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BEST PRACTICE IN PIPELINE DEFECT ASSESSMENT

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ABSTRACT

Defects in pipelines can be introduced during manufacturing (e.g. laminations), transportation (e.g. fatigue cracking), fabrication (e.g. weld defects) and installation (e.g. dents), and can occur both due to deterioration (e.g. corrosion) and due to external interference (e.g. gouges and dents). To ensure the integrity of the pipeline, operators must be able to both detect and assess the significance of pipeline defects. Furthermore, the importance of accurate engineering models, for which the model uncertainty has been quantified, is important when applying risk-based (structural reliability) methods to pipelines.

The past 40 years has seen the development of 'fitness-for-purpose' methods for assessing the significance of pipeline defects. However, there is no definitive guidance that draws together all of the assessment techniques, or assesses each method against the published test data, or recommends best practice in their application.

This paper describes the findings of a recent literature review and defines the objectives of the next phase of a Joint Industry Project which is being sponsored by thirteen international oil and gas companies (BG Technology, BP, CSM, DNV, EMC, Gaz de France, Health and Safety Executive, MOL, PII, SNAM, Statoil, Toho Gas and Total Oil Marine). The deliverable will be a Pipeline Defect Assessment Manual, which will provide the best available techniques for the assessment of pipeline defects.

INTRODUCTION

There are millions of kilometres of transmission pipelines around the world. The oil and gas transmission system in Western Europe alone is over 150,000 km in length. A pipeline, and all its associated plant, must be operated safely and efficiently. There are four key issues in the operation of these pipeline systems:

1. *Safety* - the system must pose an acceptably low risk to the surrounding population,
2. *Security of Supply* - the system must deliver its product in a continuous manner, to satisfy the owners of the product (the 'shippers') and the shippers' customers (the 'end users'), and have low risk of supply failure,
3. *Cost Effectiveness* - the system must deliver the product at an attractive market price, and generate an acceptable rate of return on the investment, and
4. *Regulations* - the operation of the system must satisfy all legislation and regulations.

An operator must ensure that all risks associated with the pipeline are as low as is reasonably practicable. Occasionally an operator will detect, or become aware, of defects in their pipeline. In the past, this may have led to expensive shut-downs and repairs. However, recent years have seen the increasing use of fitness-for-purpose methods to assess these pipeline defects.

This paper presents fitness-for-purpose methods applicable to the assessment of defects in onshore and offshore transmission pipelines, based on a review of the published literature. Assessment methods for gouges, dents, dents and gouges (external interference defects), corrosion, and girth weld defects are summarised. The construction of defect assessment plots, which is a very effective method for sentencing large numbers of defects, and an important aspect of developing intelligent pig assessment levels and repair strategies, is also discussed.

The literature review of defect assessment methods described in this paper is the preliminary result of a Joint Industry Project, managed by Andrew Palmer and Associates, which will produce a Pipeline Defect Assessment Manual for use by the thirteen sponsor companies.

NOMENCLATURE

$\bar{s}$	flow stress
s_q	hoop stress
s_z	axial stress
s_U	ultimate tensile strength
s_Y	yield strength
d	maximum depth of part wall metal loss defect

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c	half maximum axial length of defect
t	pipe wall thickness
w	half maximum circumferential length of defect
A	fracture area of a 2/3 Charpy specimen (53.55 mm^2 for a 2/3 Charpy specimen)
C_v	2/3 specimen Charpy V-notch upper shelf impact energy
D	outside diameter of pipe
E	elastic modulus
H_o	dent depth measured at zero pressure
L	maximum axial length of defect
P_f	failure pressure
R	outside radius of pipe

DEFECTS IN A TRANSMISSION PIPELINE SYSTEM: THE NEED FOR FITNESS-FOR-PURPOSE METHODS

Many fitness-for-purpose methods for assessing defects in pipelines use fracture mechanics, but modified by empirical data[1]. However, they require an engineer to work outside existing codes, and because of the potential safety hazard, 'fitness-for-purpose' methods must be used in a structured and systematic manner, by suitably qualified engineers.

Detailed procedures for assessing the significance of defects in structures are given in documents such as BS 7910 : 1999[2], but extensive research undertaken over many years by the pipeline industry has led to the development of more appropriate methods for assessing defects in pipelines[5-49] (and, indeed, BS 7910 recommends that such methods are used).

