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## HIGH-LEVEL DENT ASSESSMENT FROM ILI

*Advantica  
Restricted*

*Restricted to: National Grid plc, Northern Gas  
Networks, Scotia Gas Networks, Wales & West  
Utilities & Advantica*

**Prepared for:**

Barry Dalus

**Northern Gas Networks**

7 Camberwell Way  
Moorside Park  
Sunderland  
SR3 3XN

**Prepared by:**

Mohamed Dafea and Troy Swankie

Advantica

Holywell Park  
Ashby Road  
Loughborough  
Leicestershire  
LE11 3GR  
United Kingdom

Tel: +44 (0)1509 28 2784

Fax: +44 (0)1509 28 3119

E-mail: [Mohamed.Dafea@advanticagroup.com](mailto:Mohamed.Dafea@advanticagroup.com)

Website: [www.advanticagroup.com](http://www.advanticagroup.com)

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***Previous issues of this document shall be destroyed or marked SUPERSEDED***

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## DISTRIBUTION

Name	Company
Barry Dalus	<b>Northern Gas Networks</b> 7 Camberwell Way Moorside Park Sunderland SR3 3XN
Steve Skipp	<b>Scotia Gas Networks</b> 2 Leasons Hill, St Mary Cray, Orpington, Kent BR5 2TN
Chris Clarke	<b>Wales &amp; West Utilities</b> Spoooner Close Celtic Springs Coedkernew Newport NP10 8FZ
Robert Owen	<b>National Grid plc</b> NG House Warwick Technology Park Gallows Hill Warwick CV34 6DA

## EXECUTIVE SUMMARY

National Grid, Northern Gas Networks, Scotia Gas Networks and Wales and West Utilities (hereafter referred to as the sponsors) intend to undertake in-line inspections as part of condition monitoring of their high pressure pipelines.

Advantica has been requested to develop a '**high level**' flow chart to assist in the evaluation of the findings from the in-line inspection (ILI) tools and to identify what steps are required to undertake an initial screening level assessment of the integrity of a damaged pipeline. As requested by the sponsors, the procedure has been developed so that it is consistent with the approach outlined in P/11.

The dent assessment algorithm has been developed with consideration towards the following:

- The linepipe properties.
- The operating stress level of the pipeline.
- The size, shape and location of the dent (i.e., the position of the dent around the pipe circumference and the proximity of the dent to a girth or seam weld).
- The likelihood that the dent is due to mechanical damage.
- Whether the dent is associated with any defects.
- Whether there is a potential for the damage to reduce the fatigue life of the pipeline.
- The requirement for remediation actions and further assessments.

Section 1 of this report provides a general overview of the project requirements and definitions of the terms used. Section 2 provides an overview of the most common ILI tools and discusses their ability to locate and size dents and any associated defect/s. Section 3 provides a detailed overview of the current understanding of the effect of dents and dents combined with other defects on the integrity of a pipeline, and Section 4 presents the dent assessment algorithm.

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# 1 INTRODUCTION

National Grid, Northern Gas Networks, Scotia Gas Networks and Wales and West Utilities (hereafter referred to as the sponsors) intend to undertake in-line inspections as part of condition monitoring of their high pressure pipelines.

Advantica has been requested to develop a ‘**high level**’ flow chart to assist in the evaluation of reported dent damage from in-line inspection (ILI) tools and to identify what steps are required to undertake an initial screening level assessment of the integrity of a damaged pipeline. As requested by the sponsors, the procedure has been developed so that it is consistent with the approach outlined in P/11<sup>[1]</sup>.

The focus of this report is to review the recent work done towards the assessment of dents and to summarize the potential effects of dents and dent/defect combinations on the integrity of gas pipelines under static internal pressure loading and pressure cycling. This information is used as the basis for building a ‘high level’ assessment algorithm.

The different types of dents discussed in this report are defined as follows<sup>[1]</sup>:

- **Dent** – a dent is described as a change in the pipe geometry causing a depression in the pipe surface.
- **Kinked Dent** – a kinked dent is described as a dent that contains rapid changes of contour.
- **Smooth dent** – a smooth dent is described as a distortion of the pipe wall, not necessarily resulting in localized reduction of wall thickness.
- **Plain dent** – a plain dent is described as a smooth dent that contains no wall thickness reductions<sup>2</sup> (e.g. corrosion, gouge, or crack) and does not change the curvature of an adjacent girth weld or seam weld<sup>[2]</sup>. It should be noted that P/11 does not explicitly consider this dent type on its own. P/11 considers a plain dent as being the same as smooth dent.

For consistency with P/11, this report does not differentiate between plain and smooth dents. The term ‘smooth dent’ is used from here on when presenting information from the public domain on both smooth and plain dents. A smooth dent can be further defined based on its ability to re-round under increasing internal pressure (i.e. constrained and unconstrained)<sup>[3]</sup>. Unconstrained dents will move (i.e. re-round) with increasing internal pressure and are free to flex during pressure cycling. In contrast, constrained dents are restricted from moving or flexing.

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<sup>1</sup> A generic term relating to each sponsor’s version of P/11 at the time of the de-merger, T/PR/P/11<sup>[1]</sup>.

<sup>2</sup> It should be noted that the plastic deformation associated with the denting process will result in local wall thinning within the dented area, which is dependent on dent depth. However, this is generally not considered in the assessment of smooth dents, and is unlikely to be identified by the ILI tool.

Rebounding is a term used to describe the initial reduction in dent depth due to elastic unloading (i.e. spring back) of the dent following removal of the indenter from the pipe.

Race<sup>[4]</sup> reports that a review undertaken by the US DOT of natural gas and liquid pipeline failures in the US between 1988 and 2006 concluded that external interference accounted for 31% of failures on natural gas pipelines and 27% of failures on liquid pipelines, making this type of damage the most significant failure cause in US transmission pipelines. A further review by the DOT<sup>[5]</sup> of OPS statistics for gas and hazardous liquid pipelines up to 2003 indicated that <0.2% of incidents on liquid pipelines and <<0.1% of the incidents on gas pipelines were related to dents.

