quality	11
7	Dent Fatigue Assessment	13
7.1	Dent fatigue life assessment	14
7.2	Pipeline fatigue design life	20
8	records	25
9	References	26
	Appendix 1 – Quality Considerations for Spiral Welded Pipe	28
A1.1	UK Gas Industry Experience with Spiral Welded Line Pipe	28
A1.2	Quality of Spiral Pipe Produced Prior to 1995	29
	Appendix 2 – Pipeline Dent Fatigue Assessment Models	30
A2.1	EPRG Model for Plain Dents	30
A2.2	Dent SCF Fatigue Life Estimation Method	31

1 INTRODUCTION

Pipelines are thin shell structures which are susceptible to geometric distortions and dents during handling, construction and operation. These dents and distortions, particularly when associated with other forms of damage such as gouges, or when associated with welds, can lead to failure of the pipeline. Consequently, rigorous assessment is required. The identification of the damage mechanism which has caused the dent, the severity of the dent and an assessment of the potential for failure is essential. The severity of the dent and the assessment of its impact on pipeline integrity is dependent upon its location, its size and shape, the line pipe mechanical properties, and the applied static and cyclic stresses.

The majority of pipeline in-line inspections (ILI) are carried out using magnetic flux leakage (MFL) inspection tools. These tools are capable of identifying and locating dents in the pipeline, but most cannot currently size dents unless equipped/combined with a geometry/calliper tool. As a result, large numbers of dent features are reported by ILI companies for further consideration by the operator with little or no information for identifying any critical features which require investigation. To accurately assess dents, a high resolution geometry tool or one incorporated in an ILI tool in the first instance is required. This will avoid the requirement for two separate ILI campaigns and will provide the data required for detailed dent assessment and confirmation of repair requirements.

This document has been developed to provide UKOPA members with practical guidance to assess whether a dent identified through an MFL inspection could potentially result in a pipeline failure, resulting in a loss of containment of the fluid being transported or leak within the lifetime of the pipeline. The document also provides some rules that will assist pipeline operators in prioritising the repair of dents that are assessed as requiring further investigation or repair. This document is based on technical work sponsored by UKOPA which is summarised and reported in Reference [1].

2 SCOPE AND APPLICATION

2.1 Scope

The guidance in this document is applicable to all buried pipelines constructed from steel of grade up to and including X65, operated by the UKOPA member companies. These pipelines can be categorised as:

- Natural gas transmission and distribution pipelines
- Petrochemical liquids and gas pipelines
- Oil and refined liquid pipelines

For gas pipelines the guidance is generally applicable to steel pipelines with operating pressures above 7 bar, however the principles of the document can be equally applied to gas pipelines operating at lower pressures.

2.2 Application

The guidance in this document is considered by UKOPA to represent current UK pipeline industry good practice within the defined scope of the document. All requirements should be considered to be guidance and should not be considered to be obligatory against the judgement of the Pipeline Owner/Operator. Where new and better techniques are developed and proved, they should be adopted without waiting for modifications to the guidance in this document.

3 DEFINITIONS

The relevant definitions applied in this document are detailed below:

Dent	A depression which produces a gross disturbance in the curvature of the pipe wall, caused by contact with a foreign body, resulting in plastic deformation of the pipe wall.
Plain (or smooth) dent	A dent which causes a smooth change in the curvature of the pipe wall, causing a depression on the external surface, with no metal loss and no change of curvature at any adjacent seam or girth weld.
Dent associated with weld	A dent that changes the curvature of a seam or girth weld.
Kinked dent	A dent which causes an abrupt change in the curvature of the pipe wall. An abrupt change in curvature is defined as one where the radius of curvature (in any direction) of the sharpest part of the dent is less than or equal to five times the wall thickness <i>Note – this definition is based on the guidance in the EPRG recommendations for the assessment of mechanical damage.</i>
Unconstrained dent	A dent that is free to rebound elastically (spring back) when the object which has caused the dent is removed and the dent is free to reround as the internal pressure varies.
Constrained dent	A dent that is not free to rebound or reround, because the object which has caused the dent has remained in situ (i.e. a dent which is constrained by an underlying rock).
Interaction of dents	Dents will interact with each other when the distance between them on the pipe surface is less than or equal to a certain value, known as the interaction distance. The interaction distance between adjacent dents is 1 pipe diameter.
Spring back	(Also referred to as rebounding) The reduction in dent depth due to the elastic unloading that occurs when the object which has caused the dent is removed from the pipe.
Rerounding	The change in dent depth under internal pressure.
Position	Top of line (TOL) - 8 O'clock to 4 O'clock (top two-thirds of the pipe)
Bottom of line (BOL)	4 O'clock to 8 O'clock (bottom third of the pipe)

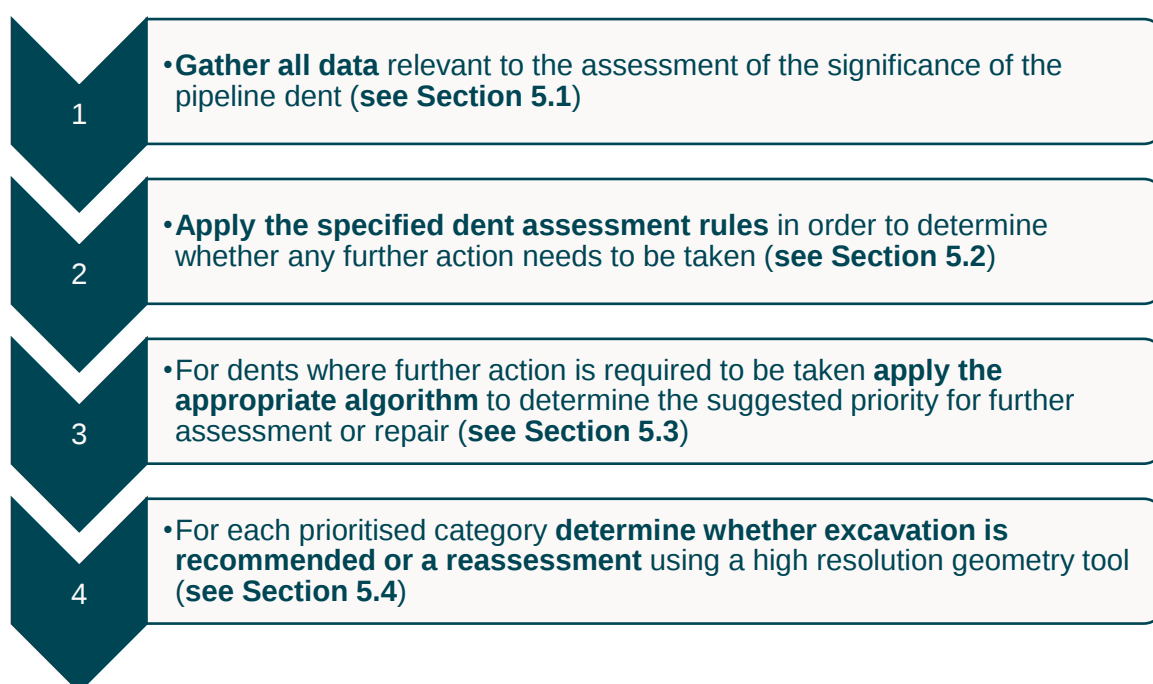
Note: TOL dents should be considered unconstrained. BOL dents may be considered constrained, except where there is evidence to the contrary. In particular, BOL dents should be considered unconstrained where there is evidence of backfill disturbance or washout which could remove support to the dent. BOL dents that have been excavated should be viewed as unconstrained if they are excavated and not repaired with a suitable repair system that restores pipeline integrity and mitigates the effects of pressure cycling. There is experience in the industry where dents that appear to be constrained have failed due to a crack, so great care should be taken if treating a dent as constrained and assessing as such. If treating a dent as constrained consideration should be given to using techniques such as FEA to model dent performance to ensure there is no risk of failure. There have been cases where line pressure reductions have resulted in dent re-rounding which means dents that were previously constrained have lost constraint, so the operator should evaluate the effect of changes in operating parameters on potential fatigue life

Definition of “Metal Loss” by In-Line Inspection Tools

Where a dent is reported as being associated with metal loss by an ILI, the metal loss may be categorised as corrosion, a milling or manufacturing feature, or gouging; or it may be reported more generically as “metal loss”. For any reported dents associated with metal loss where the more generic format is used, it is recommended that before the assessment criteria or prioritisation algorithms in section 5 are applied, additional direct current voltage gradient (DCVG) above-ground surveys are performed at the dent locations. This survey will determine if there is any coating damage associated with the dent and allow an assessment to be made as to whether an excavation is required. Previous ILI records should also be analysed to see if there is any sign of corrosion growth. If a DCVG survey or ILI run comparison suggests active corrosion is present, then repairs should be prioritised at this location as this would suggest external factors could have caused the deformation.

4 DENT ASSESSMENT PROCESS

The dent assessment process detailed in this document has the following key steps:



In addition, guidance is provided on assessment of weld quality (see Section 6) and assessment of fatigue (see Section 7 and Appendix 2).

