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THE ASSESSMENT OF CORROSION IN PIPELINES – GUIDANCE IN THE PIPELINE DEFECT ASSESSMENT MANUAL (PDAM)

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ABSTRACT

The Pipeline Defect Assessment Manual (PDAM) project is a joint industry project sponsored by fifteen international oil and gas companies, to produce a document specifying the best methods for assessing defects in pipelines. PDAM documents the best available techniques currently available for the assessment of pipeline defects (such as corrosion, dents, gouges, weld defects, etc.) in a simple and easy-to-use manual, and gives guidance in their use. In this paper the best practices for the assessment of corrosion in pipelines are presented. Full scale tests, theoretical analyses and assessment methods are also discussed, and the 'best' methods included in PDAM are described.

NOMENCLATURE

$2c$	maximum longitudinal length of metal loss defect (equals l)
d	depth of part-wall metal loss defect
t	pipe wall thickness
D	outside diameter of pipe
M	Folias factor (bulging factor)
Q	length correction term
R	outside radius of pipe
$\overline{\sigma}$	flow stress
σ_θ	hoop stress at failure
σ_Y	yield strength
σ_U	ultimate tensile strength
SMYS	specified minimum yield strength
SMTS	specified minimum ultimate tensile strength

1 INTRODUCTION

Oil and gas transmission pipelines have a good safety record. This is due to a combination of good design, materials and operating practices; however, like any engineering structure, pipelines do occasionally fail. The most common causes of damage and failures in onshore and offshore, oil and gas transmission pipelines in Western Europe and North America are

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external interference (mechanical damage) and corrosion[1-3]. Assessment methods are needed to determine the severity of such defects when they are detected in pipelines.

Defects occurring during the fabrication of a pipeline are usually assessed against recognised and proven quality control (workmanship) limits. However, a pipeline will invariably contain larger defects during its life, and these will require a 'fitness-for-purpose' assessment to determine whether or not to repair the pipeline. Consequently, the past 40 years has seen the development of a number of methods for assessing the significance of defects. Some of these methods have been incorporated into industry guidance, others are to be found in the published literature. However, there is no definitive guidance that contains all of the assessment techniques, or assesses each method against the published test data, or recommends best practice in their application.

To address this industry need, a Joint Industry Project has been sponsored by fifteen international oil and gas companies (Advantica Technologies, BP, CSM, DNV, EMC, Gaz de France, Health and Safety Executive, MOL, Petrobras, PII, SNAM Rete Gas, Shell Global Solutions, Statoil, Toho Gas and TotalFinaElf) to develop a Pipeline Defect Assessment Manual (PDAM). PDAM presents the 'best' currently available methods for the assessment of pipeline defects (such as corrosion, dents, gouges, weld defects, etc.), in a simple and easy-to-use manual, and gives guidance in their use. It is based on an extensive critical review of published 'fitness-for-purpose' methods and test data. PDAM is intended to be another tool that will assist pipeline engineers in maintaining pipeline integrity. The PDAM project was completed in June 2003. PDAM is being maintained and updated through the ongoing PDAM+ joint industry project.

Fitness-for-Purpose. Fitness-for-purpose, as discussed here, means that a particular structure is considered to be adequate for its purpose, provided the conditions to reach failure are not reached[4] [2]. Fitness-for-purpose is based on a detailed technical assessment of the significance of the defect. Local and national legislation and regulations may not permit certain types of defects to be assessed by fitness-for-purpose methods or may mandate specific limits. Such issues should always be considered prior to an assessment.

Safety must always be the prime consideration in any fitness-for-purpose assessment and it is always necessary to appreciate the consequences of a failure. These will influence the necessary safety margin to be applied to the calculations.

Pipeline Integrity Management. Pipeline failures are usually related to a breakdown in a 'system', e.g. the corrosion protection 'system' has become faulty, and a combination of ageing coating, aggressive environment, and rapid corrosion growth may lead to a corrosion failure. This type of failure is not simply a 'corrosion' failure, but a 'corrosion control system' failure. Similar observations can be drawn for failures due to external interference, stress corrosion cracking, etc..

These considerations lead to the conclusion that a 'holistic' approach to pipeline defect assessment and integrity is necessary (see Figure 1); understanding the equation that quantifies the failure load is only one aspect of the problem.

Pipeline integrity management is the general term given to all efforts (design, construction, operation, maintenance, etc.) directed towards ensuring continuing pipeline integrity. The American Petroleum Institute (API) has developed an industry consensus standard that gives guidance on developing integrity management programmes (API 1160)[5]. The American Society of Mechanical Engineers (ASME) has developed a similar integrity management guidelines for a supplement to ASME B31.8[6].

[2] Note that fitness-for-purpose may also have a legal and contractual meaning in different countries.

Figure 1 – The Key Elements of Pipeline Integrity Management

This paper summarises some of the methodology and contents of the Pipeline Defect Assessment Manual (PDAM). The best methods for assessing a variety of different types of defect are summarised (see Table 1) but this paper focuses on the assessment of corrosion with reference to previous reviews of corrosion assessment methods and published full scale test data.

2 THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM is based upon a comprehensive, critical and authoritative review of available pipeline defect assessment methods. This critical review includes a compilation of published full-scale test data used in the development and validation of existing defect assessment methods. The full-scale test data is used to assess the inherent accuracy of the defect assessment methods, and to identify the 'best' methods (considering relevance, accuracy and ease of use) and their range of applicability. PDAM describes the 'best' method for assessing a particular type of defect, defines the necessary input data, gives the limitations of the method, and defines an appropriate factor to account for the model uncertainty. The model uncertainty for each assessment method has been derived from a statistical comparison of the predictions of the method with the published test data, based on the prediction interval of the classical linear regression model.

PDAM provides the written text, the methods, recipes for application, acceptance charts and simple examples, and is supported by background literature reviews. Simple electronic workbooks have been developed to permit easy implementation of the 'best' methods. The role of PDAM in the fitness-for-purpose assessment of a defect in a pipeline is summarised in Figure 2 (at the end of the paper).

PDAM has been closely scrutinised throughout its development by the sponsors, and all literature reviews and chapters have been independently reviewed by international experts in the field of pipeline defect assessment.

PDAM does not present new defect assessment methods; it presents the current state of the art in the fitness-for-purpose assessment of defective pipelines. Limitations of the methods recommended in PDAM represent limitations of the available methods and of knowledge.

3 TYPES OF DEFECT CONSIDERED IN THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM contains guidance for the assessment of the following types of defect:

- defect-free pipe
- corrosion
- gouges
- plain dents
- kinked dents
- smooth dents on welds
- smooth dents containing gouges
- smooth dents containing other types of defects
- manufacturing defects in the pipe body
- girth weld defects
- seam weld defects
- cracking
- environmental cracking

In addition, guidance is given on the treatment of the interaction between defects (leading to a reduction in the burst strength), and the assessment of defects in pipe fittings (pipework, fittings, elbows, etc.). Guidance is also given on predicting the behaviour of defects upon failing (i.e. leak or rupture, and fracture propagation).

The following types of loading have been considered in the development of the guidance: internal pressure, external pressure, axial force and bending moment.

Methods are given in PDAM for assessing the burst strength of a defect subject to static loading and for assessing the fatigue strength of a defect subject to cyclic loading. There are some combinations of defect type, orientation and loading for which there are no clearly defined assessment methods. In summary, the assessment of defects subject to static or cyclic internal pressure loading is well understood, but, in general, other loads and combined loading are not.

4 THE FORMAT OF THE PIPELINE DEFECT ASSESSMENT MANUAL

The Pipeline Defect Assessment Manual broadly follows the following format for each defect type and assessment method:

1. A brief definition of the type of defect.
2. A figure illustrating the dimensions and orientation of the defect relative to the axis of the pipe, and a nomenclature.
3. Brief notes that highlight particular problems associated with the defect.
4. A flow chart summarising the assessment of the defect.

5. The minimum required information to assess the defect.
6. The assessment method.
7. The range of applicability of the method, its background, and any specific limitations.
8. An appropriate model uncertainty factor to be applied to the assessment method.
9. An example of the application of the assessment method.
10. Reference is made to alternative sources of guidance available in national or international guidance, codes or standards.

The flow charts included for each defect type generally consist of a number of yes-no type questions designed to identify whether or not the methods contained in that chapter are appropriate to the given case, and to indicate the appropriate method to use. An example of the flow chart for the assessment of corrosion is given in Figure 3.

5 ASSESSMENT METHODS IN THE PIPELINE DEFECT ASSESSMENT MANUAL

A summary of all of the methods recommended in the Pipeline Defect Assessment Manual for predicting the burst strength of a defect subject to internal pressure is given in Table 1[7-16]. Longitudinally and circumferentially-orientated defects are considered. The 'primary' methods (indicated in normal font) are plastic collapse (flow stress dependent or limit state) failure criteria, and are only appropriate if a minimum toughness is attained[18]. The secondary methods (indicated in *italic font*) are the alternative methods recommended when a minimum toughness is not attained. Upper shelf behaviour is assumed throughout. The general procedures for assessing flaws in structures, based on fracture mechanics, given in BS 7910[4] (and API 579[17]) can be applied in general (irrespective of upper or lower shelf behaviour), but will generally be conservative compared to the pipeline specific methods[3].

Having given an overview of the contents of PDAM, the remainder of this paper: (1) describes in general terms the various methods for the assessment of corrosion, (2) summarises the available full scale test data, (3) considers the role of toughness, (4) identifies what are generally recognised as the 'best' methods for assessing corrosion, and (5) presents the key considerations when assessing a corrosion defect in a pipeline.

6 CORROSION IN PIPELINES

Corrosion is an electrochemical process. It is a time dependent mechanism and depends on the local environment within or adjacent to the pipeline. Corrosion usual appears as either general corrosion or localised (pitting) corrosion. There are many different types of corrosion, including galvanic corrosion, microbiologically induced corrosion, AC corrosion, differential soils, differential aeration and cracking. Corrosion causes metal loss. It can occur on the internal or external surfaces of the pipe, in the base material, the seam weld, the girth weld, and/or the associated heat affected zone (HAZ).

