4th International Pipeline Technology Conference
9-13 May 2004, Oostende, Belgium

AN OVERVIEW OF THE PIPELINE DEFECT ASSESSMENT MANUAL (PDAM)

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ABSTRACT

The integrity of oil and gas transmission pipelines is now the subject of new regulations, codes and standards in the USA and elsewhere. A key element of pipeline integrity and these new initiatives is the evaluation of defects that inevitably occur over the lifetime of a pipeline; therefore, assessment methods are needed to determine the severity of defects when they are detected in pipelines.

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 compares the assessment methods, 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 sixteen international oil and gas companies[1] to develop a Pipeline Defect Assessment Manual (PDAM). PDAM documents the best available techniques currently available for the assessment of pipeline defects (corrosion, dents, gouges, weld defects, etc.) in a simple and easy-to-use manual, and gives guidance in their use. PDAM is based on an extensive critical review of pipeline 'fitness-for-purpose' methods and published test data.

PDAM is now in use, but it is also being updated by the sponsors. This paper presents an overview of PDAM, and describes some of its novel features.

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 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

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1 Advantica Technologies, BP, CSM, DNV, EMC, Gaz de France, Health and Safety Executive, MOL, Petrobras, PII, Promigas, SNAM Rete Gas, Shell Global Solutions, Statoil, Toho Gas and TotalFinaElf.

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.

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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; understanding the equation that quantifies the failure load is only one aspect.

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[6,7].

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).

2. PIPELINE DEFECT ASSESSMENT: HISTORICAL PERSPECTIVE

The 1950s and 1960s was a period where the safety of transmission pipelines became of interest, primarily in the USA, due to its large and aging pipeline system. Pipelines were thin walled, increasingly being made of tougher steels, and typically exhibited extensive plasticity before failure. The fracture mechanics methods (using the stress intensity factor, K) at that

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

time used linear-elastic theories that were not appropriate to predicting the failure of defects in pipelines, because the following information would have been needed:

- quantitative fracture toughness data, including measures of initiation and tearing (only simple impact energy values (e.g. Charpy V-notch) were available),
- a measure of constraint (this concept was not quantifiable in the 1960s, other than by testing), and
- a predictive model for both the fracture and the plastic collapse of a defect in a thin-walled pipe.

Workers at the Battelle Memorial Institute in Columbus, Ohio, under the auspices of the then Pipeline Research Committee of the American Gas Association, developed methods based on existing fracture mechanics models, but they overcame the above deficiencies by a combination of expert engineering assumptions, and calibrating the methods against the results of full-scale tests on defects in line pipe.

Battelle have published many papers on the behaviour of defects in pipelines, but the most widely known are those describing the failure criteria developed for through-wall and part-wall defects, referred to as the NG-18 equations[9]. These equations formed the basis of methods for pipeline defect assessment such as: ASME B31G[10], RSTRENG[11] the Ductile Flaw Growth Model (DFGM) (implemented as PAFFC (Pipe Axial Flaw Failure Criteria))[12,13].

The past thirty years has seen other organisations develop methods and guidelines for assessing defects in pipelines, for example:

- the European Pipeline Research Group (EPRG) produced guidelines for the assessment of girth weld defects[14], mechanical damage[15] and ductile fracture propagation[16];
- Det Norske Veritas (DNV) in Norway produced DNV-RP-F101, a recommended practice for assessing corrosion in pipelines (based on JIP's conducted by BG Technology (now Advantica) and DNV)[17];
- the American Petroleum Institute published guidelines on dents in a pipeline[18]; and
- the Gas Research Institute conducted a study of research and operating experience of mechanical damage, and developed guidance for inclusion in the supplement to the ASME B31.8 code for gas transmission pipelines (ASME B31.8S)[19].

More recently, documents such as API 1160 and ASME B31.8S have recommended specific defect acceptance limits, based on fitness-for-purpose criteria, for various different types of pipeline defect.

In parallel, as the science of fracture mechanics developed, particularly in the area of post yield (elastic-plastic) fracture mechanics, generic defect assessment methods have been published in standards such as BS 7910 : 1999[4] and API RP 579[8]. BS 7910 : 1999 and API RP 579 contain detailed engineering critical assessment methods and procedures which can be applied to defects in pipelines. These standards can be conservative or difficult to apply to specific structures such as pipelines. Consequently, the pipeline industry has developed its own fitness-for-purpose methods over the past 40 years, as listed above (and, indeed, documents such as BS 7910 recommend that such methods be used).

The pipeline-specific methods listed above are generally based on experiments, sometimes with limited theoretical validation. The methods are semi-empirical. Consequently, the methods may become invalid if they are applied outside their empirical limits, or to new materials and loadings.