The DOT data was also reviewed by Kiefner et. al.<sup>[6]</sup>, to determine the time dependency of mechanical damage failures. They concluded that 83% of releases in liquid pipelines and 90% of releases in gas pipelines due to mechanical damage occurred immediately. Of the time dependant failures, 19% were associated with rock dents. A review of the UK and European data<sup>[4]</sup> showed that external interference account for the second largest number of failures. The number of failures due to construction dents from 1971 to 2004 was 6, which represents 1.6% of the total number of spillages from oil pipelines during this period.

The failure data from the US, UK, and Europe is recognized as being too coarse to draw any firm conclusions about the exact role of smooth dents in pipeline failures, but it is evident that failures from dents alone do not form a significant proportion of incidents<sup>[4]</sup>.

Industry often use the terms 'top of the line' dents and 'bottom of the line' dents to describe the position of the dent around the circumference of the pipe. A 'top of the line' dent is defined as a dent on the top two thirds of the pipe between the 8 and 4 o'clock positions. A 'bottom of the line' dent is defined as a dent on the bottom third of the line between the 4 and 8 o'clock positions.

Top of the line dents are more likely to be a result of third party interference. Such dents are considered unconstrained dents and are generally free to re-round due to internal pressure.

Previous research<sup>[7]</sup> has suggested that bottom of the line dents can reliably be characterized as constrained dents caused by hard rocks during pipeline laying. Such dents are more likely to be constrained by an underlying object (e.g., rock), and are not free to move under internal pressure.

The fatigue life of a constrained dent is typically one order of magnitude higher than an unconstrained dent<sup>[5]</sup>. However, failures from shallow unconstrained bottom of the line dents have been reported<sup>[4,8,9]</sup>. These are considered in section 3.5.

When an assessment of a dent is based on ILI data, dent shape can be very important as it distinguishes between a smooth dent and a kinked dent. Accurate

mapping of the dent profile allows the stresses and strains to be calculated for that dent which Industry now consider to be the most accurate method for determining the integrity of a dented pipeline<sup>[4,5]</sup>.

This has challenged the ILI vendors to improve tool tolerances and reporting thresholds. Although it is recognized that there is no one tool that can provide all the required data to enable such a dent assessment, new technologies that allow a combination of different tools have recently been introduced to the market. Such combinations may allow accurate identification and sizing of dents and associated defects.

Section 2 provides an overview of the most common ILI tools and discusses their ability to locate and size dents and any associated defect. This review is generic and does not consider the capability of specific vendor ILI tools.

Section 3 provides a detailed account of the current understanding of the effect of dents and dents combined with other defects on the integrity of a pipeline.

Based on the review undertaken during this project, a high level assessment algorithm is presented in Section 4. At different stages through the algorithm reference is given to subsections of Section 3 where further detailed information is provided.

## 2 DENT IDENTIFICATION

To assess dent damage against international standards and industry best practice, information about the dent depth, profile and orientation is typically required. No single ILI tool can provide all the required information, but a combination of different tool technologies and comparisons with previous inspection data can provide useful information to enable an assessment to be undertaken. This section describes the generic capabilities of magnetic flux leakage ILI tools and geometry (calliper) pigs with respect to detection of dent and dent/gouge damage.

### 2.1 Magnetic Flux Leakage (MFL) Tools

The principal design aim of inspection systems using magnetic flux leakage (MFL) pigs is to detect and size metal loss from the pipe wall. This is achieved by applying magnetic field to the pipe wall at a sufficient level to saturate the undamaged wall with magnetic flux. Since flux penetrates the entire wall, at a change of thickness — internal or external — some magnetic flux must be expelled from the wall and this is measured by field sensors on the ILI tool. The morphology of the metal loss is then inferred by analysis of the recorded field variations to solve the so-called ‘inverse problem’ of determining what feature gave rise to the observed pattern of magnetic field.

Now, in order to produce an observable field perturbation a metal loss feature must have a certain minimum volume and a minimum cross section perpendicular to the applied field. Thus it will be appreciated that an axial field MFL tool for volumetric metal loss, which uses a magnetic field applied parallel to the pipe axis, will become less sensitive to metal loss features as their circumferential extent reduces. Therefore these tools have restricted capabilities for detection of narrow axial features such as axial notches and gouges. This limitation can be addressed by using a tool where the field is applied circumferentially (also known as transverse field inspection).

While the main purpose of MFL tools is to detect metal loss, they also respond to deformation anomalies through the field sensors ‘lifting off’ the inside pipe surface and causing a signal change that is distinguishable from that due to metal loss. Careful analysis of the signals can identify the presence of dents (though not their size) and associated metal loss. However, it must be appreciated that these are essentially incidental benefits outside of the main ‘mission’ of an MFL inspection, and current MFL tools are not designed to measure the depth or profile of a dent or to distinguish between metal loss due to corrosion or gouging<sup>[4,7]</sup>.

### 2.2 Geometry Tools

Geometry tools (commonly referred to as Calliper tools) measure the internal reduction in pipe diameter and are generally grouped into two categories: single channel and multi-channel tools.

Single channel tools can only provide information about minimum pipe diameter measured and distance travelled. It is generally used for new constructions and in preparation for metal loss or crack detection inspections.

Multi-channel tools are further categorized as either low-resolution or high-resolution tools based on sensor spacing and the linear sampling rate of the tool.

The main differences between the two types of multi-channel tools are summarized below<sup>[5]</sup>.

**Inspection in the circumferential direction:** a low-resolution tool tends to have wider spacing between sensor arms (e.g., 12 fingers for inspecting a 12 inch diameter pipe). New high resolution calliper tools are designed with sensors spaced as close as 0.75 inch (i.e. 19mm) which provides greater resolution for mapping the contours of a dent.

**Inspection in the longitudinal direction:** the accuracy for mapping the contour of a dent is determined by the sampling rate which can be measured by either elapsed time or travel distance. When measured by elapsed time, the resolution of the tool will vary depending on the speed of the tool. When resolution is measured by travel distance, a low-resolution calliper tends to have a sampling interval of 1 inch (i.e. 25.4mm) or higher. Contour mapping becomes less accurate the greater the sampling interval. Callipers with linear sampling every 0.25 inch (6.4mm) are classified as high-resolution tools.