Internal and external corrosion are together one of the major causes of pipeline failures. Data for onshore gas transmission pipelines in Western Europe for the period from 1970 to 1997 indicates that 17 percent of all incidents resulting in a loss of gas were due to corrosion[1]. Incident data from the Office of Pipeline Safety in the USA for the year 2001

[3] PAFFC incorporates correlations between the fracture toughness and the upper shelf Charpy impact energy; therefore, PAFFC is not applicable to lower shelf conditions (although the underlying theoretical model is applicable if the fracture toughness (K, J or δ) is measured).

attributes 29 percent of incidents in liquid pipelines, and 19 percent of incidents in gas pipelines, to corrosion[3].

Environmentally assisted cracking, such as stress corrosion cracking (low pH and high pH SCC), hydrogen induced cracking (HIC), etc., must be assessed using different methods to those describe here, because the degradation mechanism causes cracking, blistering, etc., rather than blunt metal loss.

Corrosion in a pipeline may be difficult to characterise. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions (as illustrated in Figure 4). It may occur as a single defect or as a cluster of adjacent defects separated by full thickness (uncorroded) material. There are no clear definitions of different types of corrosion defects. The simplest and perhaps most widely recognised definitions are as follows: pitting corrosion, defined as corrosion with a length and width less than or equal to three times the uncorroded wall thickness, and general corrosion, defined as corrosion with a length and width greater than three times the uncorroded wall thickness. The Pipeline Operators Forum (POF) has developed a set of specifications and requirements for the inspection of pipelines by intelligent pigs, including definitions of types of metal loss features (pinhole, pitting, slotting, grooving and general)[19]. 'Blunt' has been defined in the literature as defects whose minimum radius equals or exceeds half of the pipe wall thickness[20], and defects with a width greater than their local depth[21].

A considerable amount of time and effort has been devoted to the study of the static strength of corrosion defects in pipelines. Initially, research concentrated on the behaviour of sharp defects (machined V-shaped notches and slits), but subsequently the work was extended to consider artificial and real corrosion defects. The primary focus of research into the significance of corrosion defects has been towards longitudinally-orientated defects subject to internal pressure loading. Several recently published papers have discussed the background to the various methods for assessing corrosion that exist in the literature (B31G, modified B31G, RSTRENG, DNV-RP-F101, etc.)[22-24], so such information is not repeated here.

7 FULL SCALE BURST TESTS OF REAL AND ARTIFICIAL CORROSION DEFECTS

Full scale vessel burst tests of predominantly longitudinal real and artificial corrosion defects in line pipe subject to internal pressure have been carried out by a number of different organisations. Artificial corrosion defects are machined pits, grooves and patches, blunt, flat-bottomed defects with a uniform profile. A smaller number of tests have been conducted on longitudinal corrosion subject to axial and/or bending loads in addition to internal pressure, and on circumferential and helical defects; these tests are not considered here.

The total number of published burst tests of 'corrosion' defects considered here is 343 (including 215 tests in the AGA/PRCI Database of Corroded Pipe Burst Tests), although only 157 tests are considered to be 'reliable' tests of longitudinally orientated corrosion subject to internal pressure (see below). The number and type of tests conducted by each organisation is given below.

Barkow (1972)[25]	4 vessel tests (real corrosion)
Texas Eastern (1972)[26]	15 vessel tests (real corrosion)
Battelle (1973)[27]	47 vessel tests (real corrosion)
British Gas (1974)[28]	22 vessel tests (real corrosion)
University of Waterloo (1990, 1991)[29-32] (Mok et al.)	20 burst tests (machined grooves)
British Gas (1992)[33]	23 vessel tests (machined)
Vieth and Kiefner (1994)[34] (AGA/PRCI)	124 vessel tests (most real corrosion)

Kiefner et al. (1995)[35] (AGA/PRCI)	91 vessel tests (some real corrosion)
Battelle (1995)[20]	2 vessel tests (machined)
University of Waterloo (1992)[36]	12 vessel tests (real corrosion pits)
University of Waterloo (1994 - 1996)[37-39]	26 vessel tests (machined pits)
Fu and Batte (1999)[40] 4 (British Gas) (LPC)	2 vessel test (machined patch)
Transgas (2000)[41]	17 vessel tests (some real corrosion)
Petrobras (2000)[42]	9 vessel tests (machined grooves)
University of Waterloo (1996, 2000)[43-45]	40 vessel tests (real corrosion)
British Gas (1992)[33]	4 ring tests (machined slits)
British Gas, Shell (1992, 1994)[46,47]	9 ring tests (machined grooves)
University of Waterloo (1998)[48] (Roberts and Pick)	10 vessel tests (machined)
DNV (2000)[49]	12 vessel tests (machined)

The AGA/PRCI Database of Corroded Pipe Tests[34,35] is the most comprehensive source of publicly available burst tests of real and simulated corrosion in line pipe material, although it does not included all of the tests identified above (based on the 1995 edition of the database, there are an additional 108 vessel tests and 21 ring tests in the published literature).

The tests include artificial (simulated) corrosion defects (machined pits, slots and patches) and real corrosion defects, single defects and interacting defects, burst tests (internal pressure only) and combined loading (pressure, bend and axial compression) tests. Given the large number of tests from different sources contained in the Database of Corroded Pipe Tests and in the wider published literature, the data must be used with some care, otherwise tests that are not directly comparable may be considered together. Some of the test data is not reliable, due to the test having been subject to a number of pressure cycles (as is the case when a vessel containing multiple defects is tested repeatedly), or the test being terminated prior to failure of the defect. Other tests involve interaction, or the effects of combined loading, and should not be considered with tests of single defects. For some tests the available information is incomplete.

The ‘reliable’ test data has been identified as above and guided by the tests omitted from the further validation of RSTRENG[35]. The range of the experimental parameters of all of the ‘reliable’ burst tests of predominantly longitudinally orientated (real or artificial) ‘corrosion’ defects (a total of 159 tests) is:

Pipe Diameter, mm	273.0	to	914.4
Wall Thickness, mm	4.57	to	22.1
$2R/t$ ratio	31.5	to	130.3
Grade (API 5L)	A25	to	X65
Yield strength, Nmm^{-2}	196.0	to	515.0
Tensile strength, Nmm^{-2}	277.0	to	658.0
yield to tensile ratio	0.60	to	0.85
2/3 Charpy Impact Energy, J	18.0	to	90.0
Maximum Defect Depth (d), mm	1.60	to	17.1
d/t	0.25	to	0.97
Defect Length ($2c$), mm	19.35	to	3048.0

4 The Linepipe Corrosion Group Sponsored Project (conducted by British Gas) conducted approximately 81 full scale vessel burst tests and 52 ring expansion tests of artificial corrosion defects (both single defects and interacting defects). However, most of these tests have not been published.

$2c/(Rt)^{0.5}$	0.527	to	49.7
Defect Width, mm	0.15	to	304.8
Burst Pressure, Nmm^{-2}	4.88	to	25.2
Burst Stress, Nmm^{-2}	145.9	to	589.5
Burst Stress (percent SMYS)	45.4	to	186.3

Real corrosion defects have an irregular profile, whereas artificial (machined) corrosion defects are typically flat bottomed. The profile of a corroded area must be considered if an accurate prediction of the burst pressure is desired. River-bottom profiles are available for all of the defects in the Database of Corroded Pipe Tests. This information is not available for some of the additional published tests of real corrosion.

A number of conclusions on the behaviour of corrosion defects from various authors are listed below:

1. The longitudinal extent of a corroded area is the most important length parameter for the burst strength under internal pressure loading. The circumferential extent has a small influence on the burst strength, but the effect is sufficiently small to not need considering. However, the circumferential extent must be considered if external axial and/or bending loads are present.
2. External loads reduce the burst pressure compared to the case of an end-capped pressure vessel (axial stress equal to half the hoop stress). The effect of tensile external loads is generally small, whilst compressive loads can cause a significant reduction in the burst pressure.
3. No difference between the behaviour of internal and external corrosion has been noted in full scale tests or finite element analyses (but noting that pipelines are thin walled geometries).
4. Short defects (typically less than 3*t* in length) of any depth record high burst pressures, typically above the pressure required to yield the uncorroded pipe.
5. In modern, tough, line pipe steel the flow stress for smooth corrosion defects is the ultimate tensile strength of the material.
6. The effect of toughness of an sharp defect is more significant than that on a blunt defect.

8 THE ROLE OF GEOMETRY AND FLOW STRESS

8.1 Ductile Failure

Two possible scenarios for the ductile failure of a blunt part-wall defect in a tough line pipe steel (i.e. excluding the possibility of cleavage fracture) have been identified, as described by Leis and Stephens (1997)[50,51] and Fearnehough et al.[52,53]).

(1) As the load (pressure) increases, local wall thinning will occur in the remaining net section. This local wall thinning could continue, leading to necking of the wall and failure due to void nucleation, growth and coalescence in a manner comparable to that of a tensile test specimen.

(2) Alternatively, a crack could initiate at the base of the defect due to the presence of micro-stress raisers (e.g. local surface irregularities caused by a corrosion mechanism) through a process of void nucleation and growth. The behaviour after the initiation of a crack would depend on the toughness of the material. In a high toughness material, initiation would be delayed to a higher load and further stable ductile tearing would be slower, or a growing crack could blunt; wall thinning would continue and the failure load would tend to that of plastic collapse. However, in a lower toughness material, once initiated, the crack would extend by stable ductile tearing, reducing the remaining wall thickness and hence reducing

the degree of wall thinning that occurs before failure. The load at failure would be less than that predicted by the plastic collapse limit state because of the stable ductile tearing.

8.2 The Role of Geometry

The failure of a part-wall defect in a pipeline subject to internal pressure has two limits:

(1) a defect with a length and depth tending towards zero (i.e. defect-free pipe), and

(2) an infinitely long defect of finite depth (see Figure 5).

It is assumed that the line pipe material is tough and that failure occurs due to plastic collapse (i.e. unstable plastic flow). In the first case, the failure stress tends towards the failure stress of defect-free pipe, based on the full wall thickness (t), and in the second case it tends towards the failure stress of defect-free pipe, but based on the reduced wall thickness (t-d).

The failure stress of a part-wall flaw of finite length lies between the above two extremes; it is a function of (1) the geometry of the pipe and the geometry of the defect, and (2) the material.