Line pipe steels are (in most practical circumstances) tough and ductile, even older steels will generally exhibit ductile fracture initiation. Consequently, the assessment of defects in pipelines is primarily based on plastic collapse (limit load) methods.

All defect assessments should consider the particular operational conditions of the pipeline, the environment around the defect, and the potential risk to personnel, environment and property. A fitness-for-purpose assessment must always ensure that the pipeline is left in a fit and safe state.

Defects in Pipelines

The major cause of damage and failures in transmission pipelines in Western Europe and North America is external interference ('mechanical damage'), e.g. a farmer gouging a pipeline accidentally, while ploughing, or a supply boat denting an offshore pipeline by dragging an anchor across it[3,4]. Table 1 summarises some failure data, and the major causes of failures in certain pipeline systems (note that different definitions of failure means that comparisons of failure statistics are not straightforward, see Reference [4]).

The variety of failure causes is not surprising as pipelines operate in a variety of hostile environments. Some North American pipelines are affected by stress corrosion cracking (SCC). Eastern Europe has problems with construction and material defects, and also with girth weld defects. However, problems with girth weld defects are not confined to Eastern Europe; one Western European operator has reported the following defects in girth welds, see Table 2[1]

Clearly, older girth welds may contain unacceptable defects. These welds are unacceptable to workmanship standards, but they may be acceptable when assessed using an appropriate fitness-for-purpose method.

CAN I APPLY, AND DO I NEED TO USE, FITNESS-FOR-PURPOSE METHODS?

Any engineer with a potential defect problem should question the need for a fitness-for-purpose assessment as follows:

PHASE 1 - Appraisal

Is it really there, and can I readily dismiss it?

- Is it really a defect, or is it some feature of the inspection method (e.g. a low level anomaly reported during pigging)?
- Are the operating conditions able to create such a defect and can operational conditions be controlled to prevent growth (e.g. corrosion inhibition, re-coating)?
- Is the defect within design and fabrication acceptance levels?
- What is industry experience of similar defects? For example, have other companies faced this problem, and produced a solution that concludes that the defect is acceptable?

Is it a defect?

- Do I know how the defect was formed, and how it may develop in the future?
- Is the defect indicative of poor practice during construction or operation, and as such can be controlled by other methods?

Who is competent to assess the defect?

- What are the legal ramifications (e.g. professional liability), what are the views of the regulatory body, and who would be responsible for the structure, and any defect assessment relating to it?
- Are current staff capable and experienced enough to apply fitness-for-purpose methods?

Is it worth the effort?

- Is it cheaper to repair than assess?

PHASE 2 - Assessment

Can fitness-for-purpose methods provide an answer?

- Can fitness-for-purpose methods solve the problem? For example, are the methods robust for the particular defect and loading?
- What data exists, and how reliable is it? If the data is sparse, what confidence is there in any engineering judgement, or are special tests required?

PHASE 3 - Safety Factors and Probabilistic Aspects

What safety margins should be used?

- If fitness-for-purpose methods are applied, what safety factors should be used?
- How should the safety factors be set, and would it be better to conduct a probabilistic analysis?

PHASE 4 - Consequence

What are the consequences of getting it wrong?

- Is a risk analysis required?

ASSESSING DEFECTS AND DAMAGE IN A TRANSMISSION PIPELINE

Having decided that a defect assessment can be conducted, it is now necessary to determine the level of detail and complexity that is required.

Different levels of defect assessment, ranging from simple ‘screening’ methods to very sophisticated three-dimensional elastic-plastic finite element stress analyses, are available. The method used depends upon the type of defect detected, the loading conditions, the objective of the assessment, and the type and quality of data that is available. Figure 1 summarises the differing levels of defect assessments, and the required data.