5 ASSESSMENT OF DENTS

5.1 Data Gathering

In order to undertake an appropriate assessment of any dents identified through ILI, all relevant pipeline data should be collected and documented. This would normally include, but not be limited to:

- Details of the product transported through the pipeline and, for pipelines that have transported different products, the pipeline product history
- Pipeline dimensions, i.e. diameter and wall thickness

- Year of construction
- Linepipe weld type, e.g. SAWL, SAWH, ERW, HFI seamless, spiral welded etc.
- Material grade
- Current pipeline MOP (and MOP history if this was different in the past)
- The dent depth reported by the ILI company
- Dent orientation, e.g. BOL or TOL
- Whether the dent is known to interact with a weld
- The axial and circumferential interaction distance to adjacent dents
- The presence of corrosion and corresponding ILI measured depth in the dent
- Orientation of the pipe seam weld (if applicable)
- The pipeline pressure history
- Pipeline pressure test details
- Any known information regarding the quality of the pipeline welds (see Section 6)
- Details of previous ILI inspections including construction footprint ILI run if available
- Any known construction issues that might have increased the potential for a dent to have occurred, e.g. pipeline known to have been laid in rocky soil
- Any known integrity issues, e.g. known CP or coating issues

5.2 Apply Dent Assessment Rules

The rules in Table 1 below should be applied to determine whether any further action needs to be taken to assess and/or repair a dent identified through ILI.

The rules are only applicable to the assessment of dents in pipelines constructed from steel of grade up to and including X65.

Limits on dent depth are given as a percentage of the pipe outside diameter, D . Limits on depth of metal loss are given as a percentage of the pipe wall thickness, t .

If any one or more of the requirements detailed below are not met for any one dent, then further assessment will be required. If all the relevant requirements are met, then no further action need be taken.	
A	Any kinked dents must be repaired. See Section 3 for definition of a kinked dent.
B	For plain dents (see Section 3) the maximum dent depth must be less than 7% D unless the strain in the dent can be calculated, in which case the maximum calculated strain must be less than 6%.
C	For any dents associated with welds that are of good quality, the maximum depth of the dent must be less than 2% D unless the strain in the dent can be calculated, in which case any plain

	dent associated with a weld of good quality must have a calculated strain which is less than 4%.
D	Where the dent is associated with corrosion, the depth of the corrosion must be less than 20% t and either the maximum dent depth must be less than 7% D, or the calculated maximum strain must be less than 6%. If either the dent depth/strain or the corrosion depth exceeds these limits, then the combined effect of the dent plus the corrosion must be subject to detailed assessment or repaired.
E	If metal loss associated with a dent is caused by gouging, suspected to be caused by gouging, or caused by another mechanism that could cause mechanical deformation or localised hardening, the features should be assessed on a case-by-case basis.
F	If the edge to edge spacing between adjacent dents is less than 1 x diameter in the axial direction, high resolution geometry ILI and finite element analysis is required.
G	Any dents associated with welds of poor quality must be repaired.
H	For pipelines which are subject to pressure cycling, a fatigue assessment must confirm that the cumulative damage over the operating life of the pipeline is acceptable, or the cumulative damage over the length of time up until a repair can be carried out is acceptable. <i>Note: In cases where the fatigue life is exceeded, finite element analysis is required to determine the impact of the dent behaviour when excavated.</i>

Notes:-

- 1 Where both dent depth and dent strain are available, dent strain should be used to prioritise dents.
- 2 If a dent strain assessment has not been completed, dents greater than 7%D in depth should not be allowed without seeking expert advice. This limit is reduced to 2%D for dents on welds.

Table 1 Criteria applied to Assessment of Dents in Gas and Liquid Pipelines Constructed from Line Pipe of Material Grade Up to and Including Grade X65 (L450)

In developing the above criteria it has been assumed that the integrity criteria in ASME B31.8 [2], which addresses gas pipelines, apply to all products.

The peak strain in a dent may be calculated from high resolution geometry ILI data or from direct measurement of the dent profile using the method described in Appendix R of ASME B31.8. Most geometry inspection data contains irregularities, for example due to sensor lift-off or debris in the pipeline, which can cause large over-estimates in the calculated strain values. Some smoothing of the geometry data is usually required, but this must be done carefully to preserve the essential features of the dent shape. No particular smoothing method has been widely accepted by the pipeline industry but methods using B-splines and local polynomial regression have been used.

Recent developments in inspection technologies mean that dent profiles can be accurately measured with laser scanners following excavation. This data can be used to determine dent strain or incorporated into a finite element model to allow for completion of an advanced assessment.

Dents which cannot be assessed and sentenced using the criteria in Table 1 must be investigated, and a repair undertaken if necessary.

5.3 Prioritisation of Dents

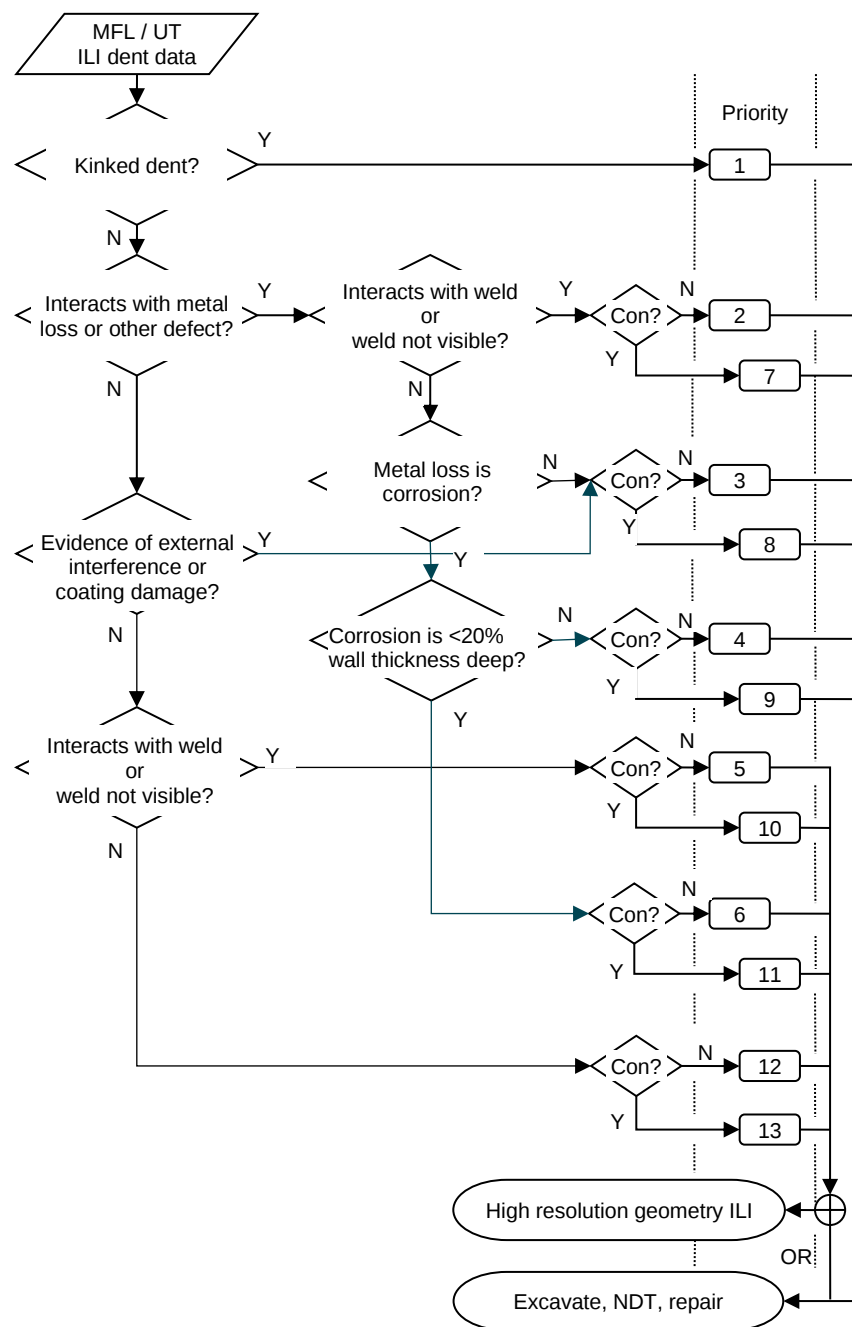
Dent features detected by ILI should be prioritised for investigation by following the appropriate algorithms, either Figure 1 or Figure 2.

Figure 1 should be used where MFL/UT Inspection results are available, but no geometry inspection results are available. The algorithm identifies where dent features require immediate investigation and repair and where further inspection with a geometry inspection tool is suggested.

Table 2 Prioritisation Rationale – MFL/UT Inspection provides a summary of the ranking provided by the algorithm in Figure 1 and identifies where a geometry inspection is suggested.

Figure 2 should be used where both MFL and geometry Inspection results are available.

Table 3 Prioritisation Rationale – MFL/UT + Geometric Inspection provides a summary of the ranking of dents requiring repair provided by the algorithm in Figure 2.



Note: 'Con' means 'constrained', as defined in Section 2.