8.3 The Role of Flow Stress

The failure stress of defect free pipe tends towards the ultimate tensile strength of the material, as measured in a uniaxial tensile test, although account must be taken of large scale geometry effects (a cylinder under internal pressure exhibits geometric softening: as the pressure increases, the diameter increases; the hoop stress increases because of both the increase in pressure and the increase in diameter). Theoretically, the failure stress depends upon the strain hardening characteristics of the material and the assumed yield criterion (Tresca or von Mises)[46,50,51,54,55]; experimental results indicate that the failure stress lies between the Tresca and von Mises bounds, and is reasonably approximated by the ultimate tensile strength.

The failure stress of defect free pipe can be interpreted as a flow stress, although the term reference stress[5] has also been proposed (by researchers at Battelle[50,51]) to differentiate it from the term flow stress as used in fracture mechanics[6]. The flow or reference stress describes the role of the material.

8.4 The Failure of a Blunt, Part-Wall Defect

Therefore, the failure stress of a blunt, part-wall defect subject to internal pressure can be predicted by a failure criteria that comprises a flow stress term and a geometry term. The geometry term includes the effects of bulging, the global stiffness, the stiffness of the defect, defect acuity, etc.. The flow, or reference, stress represents the material behaviour. Note that the complete separation of material and geometry terms is an approximation, introducing some scatter into predictions of test data or numerical data.

8.5 The Role of Geometry and Flow Stress in the Published Methods

Failure criteria such as the flow stress dependent forms of the NG-18 equations[7] (and ASME B31G[27,56], modified B31G[14], etc.) have been described as plastic collapse failure criteria.

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[5] The reference stress is the failure stress of defect-free pipe; it represents the plastic collapse limit state. The reference stress is independent of the defect geometry.

[6] The flow stress is an empirical concept. It was introduced to incorporate plasticity into a linear-elastic fracture mechanics analysis. The flow stress is not necessarily the stress at plastic collapse (where plastic collapse is failure due to plastic flow).

However, in many of the tests on which these older semi-empirical failure criteria are based, failure was preceded by significant amounts of ductile tearing and some of the steels had a low toughness. Furthermore, the geometry term was empirical and the flow stress was adjusted to fit the test results. This lead to empirical definitions of the flow stress (reference stress) that were conservative, since they were biased towards the behaviour of older steels. The NG-18 equations were developed from tests of V-shaped notches, not blunt, part-wall defects. Therefore, the methods for assessing corrosion based on the NG-18 equations (ASME B31G, modified B31G, etc.) have a conservative bias when applied to tests of blunt, part-wall defects.

Developments in the accuracy of failure criteria follow from their being better able to describe the effects of reference stress and geometry. The more recent failure criteria for corrosion (DNV-RP-F101[13], PCORRC[21]) have used finite element analyses of blunt, part-wall defects to determine the form of the geometry term, and have considered the form of the reference stress in more detail. These failure criteria were validated against burst tests of modern line pipe steels containing blunt, part-wall defects or real corrosion defects. Modern line pipe steels have a higher toughness than older steels, such that the failure of blunt part-wall defects is controlled by plastic collapse (where plastic collapse is defined in terms of the defect-free failure stress (i.e. the ultimate tensile strength)), and the effect of toughness is negligible. However, difficulties can then arise in applying the more recent methods to older, lower toughness, line pipe. The more recent methods may be none conservative.

9 THE EFFECT OF TOUGHNESS

The effect of toughness on the failure stress of blunt, part-wall defects can be observed through comparisons with the published burst tests of real and artificial corrosion. The influence of toughness is clear in tests of part-wall V-shaped notch tests, as conducted by Battelle during the development of the NG-18 equations[7] (see Figure 6): as the toughness decreases, a flow stress dependent failure criterion becomes inappropriate (the predictions become increasingly non-conservatively). The influence of toughness on the failure of corrosion defects is less clear (see Figure 7 and Figure 8) because: (1) corrosion defects are blunt, and (2) the irregular profile of a real corrosion defect introduces experimental scatter. Increasing conservatism with increasing toughness is apparent for modified B31G (Figure 7), but not for DNV-RP-F101 (Figure 8). The toughness of the line pipe steel is not known for a large number of the tests in the AGA/PRCI Database of Corroded Pipe Tests[7].

Figure 7 and Figure 8 include those AGA/PRCI tests of defects which have not been subject to multiple pressure cycles are shown (since removing all of the ‘unreliable’ tests would remove some tests of low toughness line pipe and give an incomplete picture). The tensile strength is not available for all of the tests, so some tests in Figure 7 are not to be found Figure 8. A number of test results are noteworthy[8]: test index 107 is a corrosion pit that contained a prior through-wall crack and can therefore be excluded, test indices 215, 9, 6 have transition temperatures at or above the test temperature, and test index 1 is of a line pipe steel with an unreported transition temperature. Test indices 1, 6 and 9 are all the first test of a series of multiple tests of a single vessel. No metallurgical analysis of the fracture surfaces is reported, so the actual failure mechanism (ductile or cleavage) is the subject of conjecture.

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[7] Tests with an unknown toughness are plotted as having a zero toughness, to illustrate the range of the predictions.

[8] The test index number refers to the number of the test in the AGA/PRCI Database of Corroded Pipe Tests.

The tests of real corrosion defects that are non-conservatively predicted by modified B31G and DNV-RP-F101 involve line pipe steels tested at a temperature below the transition temperature (or the transition temperature is unknown). None of the assessment methods are applicable to line pipe steel that is in the transitional region or on the lower shelf.

Considering all of the published full scale tests, the lowest toughness is 18 J (13 ftlbf) and the maximum wall thickness is 22.5 mm (1.0 in.)[9]. Consequently, considering the basis of the various criteria and a comparison with full scale test data, ASME B31G, modified B31G and RSTRENG are applicable to low, moderate and high toughness steels (assuming upper shelf behaviour), whilst DNV-RP-F101[13] and PCORRC[21] are only proven for moderate to high toughness steels (see sections 11 and 12).

10 METHODS FOR ASSESSING CORROSION DEFECTS

Numerous methods have been developed for predicting the burst pressure of blunt part-wall defects, which characterise the behaviour of typical corrosion defects. A number of these methods are listed below (see also Table 2). All of these methods are primarily concerned with the longitudinal extent of the corroded area and internal pressure loading. The methods are empirical or semi-empirical; the older methods are based on the original Battelle part-wall failure criterion (the NG-18 equations), whilst the more recent methods have partly developed from extensive numerical studies validated against test data (see below).

i. *ASME* B31G[56]

ii. *modified* B31G (RSTRENG 0.85) (Kiefner and Vieth (1989))[14]

iii. *RSTRENG* (Kiefner and Vieth (1989))[14]

iv. *Klever* (1992)[54], Stewart et al. (1994)[46]

v. *SHELL92* (Ritchie and Last (1995))[55]

vi. DNV-RP-F101 (LPC)[13,40] *

vii. *PCORRC* (Stephens and Leis (2000))[21,51] *

viii. CPS (Cronin and Pick (2000))[44] *

ix. SAFE (SwRI) (Wang et al. (1998))[57] *

(an asterisk denotes the 'new' methods)

The DNV-RP-F101 and SAFE methods can be applied to corrosion subject to axial and bending loads.

A detailed description of all of these methods can be found in the published literature.

i. Real corrosion

Corrosion defects are orientated and spaced in a random manner. In the analysis of such a defect an attempt is made to characterise the corroded area by its projected length and area. The difficulty in describing a three-dimensional corroded area by a few parameters introduces large scatter in comparisons of predicted to actual failure stress. The scatter is significantly reduced by the use of assessment methods based on a river-bottom profile, but

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[9] Fu (1999) has tested line pipe up to 25.4 mm, but the test results have not been published[22].

there is still more scatter than for flat-bottomed defects. River-bottom methods (such as RSTRENG and those given in DNV-RP-F101 and CPS) are based on iterative algorithms and are not suited to hand calculations. The methods based on a simple geometric approximation are closed-form methods.

Interaction between defects has been considered empirically, or through finite element analysis of a narrow range of pipe and defect geometries. Limited guidance is available in the published literature.

ii. Approximate methods for assessing real corrosion

The original ASME B31G criterion[56], modified B31G criterion[14], DNV-RP-F101 (LPC), and PCORRC define simple approximations to the exact corroded area, based on the maximum length and the maximum depth of the defect. Corrosion typically has an irregular profile. The most conservative idealisation is a rectangular profile (as in DNV-RP-F101 and PCORRC). ASME B31G assumes a parabolic profile (the 2/3 factor in the equation, see Table 2) and modified B31G assumes an arbitrary profile (the 0.85 factor in the equation). The methods for assessing a river-bottom profile are also approximations, because a river-bottom profile is an idealisation of the actual three-dimensional shape of a corroded area.

All of the methods considered here assume that failure is due to a flow stress dependent mechanism and can, therefore, be described by the tensile properties (yield strength, ultimate tensile strength) of the line pipe steel. It is further assumed that the steel is on the upper shelf; the transition temperature is conventionally defined as the temperature at which a DWTT specimen exhibits an 85 percent shear area. A minimum toughness may need to be satisfied. This is specifically the case for the recent, alternative, assessment methods (DNV-RP-F101 (LPC), PCORRC, CPS[44], SAFE[57]) which assume that failure is controlled by plastic collapse (plastic flow) (i.e. the flow stress is the ultimate tensile strength).

The methods are all similar in their general form, being based on the NG-18 equation for the failure of a part-wall flaw, but differ in respect of assumptions and simplifications made in their derivation. These differences can be classified in terms of:

i. the flow stress.

ii. the geometry correction factor (also referred to as the Folias factor, or the length correction factor, or the bulging correction factor), and

iii. the defect profile.

Stephens and Francini (2000) have concluded that two categories of assessment methods for corrosion defects can be described[24]: (1) empirically calibrated criteria that have been adjusted to be conservative for almost all corrosion defects, irrespective of the toughness of the line pipe (these criteria are variously based on the yield strength, the flow stress, or the ultimate tensile strength) (the ‘old’ methods), and (2) plastic collapse criteria that are only appropriate for blunt defects in moderate to high toughness line pipe (these criteria are based on the ultimate tensile strength) (the ‘new’ methods). DNV-RP-F101 (LPC), PCORRC, SAFE and CPS should be regarded as belonging to the second category of assessment method.