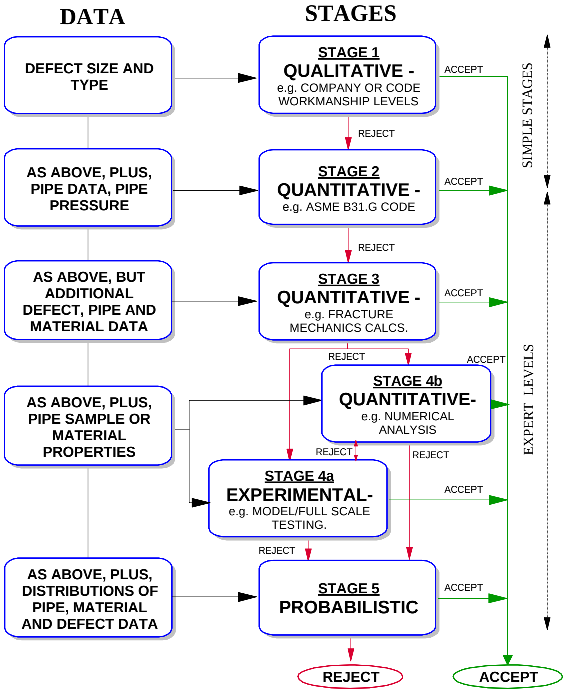

Figure 1- Pipeline Defect Assessment: The Five Stages

Generally, defect assessments are conducted up to stage 3. If defects still remained ‘unacceptable’ at this stage, a higher level assessment, or repair would be necessary. 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.

The higher levels may require risk analyses. Risk is a function of the probability of failure and the consequences of failure. Such analyses are becoming increasingly popular, but are also very complicated.

A fitness-for-purpose analysis of defects does not entail a risk analysis, although due account of the consequences of failure will be taken in a qualitative manner, and the recommended safety factor will reflect this.

A fitness-for-purpose assessment will usually involve a deterministic assessment of the defects, to determine whether or not the defect is acceptable. Probabilistic methods are useful when dealing with uncertainty over the data used in the assessment or future conditions, such as corrosion rates. These methods can be used as an aid to deciding future inspection and maintenance requirements. Underlying such probabilistic analyses are fitness-for-purpose methods for assessing defects (i.e. the limit states).

It should be noted that safety factors are not given or recommended for the following defect assessment methods - they will depend on the type of defect, the reliability of the data used in the assessment, the reliability of the assessment method, and the consequences of the failure of the defect. It is the responsibility of the engineer conducting an assessment to select an appropriate safety factor.

LOADS

Most of the methods for assessing defects in a pipeline are for the case of internal pressure loading. Methods have been proposed for assessing corrosion subject to internal pressure and external loads (axial stresses, bending moments), but for most other defects no such methods exist.

DEFECT-FREE PIPE UNDER INTERNAL PRESSURE

The simplest and, in general, the most conservative formula for the range of transmission pipeline D/t ratios is given by using s_U and the mean pipeline diameter (D-t) in the simple Barlow equation (although it becomes increasingly conservative for thicker walled pipe)

$$P_f = \frac{2ts_U}{(D-t)} \qquad \textbf{... 1}$$

For a more accurate assessment the analytical method proposed by Stewart, Klever and Ritchie[5] is recommended. This analysis incorporates material work hardening and large displacement theory, and is accurate over a wide range of D/t ratios.

GOUGES OR SIMILAR METAL LOSS DEFECTS

External interference, or damage during construction, can cause gouges or scratches on the surface of the pipe. These metal loss defects may be accompanied by local plastic deformation. If this deformation has caused a dent, then the damage must be assessed using alternative methods (see below). There may be a work hardened layer at the base of the gouge which may reduce the local ductility and may contain cracking.

Axially-Orientated Gouges

In ductile line pipe, the failure stress of an axially-orientated gouge subject to internal pressure loading is described by[6-8]

$$\frac{s_q}{\bar{s}} = \frac{1-\left(\frac{d}{t}\right)}{1-\left(\frac{d}{t}\right)M^{-1}} \qquad \textbf{... 2}$$

where

$$M = \sqrt{1+0.26\left(\frac{2c}{\sqrt{Rt}}\right)^2} \qquad \textbf{... 3}$$

$$\bar{s} = 1.15 s_Y \qquad \textbf{... 4}$$[2]

Circumferentially-Orientated Gouges

For a circumferential gouge (orientated at an angle of 90 degrees to the pipeline axis) in ductile line pipe, the following plastic collapse failure criterion due to Kastner[9] may be used to calculate the axial failure stress

$$\frac{s_z}{\bar{s}} = \frac{h(p - b(1-h))}{hp + 2(1-h)\sin(b)} \qquad \textbf{... 5}$$

where

$$b = \frac{w}{R} \qquad h = 1-\frac{d}{t} \qquad \textbf{... 6}$$

PLAIN DENTS

Burst Strength of Plain Dents

A dent in a pipeline is a permanent plastic deformation of the circular cross section of the pipe. A plain dent is defined as damage which causes a smooth change in curvature of the pipe wall without a reduction in pipe wall thickness, i.e. it contains no defects or imperfections, such as a girth or seam weld. A kinked dent contains rapid changes in contour.