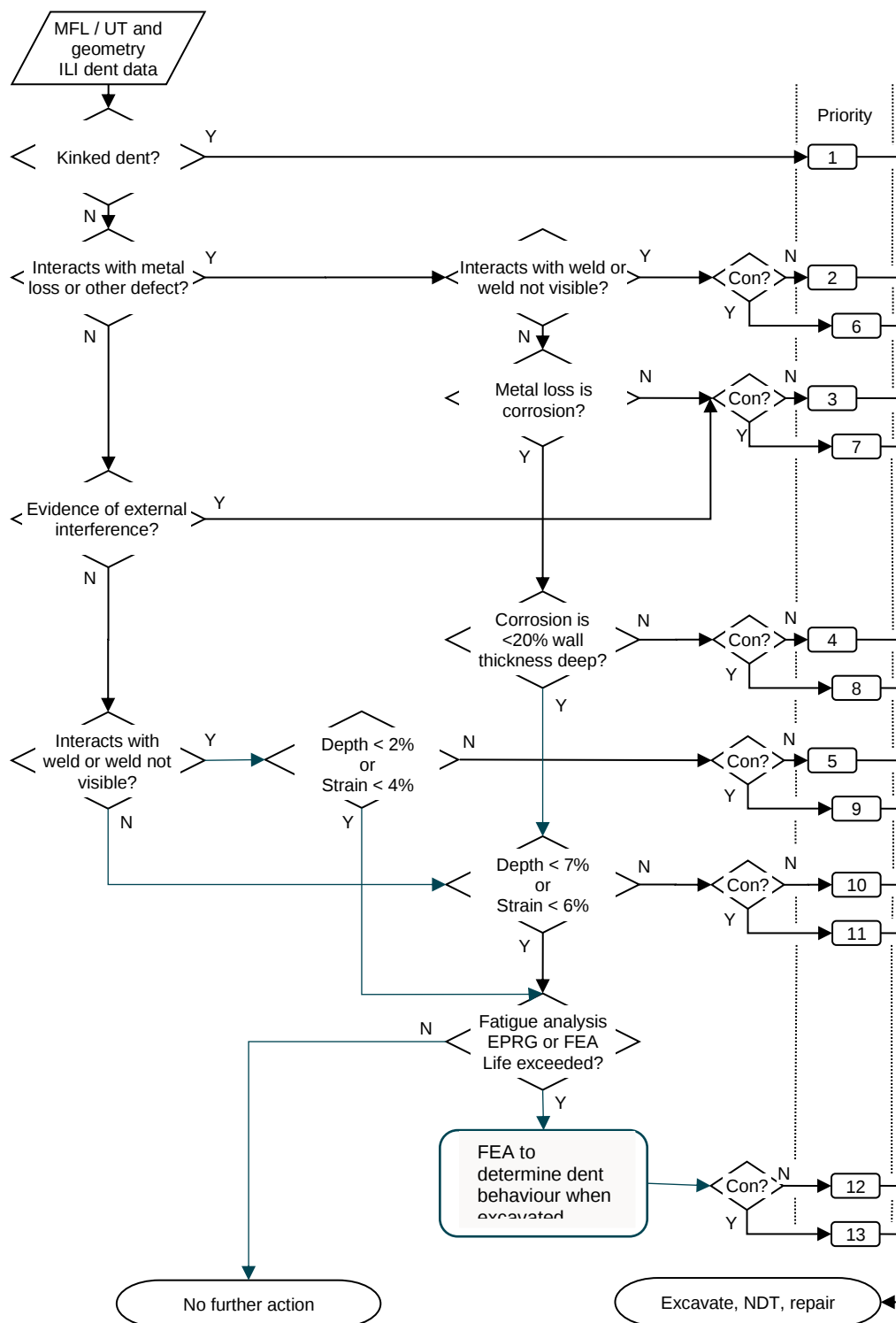
Figure 1 Dent Prioritisation Algorithm Where Geometry ILI Data Is Not Available

Priority	Description	Action
1	Kinked dent	1
2	Unconstrained + associated with metal loss + associated with weld	1
3	Unconstrained + associated with non-corrosion metal loss ¹	1
3	Unconstrained + associated with evidence of external interference or coating damage from CIPS / DCVG ²	1
4	Unconstrained + associated with corrosion deeper than 20% of wall thickness depth	1
5	Unconstrained + associated with weld	1 or 2
6	Unconstrained + associated with corrosion less than 20% of wall thickness depth in grade X65 material or lower	1 or 2
7	Constrained + associated with metal loss + associated with weld	1
8	Constrained + associated with non-corrosion metal loss ¹	1
8	Constrained + associated with evidence of external interference or coating damage from CIPS / DCVG ²	1
9	Constrained + associated with corrosion deeper than 20% of wall thickness depth	1
10	Constrained + associated with weld	1 or 2
11	Constrained + associated with corrosion less than 20% of wall thickness depth in grade X65 material or lower	1 or 2
12	Unconstrained ³	1 or 2
13	Constrained ³	1 or 2

Notes:

- 1 Non corrosion metal loss categorised as a mill or manufacturing defect will have been subject to the mill hydrotest and the precommissioning hydrotest, and therefore may be considered acceptable.
- 2 Unconstrained (TOL) dents associated with evidence of external interference must be investigated.
- 3 Where the edge to edge spacing of adjacent dents less 1xD in the axial direction from another plain dent, the dents should be considered as interacting and should be investigated.

Table 2 Prioritisation Rationale – MFL/UT Inspection



Note: 'Con' means 'constrained', as defined in Section Error! Reference source not found..

Figure 2 Dent Prioritisation Algorithm Where Geometry ILI Data Is Available

Priority	Description	Action
1	Kinked dent	1
2	Unconstrained + associated with metal loss + associated with weld	1
3	Unconstrained + associated with non-corrosion metal loss ¹	1
3	Unconstrained + evidence of external interference or coating damage from CIPS / DCVG ²	1
4	Unconstrained + associated with corrosion greater than 20% wall thickness depth	1
5	Unconstrained + associated with weld + depth $\geq$ 2%D or strain $\geq$ 4%	1
6	Constrained + associated with metal loss + associated with weld	1
7	Constrained + associated with non-corrosion metal loss ¹	1
7	Constrained + evidence of external interference or coating damage from CIPS / DCVG ²	1
8	Constrained + associated with corrosion greater than 20% wall thickness depth	1
9	Constrained + associated with weld + depth $\geq$ 2%D or strain $\geq$ 4%	1
10	Unconstrained + depth $\geq$ 7%D or strain $\geq$ 6% ³	1
11	Constrained + depth $\geq$ 7%D or strain $\geq$ 6% ³	1
12	Unconstrained + predicted fatigue life exceeded (further prioritise dents within this priority level by predicted remaining fatigue life)	1
13	Constrained + predicted fatigue life exceeded (further prioritise dents within this priority level by predicted remaining fatigue life)	1

Notes:

- 1 Non corrosion metal loss categorised as a mill or manufacturing defect will have been subject to the mill hydrotest and the precommissioning hydrotest, and therefore may be considered acceptable.
- 2 Unconstrained (TOL) dents associated with evidence of external interference must be investigated.
- 3 Where the edge to edge spacing of adjacent dents less 1xD in the axial direction from another plain dent, the dents should be considered as interacting and should be investigated.

Table 3 Prioritisation Rationale – MFL/UT + Geometric Inspection

5.4 Action Required

Where the assessment confirms that the dent parameters are within the limits defined in Section 5.2 no further action is required. If the application of the criteria in Section 5.2 identify that remedial action is required then, depending on the outcome of applying the algorithms in Section 5.3, either Action 1 or 2 in Actions required below should be taken.

Action	Description
1	Excavate the dent, carry out NDT, assess and repair if necessary
2	Carry out a high resolution geometry ILI and re-assess dent

Table 4 Actions required

The actions for dents in higher priority levels should be given priority over those in lower priority levels where practical. Where two potential actions are suggested for a given priority level, the operator should choose the most appropriate action based on operational and cost considerations.

If it is indicated that a constrained dent must be excavated, it should be noted that the object which is constraining the dent will be removed. Therefore, the resulting dent must be assessed as an unconstrained (TOL) dent before excavation and repair. This is of particular importance for liquid pipelines and pipelines which are known to experience high fatigue loading, because there is evidence that fatigue failure can occur more rapidly once the constraint is removed. In such cases a permanent repair should be considered.

See section 7.1 on assessment of dent behaviour below.

NOTE: Even if the flowcharts above determine that no repair is necessary it is still advisable for operators to complete a detailed interrogation of the ILI data (including analysis of raw ILI data and traces) to confirm there are no features evident that may impact the outcome of the screening assessment. The reporting threshold of ILI tools may mean that small defects interacting with a dent or minor weld defects which may be detected by the ILI tool are not always reported in pipeline listings.

5.5 Applying the Specified Prioritisation

Section 5.3 provides a prioritisation for the dents that have been identified through ILI. It is outside of the scope of this guidance to provide a suggested timescale upon which the suggested remedial action needs to be taken. This timescale will be very dependent on the risks associated with individual pipelines which in turn will be dependent upon a number of factors including the pipeline's age, operating history, fluid being transported, operating pressure, pressure cycle duty, known condition and population around the pipeline at risk.

In line with UK health and safety legislation it is the responsibility of individual pipeline operators to ensure that risks have been made 'as low as reasonably practicable' (ALARP). Pipeline operators must therefore schedule their remedial work taking all potential risk factors into account and the costs associated with any further inspection, assessment and remedial work.

Further guidance on undertaking ALARP demonstrations for hazardous pipelines can be found in IGEM/TD/2 [3] and PD 8010-3 [4]. The HSE document 'Reducing Risks Protecting People' also provides guidance on the meaning of ALARP and how duty holders can demonstrate that risks have been made ALARP [5].

6 ASSESSMENT OF WELD QUALITY

Weld quality should be established through material and construction records. It may be difficult to determine weld quality, particularly for older pipelines. Weld toughness is a good indicator of weld quality, but older welding standards did not require toughness tests to be carried out, so other indicators are required.