Multi-channel high resolution Calliper tools are able to provide detailed information about the geometry of the dent, and provide additional information such as dent location and orientation. Such data can be used to build up a 3-D representation of the dent which may allow accurate strain analysis provided that accurate filtration and interpretation of the inspection data with appropriate tool accuracies can be guaranteed.

It should be noted that these types of tools are not designed to detect metal loss defects associated with dents. Therefore, other ILI tools, or combinations of, are typically required to identify other defects associated with a dent.

## 2.3 Tool Combinations

Combinations of high-resolution multi-channel calliper tool and other ILI tools have recently been introduced to the market<sup>[14]</sup>. Such combinations have the potential for accurately identifying and sizing damage associated with a dent. For instance, combining a Calliper tool with a MFL tool may allow a cost effective screening assessment based on the size and profile of the dent, the strain within the dent, and the corresponding size of any associated metal loss or defects. This may lead to avoiding unnecessary excavations.

## 3 DENT ASSESSMENT REVIEW

### 3.1 General

A dent on a pipeline may occur as a result of third-party damage or when a pipeline is laid on a rock (or other foreign object). Dent damage caused by third-party interference generally occurs on the top of the line and may result in additional mechanical damage to the pipe surface (e.g. gouge and/or crack). Moreover, such dents are unconstrained and are therefore able to re-round as the pressure in the pipeline is increased (the extent of any re-rounding depends on the magnitude of internal pipe pressure). Such dents have historically contributed to the highest number of pipeline failures<sup>[4]</sup>. They can also increase the pipeline sensitivity to fatigue damage. If denting is caused as a result of third party interference, it is likely that these dents will contain mechanical damage and over 80% will result in immediate failure<sup>[15]</sup>. Therefore, the remainder are understood to be less severe (i.e. will not lead to immediate failure but may significantly reduce the life of the pipeline). Recent research<sup>[3,7]</sup> has suggested that dents can reliably be characterized, and ranked according to the severity of the damage, based on their circumferential position. Baker<sup>[5]</sup> has concluded that the most likely failure scenarios of a dented pipeline are:

1. **Failure due to coating damage** - corrosion in and around the dented area causing a stress concentration which increases the local stress associated with the dent.
2. **Failure due to additional mechanical damage** – additional defects within the dented region will act as a stress concentrator and increase the local stress, hence increasing the likelihood of failure.
3. **Failure due to fatigue loading** – the stress concentration associated with the dent (and additional defects) may increase the cyclic stress range as well as introducing additional bending loads, thus reducing the life of the pipeline.

Dents caused by hard terrain such as rocks are likely to introduce bottom of the line dents. Dents of this type are generally restrained by the indenter and are constrained from flexing as the internal pressure is increased or decreased.

P/11 does not distinguish between constrained and un-constrained dents, neither does it consider the shape of the dent (i.e., sharp, round, elongated). If a dent is identified in a pipeline, it is only necessary to measure the depth of the dent to undertake an assessment. For static internal pressure loading, a dent is categorised as 'Superficial' if the depth of the dent does not exceed 12%OD. This limit is specified for pipelines operating at a hoop stress level up to 72% SMYS. Deeper dents are categorised as either 'Severe' or 'Extreme', depending on the operating hoop stress of the pipeline, and an appropriate repair is undertaken (for those pipelines that are designed to operate at pressures not greater than 7bar in accordance with IGE/TD/3, then the superficial limit is increased to 15%OD). The document does acknowledge the detrimental effect of a dent on reducing the fatigue life of a pipeline and specifies that if a pipeline is subjected to pressure cycling expert assistance must be sought.

The 12%OD limit on dent depth is not reflected in other codes and guidance documents such as ASME B31.8<sup>[16]</sup>, API 1156<sup>[3,17]</sup>, EPRG<sup>[18]</sup> and PDAM<sup>[19]</sup>, which specify the following:

- ASME B31.8: up to 6%OD or 6% strain (constrained and un-constrained)
- API 1156: up to 6%OD, with dents >2%OD requiring a fatigue assessment (constrained and un-constrained)
- EPRG: up to 7%OD for pipelines operating at hoop stress levels not greater than 72% SMYS (constrained and un-constrained)
- PDAM: up to 10%OD (constrained) and up to 7%OD (un-constrained)

Despite the differences in acceptance limit between the different codes, it is not recommended that the 12%OD limit for static pressure loading in P/11 be reduced, as the limit is supported by an extensive database of full-scale tests and ring tension tests from over 3 decades of testing. Those tests were designed to encompass the different pipe sizes (up to 48 inch), pipe types (e.g., seamless, SAW) and material grades (up to grade X65) used in the UK gas transmission and distribution system. The dents tested are also considered a true reflection of the type of dent/indenter found in the field. Furthermore, the 12%OD limit incorporates a safety factor of 2 on dent depth.

An algorithm has been developed, in the spirit of the existing P/11 algorithm, for the assessment of dent and dent plus defect combinations, and is presented in Section 4. The algorithm is based on a comprehensive review of pipeline codes, guidance documents and research work undertaken for the sponsors. The following sub-sections of Section 3 describe dent damage in greater detail (i.e., the position of the dent around the pipe circumference and whether it is related to parent pipe or a weld, the presence of additional defects, the effect of static internal pressure and pressure cycling) and are referenced at various stages in the algorithm.

## 3.2 Material Properties

This report only considers damage identified on pipelines constructed from linepipe that achieves the minimum required properties (e.g. yield and tensile strength and Charpy impact energy) of the relevant in-house linepipe specifications L1, LX1, LX4, LX5 and TS-C4Gas-Pip0<sup>[20]</sup>. For pipelines whose material properties do not achieve these requirements, or their properties can not be verified, expert assistance must be sought. This is consistent with the requirements of P/11.

## 3.3 Pipeline Stress Level

In P/11, for pipelines designed to operate at pressures not greater than 7 bar in accordance with IGE/TD/3<sup>[21]</sup> a dent depth not greater than 15%OD is categorised as Superficial. Deeper dents are categorised as 'Severe'. For a pipeline designed in accordance with IGE/TD/1 to operate at a hoop stress level not greater than 72% SMYS, a dent depth not greater than 12%OD is also considered 'Superficial'. Deeper dents are categorised as 'Extreme' damage, unless the pipeline operating stress level is less than 20% SMYS (i.e., design factor not greater than 0.2) in which case dents greater than 12%OD are categorised as 'Severe'.