A plain dent introduces high localised stresses and strains. These high stresses and strains are accommodated by the ductility of the pipe. Full scale tests indicate that plain dents do not significantly reduce the burst strength of a pipeline[10-18]. On pressurisation the dent attempts to move outward, allowing the pipe to regain its original circular shape. Provided that nothing restricts the movement or acts as a stress concentration (e.g. a gouge or a kink), then the dent will not reduce the burst strength of the pipe.

There are no published methods for assessing the burst strength of a plain dent; the results of full scale tests have been used to derive limits for the acceptability of plain dents. Over 75 burst tests of plain dents have been published, but failure in the dented area only occurred in four tests.

Empirical limits for plain dents under static internal pressure loading have been derived from extensive full scale testing. British Gas quote that a plain dent of less than 8 percent of the pipe diameter (and possibly up to 24 percent) has little effect on the burst strength of pipe[14,15]. Analysis of more recent test data suggests 10 percent (including a factor of safety on the dent depth).

In all of the full scale tests on plain dents, the dent depths were measured at zero pressure after spring back. Consequently, a rerounding correction factor is required when assessing dents measured in the field, to account for the difference in the dent depth measured at pressure and at zero pressure, and the differences between denting a pipe at zero pressure and at pressure. Empirical rerounding correction factors have been proposed by the EPRG[15,19] and Rosenfeld[20].

Full scale tests on plain dents on welds and dents containing defects have demonstrated very low burst pressures (see below).

It should be noted that a deep dent may restrict product flow, and the passage of intelligent pigs.

Fatigue Life of Plain Dents

Large cyclic stresses and strains are localised in a dent under cyclic pressure loading. The depth of a dent changes with internal pressure, meaning that the magnitude of the stress concentration changes. Dents have been observed to incrementally reround under cyclic internal pressure loading[13,20,21]. Full scale fatigue tests[11,13-15,17,21] on plain dents indicate that they reduce the fatigue life compared to plain circular pipe. The greater the dent depth the shorter the fatigue life. No fatigue failures occurred in those tests where the pipe was hydrotested prior to fatigue cycling, because the dent was permanently pushed out (rerounded), reducing the stress concentration[13-15].

A number of semi-empirical or empirical methods for predicting the fatigue life of a plain dent subject to cyclic pressure loading have been developed, including models by the European Pipeline Research Group (EPRG)[19], SES[17,21], Rosenfeld[20] and Shell[22]. One of the relationships developed by SES is[17]

$$N = 2.0\times10^6\left(\left[\frac{\Delta s}{\Delta p}\right]\Delta p\,\frac{1}{11400}\right)^{-3.74} \qquad \textbf{... 7}$$

where

N	number of cycles to failure
$\left[\frac{\Delta s}{\Delta p}\right]$	stress intensification factor
Dp	cyclic pressure (psi)

The fatigue model is based on an S-N curve, modified for the stress concentration due to the dent. The 'stress

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[2] This definition of the flow stress may not be appropriate for higher grade steels (above X65).

intensification factor' was derived from non-linear elastic-plastic finite element analyses to account for the stress concentration due to the dent. It is a function of the diameter to wall thickness ratio (*D*/*t*), the ratio of the dent depth to nominal diameter (*H*/*D*), and the average pressure (p_{av}). The reader is directed towards the original references if they wish to apply the method. A modified (and improved) method is described in reference [21], but it can only be applied to a limited number of cases.

SMOOTH DENT CONTAINING A DEFECT

Burst Strength

Dents containing defects can record low failure pressures. A defect in the dent is effected by the stress concentration and the large strains due to the dent; these promote crack initiation and ductile tearing of the defect through the remaining ligament. The structure comprising the dent and the defect is complex and unstable.

Full scale tests and ring tests investigating the burst strength of combined dents and defects have been undertaken by a number of organisations[12,15,16,18,23-26].