The ASME B31G, modified B31G, RSTRENG, SHELL92[55], LPC, DNV-RP-F101 and PCORRC[21] methods are summarised in Table 2 and Figure 9[10]. The LPC and DNV-RP-F101 methods are essentially the same. LPC, DNV-RP-F101 and PCORRC were developed from curve fitting to the results of parametric finite element analyses of blunt, part-wall defects. These are theoretically calibrated methods (i.e. calibrated to average data in the

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[10] All of the curves in this figure represent the failure locus of critical defect depth and defect length for a hoop stress equal to 100 percent SMYS. For all of the methods except ASME B31G, the failure loci are dependent on the line pipe steel grade. The curves are presented for two grades, X42 and X65.

form of an experimentally validated finite element model and associated numerical failure criterion), as compared to ASME B31G and related methods, which are based on curve fits to empirical data (originally tests on V-shaped notches, then real corrosion defects). PCORRC and DNV-RP-F101 give similar results (see Figure 9).

11 COMPARISON OF METHODS FOR ASSESSING CORROSION DEFECTS

11.1 Problems with Scatter in the Data

Large scatter is apparent in the predictions of the burst strength of real corrosion when using a method based on a simple geometric idealisation (rectangular, parabolic, etc.), because maximum depth and maximum length are insufficient to describe the irregular shape of a real corrosion defect (see Figure 10).

11.2 Problems with Comparing the Methods

There is insufficient data in the published literature to do a thorough comparison of the methods for assessing corrosion. If there were enough detailed data, then the first step in a comparison would be burst tests of artificial, flat-bottomed corrosion defects, to avoid scatter associated with approximations to an irregular profile. The approach would be to (1) consider those tests which are known to have failed by plastic collapse (i.e. the flow stress or reference stress (defect-free failure stress) is equal to the ultimate tensile strength) and define an appropriate failure criterion (as has been done for DNV-RP-F101 and PCORRC), then (2) identify those tests which do not follow the predictions of the criterion, and then (3) determine what is different about these outliers and thence define the limitations of the failure criterion. Only then would the methods be compared against burst tests of real corrosion defects.

11.3 Comparisons of Methods in the Published Literature

Several reviews or comparisons of methods for assessing corrosion defects are described in the published literature. The Linepipe Corrosion Group Sponsored Project and the DNV Joint Industry Project both conducted a review of existing assessment methods as part of the development of an improved method[22,23] [11]. Battelle have also reviewed methods for assessing corrosion[24]. Other authors have conducted limited comparisons of methods with test data during the course of the development and validation of new or modified assessment methods. The conclusions of the various reviews are:

1. Recently developed methods such as DNV-RP-F101 and PCORRC are based on equations fitted to the results of a large number of finite element analyses of blunt, part-wall defects, these analyses incorporated a failure criterion validated against actual burst tests. The DNV-RP-F101 and PCORRC methods were developed to be mean fits to the experimental and numerical data, and so should be the most accurate methods; this is the consensus view of the reviews in the literature[22-24] (see Figure 10 and note the accurate predictions of the artificial corrosion defects[12]).
2. The modified B31G method is more accurate than the original ASME B31G method[14,24].

[11] A PRCI sponsored project is being conducted to further compare existing assessment methods for corrosion subject to internal pressure and to clarify issues surrounding the behaviour of blunt defects in low and moderate to high toughness line pipe steels. The result of this study are not currently in the public domain.

[12] The AGA/PRCI tests include tests of older, lower grade line pipe steels, hence some of the non-conservative predictions.

3. RSTRENG gives a further improvement in accuracy[14,22,24].
4. The more recent methods, such as DNV-RP-F101 and PCORRC, are only applicable to blunt defects in tough materials[23,24].

The ASME B31G method (or modified B31G and RSTRENG) for predicting the burst pressure of a corroded pipeline (the 'old' methods) were, predominantly, developed and validated through full scale tests on older line pipe steels. The 'new' methods (DNV-RP-F101 and the pipeline specific appendix of BS 7910, and PCORR) were developed and validated through tests on modern, high toughness, line pipe steels. The 'new' methods are biased towards the behaviour of modern, high toughness, line pipe steels and the 'old' methods are biased towards older, relatively lower toughness, steels. The difference between the behaviour of older line pipe steels and modern steels can largely be attributed to the general increase in the toughness of line pipe, due to improvement in steel production and technological advances. The 'old' methods demonstrate greater scatter than the 'new' methods when compared to the (relevant) published full scale test data; the 'new' methods are more accurate.

12 RECOMMENDATIONS IN PDAM

The recommendations in PDAM for assessing the burst strength of a corrosion defect (considering depth and longitudinal length) are:

1. DNV-RP-F101 for moderate to high toughness line pipe, and
2. modified B31G and RSTRENG in older, lower grade line pipe, and when there is no confidence that the requirements for the application of the more recent methods are satisfied.

Moderate to high toughness line pipe is defined as:

i. modern (clean) line pipe with a 2/3 thickness specimen size upper shelf Charpy V-notch impact energy equal to at least 18 J (13 ftlbf) (the full size equivalent is 27 J (20 ftlbf)),
ii. meeting the minimum elongation requirements in API 5L[58], and
iii. excluding line pipe steels suspected of containing a significant number of inclusions, second phase particles or other contaminants; typically, this means lower grade line pipe (such as grades A and B) and other older line pipe.

Note that none of the methods have been proven in line pipe with a wall thickness greater than 25.4 mm.

13 ASSESSING A CORRODED AREA

13.1 The Assessment Method

The best methods for assessing a corrosion defect (considering depth and longitudinal length) in a pipeline subject to internal pressure have been identified, and their limitations highlighted in section 12.

13.2 The Assessment Procedure

The flowchart in Figure 3 provides a general overview of the issues that need to be considered when assessing an area of corrosion in a pipeline, and identifies the appropriate method to be used. The flowchart does not give practical guidance of how to conduct the assessment.

What follows is some practical guidance that can be applied to assessing an area of corrosion: it can be applied to direct measurements obtained from excavating and inspecting a pipeline by hand, or to the results of an intelligent pig run. The approach adopted is to use the most conservative geometric idealisation to determine if the defect(s) are acceptable. These assumptions are then revisited and revised systematically to move from a conservative assessment to a more accurate (but still conservative) assessment. The approach can be applied to any suitable assessment method. DNV-RP-F101 and modified B31G specify an acceptance criterion, providing a necessary safety margin between failure and acceptance.

Specified minimum material properties (as given in the line pipe steel specification) and the specified minimum wall thickness should be used. The longitudinal and circumferential dimensions of the defect are defined by a projection in the respective transverse direction. Inspection tolerances should be added to all defect dimensions.

The corrosion is assumed to be in undented pipe and away from any welds. The pipeline is assumed to be subject to only internal pressure loading. The longitudinal extent of the corrosion is likely to be more important that the circumferential extent. In general, however, the various steps of the assessment should be applied to both the longitudinal and circumferential extent of the corrosion.

These assumptions simplify the assessment procedure, because it is only necessary to consider single defects and interacting defects. However, in practice corrosion coincident with dents, welds or other defects, and external loads, must be considered to complete the assessment, since they can lead to a very different picture of the significance of the defects (see Figure 11).

The corrosion is assumed to be inactive. The guidance is also applicable to active corrosion, except that it is also necessary to consider the implications of defect growth. It is important to establish the cause of any corrosion in a pipeline.

SCREENING

1. Identify the critical defects (i.e. depth greater than 80 percent of the wall thickness, failure pressure less than the maximum operating pressure). This assessment assumes that all defects are single defects, it does not take account of defect interaction. This is non-conservative; therefore the assessment cannot stop at this stage.

INTERACTION

2. Determine whether the defect(s) can be considered as a single feature or as part of a group of interacting features.

   A number of different interaction rules have been described in the literature. One commonly used rule is that adjacent defects are considered to interact if the spacing (in the longitudinal or circumferential direction) between the defects is less than the respective dimension (i.e. length or width) of the smaller defect[13]. The depth of the composite defect is defined by the maximum depth[14], and the length and width by the dimensions of an enveloping rectangle

   It is always conservative to assume that all of a cluster of adjacent defects interact. The dimensions of the composite defect are defined as above.

ASSESSMENT

3. Assess the single defect(s).

[13] This interaction rule is based on linear elastic fracture mechanics. It is to be found in documents such as BS 7910[4].

[14] Assuming that all of the defects are on a coincident surface.

4. Assess the interacting defect(s), using the dimensions of the composite defect(s).

   REVIEW

5. Consider more accurate assessment methods (less conservative) interaction rules, a river-bottom profile, etc.) for those defect(s) which are not acceptable. Alternatively, repair the defect or downrate the pipeline.

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	internal pressure (static) longitudinally orientated	**internal pressure (static) circumferentially orientated**
corrosion	DNV-RP-F101[13] *modified B31G*[14] *RSTRENG*[14]	Kastner local collapse solution[15]
gouges	NG-18 equations[7] *PAFFC*[8,9] *BS 7910*[4] *(or API 579*[17]*)*	Kastner local collapse solution *BS 7910 (or API 579)*
plain dents	empirical limits	
kinked dents	no method[1]	
smooth dents on welds	no method	
smooth dents and gouges	dent-gouge fracture model[11,12]	no method
smooth dents and other types of defect	dent-gouge fracture model	no method
manufacturing defects in the pipe body[2]	NG-18 equations *BS 7910 (or API 579)*	Kastner local collapse solution *BS 7910 (or API 579)*
girth weld defects	-	workmanship, EPRG[10] *BS 7910 (or API 579)*
seam weld defects	workmanship *BS 7910 (or API 579)*	-
cracking	*BS 7910 (or API 579)* *PAFFC*	
environmental cracking[3]	*BS 7910 (or API 579)* *PAFFC*	
leak and rupture	NG-18 equations *PAFFC*	Schulze global collapse solution[16]

Note:

1. 'No method' indicates limitations in existing knowledge, and circumstances where the available methods are too complex for inclusion in a document such as PDAM.
2. The term 'manufacturing defect' covers a wide range of pipe body defect (laminations, inclusions, seams, gouges, pits, rolled-in slugs, etc.). Consequently, it may not be possible to characterise a manufacturing defect in the pipe body as a metal-loss or crack-like defect. In these circumstances it is necessary to rely on workmanship limits and industry experience.
3. Environmental cracking (stress corrosion cracking, hydrogen blisters, hydrogen stress cracking, etc.) can be very difficult to measure and assess.