Should failure of a dented pipeline occur, damage categorised as Severe will fail as a leak. Damage categorised as Extreme has the potential to fail as a rupture.

Severe and Extreme damage is repaired. The damage category dictates what pressure/stress reduction is required to ensure continued safe operation of the pipeline and safety of personnel while any remedial works are undertaken.

For damage categorised as 'Severe' there is a requirement to reduce the pressure in the pipeline to the lesser of 85% of the pressure at the time of damage or a pressure sufficient to give a hoop stress of 30% SMYS, and for damage categorised as 'Extreme' the pressure is required to be reduced to the lesser of 50% of the pressure at the time of damage or a hoop stress of 20% SMYS.

As noted above, should failure of a pipeline occur at 30% SMYS it is likely to be as a leak rather than a rupture, although a rupture cannot be discounted. However, at 20% SMYS the stress would be sufficiently low to ensure that should failure occur it would be as a leak.

Baker<sup>[5]</sup> proposes that dent damage in a pipeline is not significant provided the operating hoop stress is not greater than 30% SMYS. However, it is not considered necessary to revise the limits already enforced in P/11.

### **3.4 Top of the Line Dents**

Top of the line smooth dents may contain gouging and/or cracking or corrosion and are generally free to re-round with internal pressure fluctuations. The severity of such dents cannot be reliably determined by ILI<sup>[7]</sup> as the re-rounding that may have occurred could mask the severity of the damage. Therefore, codes and guidance documents have set strict limits for top of the line dents. If a dent, with or without additional defects, exceed such limits, it is recommended that expert assistance be sought or the damage is addressed for timely excavation and repair.

#### **3.4.1 Smooth Dents Subject to Static Loading**

Smooth dents do not significantly reduce the static strength of the pipe<sup>[2]</sup>. This is reflected in the acceptance limits in P/11 where a smooth dent is categorised as superficial if its depth does not exceed 12%OD (15%OD for IGE/TD/3 pipelines designed to operate at pressures not greater than 7bar).

International codes and industry best practice guidance documents propose different dent acceptance limits. Tests done by Battelle<sup>[22]</sup> have shown that smooth dents up to 8%OD can remain safely in the pipeline (the maximum depth tested was 8.6%OD, and in all cases failure occurred elsewhere on the pipe). Tests done by British Gas<sup>[23,24]</sup> considered a wider range of dent depths and concluded that smooth dents up to 24%OD have a failure stress greater than 72% SMYS.

Although ASME B31.8 considers a limit of 6%OD for smooth dents, it is understood that this limit also takes into consideration the safe passage of ILI tools. However, some ILI tools are now capable of safely negotiating much greater bore reductions than this and the capabilities of a given pig in this area would need to be checked with the inspection vendor.

In recognition that perhaps dent depth is not the most appropriate method for assessing a dent, industry is turning attention to assessing the severity of a dent based on calculating the strain within the dent. It is understood that due to the rebounding effect that occurs when the indenter is removed, the stress and strain distribution within the dented area will change due to changes in the pipe geometry. Baker<sup>[5]</sup> states that strain is more often a better indicator of dent severity than depth alone. This has also been recognized in ASME B31.8 which has a limit on strain of 6%, but no limit on depth. However, the use of such calculations requires detailed dent profiling and expert assessment. A method is provided in Appendix R of ASME B31.8 for calculating the strain within a dent<sup>3</sup>.

Despite the difference in limits between the different codes and guidance documents, the 12%OD limit in P/11 should remain as it is supported by a substantial database of full-scale tests and ring tests on dented linepipe, and reflects the requirements of the sponsors for gas transmission and distribution within the UK.

### 3.4.2 Smooth Dents Subject to Fatigue Loading

The fatigue life of a pipe containing a top of the line (i.e. unconstrained) smooth dent in parent pipe is less than that for a plain circular pipe<sup>[2]</sup>. The reduction in fatigue life is due to an increase in stress and strain within the dent, and the deeper the dent the greater the reduction in fatigue life. The shape of the dent (i.e., sharp, round, elongated) can also have a significant effect on fatigue life.

However, unconstrained smooth dents are more likely to rebound to a lesser depth once the indenter is removed. Rosenfeld<sup>[15]</sup> concluded that smooth unconstrained dents with a residual depth not greater than 2%OD exhibits fatigue lives between 100,000 and 1,000,000 pressure cycles where the pressure range gives a corresponding hoop stress range between 36% and 72% SMYS. Based on this result, Baker<sup>[5]</sup> proposed that a 2%OD deep dent will have a negligible effect on the fatigue life of a gas transmission pipeline. Furthermore, Alexander and Kiefner<sup>[3]</sup> concluded that the 2%OD depth is also applicable to liquid pipelines.

For unconstrained smooth dents deeper than 2%OD, a fatigue assessment is typically required. In contrast, despite categorising dents up to 12%OD as superficial, P/11 states that, regardless of depth, all pipelines containing dent damage that are subject to pressure cycling can experience a reduction in fatigue life, and recommends that expert assistance be sought.

A review that was undertaken as part of PDAM<sup>[2,19]</sup> identified several empirical and semi-empirical methods for calculating the fatigue life of an unconstrained smooth dent in a pipe. All but one method is based on an S-N approach, taking into account the stress concentration due to the dent. Two empirical methods and a semi-empirical method were used to determine the fatigue life of a substantial database of fatigue tests on smooth dents. Other methods could not be compared due to insufficient test details. A comparison of the three methods indicated that the original

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<sup>3</sup> The dent strain calculation method presented in previous versions of ASME B31.8 is incorrect. The error has been addressed in the current edition of the document, ASME B31.8:2007<sup>[16]</sup>

EPRG method<sup>[18]</sup> provided the best fit to the experimental data. It should be noted that fatigue life calculated using the EPRG method is independent of the size and shape of the indenter object.