An empirical method for determining the limiting dent depth or defect depth, as a function of the defect depth or dent depth, respectively, the hoop stress and the Charpy impact energy, has been proposed by the EPRG[19]. The empirical method is expressed in the form of simple defect acceptance limits[19]. Battelle have developed an empirical method for predicting the burst strength of a dent-gouge[23,25].

A semi-empirical dent-gouge fracture model for predicting the failure stress of a combined dent and gouge has been developed by British Gas[14,27], and has subsequently been incorporated in the EPRG recommendations for the assessment of mechanical damage[19].

The fracture model makes the following assumptions and simplifications about the geometry of the combined dent and gouge defect:

i. the dent is continuous and has a constant width,
ii. a sharp notch is located at the deepest point in the dent and extends longitudinally along the dent, and
iii. the notch is of constant depth in longitudinal direction (flat bottomed).

The fracture model is defined as follows (in S.I. units)[3]

$$\frac{s_q}{\bar{s}} = \frac{2}{p}\cos^{-1}\left[\exp-\left\{113\frac{1.5pE}{\bar{s}^2 Ad}\left[Y_1\left(1-\frac{1.8H_o}{2R}\right)+Y_2\left(10.2\frac{R}{t}\frac{H_o}{2R}\right)\right]^{-2}\exp\left[\frac{\ln(0.738C_v)-K_1}{K_2}\right]\right\}\right] \quad \textbf{... 8}$$

where

$$\bar{s} = 1.15s_Y\left(1-\frac{d}{t}\right)$$

$$Y_1 = 1.12 - 0.23\left(\frac{d}{t}\right) + 10.6\left(\frac{d}{t}\right)^2 - 21.7\left(\frac{d}{t}\right)^3 + 30.4\left(\frac{d}{t}\right)^4$$

$$Y_2 = 1.12 - 1.39\left(\frac{d}{t}\right) + 7.32\left(\frac{d}{t}\right)^2 - 13.1\left(\frac{d}{t}\right)^3 + 14.0\left(\frac{d}{t}\right)^4$$

$$K_1 = 1.9$$
$$K_2 = 0.57$$

(K_1 and K_2 are non-linear regression parameters)

The dent-gouge fracture model is based on tests in which the damage was introduced at zero pressure, and the dent depth after spring back was measured at zero pressure[12,27]. A rerounding correction factor must be applied to convert the dent depth measured at pressure (the typical field measurement) to the dent depth measured at pressure. This correction is important, because the dent-gouge model can give non-conservative predictions if the dent depth measured at pressure is used[15].

Other dent-gouge fracture models have been developed, but none have addressed the limitations of the above approach[26,28]. Work is ongoing at Battelle to develop a more accurate failure criterion for dent-gouge defects, through a more accurate characterisation of the failure process[29].

Fatigue Life

The fatigue life of a smooth dent containing a gouge is difficult to predict. Full scale tests indicate that the fatigue life of a combined dent and gouge can be of the order of between ten and one hundred times less than the fatigue life of an equivalent plain dent[14-16,21,30,31]. In some cases even shorter fatigue lives have been observed during testing. Empirical methods for assessing the fatigue life have been proposed by the EPRG)[19], Tokyo Gas[30] and SES[21]. Semi-empirical methods have been proposed by Gaz de France[32] and Shell[22].

DENTS ON WELDS

Burst Strength

Full scale tests have shown that dented seam welds can exhibit very low burst pressures[11,14,15,17]; the minimum burst pressure in one test was 7 percent of the SMYS (specified minimum yield strength). The low burst pressures can be attributed to the weld cracking during indentation, spring back or rerounding. The burst strength of a dented weld is critically dependent on whether or not the weld cracks during the denting process. There are no methods for reliably predicting the failure pressure of a smooth dent on a weld. Therefore, dented welds are usually repaired if found in an operational pipeline. It may be possible to accept a dented weld if it can be demonstrated that the weld is tough and free from defects.

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[3] The non-linear regression parameters, K_1 and K_2, are not dimensionless.

Fatigue Life

There have been a number of fatigue tests on pipe rings containing dented seam welds[14], and fatigue tests on vessels containing dented seam welds and dented girth welds[16,21]. These tests have shown that the fatigue life of a dent containing a weld can be considerably lower than the fatigue life of an equivalent plain dent, by a factor of the order of ten. There are no methods for reliably predicting the fatigue life of a dented weld.