The pipeline-specific methods have been applied successfully for over 30 years. Their use was limited in the 1960s and 1970s as most pipelines were not directly inspected for defects, and hence defects were only reported or investigated following a failure, or reports of poor coating or cathodic protection.

But, starting in the 1970s, three major changes were occurring in the pipeline industry:

1. pipeline systems were being both introduced and expanded in many countries around the world,
2. the extensive pipeline system in the USA was ageing and needed closer attention, and
3. pipeline operators started to use 'intelligent' pigs[3] to inspect their lines for defects. The ability of these pigs to detect and size a variety of defects meant that operators needed to repeatedly use the assessment methods, otherwise they would need to carry out many repairs.

These changes meant that defect assessment methods were regularly used. There was some consensus on the 'best' methods for some types of defect (e.g. ASME B31G was recognised in the 1980s as 'best practice' for assessing corrosion), but there was no consensus document published by the pipeline industry that listed the 'best' defect assessment methods for all defects, nor listed the limitations of the methods.

In 1997, Andrew Palmer and Associates, UK (now Penspen) asked three UK-based companies (Transco (now National Grid Transco), Total, and BP) to support a project called the Defect Assessment Manual. The objective was to produce a document describing best practice for assessing defects in pipelines. A simple version was produced in 1997. Subsequently, the scope of the project was extended and other sponsors joined the project to develop a Pipeline Defect Assessment Manual (PDAM), see section 1.

The Pipeline Defect Assessment Manual was issued to the sponsors in 2003. It is the first document that provides the pipeline industry with best practices for the assessment of a wide range of pipeline defects.

3. 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.

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 1 (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] 'Intelligent' or 'smart' pigs were first used in the USA in the 1960s. However, extensive use of the higher resolution pigs did not commence until the late 1970s.

4. THE SCOPE OF THE PIPELINE DEFECT ASSESSMENT MANUAL

The scope of PDAM encompasses steel line pipe manufactured to API 5L[20] or equivalent national or international standards. The assessment methods given in PDAM are for defects in onshore and offshore transmission pipelines designed to an internationally recognised pipeline design code.

The assessment methods given in PDAM are not applicable to defects in low toughness line pipe steel. Indications of low toughness are (1) old line pipe[4], (2) line pipe not manufactured to API 5L (or equivalent), (3) line pipe with a DWTT (Drop Weight Tear Test) transition temperature that is greater than the minimum design temperature of the pipeline.

5. 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, including both 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, see Table 1. There are some combinations of defect type, orientation and loading for which there are no clearly defined assessment methods. 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. A summary of the available assessment methods, by defect type and loading is given in Table 2. Many of the methods in PDAM are semi-empirical. Consequently, the methods may become invalid if they are applied outside their empirical limits. Accordingly, PDAM considers the limits of the experimental validation of the methods.

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[4] There is no clear definition of what constitutes old line pipe, since it depends upon steel and pipe making practices, etc. Modern line pipe steel is fully-killed and continuously cast.

The general guidance on the defect assessment given in PDAM includes safe working practices in the vicinity of a damaged pipeline (i.e. pressure reductions), the treatment of measurement uncertainty, and an indication of appropriate repair methods. The specific guidance given in the PDAM for each type of defect includes information on the use of the assessment method, its range of applicability, the model uncertainty, and any limitations. The range of applicability is based on the range of the published test data relevant to the method. 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.

6. THE FORMAT OF THE PIPELINE DEFECT ASSESSMENT MANUAL

PDAM 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.

7. METHODOLOGY FOR CONDUCTING A FITNESS-FOR-PURPOSE ASSESSMENT

7.1 Is an assessment appropriate?

Before undertaking a fitness-for-purpose assessment of a pipeline containing a defect, the need for undertaking the assessment should be questioned. It is necessary to establish the cause of the defect, whether it can be assessed, and what the consequences of a failure would be. It may be simpler and more cost effective to repair a defect, rather than to assess it.

7.2 What is the appropriate level and complexity of the assessment?

Having decided that a defect assessment is required and can be conducted, it is necessary to determine the level of detail and complexity that is required. A sensible approach to adopt in any fitness-for-purpose assessment is to use the most conservative data and assessment method to demonstrate that the defect is acceptable, and apply more accurate (less conservative) methods only as required. More accurate assessment methods generally require more data, and are more difficult to apply.

7.3 Loads

When assessing a defect in a pipeline it is essential that all of the loads acting on the pipeline are considered. This will require an appreciation of the design of the pipeline. In most cases the only significant load will be the internal pressure. Circumstances where additional loads are possible include: high temperature high pressure (HTHP), pipe-in-pipe, anchor blocks, pipe crossings, subsidence (ground movement), spans, above ground pipeline, pipe bridges, etc..