Advantica undertook a review of all available full-scale fatigue test data of linepipe containing smooth dent damage<sup>[25]</sup> (this included data from 49 fatigue tests undertaken on full-scale vessels<sup>[26,27]</sup> and 33 tests undertaken on ring expansion specimens<sup>[28,29]</sup>). From that review a tentative conclusion was made that provided the dent depth was less than 5% of the pipe diameter the pipeline would achieve the fatigue design life of IGE/TD/1<sup>[30]</sup>. However, that conclusion was based on a limited and confusing (i.e., insufficient test detail, variation in pipe size and type, different indenter types) set of test data and National Grid agreed that additional full-scale fatigue tests should be undertaken on pipe containing dents of type and depth specific to the requirements of P/11.

The following trends were identified from the review:

- The majority of tests were undertaken on 12inch diameter pipe. The pipe diameter to thickness ratio, D/t ranged from 19 (thick walled pipe) to 65 (thin walled pipe).
- The materials tested were grade X52 or lower.
- Fifty percent of the vessel tests were pressure cycled to failure.
- For a given dent depth, as the D/t ratio increases the fatigue life also increases.
- For a given dent depth, the higher the D/t ratio the greater the extent of dent re-rounding (i.e., dent push-out) on initial pressurisation of the pipe to the same internal pressure.
- The data suggest no/weak effect of material grade (PDAM states that the static strength of the pipe containing a dent is independent of the material's yield to tensile strength ratio, although the fatigue life model presented does require input of the material's tensile strength).

On the basis of those observations pipe with a low D/t ratio was used for the full-scale vessel fatigue tests as it would provide a lower bound fatigue life for a given dent depth. The tests were undertaken on two 12m lengths of 12inch diameter grade X52 linepipe, which had a D/t ratio of 34. Each vessel comprised spherical and cylindrical dents of depth up to 6%OD (measured at the peak pressure in the fatigue cycle)<sup>[31]</sup>. The vessels were pressure cycled such that the remote hoop stress range in the pipe was 125N/mm<sup>2</sup>. The purpose of this was to enable a comparison with IGE/TD/1, where the fatigue design life of a pipeline that has been given a high level hydrostatic test is 15,000 cycles of 125N/mm<sup>2</sup> hoop stress range. All spherical dents of depth up to 6%OD survived in excess of 150,000 pressure cycles (note, 150,000 cycles was the target life in the tests as the fatigue design line in IGE/TD/1 nominally incorporates a factor of safety of 10 on life), as did a 2.3%OD deep cylindrical dent. The remaining cylindrical dents failed at a reduced number of cycles. That data has enabled the following limits on fatigue life to be recommended for dent depths up to 7%OD:

- A pipeline with a dent depth not greater than 2.5%OD will have a fatigue life not less than 15,000 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 2.5%OD, but not greater than 3.0%OD will have a fatigue life not less than 7,000 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 3.0%OD, but not greater than 3.5%OD will have a fatigue life not less than 5,000 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 3.5%OD, but not greater than 4.0%OD will have a fatigue life not less than 3,000 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 4.0%OD, but not greater than 4.5%OD will have a fatigue life not less than 2,000 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 4.5%OD, but not greater than 5.0%OD will have a fatigue life not less than 1,500 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth greater than 5.0%OD, but not greater than 7.0%OD will have a fatigue life not less than 550 cycles of 125N/mm<sup>2</sup> remote hoop stress range.

The Advantica tests also support the statement by Baker<sup>[5]</sup> and Alexander and Kiefner<sup>[3]</sup> that a 2%OD dent will have a negligible effect on the fatigue life of a gas transmission pipeline (the Advantica tests demonstrated that a 2.5% deep dent will endure in excess of 15,000 cycles of 125N/mm<sup>2</sup> hoop stress range, which includes a factor of 10 on life).

Most of the full-scale fatigue tests of smooth dents have been undertaken on dents introduced at zero pressure. To relate these tests to a pipeline, consideration has to be given to the effect of internal pipe pressure on dent depth. EPRG guidelines recommends a factor of 1.43 be used to relate a dent depth at pressure to that at zero pressure. In recognition that the extent of dent re-rounding is dependent on the magnitude of internal pipe pressure, Gaz de France has developed an alternative, more complex, equation that considers both internal pressure and dent length<sup>[4]</sup>.

When using the above methods to predict the fatigue life of a dented pipeline consideration needs to be given to the pressure in the pipeline when the dent depth was measured. Furthermore, consideration needs to be given to when the damage occurred, as it is from this date that the predicted fatigue life must be referenced. If the assessment is not in response to an immediate incident, pipeline records (for example, 'fingerprint' ILI inspection, service scheduled ILI inspections, CIPS, DCVG and Pearson surveys) should be reviewed to identify when the damage first occurred.

It is recommended that the limits on fatigue life proposed by Advantica for dents up to 7%OD be included in P/11. For a more accurate prediction of fatigue life (i.e., for a specific pipe size and dent depth) expert assistance should be sought.

### 3.4.3 Smooth Dents with Defects Subject to Static Loading

A dent in a pipeline may be associated with other damage types such as gouges or spalling due to the way the dent was introduced. As discussed above, a dent under internal pressure induces high stresses and strains within the dent as it springs back when the indenting object is removed, and as it is pushed out under the action of internal pressure. In a smooth dent, these stress and strain concentrations are accommodated by the ductility of the line pipe. However, if there is a defect in the dent then these stresses and strains are further concentrated in the defect (which is itself a source of a stress concentration) with the result that there are large strains and large bending stresses acting on the remaining ligament of the defect. This complex stress and strain state promotes plastic flow and crack initiation and growth through the remaining ligament. The toughness of the linepipe steel is an important factor, particularly if the dent is associated with spalling, cracking or gouging as it determines the relative dominance of plastic flow or ductile crack growth, with respect to failure.

P/11 provides defect acceptance limits for smooth dents with associated spalling or cracking, and smooth dents with associated gouge damage. The limits are for static internal pressure loading only. If spalling or cracking is associated with a dent, the damage is categorised as 'Moderate' if the spalling or cracking is not greater than 0.5mm. Any deeper than this and the damage must be repaired. Depending on the dimensions of the damage it is either categorised as 'Severe' or 'Extreme', which dictates what pressure reduction is required for any remedial works to ensure safety of personnel and safe continued operation of the pipelines while the damage is addressed (see Section 3.3). Dent plus gouge damage is approached differently in P/11 as loci are provided of dent depth versus damage depth for different pipeline operating hoop stress levels.