Table 1 – Recommended methods from the Pipeline Defect Assessment Manual for assessing the burst strength of defects subject to internal pressure

method	basic equation	'flow stress'(5)	defect shape	'bulging' factor(4)
NG-18	NG-18(1)	σ_Y + 10 ksi	rectangular (*d*/*t*) or defect area (A/A_o)	$\sqrt{1+0.6275\left(\frac{2c}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{2c}{\sqrt{Dt}}\right)^4}$
ASME B31G	NG-18	$1.1\sigma_Y$	parabolic 2/3(*d*/*t*)	$\sqrt{1+0.8\left(\frac{2c}{\sqrt{Dt}}\right)^2}$
modified B31G	NG-18	σ_Y + 10 ksi	arbitrary 0.85(*d*/*t*)	$\sqrt{1+0.6275\left(\frac{2c}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{2c}{\sqrt{Dt}}\right)^4}$
RSTRENG	NG-18	σ_Y + 10 ksi	effective area and effective length (river bottom profile)	$\sqrt{1+0.6275\left(\frac{2c}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{2c}{\sqrt{Dt}}\right)^4}$
SHELL92	NG-18	σ_U	rectangular (*d*/*t*)	$\sqrt{1+0.8\left(\frac{2c}{\sqrt{Dt}}\right)^2}$
LPC	NG-18	σ_U	rectangular (*d*/*t*)	$\sqrt{1+0.31\left(\frac{2c}{\sqrt{Dt}}\right)^2}$
DNV-RP-F101	NG-18	σ_U	rectangular (*d*/*t*) (and river bottom profile)	$\sqrt{1+0.31\left(\frac{2c}{\sqrt{Dt}}\right)^2}$
PCORRC	new(2)	σ_U	rectangular (*d*/*t*)	(3)

Note:

1. 2c is equivalent to L.
2. The basic equation of the part-wall NG-18 failure criterion is (where M is the bulging factor and $\overline{\sigma}$ is the flow stress)

$$\sigma_\theta = \overline{\sigma}\left[\frac{1-\left(\frac{A}{A_o}\right)}{1-\left(\frac{A}{A_o}\right)\frac{1}{M}}\right] = \overline{\sigma}\left[\frac{1-\left(\frac{d}{t}\right)}{1-\left(\frac{d}{t}\right)\frac{1}{M}}\right]$$

3. The basic equation of the PCORRC failure criterion is

$$\sigma_\theta = \overline{\sigma}\left[1-\left(\frac{d}{t}\right)\left(1-\exp\left[-0.16\left(\frac{2c}{\sqrt{Rt}}\right)\left(1-\frac{d}{t}\right)^{-0.5}\right]\right)\right]$$

4. The bulging factor in NG-18, ASME B31G, modified B31G, RSTRENG and SHELL92 is one of the various forms of the Folias factor. The bulging factor in LPC and DNV-RP-F101 was derived by curve fitting results to a non-linear geometry, elastic-plastic finite element parametric study. The bulging factor in PCORRC is incorporated into the basic equation (see above).
5. SHELL92, LPC and DNV-RP-F101 state that using $0.9\sigma_U$ gives a conservative bias to the predictions (the 0.9 factor is not included in Figure 9).

Table 2 – Methods for Assessing the Burst Strength of a Corroded Area (based on longitudinal extent) subject to Internal Pressure Loading

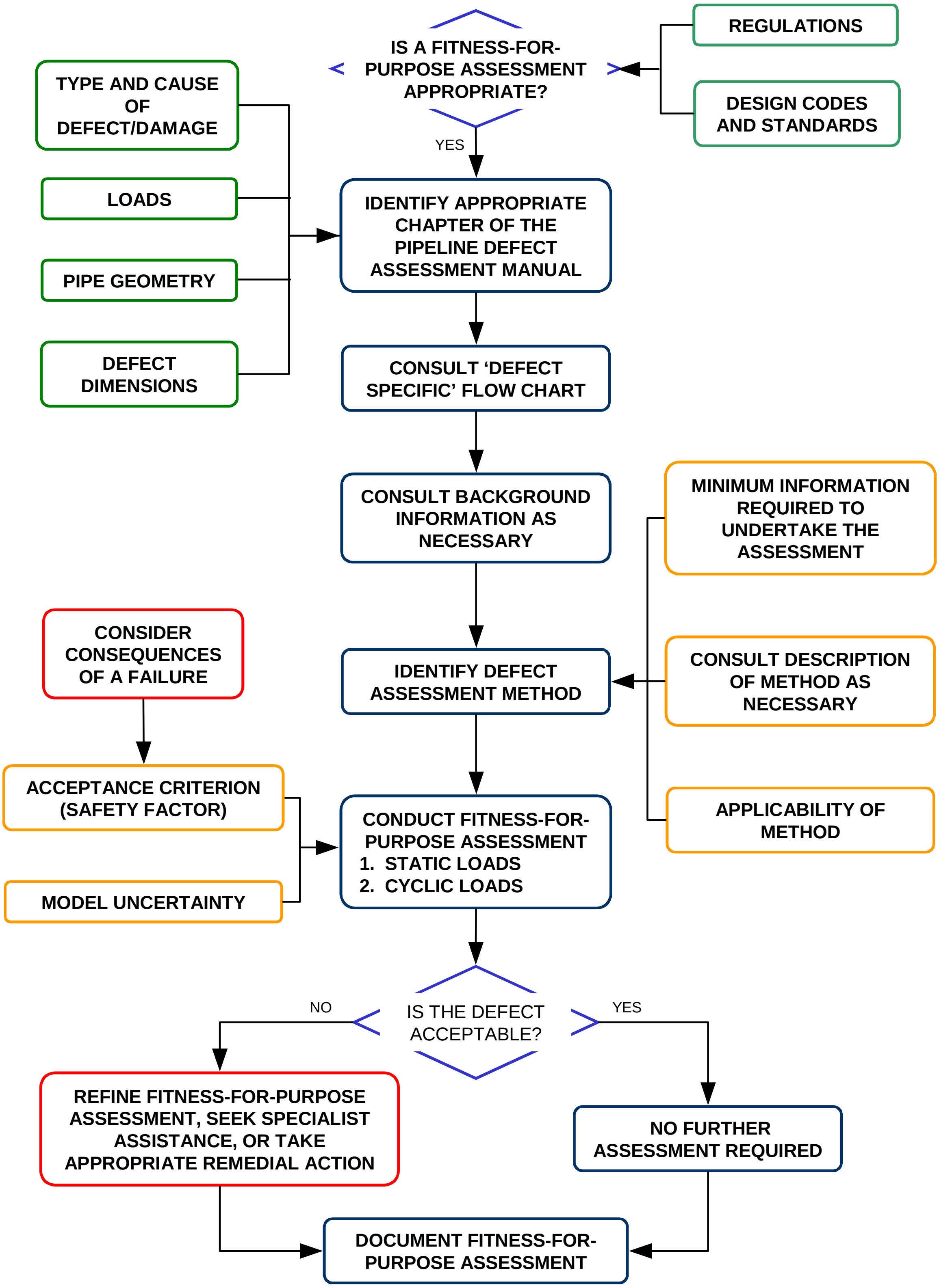
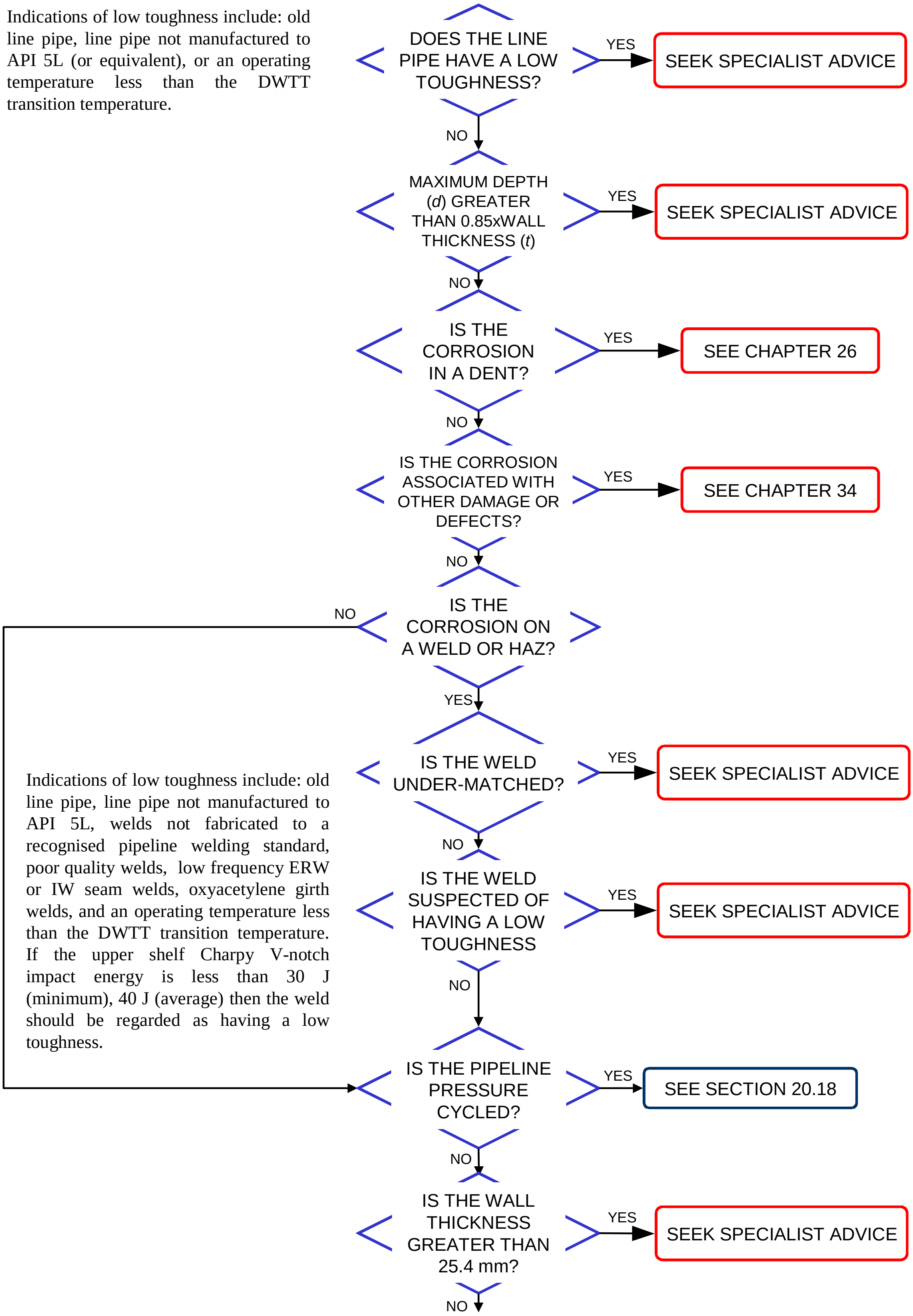
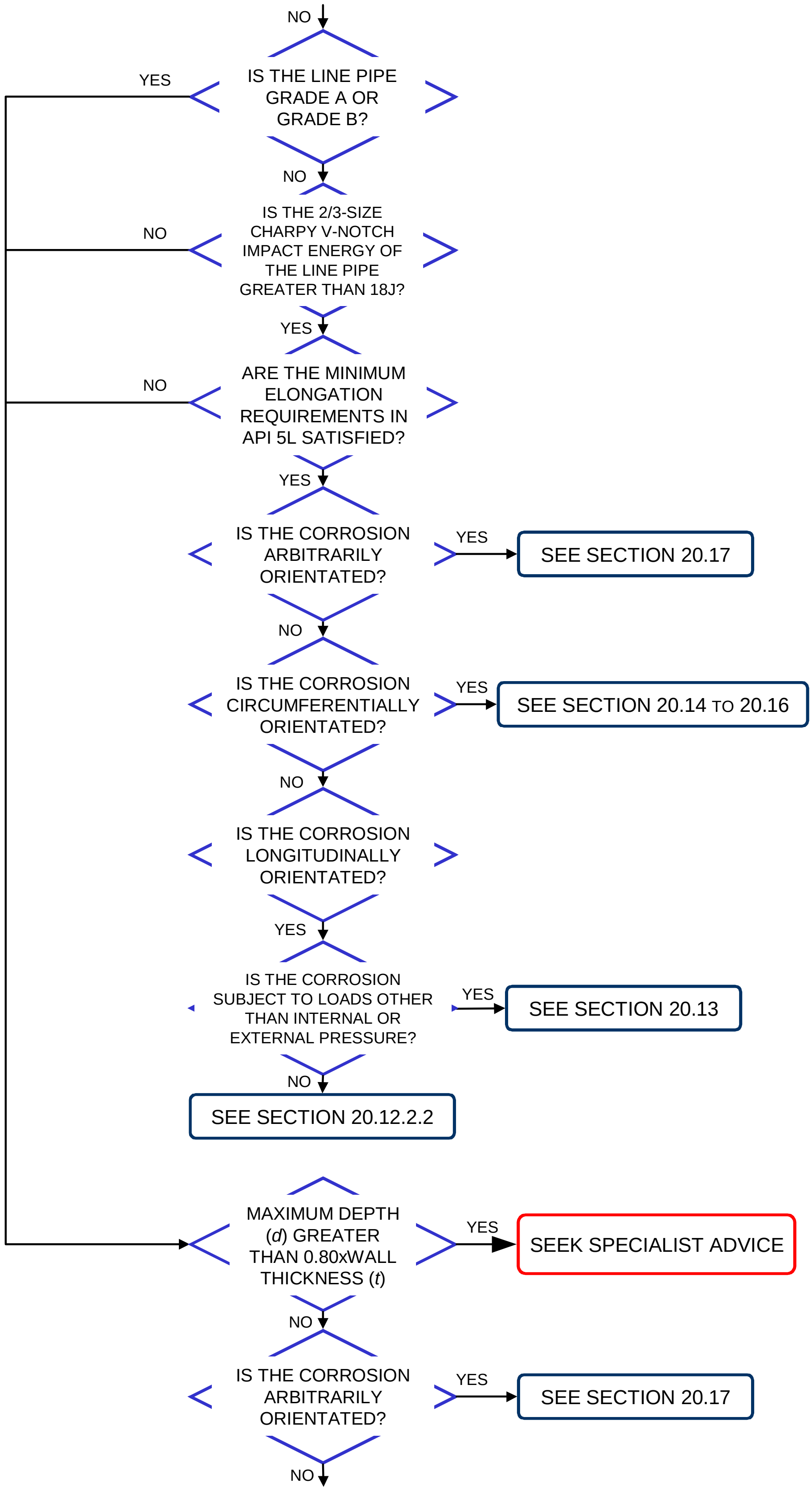