It is important to consider both static and cyclic (fatigue) loading. A defect may be assessed as acceptable under static loading, but as unacceptable under cyclic loading.

7.4 Specified minimum material properties and specified minimum wall thickness

PDAM recommends that the specified minimum material properties (yield strength, tensile strength, Charpy V-notch impact energy, etc.) are used when assessing a defect. This will be conservative. Determining the actual material properties of a length of pipe containing a defect is difficult.

Similarly, PDAM recommends that the specified minimum wall thickness is used, unless the local minimum wall thickness of the plain (i.e. undamaged) pipe is known (either from an intelligent pig inspection report or a direct measurement). If the measured local minimum wall thickness of the plain pipe is used, then it is recommended that the appropriate inspection tolerance is subtracted from the measured wall thickness.

These recommendations are consist with the suggest approach of using the most conservative data and assessment method to demonstrate that the defect is acceptable (see above).

7.5 Measurement uncertainty and inspection tolerances

PDAM recommends that inspection tolerances are added to the report dimensions of a defect.

All measurements have an associated tolerance. For measurements taken with simple equipment such as rulers and depth micrometers, the inspection tolerance can be defined straightforwardly, although account should be taken of practical difficulties on site. For measurements taken with more complicated equipment, such as ultrasonic probes, or for the results from intelligent pigs (magnetic flux leakage, ultrasonic, geometry, calliper, etc.), the situation is more complicated because of the often significant amount of interpretation of the raw inspection data that is required to determine the defect dimensions.

An inspection tool provider should define the inspection tolerances of the tool (whether it be a simple hand held ultrasonic probe or an intelligent pig). Three types of error can typically be identified:

1. Threshold (detection) levels, also referred to as the probability of detection.
2. Sizing accuracy or inspection tolerance.
3. Data interpretation and feature identification.

Ideally, the first two types of error should be quantified, and a clear explanation of how different types of feature (e.g. corrosion, gouge, manufacturing defect, etc.) are identified, together with an estimate of how accurate this identification is, should be given by the tool provider. Nevertheless, it may be necessary to verify the results of an inspection, either through verification or investigation digs, or through independent (blind) calibration of the tool.

7.6 What is the acceptance criterion to be applied?

The objective a fitness-for-purpose assessment of a defect is to determine whether or not, with a sufficient safety margin, the defect will cause the pipeline to fail under the given loads. To establish whether or not the defect is acceptable, three factors must be considered:

1. the failure pressure (load) of the defective pipe,

2. the model uncertainty inherent in the prediction of the failure pressure (load), and
3. an appropriate factor of safety on the failure pressure (load).

The factor of safety accounts for uncertainties in the applied load, material properties, pipe geometry and defect dimensions, and the consequences of a failure. The factor of safety may be a single number (such as the 1.39 factor in ASME B31G) or a combination of partial safety factors (as in part A of DNV-RP-F101).

8. ASSESSMENT METHODS IN THE PIPELINE DEFECT ASSESSMENT MANUAL

A summary of all of the methods recommended in PDAM for predicting the burst strength of a defect subject to internal pressure is given in Table 1[9-19,21-23]. 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[24-26]. 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[8] can be applied in general (irrespective of upper or lower shelf behaviour), but will generally be conservative compared to the pipeline specific methods[5].

9. THE FUTURE OF THE PIPELINE DEFECT ASSESSMENT MANUAL

It is intended that PDAM be maintained as a 'living' document. The PDAM Joint Industry Project is ongoing, and new sponsors have joined the original group of companies. PDAM will be maintained and updated in line with developments in the published literature and comments from the users of PDAM.

10. ACKNOWLEDGMENTS

The authors acknowledge the sponsors of the Pipeline Defect Assessment Manual Joint Industry Project for their contributions and permission to publish this paper.

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[5] 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 is measured).

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	internal pressure (static) longitudinally orientated	internal pressure (static) circumferentially orientated
corrosion	DNV-RP-F101[17] *modified B31G*[11] *RSTRENG*[11]	Kastner local collapse solution[22]
gouges	NG-18 equations[9] *PAFFC*[12,13] *BS 7910*[4] *or API 579*[8]	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[15,21]	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[14] *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[23]

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

	internal pressure (static)	**internal pressure (cyclic)**	**external pressure**	**axial force**	**bending moment**	**combined loading**
defect-free pipe	YES	YES	YES	YES	YES	YES
corrosion	YES	YES	NO	YES	YES	YES
gouges	YES	YES	NO	YES	YES	YES
plain dents	YES	YES	NO	NO	NO	NO
kinked dents	NO	NO	NO	NO	NO	NO
smooth dents on welds	NO	YES	NO	NO	NO	NO
smooth dents and gouges	YES	YES	NO	NO	NO	NO
smooth dents and other types of defect	YES	YES	NO	NO	NO	NO
manufacturing defects in the pipe body	YES	YES	NO	YES	YES	YES
girth weld defects	YES	YES	NO	YES	YES	YES
seam weld defects	YES	YES	NO	YES	YES	YES
cracking	YES	YES	NO	YES	YES	YES
environmental cracking	YES	YES	NO	YES	YES	YES

Note:
1. **Red** denotes cases where specialist assistance is required.
2. **Yellow** denotes cases where specialist assistance may be required.