Empirical and semi-empirical methods for predicting the burst strength of a smooth dent containing a gouge have been proposed by a number of different organisations and individuals. The background to these methods is discussed in detail in PDAM<sup>[2]</sup>. Since the review, Advantica has developed a dent-gouge fracture model for UKOPA, which is based on the 'failure assessment diagram' (FAD) approach which is commonly used in fracture mechanics assessments. The model has recently been reviewed for consideration towards updating PDAM, however, the reviewers concluded that a semi-empirical dent-gouge fracture model developed by British Gas in the early 1980s and subsequently adopted by the EPRG remains the most accurate method currently available. It should be highlighted that the Advantica model is not complete but provides the foundations for a new approach to the assessment of dent-gouge damage. The model addresses the effect of all 'features' associated with dent-gouge damage such as micro-cracking at the base of the gouge and residual stresses, unlike earlier generation models. The potential for this model has been acknowledged by the reviewers, and although correct in its approach, modelling of some of these effects requires further consideration. Enhancements to the model are currently being addressed by both EPRG and PRCI.

There is no experimental evidence to indicate the severity of a dent and other defects. However, it is likely that a dent with an additional defect will be no more severe than an equivalent dent and gouge defect, given that gouges are often associated with micro-cracking in the base of the gouge. The methods for assessing

the burst strength of a dent plus gouge defect should be applicable to a dent containing a part-wall defect such as a crack.

### 3.4.4 Smooth Dents with Defects Subject to Fatigue Loading

There has been a large number of full-scale vessel and ring expansion fatigue tests of a smooth dent containing a single 'gouge' which have been conducted by a number of different organisations<sup>[32-45]</sup>. In most of the tests the 'gouge' was a machined notch. The tests have demonstrated that dents and defects can record short fatigue lives. Empirical and semi-empirical methods for predicting the fatigue strength of a smooth dent containing a gouge have been proposed by a number of different organisations, which have been reviewed under PDAM<sup>[2,19]</sup>. In conclusion, PDAM recommends that a conservative estimate of fatigue life of a smooth dent containing a gouge can be obtained by reducing the predicted fatigue life of an equivalent smooth dent, calculated using the original model proposed by the EPRG, by a factor of 100, subject to several empirical constraints:

- The maximum dent depth is limited to 4%OD (measured at zero pressure, after springback), which is approximately 2.8%OD when measured at pressure.
- The maximum depth of the gouge is no greater than 20% of the pipe wall thickness, and
- The 2/3 specimen size Charpy energy is not less than 47J.

PDAM has demonstrated that this simple approach is 'as accurate' as the other empirical and semi-empirical methods for predicting the fatigue life of a smooth dent plus gouge, when compared against the published test data.

There have been no full-scale fatigue tests of dents containing other defects, neither are there any published methods for assessing dents containing other defects. However, the above approach should be conservative when used to predict the fatigue strength of a smooth dent containing another defect.

In 2006 Advantica completed a series of full-scale fatigue tests that were designed to investigate the fatigue performance of dent plus dressed gouge defects<sup>[46]</sup>. Pipe identical to that used by Advantica in a series of smooth dent fatigue tests (see Section 3.4.2) was used to assess the fatigue performance of dent plus gouge defects removed by dressing. Two vessels, each comprising 7 dents with dressed areas (the method of dressing was in accordance with P/11) were pressure cycled to give a remote hoop stress range of 125N/mm<sup>2</sup> for comparison with the IGE/TD/1 fatigue design life for a pipeline that has been subjected to a high level hydrostatic test. For a range of different dent depths, the corresponding dressing depth was consistent with the acceptance limits in P/11 for dent plus defect combinations subject to internal pressure loading. The majority of the dents were elongated, with a select number of spherical dents for comparison. This decision was based on the findings of the earlier Advantica dent fatigue tests, where cylindrical dents were found to give shorter fatigue lives compared with spherical dents of comparable depth. The following was concluded from that work:

- A pipeline with a dent depth of 0.9% and a dressing depth of up to 23.1% will have a fatigue life in excess of 15,012 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth of 1.5% and a dressing depth of up to 14.5% will have a fatigue life in excess of 15,012 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth of 1.5% and a dressing depth greater than 14.5% but not greater than 18.8% will have a fatigue life in excess of 11,838 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth of 2.6% and a dressing depth of up to 7.3% will have a fatigue life in excess of 15,012 cycles of 125N/mm<sup>2</sup> remote hoop stress range.
- A pipeline with a dent depth of 2.6% and a dressing depth greater than 7.3% but not greater than 12.6% will have a fatigue life in excess of 12,345 cycles of 125N/mm<sup>2</sup> remote hoop stress range.

For consistency with EPRG recommendations, the fatigue life given above for the different dent-dressing depth combinations incorporates a safety factor of 10 on the actual fatigue life. It is recommended that these limits be incorporated into P/11.

### **3.4.5 Smooth Dents with Corrosion**

ILI tools are not able to reliably confirm whether an area of 'metal loss' within a dent is a gouge defect or an area of corrosion.

If the metal loss is located on the top of the line, it is likely to be as a result of third party interference; hence the damage is likely to be a gouge. Such damage should be assessed as though it is a dent-gouge combination.

However, it is possible that the metal loss is corrosion, caused by coating disbondment and shielding from the cathodic protection. If it can be proven through further investigations (e.g. a review of CIPS, DCVG, and Pearson surveys, field investigations, or new ILI technologies) that the area of metal loss is corrosion, then corrosion up to 20% of the wall thickness in depth would be considered acceptable. This opinion is based on the fact that codes such as the modified ASME B31G<sup>[47]</sup> which are for the assessment of the remaining strength of linepipe containing corrosion, consider corrosion to have a negligible effect on the integrity of a pipeline if the depth of the metal loss is less than 20% of the pipe wall thickness (for pipelines operating at stress levels not exceeding 72% SMYS and as long as the remaining thickness is not less than 80% of that required by the design stress level).

The literature contains many tests on dents containing gouges or notches, and a small number of tests of dents containing blunt grooves or slots, or dents containing notches that have subsequently been ground smooth. However, there is no research reported in the literature that describes the behaviour of a smooth dent containing a defect such as corrosion.