Figure 2 – The fitness-for-purpose assessment of a pipeline defect (algorithm from PDAM)

CORRODED PIPELINE




NO
IS THE LINE PIPE GRADE A OR GRADE B?
YES
NO
IS THE 2/3-SIZE CHARPY V-NOTCH IMPACT ENERGY OF THE LINE PIPE GREATER THAN 18J?
NO
YES
ARE THE MINIMUM ELONGATION REQUIREMENTS IN API 5L SATISFIED?
NO
YES
IS THE CORROSION ARBITRARILY ORIENTATED?
YES
SEE SECTION 20.17
NO
IS THE CORROSION CIRCUMFERENTIALLY ORIENTATED?
YES
SEE SECTION 20.14 TO 20.16
NO
IS THE CORROSION LONGITUDINALLY ORIENTATED?
YES
IS THE CORROSION SUBJECT TO LOADS OTHER THAN INTERNAL OR EXTERNAL PRESSURE?
YES
SEE SECTION 20.13
NO
SEE SECTION 20.12.2.2
MAXIMUM DEPTH (d) GREATER THAN 0.80xWALL THICKNESS (t)
YES
SEEK SPECIALIST ADVICE
NO
IS THE CORROSION ARBITRARILY ORIENTATED?
YES
SEE SECTION 20.17
NO

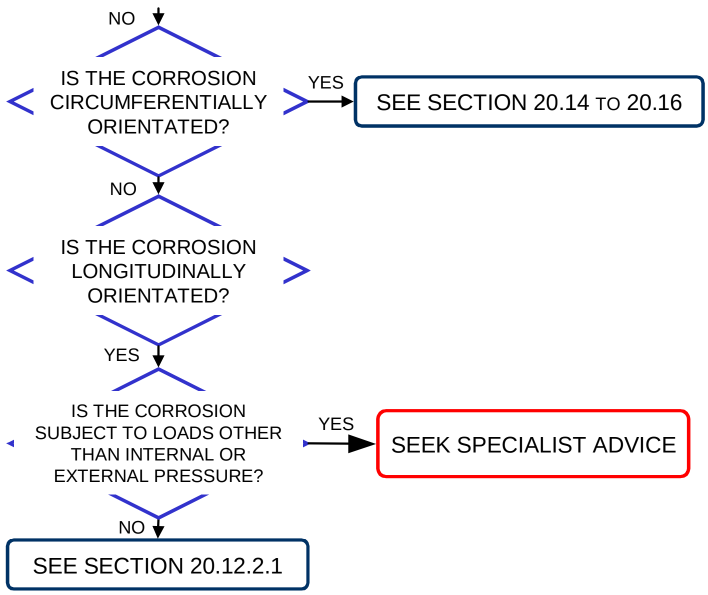


Figure 3 – The Assessment of a Corrosion Defect in a Pipeline (algorithm from PDAM)