Table 2 – Summary of assessment methods in the Pipeline Defect Assessment Manual by defect type and loading

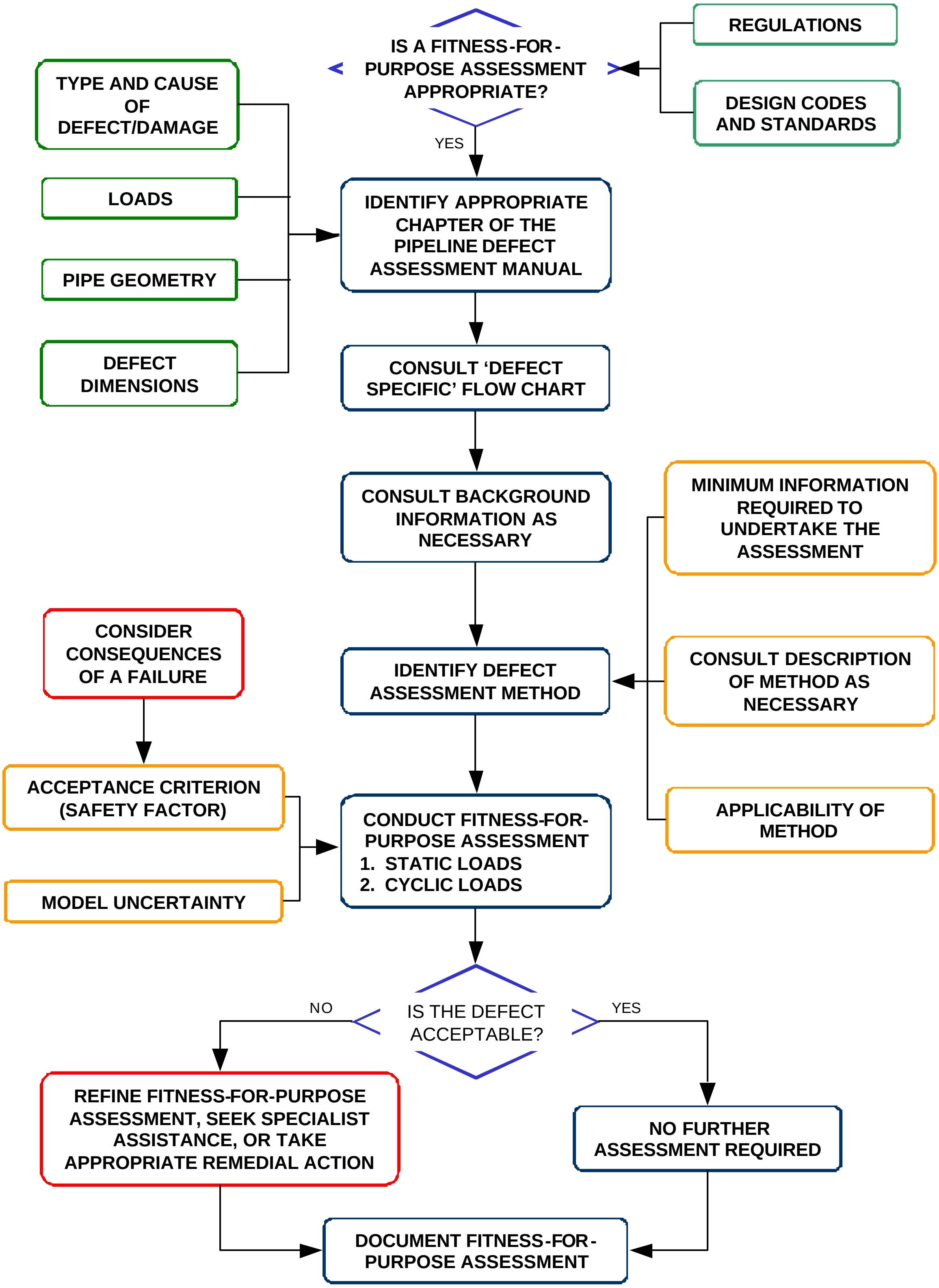

Figure 1 – The fitness-for-purpose assessment of a pipeline defect