A dent and gouge is the most severe type of dent and defect combination. Therefore, if either a static or fatigue assessment is required of a dent plus corrosion defect, a reasonable approach to adopt would be to assess the defect combination as a dent

plus gouge defect. Such an assessment will be conservative, but there is insufficient information with which to quantify this conservatism.

### 3.4.6 Smooth Dents on Welds

A dent is considered to be on a weld if the presence of the dent has changed the curvature of the adjacent girth weld or seam weld. P/11 categorises a dented weld as Severe if the operating stress level is less than 20% SMYS (i.e., design factor less than 0.2), else Extreme. A pressure reduction is then enforced and a suitable repair undertaken.

Compared with an equivalent smooth dent, a dent on a weld (seam or girth weld) can result in a significantly lower burst strength and a very low fatigue life due to the following:

- The material properties (yield and tensile strength and Charpy impact energy) of a weldment are different from those of the parent pipe.
- Welds contain natural welding defects, stress concentrations associated with the weld profile and residual stresses due to the welding process.
- A weld may contain cracking due to the large stresses and strains during the denting process, or during spring back or re-rounding
- Girth welds are more susceptible to damage during denting than a seam weld as they generally have poorer material properties and contain more welding defects.

There are no methods in the published literature for assessing the burst strength of a dented weld. There are a number of published results from full-scale burst tests<sup>[3,48,22,33,36]</sup>, but insufficient detail about the test is provided to enable simple empirical limits to be set. It is proposed in PDAM<sup>[19]</sup> that if it could be established with confidence that the dent and weld did not contain any defects, was overmatched and had high toughness (greater than 30J minimum and 40J average from a set of 3 full-size Charpy specimens) then it may be reasonable to assess the static strength of a dented weld as though it was a smooth dent (see Section 3.4.1).

It is acknowledged that limits on dent depth at welds are prescribed in ASME B31.8 (dent depth up to 2%OD, or 4% strain on 'ductile welds') and API 1156 (up to 2%OD on 'ductile welds'), but it is not recommended that they be adopted for P/11 without a rigorous review of the test data and analyses that support these limits. Furthermore, application of such a limit would be dependent on many factors, such as weld type (e.g., SAW, HFI), and the weld being of good quality and defect free. Some of these factors may be difficult to prove from historical pipeline records and the ability/resolution of the inspection tool. It is recommended that if this data is available any assessment undertaken should be done by an expert.

There are a number of published results from fatigue tests on dented welds (full-scale vessel tests and ring expansion tests)<sup>[3,22,26,33,36]</sup>, although there are no analytical methods in the published literature for predicting fatigue performance. However, guidelines have been published for undertaking an assessment<sup>[49]</sup> which is based on an semi-empirical model for predicting the fatigue strength of a smooth dent<sup>[26]</sup>. The

model was reviewed as part of PDAM and it was concluded that there were too many uncertainties in the test data which was used to develop the approach to recommend use of the method in the PDAM document. Instead, PDAM recommends that the fatigue strength of a smooth dent on a weld can be estimated using the original empirical method developed by the EPRG for predicting the fatigue life of a smooth dent subject to cyclic internal pressure loading<sup>[18]</sup>, but reducing the fatigue life by a factor of 10 to account for the presence of the weld. This empirical criterion is subject to the following limitations however:

- The maximum depth of the smooth dent (as measured at zero pressure after elastic spring back) is limited to 3.9 percent of the pipe diameter.
- The dent and weld do not contain any defects.
- The weld is overmatched and has high toughness (greater than 30J minimum and 40J average from a set of 3 full-size Charpy specimens).

Although Alexander and Kiefner<sup>[3]</sup> have suggested that the limit on dent depth in ASME B31.3 of 2%OD is also applicable to a dented weld subjected to fatigue loading, it was concluded in the PDAM review<sup>[2]</sup> of available test data that this limit is potentially non-conservative. Therefore it is not recommended that this limit be adopted for P/11 without further investigation.

It is recommended that if a fatigue assessment is required of a dented weld then this should be undertaken by an expert, otherwise an appropriate repair should be undertaken.

### **3.5 Bottom of the Line Dents**

Smooth dents on the bottom of the line are likely to be the result of original construction damage<sup>[7]</sup>. Dents greater than 2%OD are likely to be constrained by soil or rocks<sup>[15]</sup>. Provided that the underlying object remains in place, bottom of the line dents are unlikely to re-round with increasing internal pressure. Previous research<sup>[5]</sup> suggests that bottom of the line constrained dents subject to pressure cycling will have a fatigue life an order of magnitude greater than an unconstrained dent of equivalent depth.

The primary mode of failure for bottom of the line constrained dents is a puncture, provided the object is sufficiently sharp<sup>[3,17]</sup>. If the pipeline is subject to pressure cycling it would be preferable for the underlying object to remain in place, constraining the dent from flexing. However, there is the possibility that the pipeline coating may be damaged by the foreign object, hence corrosion would be an additional threat. It is considered prudent, prior to excavating such dents, to review the pipeline inspection history (e.g. CIPS, DCVG and Pearson surveys) to confirm the condition of the coating in the dented section. If it can be confirmed that coating remains intact it is impossible for the dent to be anything but smooth<sup>[50]</sup> and is therefore unlikely to pose an immediate threat to the integrity of the pipeline.

However, dents less than 2%OD may be unconstrained<sup>[15]</sup>. Furthermore, there have been reports of failures of shallow bottom of the line unconstrained dents when subject to pressure cycling<sup>[8,9]</sup>. Although there is the possibility of shallow dents being

constrained, it is considered prudent to regard bottom of the line shallow dents as unconstrained, with the possibility of additional damage associated with the dent.

If a bottom of the line dent is associated with any other defects it is recommended that either an expert assessment is undertaken (depending on the available information) or a repair is undertaken as per P/11.

### **3.6 Kinked Dents**

There have been no full-scale tests to determine the burst strength of kinked dents. Neither are there any published methods for predicting the behaviour of kinked dents. However, research undertaken on locally buckled pipe and wrinkled pipe would suggest that kinked dents are more onerous than smooth dents<sup>[51,52]</sup>. P/11 requires that all kinked dents are categorized as extreme damage, regardless of depth, and must be repaired.