High pressure steel pipeline welding carried out in the mid-1960s and earlier was generally carried out by major consultancies and contractors with knowledge of the international gas and petroleum industry and the American pipeline design and construction standards. The welding standard at this time was API 1104 1953 [6] which contained:

- Part 1 – Welding Specification
- Part II – Radiographic Inspection (10% gamma)
- Part III – Standards of Acceptability
- Part IV – Inspection & Testing

Experts in this field had to be familiar with American standards, the level of standardisation and availability of equipment to these standards made change difficult. The growth of the UK pipeline industry led to changes in the UK and the development of IGE (now IGEM) and BSI standards.

The publication of Gas Industry standards commenced with Communication 674 in 1965 [7]. The Gas Council issued an Instruction for 100% radiography in 1969. This coincided with the publication of BS 4515 [8].

Prior to the publication of the UK pipeline standards and the establishment of formal industry requirements for independent welding inspection and on site supervision, the need to construct and commission pipelines in short timescales and in difficult terrain led to the use of welders untrained in pipeline welding, working with little supervision and inspection. This practice resulted in poor quality field welds. Reviews of pipeline welding from this era show that the quality of such welds can be identified through visual examination and the operational history of leaks, particularly during work on such pipelines.

The UKOPA weld quality project [9] investigated the quality of girth welds in pre-1972 pipelines operated by UKOPA members. The results confirmed that while the historical welds may contain defects that would not meet modern construction standards, mechanical and metallurgical tests showed that the welds were fit for continued service. In addition, analysis of the UKOPA Fault Database confirms that for pipelines which were constructed in accordance with American practices and used the welding standard API 1104:1953, girth weld loss of product incidents occurred as pinholes or small holes only, there have been no large or catastrophic failures.

Based on published industry practice [2] [10] [11] the following quality levels are proposed for both seam and girth welds (based on work reported in [12] [13] and Phase 1 of the UKOPA Weld Quality Project [9]):

Good quality welds

'Good quality' welds meet all of the material and construction criteria or relevant inspection criteria (selected in relation to a specific dent assessment) in Table 5.

Poor quality welds

Poor quality welds are welds where cracking is credible during the denting process. This includes any of the material and construction or inspection criteria in Table 6.

If it is not clear which category applies to a particular weld, either the worst credible category should be assumed, or expert advice should be sought.

Item	Criterion
1	The welds have a full size Charpy toughness of greater than 30 J minimum and 40 J on average from three specimens, at the pipeline's minimum operating temperature.
2	The line pipe was manufactured to API 5L Edition 25 (1970) or later, or equivalent.
3	The weld was fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L.
4	Records show, or it is considered likely that, a hydrotest has been completed at an internal pressure of at least 1.25 times Maximum Operating Pressure (MOP), and there is no evidence that hydrotest failures were caused by welds.
5	There has been no more than one minor leak at the seam or girth weld due to a material and construction defect during operation.
6	Visual examination of more than one girth weld shows a good workmanship e.g. a clean cap, no spatter and clean completion of the weld at the BOL location.
7	Records show that the pipeline was inspected according to the requirements of the applicable pipeline design standard.

Table 5 Indicators of a 'good quality' weld

Quality issues to be considered for spiral welded pipe are presented in Appendix 1.

Item	Criterion
1	Welds of known low toughness (full size Charpy toughness less than 30 J minimum and 40 J on average from three specimens), or operating temperature less than the drop weight tear test transition temperature, or welds which are under-matched (the tensile strength of the weld is less than the line pipe, or the yield strength of the weld is less than the line pipe).
2	Pipe not manufactured to API 5L or equivalent.
3	Welds not fabricated to a recognised pipeline welding standard such as API 1104, or equivalent, or as defined in API 5L.
4	Low frequency electric resistance welds, induction welds, flash welds or oxyacetylene welds.
5	Welds with a history of causing hydrotest failures.
6	There has been more than one minor leak at the seam or girth weld due to a material and construction defect during operation.
7	Visual examination of more than one girth weld shows indications of poor workmanship e.g. an irregular cap, no spatter and irregular completion of the weld at the BOL location.
8	Records confirming the pipeline was inspected to the requirements of the applicable pipeline design standard are not available.

Table 6 Indicators of a 'poor quality' weld

Quality issues to be considered for spiral welded pipe are presented in Appendix 1.

7 DENT FATIGUE ASSESSMENT

A number of methods have been developed to estimate the fatigue resistance of a dent in a pipeline. These range in complexity from screening criteria, presented in tabular form, to detailed FEA and use of appropriate S-N curves. The methods presented below in Section 7.1 are used by the UK gas networks, but their use is considered equally applicable to liquid pipelines.

Once the fatigue resistance of a dent has been estimated, it is necessary to compare that with the design fatigue life of the pipeline and its pressure cycle duty to determine the impact of the dent on the long-term integrity of the pipeline and to schedule a repair, if considered necessary. In addition, the fatigue life of a dent, using one of the methods presented below, is commensurate from when the dent was first introduced into the pipeline. If this cannot be confirmed it is recommended that it is assumed that the dent was introduced at time of commissioning of the pipeline.

The pressure cycle duty of a pipeline is monitored. However, the fatigue design life of a pipeline is not always known. For such cases, guidance is given in Section 7.2 on how this can be estimated.

7.1 Dent fatigue life assessment

The following methods are used in the UK to determine the fatigue resistance of a dent in a pipeline.

The first of these is screening criteria that were developed by the UK gas networks to quickly assess whether the dent threatens the long-term integrity of their pipelines. If a more detailed assessment is considered necessary, the method(s) recommended by PDAM and UKOPA are used. An overview of these is given below, with more detail provided in Appendix 2.

7.1.1 [Fatigue life screening criteria developed by the UK gas networks](#)

Following a review of available full-scale tests that have been undertaken to characterise the fatigue resistance of dent damage in plain pipe, and additional full-scale tests undertaken by the UK gas networks, simple criteria were developed to enable a conservative estimate of the remaining life of plain dent damage.

The UK gas networks index the pressure cycle duty and fatigue design life of their pipelines to an equivalent hoop stress range of 125 N/mm² [14].

Hence, the fatigue life presented below corresponds to the number of cycles of an equivalent hoop stress range in undamaged pipe of 125 N/mm². Consideration is given to both BOL and TOL dents, noting that if a BOL dent is excavated for further investigative works, its remaining life is then equivalent to that of a TOL dent.

The criteria used by the UK gas networks [14] are given below:

Dent depth	Fatigue life ¹
Damage on the top two-thirds of the pipe (TOL dent)	
$H \leq 2.5 \%D$	15,000
$2.5 < H \leq 3.0 \%D$	7,000
$3.0 < H \leq 3.5 \%D$	5,000
$3.5 < H \leq 4.0 \%D$	3,000
$4.0 < H \leq 4.5 \%D$	2,000
$4.5 < H \leq 5.0 \%D$	1,500
$5.0 < H \leq 7.0 \%D$	550
$H > 7.0 \%D$	Expert assessment required, or repair
Damage on the bottom-third of the pipe (BOL dent)²	
$H \leq 5.0 \%D$	15,000
$5.0 < H \leq 7.0 \%D$	5,500
$H > 7.0 \%D$	Expert assessment required, or repair
Notes: 1. fatigue life is expressed as the number of cycles of a remote hoop stress range in undamaged pipe of 125 N/mm ² . 2. If a BOL dent is excavated and subsequently backfilled, its fatigue life will be equivalent to that of a TOL dent	

Table 7 Fatigue Life of Gas Pipelines Containing Dents

The criteria given in Table 7 are applicable to liquid pipelines.

7.1.2 [EPRG model for estimating the fatigue life of an unconstrained dent](#)

A review carried out by PDAM of the different dent assessment methods confirmed that an empirical method developed in 1995 by the EPRG for predicting the fatigue life of an unconstrained plain dent is the best method in terms of the quality of fit with the published full scale test data. The method is based on an S-N curve for a submerged arc welded pipe given in DIN-2413, modified by a dent stress concentration factor (SCF) which has been derived empirically and is a function of dent depth and pipe geometry.

The SCF is not dimensionless and does not take account of the re-rounding behaviour that has been observed in full-scale tests. The method was calibrated using test results generated by EPRG and British Gas [15] [16].

An update to the model was proposed in 2000, taking account of dent shape. Although the 2000 method is recommended in API 1183 for undertaking a Level 2 dent assessment, PDAM [10] found the 1995 model to be slightly more accurate when compared with the test data.

Fatigue life, N is estimated from:

$$N = 1000 \left(\frac{\sigma_U - 50}{2\sigma_A K_s} \right)^{4.292} \quad [1]$$

Where, σ_U : Tensile strength of the pipe (units: N/mm²)

The equations that define $2\sigma_A$ and K_s are explained in detail in Appendix 2.

The S-N curve used in this method is based on a lower bound fit to full-scale experimental fatigue data on different pipe types; seamless and welded (approximately 95% confidence limit). Although there is no factor of safety on predicted life, following the recommendations in the PDAM document, the UKOPA dent management strategy recommends that a safety factor of 6.42 is applied to the predicted fatigue life, which corresponds to a 95% one-tail confidence interval (i.e., a 5% probability of a non-conservative prediction).

For application to a dent on weld, both PDAM and UKOPA recommend that the fatigue life should be estimated using the EPRG 1995 model for plain dents [15], as detailed above (including applying the safety factor of 6.42), and then reducing the fatigue life by an additional factor of 10.