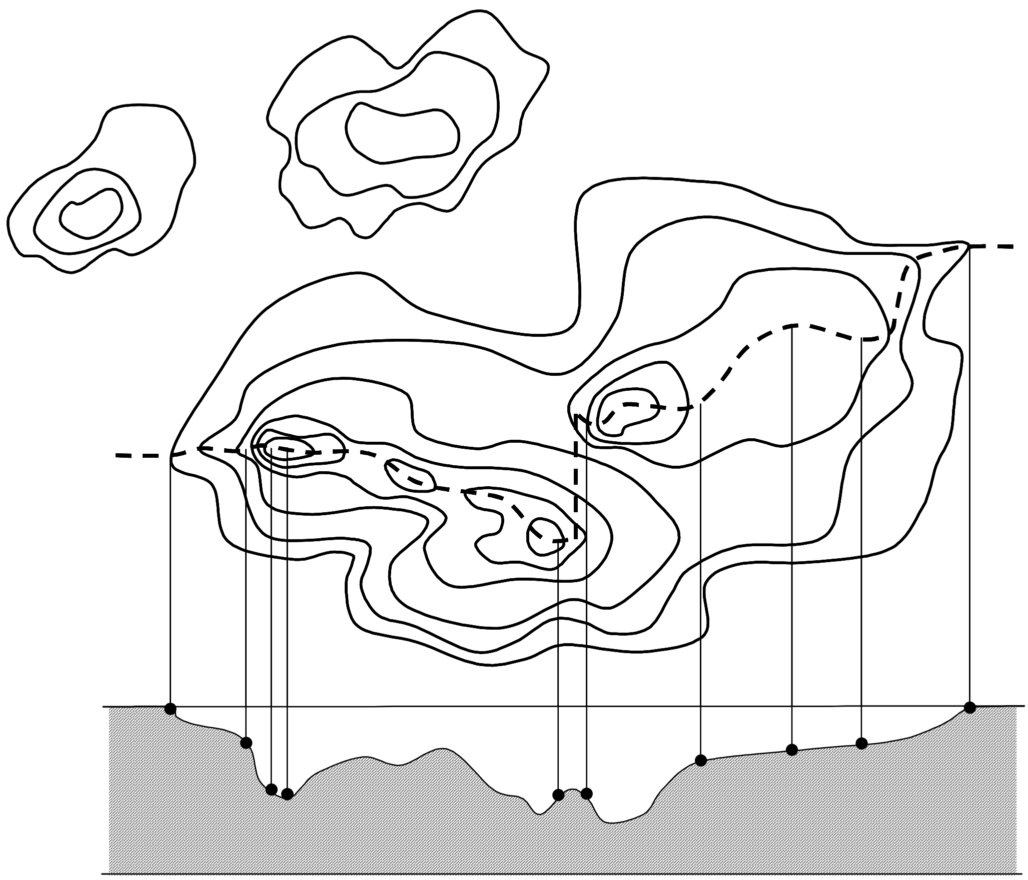


Figure 4 – The irregular length, width and depth of a typical corrosion defect

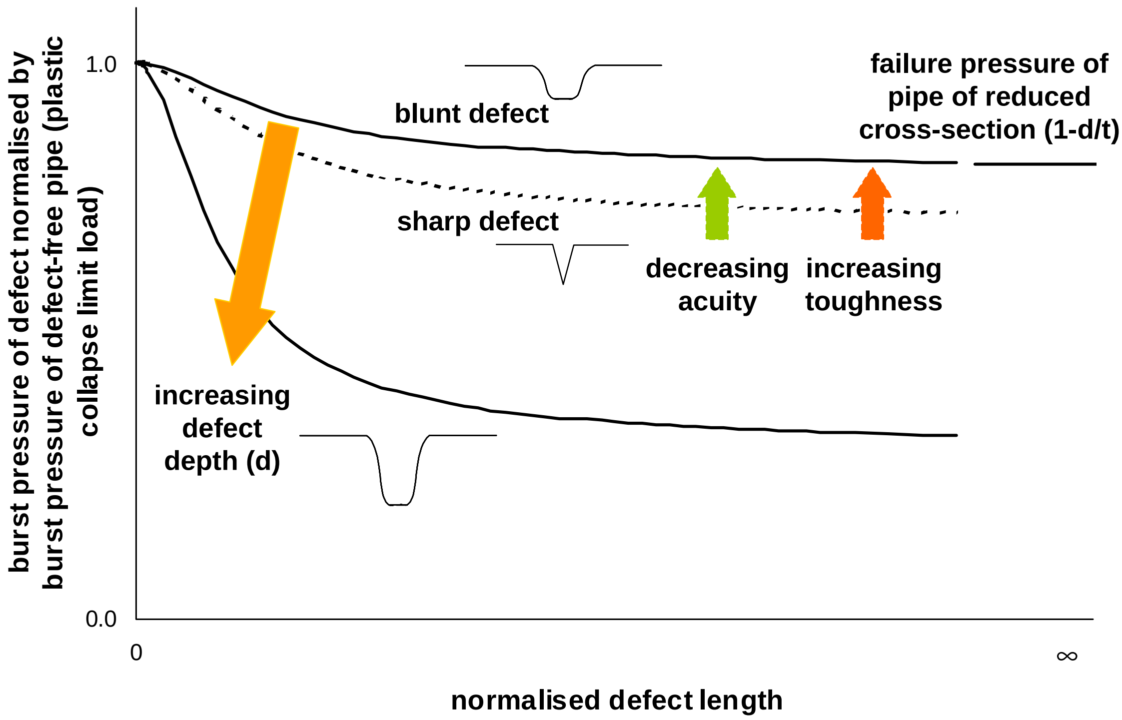


Figure 5 – The effect of material toughness, defect depth, length and acuity on burst strength

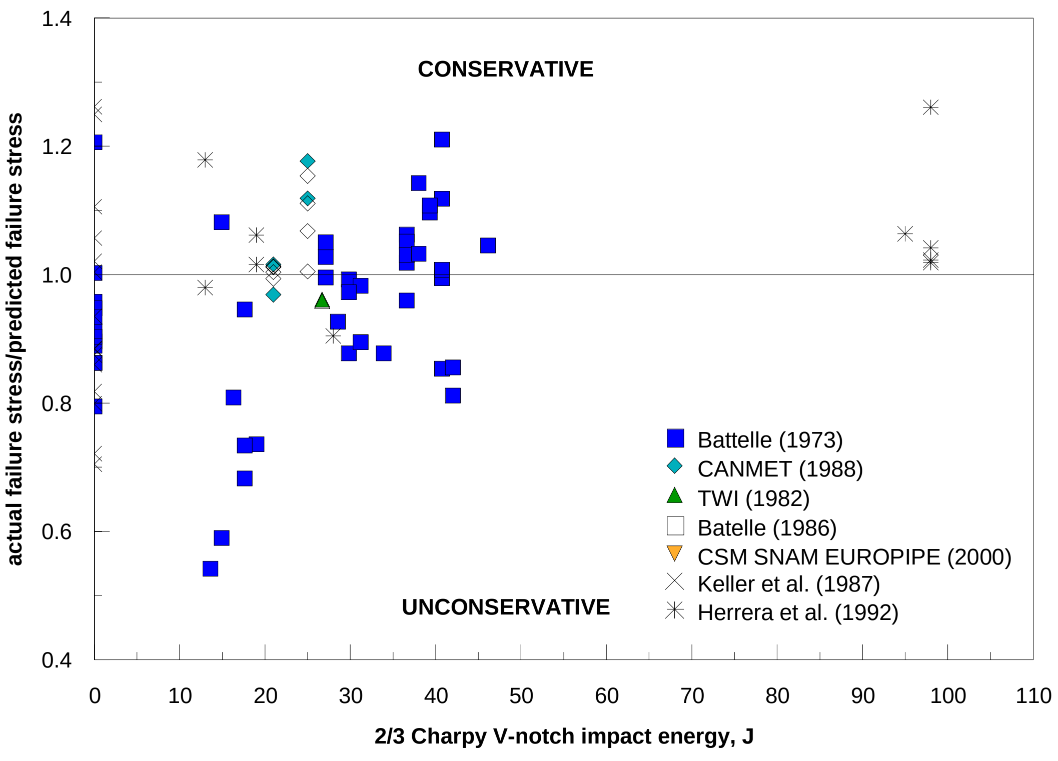


Figure 6 – The effect of toughness on flow stress dependent NG-18 predictions of burst tests of machined V-shaped notches and slots

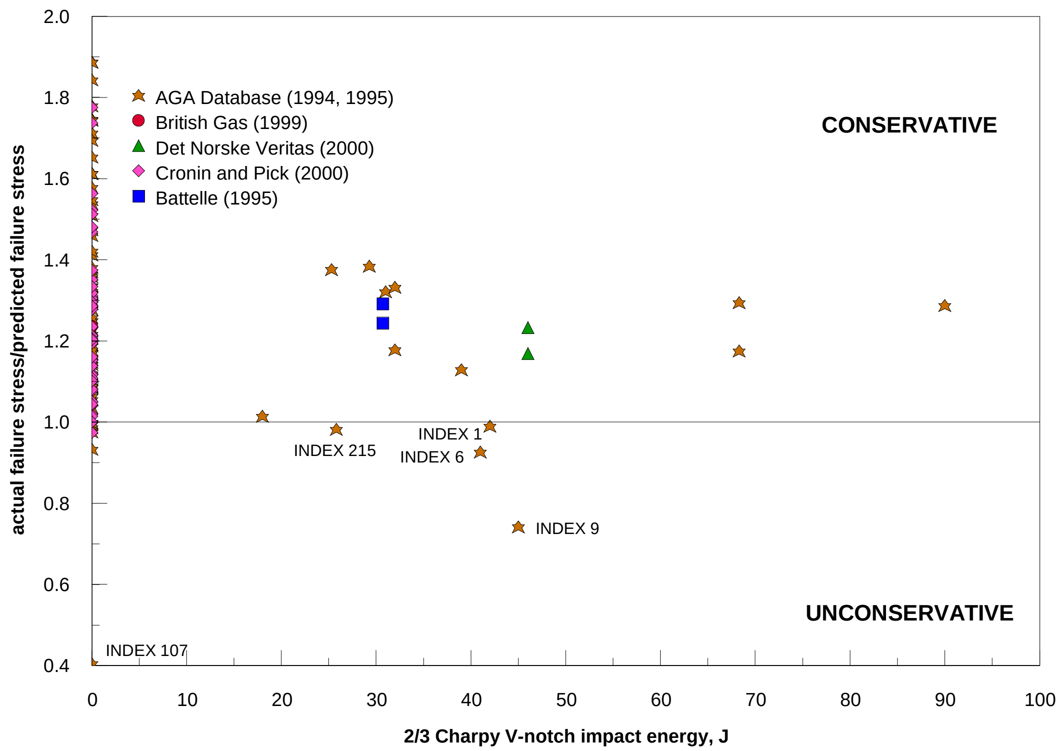


Figure 7 – The effect of toughness on modified B31G predictions of burst tests of real and artificial corrosion defects