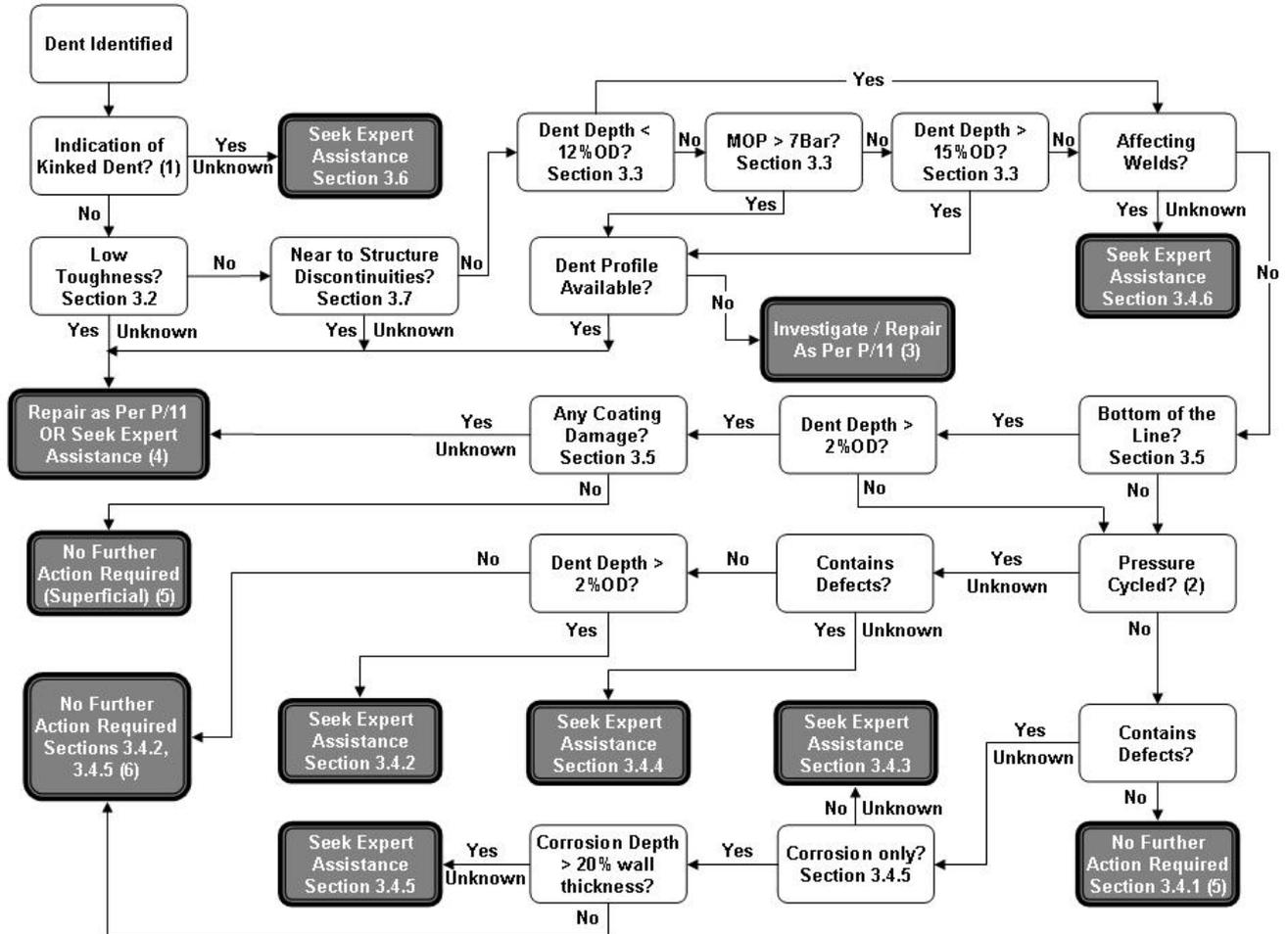
### **3.7 Adjacent Dents and Dents Near to Structural Discontinuities**

It is understood that dents adjacent to one another and dents near to structure discontinuities (e.g. off-takes, valves) can interact and affect the fatigue life of the pipeline. Limited tests<sup>[3]</sup> have been carried out to investigate interaction effects, but no clear conclusion has been drawn.

While constrained (bottom of the line) dents are considered to have longer fatigue life compared with an unconstrained dents, Rosenfeld<sup>[17]</sup> proposes that the fatigue life of closely spaced constrained dents can be reduced as the 'saddle' shaped area between the dents is actually unconstrained.

There have been a limited number of fatigue tests to look at the effect of separation distance between smooth unconstrained dents<sup>[3]</sup>. It was observed that the closely spaced dents re-rounded less and had the shortest fatigue life. This was attributed to the pipe possibly being geometrically stiffer due to the close proximity of the dents or material variations, despite being nominally identical pipes. Based on a review of the data, Cosham<sup>[2]</sup> proposed an interaction criteria whereby if the edge-to-edge distance between two smooth dents is less than 762mm (approximately 1600mm between centres), they are considered to interact and expert assistance is required.

## 4 DENT ASSESSMENT ALGORITHM



- (1) The presence of a kinked dent should be identified by the ILI inspection tool. If there is uncertainty undertake site investigation or consider use of a more appropriate ILI inspection tool.
- (2) If the pipeline is subjected to pressure cycling previous inspection records (for example, but not limited to, 'fingerprint' ILI inspection, service scheduled ILI inspections, CIPS, DCVG, Pearson survey) must be consulted to identify when the dent first occurred. The pipeline historical duty must be considered when determining the remaining life of the damaged pipeline.
- (3) The investigation/repair work shall be undertaken according to the procedures in P/11.
- (4) It may be possible to undertake a case specific assessment depending on the available pipeline/damage information.
- (5) The defects in this termination box shall receive further consideration (refer to P/11)
- (6) At the next scheduled coating survey attention must be given to the condition of the coating associated with the area of damage. If coating damage is confirmed the damaged area must be excavated and the extent of the damage measured and assessed accordingly.

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