7.1.3 Dent fatigue life estimated using stress concentration factors

This approach was developed by DNV for UKOPA [17]. A review was carried out to identify all available dent SCFs. This was then complemented by a series of FE studies to verify and expand the database of dent SCFs. An upper bound curve was fitted to the data to enable an SCF to be determined for any dent depth, up to 7%D. The SCF does not consider dent shape.

The fatigue resistance of a dent is determined by modifying an S-N curve to take account of the stress concentration due to the dent.

The method was verified by comparing the results from the modified S-N curve with the results from a limited number of full-scale pressure cycle fatigue tests.

Fatigue life, N is estimated from:

$$N = C(SCF \times \Delta\sigma_h)^{-m} \quad [2]$$

Where, $\Delta\sigma_h$: Hoop stress range in the pipe, away from the stress concentration (units: N/mm²)

SCF : Dent stress concentration factor

C : Constant that depends on the S-N curve

m : Constant that depends on the S-N curve

The constants C and m are dependent on whether the assessment is of a dent in plain pipe, on a seam weld or on a girth weld. The constants are given below. They are taken from BS 7608:1993 [17] [18] and represent the mean minus two standard deviations S-N curve, which corresponds to a 2.3% probability of failure.

Dent in plain pipe $C = 1.01 \times 10^{15}$ $m = 4.0$ Class B

Dent on seam weld $C = 1.04 \times 10^{12}$ $m = 3.0$ Class E

Dent on girth weld $C = 0.43 \times 10^{12}$ $m = 3.0$ Class F2

There has been an update to BS 7608 [18], which includes a re-classification of some of the welded joints, including pipe seam and pipeline girth welds. However, the original constants from the 1993 edition have been retained here as they were used in the original model validation and will provide a slightly more conservative result.

There are two equations for determining the dent SCF, the choice of which is dependent on the condition of the dent when it was measured. Both equations are given in Appendix 2. For conservatism, it is recommended that the following equation is used as it gives a slightly higher SCF of the two equations:

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_h} = 1.8 \ln \left(88 \frac{H}{D} + 1 \right) + 1 \quad [3]$$

Where, $\Delta\sigma$: Maximum principal stress range (units: N/mm²)

D : Pipe outside diameter (units: mm)

H : Dent depth measured at zero pipeline pressure, after spring back and dent re-rounding (units: mm)

The definition of dent depth should be noted. In the majority of cases, the dent depth will be measured while the pipeline is at pressure, for example, following an ILI survey. To correct for this, an empirical re-rounding correction factor developed by the EPRG should be used to estimate the corresponding dent depth at zero pipeline pressure,

$$H = 1.43(H_p) \quad [4]$$

Where, H_p : Dent depth measured at pressure (units: mm)

The S-N curves used in this method represent the mean minus 2 standard deviations, which corresponds to a 2.3% probability of failure. In addition, the SCF is an upper bound fit to the dent SCF data.

A review of the safety factors in fatigue design rules indicates that where the potential fatigue location is accessible, and the consequences of failure are not substantial, then a safety factor of 1.0 should be applied when using S-N curves from BS 7608. For inaccessible locations, and where the consequences of a failure can be significant, a safety factor of 10 should be applied.

7.1.4 [Dent fatigue life estimated using finite element analysis methods](#)

A more accurate prediction of dent fatigue life can be achieved by using a combination of FEA and an appropriate S-N curve. It is recommended that expert guidance is sought for the application of this approach. The methodology applied should include,

- Use of high-resolution geometry inspection data, or a surface scan from direct inspection using a laser scanner, to produce a finite element model representative of the dent damage
- Use of an elastic-plastic material model to take account material deformation due to denting and shakedown of the dent that would occur as a result of pressure cycling

- Calibration of the dent model to ensure that the dent depth/profile is consistent with that measured in the pipeline at pressure
- Determination of the magnitude of the most onerous maximum principal stress range corresponding to the minimum and maximum pressure in the pipeline pressure cycle
- Application of a lower bound (mean minus two standard deviations) S-N curve from BS 7608, appropriate for the dent location
- Calculation of fatigue life

For application of this method, it is recommended that the updated S-N curves from BS 7608:2016 are used. Compared to the previous edition of BS 7608, there has been a re-classification of some of the welded joints. This includes those that are recommended for pipe seam and girth welds.

Fatigue life, N is estimated from,

$$N = C(\Delta\sigma_{mp})^{-m} \quad [5]$$

Where, $\Delta\sigma_{mp}$: Maximum principal stress range determined from FEA (units: N/mm²)

C : Constant that depends on the S-N curve

m : Constant that depends on the S-N curve

The constants C and m that represent the mean minus two standard deviations S-N curve from BS 7608:2016 are,

Dent in plain pipe $C = 1.01 \times 10^{15}$ $m = 4.0$ Class B

Dent on seam weld $C = 1.52 \times 10^{12}$ $m = 3.0$ Class D

Dent on girth weld $C = 1.04 \times 10^{12}$ $m = 3.0$ Class E

This approach can be used to infer the need to excavate a dent, and what the likely impact would be due to the loss of soil constraint should the damaged pipe be backfilled following inspection.

FEA can also be used to identify the location and magnitude of the peak strain within the dent. Where the peak strain is coincidental with a weld, there may be an increased risk of failure in the event of the dent re-rounding during excavation. Peak strain information is important if the dent is associated with welds of poor quality or welds with pre-existing anomalies.

7.1.5 [Dent plus corrosion fatigue life estimation](#)

There is no published method for predicting the fatigue life of a dent with associated metal loss due to corrosion.

In 2010, DNV developed a method for the assessment of corrosion damage in pipelines subjected to cyclic pressure loading [19]. The method is based on an S-N curve from BS 7608, where the stress range is modified by an SCF that takes into account the stress raising effect of the area of metal loss. The method was developed as part of a consolidated program of work funded by PRCI and the US Department of Transportation (DOT) Pipelines and Hazardous Materials Safety Administration

(PHMSA). Although validation of the SCF was over a wide range of defect geometries, validation of the fatigue life approach was limited to eight full scale pressure cycle fatigue tests, using two different pipe sizes and material grades; pipe 1 (323.9x8.4mm, seamless, grade X52) and pipe 2 (323.9x15.9mm, HFI, grade X60).

By combining this method with the dent fatigue life estimation method that is presented in Section 7.1.3, a conservative estimate of fatigue life can be obtained for a dent plus corrosion feature. Fatigue life, N is estimated from,

$$N = C(SCF_d \times SCF_c \times \Delta\sigma_h)^{-m} \quad [6]$$

Where, $\Delta\sigma_h$: Hoop stress range in the pipe, away from the stress concentration (units: N/mm²)

SCF_d : Dent stress concentration factor

SCF_c : Corrosion stress concentration factor

C : 1.01×10^{15} (constant for plain pipe, Class B)

m : 4.0 (constant for plain pipe, Class B)

The stress concentration factor for the area of corrosion, SCF_c is calculated from:

$$SCF_c = A_1 + \left[A_2(CD)^2 \left(\frac{\ln(ACL)}{\ln(CCL)} \right)^2 \right] + \left[A_3 \frac{(CD)^2}{\left(\frac{CCL}{\sqrt{Dt}} \right)} \right] + \left[A_4 \frac{(CD)^2 ACL}{CCL} \right] + \left[A_5(CD)^2 \ln \left(\frac{CCL}{ACL(CD)} \right) \right] \quad [7]$$

For $CCL \leq 500\text{mm}$ and $CD \leq 0.2$

Where, D : Pipe outside diameter (units: mm)

t : Pipe wall thickness (units: mm)

ACL : **HALF** axial corrosion length (units: mm)

CCL : **HALF** circumferential corrosion length (units: mm)

CD : Ratio of corrosion depth to pipe wall thickness

A_1 to A_5 : Constants (calibrated to SI units, note above units)

The constants A_1 to A_5 are, $A_1 = 1.47$, $A_2 = 8.91$, $A_3 = -0.23$, $A_4 = -0.72$ and $A_5 = 0.67$.

Equation [7] gives a mean fit to the data (error of +5.8%, -9.5%), and is limited to the following,

D : up to 1,270 mm

t : 9.5 to 19.1 mm

D/t : 40 to 100

ACL : 13 to 500 mm (i.e., corrosion up to 1,000 mm total axial length)

CCL : 13 to 500 mm

CD : up to 0.6 (i.e., 60% of the wall thickness in depth)

Fatigue life estimated using this method assumes that the pipeline coating is reinstated (i.e., corrosion is no longer an active concern).

There have been no full-scale tests carried out to validate the above proposed method to determine the fatigue life of a dent plus corrosion feature.

7.2 Pipeline fatigue design life

If the design fatigue life of a pipeline is not specified it can be estimated using either a stress-life approach (S-N) or fracture mechanics methods.

The S-N approach gives an estimate of fatigue life from the applied stress changes without considering the underlying mechanisms of the initiation and growth of cracks. The S-N curve(s) to use will depend on pipe type and are given in standards such as BS 7608 [18], DNV-RP-C203 [20], EN 1993-1-9 [21], IGEM/TD/1 [13] and PD 5500 [22]. Note, S-N curves are not necessarily the same, even though the identifying letter for the detail classification may be the same.

The fracture mechanics approach considers the growth of cracks from an initial size to a final critical size for fast failure or leakage. Detailed guidance for carrying out fracture mechanics fatigue analyses is given in standards such as BS 7910 [23] and API 579-1/ASME FFS-1 [24].