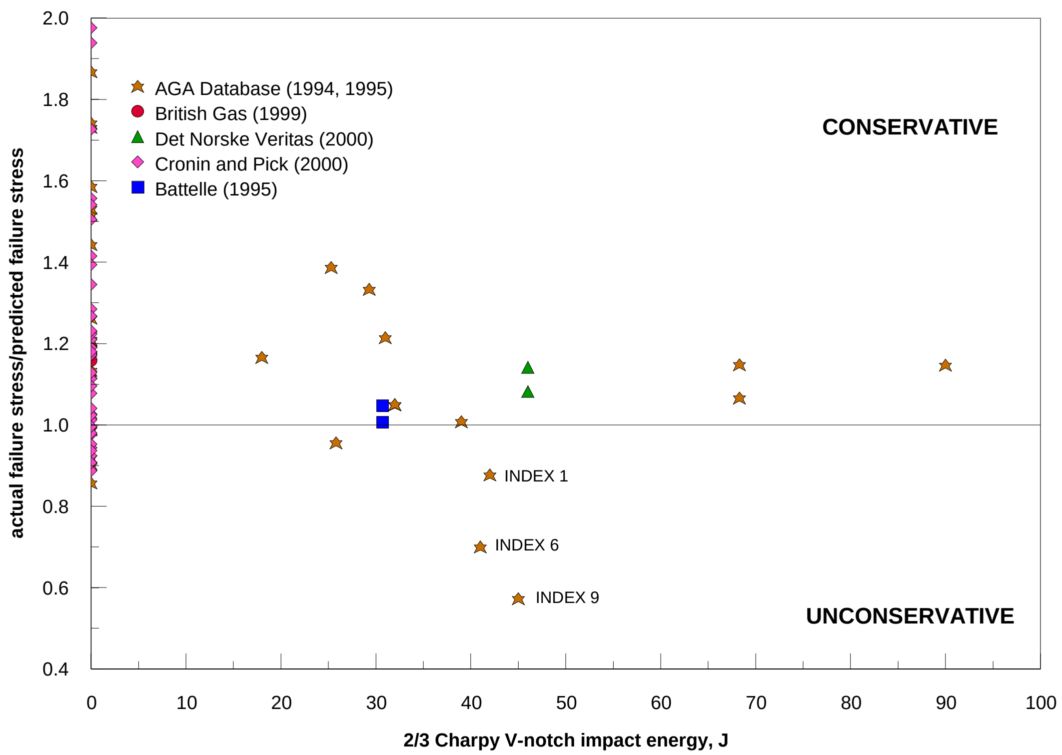
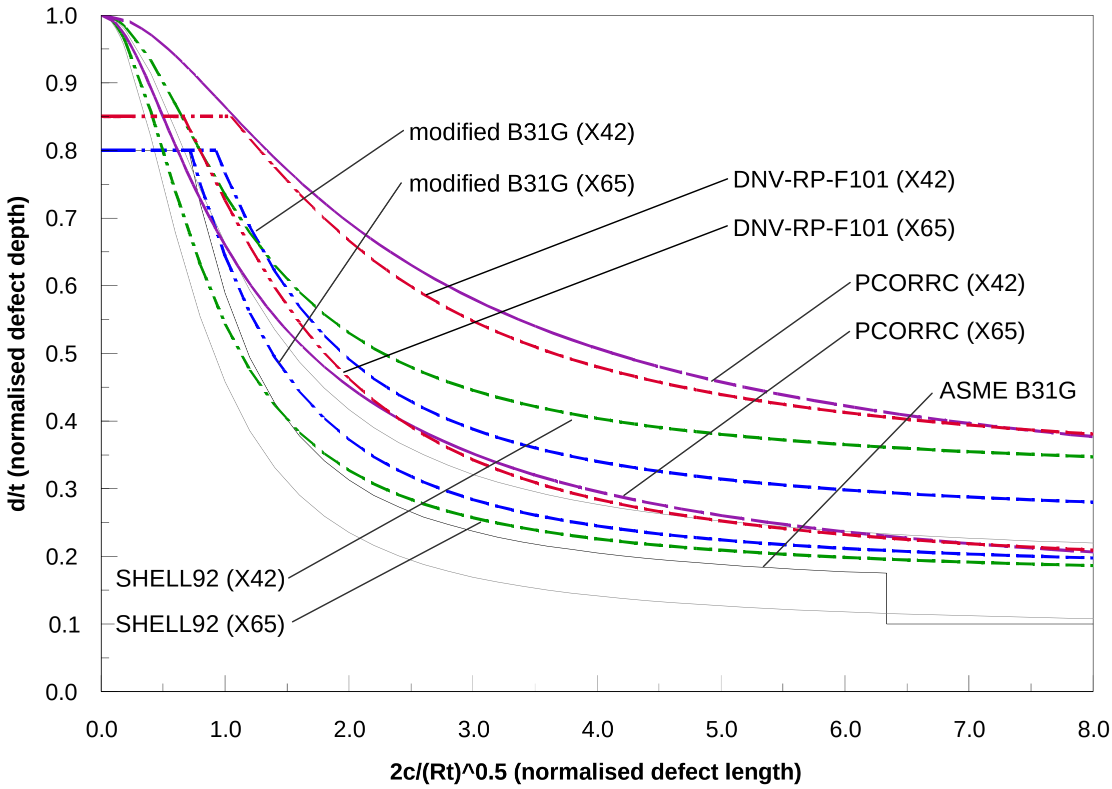


Figure 8 – The effect of toughness on DNV-RP-F101 predictions of real and artificial burst tests of corrosion defects



Note:
1. All of the failure loci are plotted for a hoop stress equal to the specified minimum yield strength.
2. The equations are as indicated in Table 2.

Figure 9 – Methods for assessing the burst strength of a corroded area

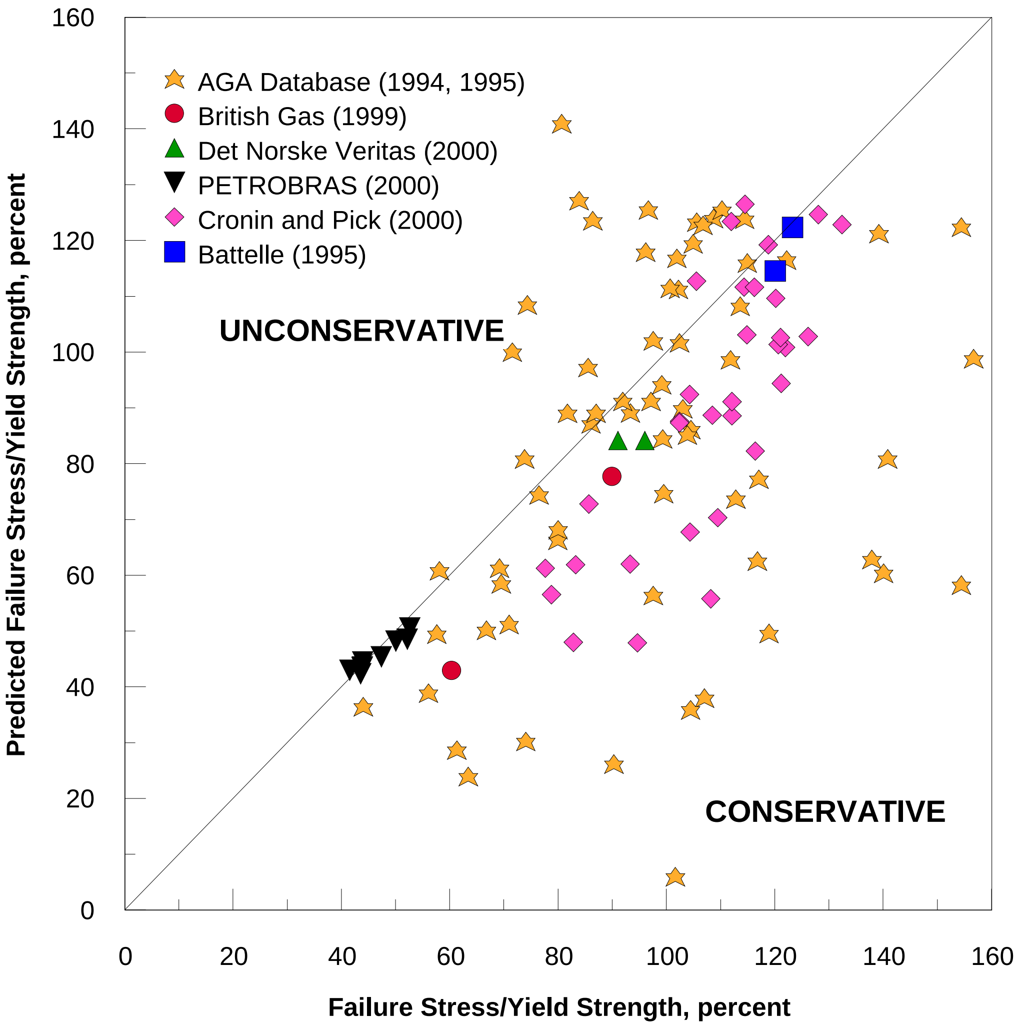


Figure 10 – DNV-RP-F101 predictions of ('reliable') burst tests of real and artificial corrosion subject to internal pressure

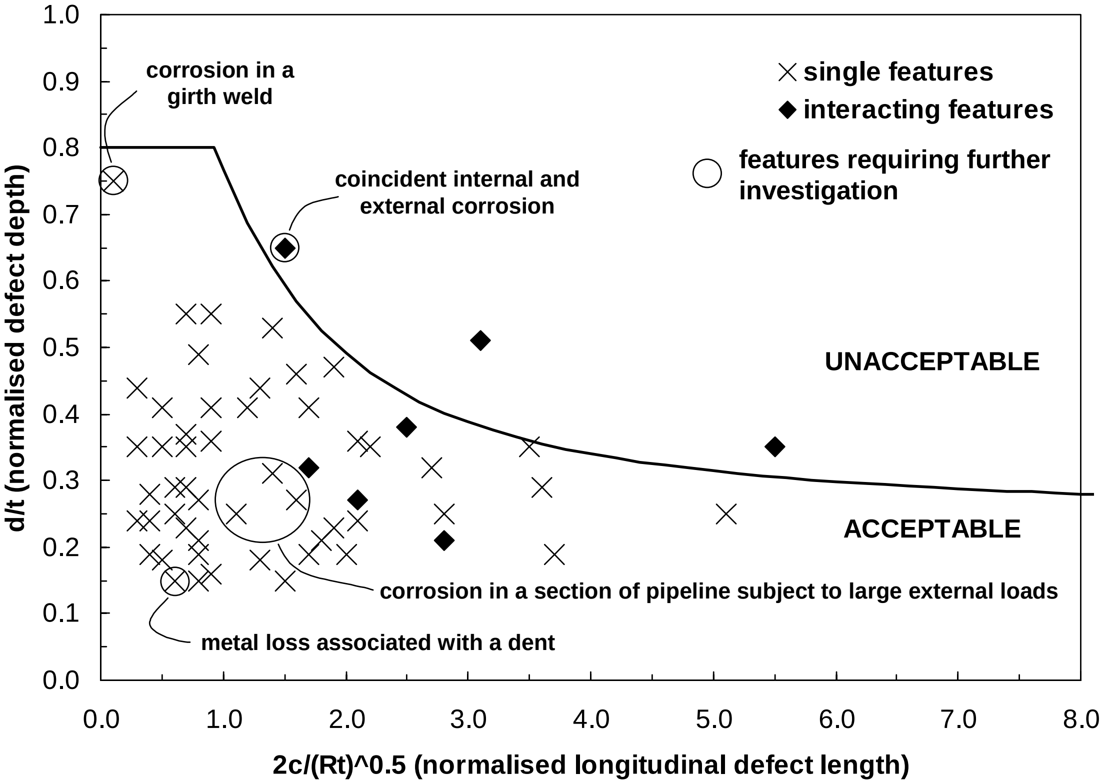


Figure 11 – Illustration of the assessment of corrosion in a pipeline, considering single and interacting features, and then identifying other issues that may influence the acceptability of the defects and require further investigation