The choice of which method to use may be dictated by the design standard or by local regulatory requirements.

The method described below outlines an approach used by the UK gas industry for defining the design fatigue life of a gas transmission pipeline that is designed in accordance with the standard, IGEM/TD/1.

7.2.1 [UK Gas Industry Approach to Defining the Design Fatigue Life of a Steel Pipeline](#)

IGEM/TD/1 provides a simplified approach for defining fatigue life. It is based on the pipeline having been subjected to a high-level hydrotest on commissioning. There are circumstances where a more detailed approach is required. These include,

- When the desired hydrotest pressure has not been achieved
- When the actual fatigue cycling exceeds that assumed in the design
- When uprating a pipeline
- When revalidating a pipeline at the end of its design life

For such cases, IGEM/TD/1 states that a detailed fracture mechanics calculation should be used to determine fatigue life and recommends the use of BS 7910.

7.2.2 Pipelines subjected to a high-level hydrotest on commissioning.

A pipeline is considered to have been given a high-level hydrotest if the test pressure on commissioning of the pipeline equates to a hoop stress level equivalent to the following,

Pipeline commission date	Pipeline standard	Pipe type		
		SAW	ERW	Seamless
1970-1993	Communication 674 IGE/TD/1 Edition 1 IGE/TD/1 Edition 2	105% SMYS		90% SMYS
1993-present	IGE/TD/1 Edition 3 IGE/TD/1 Edition 4 IGEM/TD/1 Edition 5 IGEM/TD/1 Edition 6	105% SMYS	100% SMYS	90% SMYS
Note: A UK gas pipeline commissioned prior to 1970 will not have been given a high-level test				

Table 8 Pipeline high-level hydrostatic test requirements, according to IGEM/TD/1

For comparison with Table 8, the hoop stress level, σ_h at the hydrotest pressure is given by,

$$\sigma_h = \frac{PD}{20t} \times \frac{100}{\text{SMYS}} \quad [8]$$

Where: P = hydrotest pressure (bar)

D = pipe outside diameter (mm)

t = pipe nominal pipe wall thickness (mm)

SMYS = Specified Minimum Yield Strength (N/mm²)

If a pipeline has been subjected to a high-level test its design fatigue life can be defined by an S-N curve which is given by,

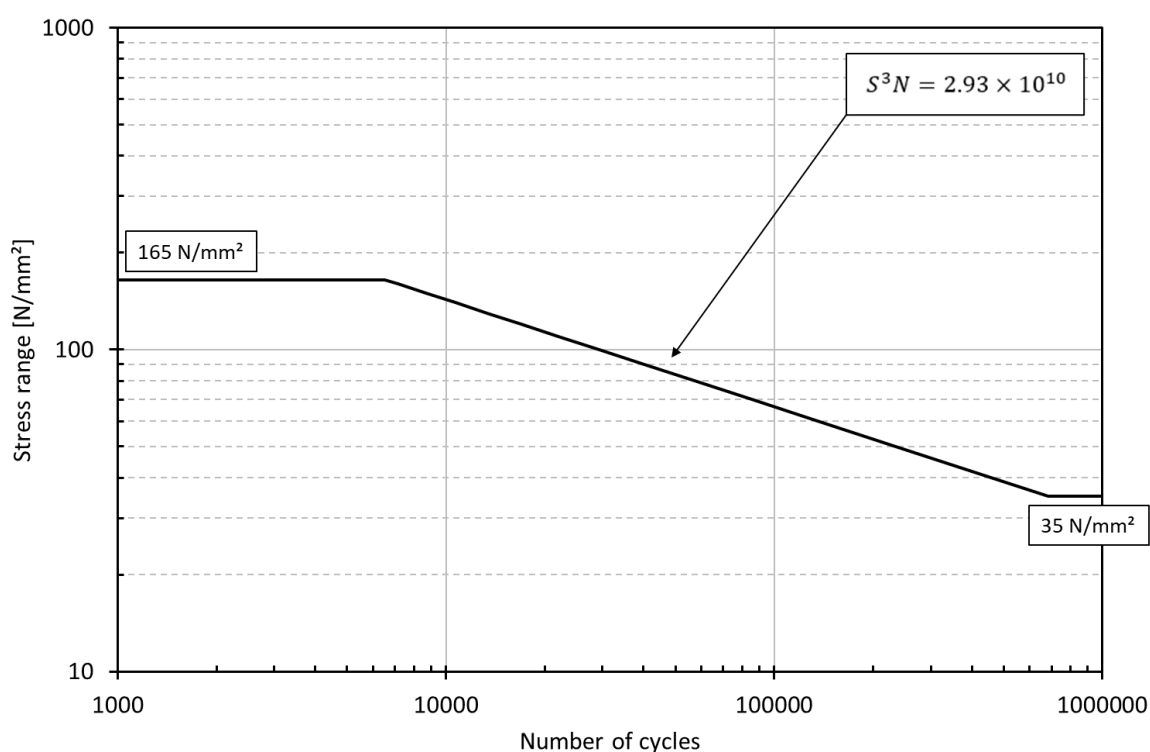


Figure 3 Relationship between stress range and number of cycles (from IGEM/TD/1)

This S-N curve can be used for all types of line pipe. It was defined using fracture mechanics analyses and pressure cycling tests. A factor of safety was applied to the test data and analyses. No additional factor of safety is required.

There is a fatigue limit at 35 N/mm², below which fatigue life is considered infinite. There is also an upper fatigue limit of 165 N/mm² based on the underlying experimental data. Where the stress range is above 165 N/mm², IGEM/TD/1 states that a detailed fracture mechanics calculation should be used to determine the fatigue life.

The UK gas networks specify the design fatigue life of a pipeline as the number of cycles of a constant amplitude hoop stress range of 125 N/mm². A pipeline subjected to a high-level hydrotest on commissioning will have a fatigue life of 15,000 cycles of 125 N/mm² hoop stress range (see Figure 3).

7.2.3 Pipeline design fatigue life based on fracture mechanics.

If the pipeline has been subjected to a low-level hydrotest on commissioning, or experiences stress ranges more than 165 N/mm², IGEM/TD/1 states that a detailed fracture mechanics calculation, using the methods in BS 7910, should be used to determine fatigue life.

Assessments using the fracture mechanics approach are complex and should only be undertaken by persons with an understanding of fracture mechanics principals and with access to suitable software.

Consequently, the UK gas networks developed a set of screening charts which give a conservative estimate of design fatigue life. Each screening chart is constructed from hundreds of detailed fracture mechanics analyses for the range of pipe sizes and material grades used by the UK gas networks. The charts present bands of constant fatigue life of 125 N/mm² stress cycles, plotted on axes of hydrotest pressure and maximum operating pressure (MOP) as functions of the material SMYS. The design

fatigue life estimated from a screening chart will likely be less than the life that would otherwise be calculated from a pipeline specific detailed fracture mechanics approach.

Each chart is specific to a range of pipe sizes (diameter and wall thickness) and material grades. However, the charts can still be used to obtain a conservative estimate of fatigue life for a pipeline that has a thinner wall thickness, a larger outside diameter, or a higher D/t ratio.

A pipeline specific detailed fracture mechanics assessment would need to be carried out for a pipeline that has a thicker wall thickness, or a smaller outside diameter, or a smaller D/t ratio.

The design fatigue life of a pipeline is estimated using the following 3 steps [14],

Step 1 : calculate the hoop stress level at the hydrotest pressure, from

$$\text{Hydrotest stress} = \frac{P_{hyd}D}{20t} \times \frac{100}{SMYS} \quad [9]$$

Where: P_{hyd} = hydrotest pressure (bar)

Step 2 : calculate the hoop stress level at the MOP, from

$$\text{MOP stress} = \frac{P_{MOP}D}{20t} \times \frac{100}{SMYS} \quad [10]$$

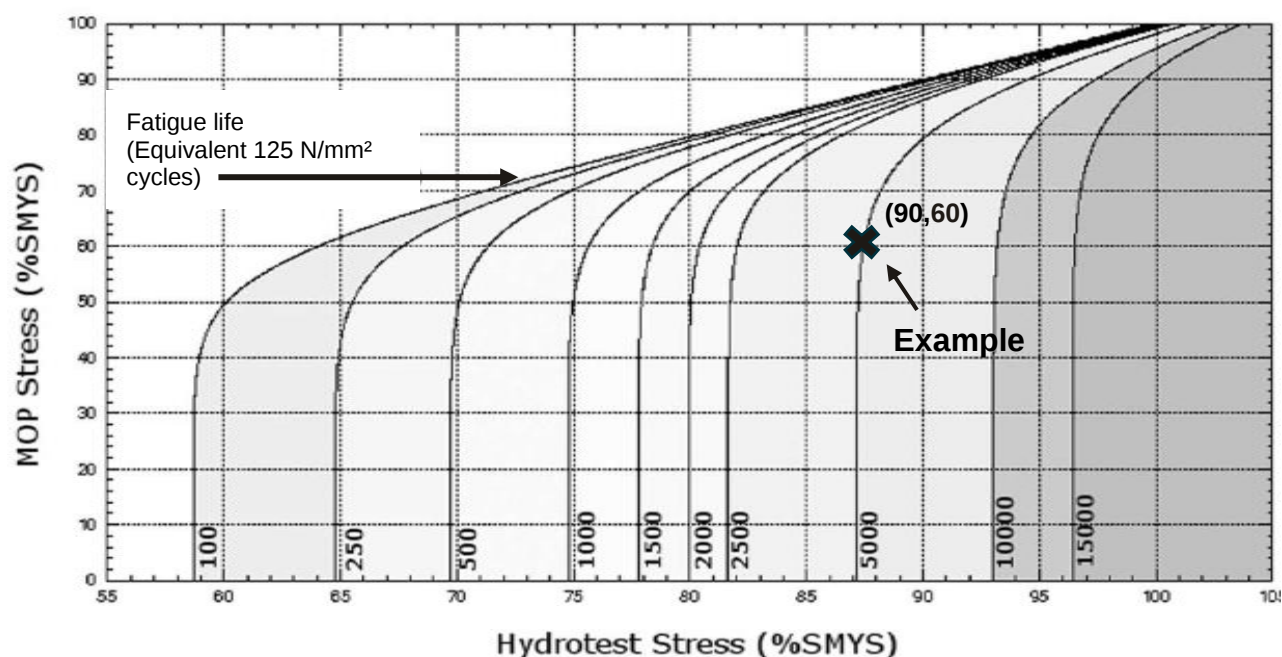
Where: P_{MOP} = Maximum Operating Pressure (bar)

Step 3 : select screening chart using Table 9 and plot point (x,y) from Step 1 and Step 2, to confirm design fatigue life.

Screening Chart	Pipe outside diameter, D [mm]	Pipe nominal wall thickness, t [mm]	D/t	Material Grade ^s
Figure X.2	$168 < D \leq 762$	$5.6 < t \leq 22.2$	$14 < D/t \leq 64$	X42, X46, X52, X60
Figure X.3	$914 < D \leq 1219$	$12.7 < t \leq 28.7$	$36 < D/t \leq 77$	X60, X65
Figure X.4	1219	$14.3 < t \leq 22.9$	$53 < D/t \leq 85$	X80
Note: \$ includes equivalent material grades to ISO 3183.				

Table 9 Screening chart selection for the estimation of design fatigue life.

An example application is shown in Figure 4, where the hydrotest stress is calculated to be 90% SMYS and the MOP stress is 60% SMYS. The assessment point lays between the 5,000 and 10,000 bands that represent a constant fatigue life of 125 N/mm² stress cycles. The design fatigue life of the pipeline is the lesser of the two, at 5,000 cycles.



Example: a pipeline with an assessment point 90,60 (hydrotest stress, MOP stress) shall have a design fatigue life of 5,000 cycles of an equivalent hoop stress range of 125 N/mm²

Figure 4 Fatigue screening chart for grades X42 to X60, diameter 163 < D ≤ 762mm, wall thickness 5.6 < t ≤ 22.2mm and D/t ratios 14 < D/t ≤ 64.

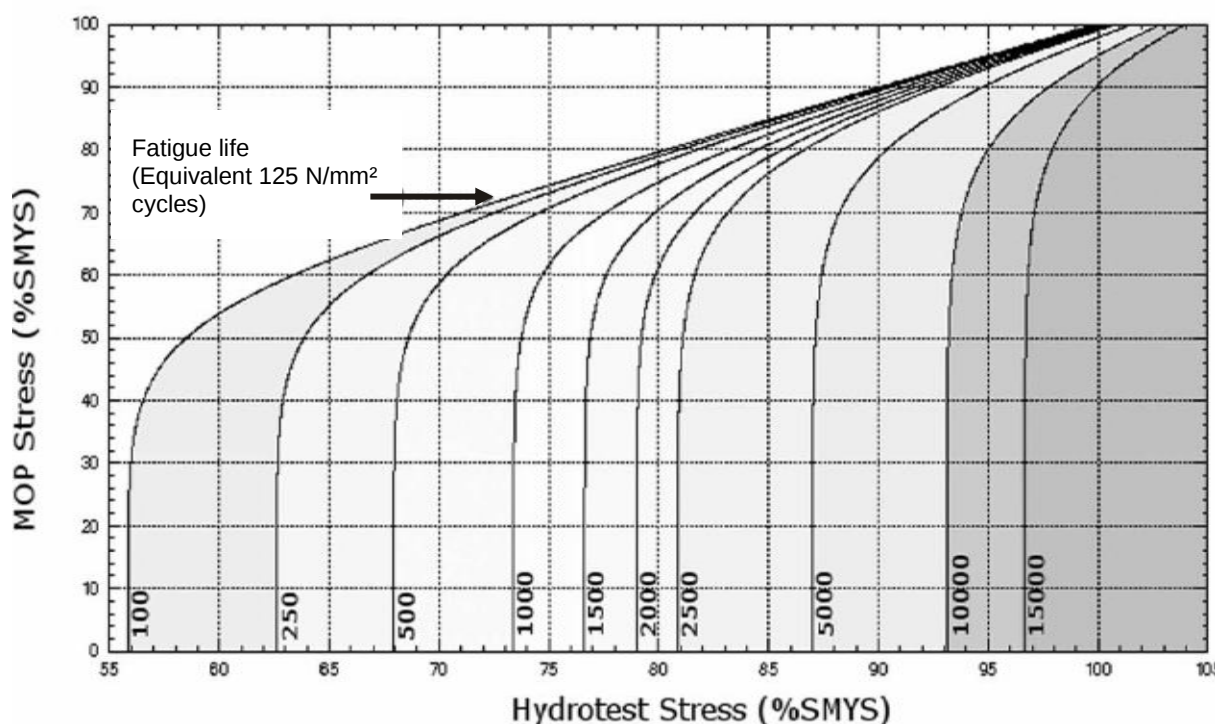


Figure 5 Fatigue screening chart for grades X60 to X65, diameter 914 < D ≤ 1219mm, wall thickness 12.7 < t ≤ 28.7mm and D/t ratios 36 < D/t ≤ 77

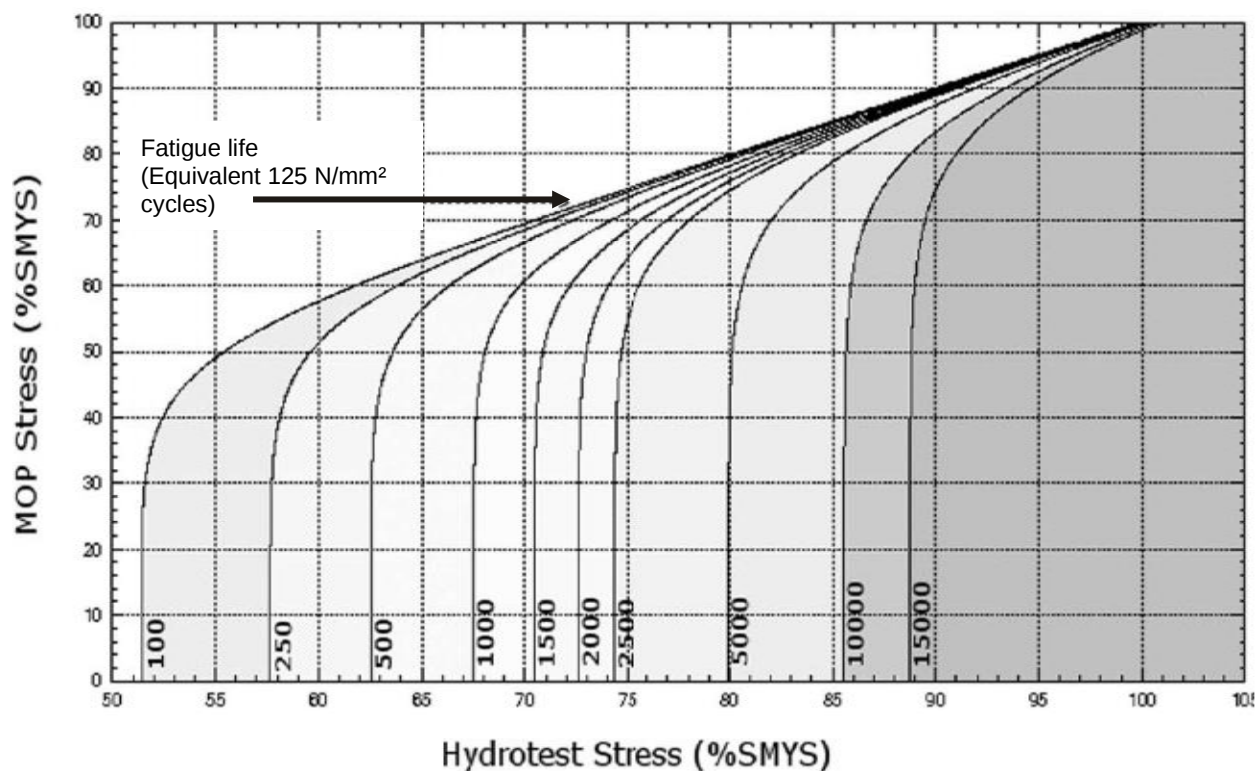


Figure 6 Fatigue screening chart for grades X80, diameter 1219mm, wall thickness $14.3 < t \leq 22.9$ mm and D/t ratios $53 < D/t \leq 85$.

8 RECORDS

It is important that accurate records of repaired dents are kept so that repaired dents can be excluded from future assessments and repair programmes.

Records should also be retained of any dent fatigue life assessments. These will need to be re-evaluated if the fatigue loading caused by internal pressure variations changes significantly during the future operation of the pipeline, for example due to changes in valve control systems or product batching arrangements. It is therefore important that all assessments are appropriately recorded and logged so that they can be re-assessed should the pressure cycling of the pipeline change significantly or if the anticipated lifetime of the pipeline is extended.

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APPENDIX 1 – QUALITY CONSIDERATIONS FOR SPIRAL WELDED PIPE

To carry out an assessment of a dent on a weld it is important to first establish weld quality. This should be confirmed from materials and construction records. However, for older pipelines this information may not be readily available.

The early perception of spiral pipe as a product, and of individual producers and their capabilities, varied from country to country. Canada, for example, produced high quality spiral pipe and a large proportion of the Canadian gas transmission system is built from spiral pipe. In contrast, in the US and the UK, spiral pipe was virtually unknown in large diameter gas transmission systems.

This was due, in part, to a number of perceived problems with spiral pipe when compared to longitudinal welded pipe, in particular,

- Distortion of the pipe during rolling and welding, and the absence of cold expansion, leading to pipe with ovality and poor dimensional tolerances. This creates problems with excessive mismatch at girth welded joints.
- Difficulties with inspection of the spiral weld during manufacture due to rotation of the pipe making it difficult to track the seam by X-Ray or ultrasonic equipment.
- There is a greater length of welded seam so an increased likelihood of welding defects.
- The pipe is more likely to change shape during pressurisation.
- Field bending and induction bending were more challenging.

This appendix has been prepared to help the engineer, absent of pipeline materials and construction records, get an indication of the likely quality of spiral pipe used, and to decide whether inspection and testing of the pipe and weld should be carried out as part of the assessment process.

The guidance below is based on a review carried out in 1997, on behalf of BG Research & Technology, of the production and properties of spiral welded pipe. This was to see what advancements had been made towards producing quality spiral welded pipe, as early UK experiences with pipeline construction using this pipe type were poor.

A brief overview is given below of the UK's early experience with spiral welded pipe. This is followed by a qualitative ranking of early spiral pipe manufacturers based on information available at the time of the review relating to their production equipment, materials used, industries supplied and pipeline projects.

A1.1 UK Gas Industry Experience with Spiral Welded Line Pipe

There is only a small amount of spiral pipe that has been used in the construction of the UK gas pipeline system. This was laid around 50 years ago. Problems with excessive mismatch between adjacent pipe ends were found during fit up for girth welding and this, together with high carbon equivalents at the time, resulted in poor weldability. There were also some Mill quality control issues associated with the spiral weld quality which was very poor at this time. It was not unusual to find spiral weld sections where there was lack of interpenetration, or even missing sections of the

internal weld bead. It was due to these early experiences that spiral pipe gained a poor reputation in the UK for gas pipelines, and its use was discontinued.

Despite the problems experienced at the time of construction, the service experience with this early spiral welded pipe has been as good as longitudinally welded pipe. But these early UK experiences

were not uncommon around the world and a large number of companies became reluctant to use spiral welded pipe for high pressure applications.

However, since around 1990, with the advent of high-quality spiral pipe it has seen a revival and has been used successfully for critical high-pressure applications in many regions of the world. The major market for spiral pipe was Europe and Canada, which was largely attributed to the presence in those areas of high-quality strip producers for line pipe manufacturers. Pipe was welded successfully using mechanised welding equipment, with no fit-up problems, highlighting the excellent dimensional tolerances now achieved.

In 2006, the UK once again used spiral pipe, this time to construct a 16km long high-pressure gas pipeline.

A1.2 Quality of Spiral Pipe Produced Prior to 1995

The 1997 review found that the capabilities of the manufacturers of spiral pipe varied widely. This was determined by several factors, which included,

- Design, construction standard and age of the production equipment.
- Quality of the source steel.
- Inspection equipment.

The review considered some 36 manufacturers of spiral pipe, all of whom had experience of supply to the oil and gas industries. The manufacturers were separated into three tiers.

Tier 1 are premier producers who continually manufactured good quality spiral pipe.

Tier 2 manufacturers were known, at the time, to have participated in major pipeline projects, but there was insufficient information to comment on their production facilities, or their track record was based on a small number of pipeline projects. It was noted that some of the manufacturers had invested heavily in up-to-date equipment and were making strenuous efforts to become world players in the spiral pipe market. Spiral pipe produced by a Tier 2 manufacturer is likely to be of good quality.

Tier 3 is for manufacturers where there was a lack of information about their capabilities, and some only being capable of supplying spiral pipe to the construction and water industries at that time. This does not necessarily mean that they supplied poor quality spiral pipe, just that there was uncertainty due to available information at the time of the review. Absent of pipeline records that include Mill test certificates and inspection reports relating to pipeline construction, it is recommended that spiral pipe produced by a Tier 3 manufacturer should be considered as potentially low quality.

Inspection and testing of sample pipes and welds should therefore be carried out to confirm quality.

APPENDIX 2 – PIPELINE DENT FATIGUE ASSESSMENT MODELS

A2.1 EPRG Model for Plain Dents

The EPRG model, which is recommended in PDAM and the UKOPA Dent Management Strategy, is based on an S-N curve for a submerged arc welded pipe given in DIN-2413, modified by a dent SCF which has been derived empirically and is a function of dent depth and pipe geometry. The fatigue life (N) of a plain dent is estimated by,

$$N = 1000 \left(\frac{\sigma_U - 50}{2\sigma_A K_s} \right)^{4.292}$$

Where, σ_U	: Tensile strength of pipe	(N/mm ²)
$2\sigma_A$	: Equivalent cyclic stress at $R=0$	(N/mm ²)
	$= \sigma_U \left[B\sqrt{(4 + B^2)} - B^2 \right]$	
B	: $= \frac{\frac{\sigma_a}{\sigma_U}}{\sqrt{1 - \left(\frac{\sigma_{max} - \sigma_a}{\sigma_U} \right)}}$	
R	: Ratio of the minimum stress (σ_{min}) to the maximum stress (σ_{max}) in the pressure cycle	
σ_{max}	: Hoop stress at the maximum pressure in the pressure cycle	(N/mm ²)
σ_{min}	: Hoop stress at the minimum pressure in the pressure cycle	(N/mm ²)
σ_a	: Stress amplitude	(N/mm ²)
	$= \frac{\sigma_{max} - \sigma_{min}}{2}$	
K_s	: Dent stress concentration factor	
	$= 2.871\sqrt{K_d}$	
K_d	: $= H_o \frac{t}{D}$	
D	: Pipe outside diameter	(mm)
t	: Pipe wall thickness	(mm)
H_o	: Dent depth measured at 'zero' pipeline pressure	(mm)
	$= 1.43H_r$	
H_r	: Dent depth measured at pressure	(mm)

The S-N curve used in this method is based on a lower bound fit to full-scale experimental fatigue data on different pipe types; seamless and welded (approximately 95% confidence limit). Although there is no factor of safety on predicted life, following the recommendations in the PDAM document, the UKOPA dent management strategy recommends that a safety factor of 6.42 is applied to the predicted fatigue

life, which corresponds to a 95% one-tail confidence interval (i.e., a 5% probability of a non-conservative prediction).

Both PDAM and UKOPA recommend that if the dent is associated with a weld, the fatigue life should be estimated using the EPRG model for plain dents, as detailed above, and then reducing the fatigue life by an additional factor of 10.

A2.2 Dent SCF Fatigue Life Estimation Method

Fatigue life is estimated using the following formulae,

$$N = C(SCF \times \Delta\sigma)^{-m}$$

Where, $\Delta\sigma$: Stress range (units: N/mm²)

C : Constant that depends on the S-N curve

m : Constant that depends on the S-N curve

The constants C and m are dependent on whether the assessment is of a dent in plain pipe, on a seam weld or on a girth weld. The constants are given below. They are taken from BS 7608:1993 and represent the mean minus two standard deviations S-N curve, which corresponds to a 2.3% probability of failure.

Dent in plain pipe $C = 1.01 \times 10^{15}$ $m = 4.0$

Dent on seam weld $C = 1.52 \times 10^{12}$ $m = 3.0$

Dent on girth weld $C = 0.43 \times 10^{12}$ $m = 3.0$

It is noted that when BS 7608 was updated in 2016 there was a re-classification of some of the welded joints, including pipe seam and pipeline girth welds. It is proposed to maintain the S-N curve constants from the 1993 edition of BS 7608 as they will give a slightly more conservative result.

For carrying out a more advanced analysis, whereby S-N curves are used in conjunction with dent SCFs that are determined by pipeline/damage specific FE modelling, then use of the S-N curves in the 2016 edition of BS 7608 would be recommended.

UKOPA specifies two equations for determining an upper bound dent SCF. The choice of which depends on the measured dent depth.

If the dent depth is measured at zero pipeline pressure after removal of the indenter and elastic spring back of the dent (H_o), the SCF is given by,

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_h} = 2.05 \ln \left(65 \frac{H_o}{D} + 1 \right) + 1$$

Where, $\Delta\sigma$: Maximum principal stress range (units: N/mm²)

$\Delta\sigma_h$: Hoop stress range in the pipe, away from the stress concentration (units: N/mm²)

D : Pipe outside diameter (units: mm)

If the dent depth is measured at zero pipeline pressure after spring back and dent re-rounding (H_r), the SCF is given by,

$$SCF = \frac{\Delta\sigma}{\Delta\sigma_h} = 1.8 \ln \left(88 \frac{H_r}{D} + 1 \right) + 1$$

Note: The above equation will give a higher SCF and therefore ensure that the assessment is conservative.