CORROSION[4]

ANSI/ASME B31G

The most well-known document for the assessment of the remaining strength of pipelines with smooth corrosion is ANSI/ASME B31G[33,34]. This supplement to the B31 code was developed over 25 years ago[35]. It is based on an empirical fit to an extensive series of full scale tests on vessels with narrow machined slots. The basis of the equation used in B31G is relatively simple and involves:

i. assuming that the maximum pipe hoop stress is equal to the pipe material's yield strength,
ii. assuming that the flow stress is 1.1SMYS, and
iii. characterising the corrosion geometry by a projected parabolic shape for relatively short corrosion (hence the two thirds factor in the equation), and a rectangular shape for long corrosion.

The underlying equation is the flow stress dependent form of the part-wall failure criterion developed by Battelle. The B31G assessment criterion can be expressed in the following form (to facilitate comparisons with other methods)

$$s_q = \overline{s}\left[\frac{1-\frac{2}{3}\frac{d}{t}}{1-\frac{2}{3}\frac{d}{t}\frac{1}{M}}\right] \qquad \textbf{... 9}$$

A two-term expression for the Folias factor (M) is used

$$M = \sqrt{1+0.8\left(\frac{L}{\sqrt{Dt}}\right)^2} \qquad \textbf{... 10}$$

It is stated in the B31G manual that the above equations should only be applied to corrosion defects which have a maximum depth and less than 80% of the nominal wall thickness. Deep corrosion is not acceptable because of uncertainties over the accuracy of defect depth measurements.

A limit is placed on the longitudinal extent of the corroded areas for which the above equation can be used, because the approximation of a parabolic shape is not appropriate for long corrosion. The limit on defect length corresponds to $M \leq 4.12$, although in the B31G manual the limit on defect length is expressed as $B \leq 4.0$. It can be shown that

$$B = \sqrt{M^2 - 1} \qquad \textbf{... 11}$$

For long areas of corrosion a rectangular shape is assumed; accordingly the failure equation is replaced by the following equation

$$s_q = \overline{s}\left[1-\frac{d}{t}\right] \qquad \textbf{... 12}$$

The B31G criterion gives procedures for determining the maximum allowable longitudinal extent of a corroded area and for calculating the safe maximum pressure of a corroded area.

Modified B31G/RSTRENG

The B31G criterion has been used successfully in the pipelines industry for many years[36,37]. However, a new and improved criterion was desired because of perceived conservatism in the original B31G criterion[36]. The sources of this perceived conservatism were identified as:

i. the expression for the flow stress,
ii. the approximation used for the Folias factor, and
iii. the parabolic representation of the metal loss (as used within the B31G limitations).

Additionally, the main limitation of the original criterion (and a source of conservatism) was recognised as the inability to consider the strengthening effect of islands of full thickness or near full thickness pipe at the ends of or between arrays of corrosion pits. A secondary limitation was that the criterion could not be applied to corrosion in the submerged arc seam weld.

The main modifications to the failure equation that forms the basis of the original B31G criterion were to change the definition of the flow stress, and the definition of the Folias factor. The modified B31G criterion uses the empirical definition of the flow stress originally proposed during the development of the Battelle part wall failure criterion[6,7]. This is reported to be a more accurate definition of the flow stress, particularly for lower grade steels. The three-term expression for the Folias factor is used in place of the two-term expression. This is a more accurate, and less conservative, expression.

In addition, the representation of the area of metal loss was revised. A simple, arbitrary, geometric idealisation was proposed for hand calculations (a factor of 0.85 rather than 0.67 was recommended), and an effective area method using the measured profile of the corroded area, was also developed to give more accurate predictions. The simple hand calculation is often referred to as modified B31G, the effective area method is most commonly known as RSTRENG.

The modified B31G equations are given by

$$s_q = \overline{s}\left[\frac{1-0.85\frac{d}{t}}{1-0.85\frac{d}{t}\frac{1}{M}}\right] \qquad \textbf{... 13}$$

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[4] The most difficult data to obtain when assessing corrosion is usually the expected corrosion growth rate. This is important because corrosion is a time dependent failure mechanism, and an assessment needs to consider the significance of the defect both now and in the future (assuming that the corrosion mechanism is not arrested).

where

$$\bar{s} = SMYS + 10\ \text{ksi}\ \left(68.94\ \text{Nmm}^{-2}\right) \qquad \textbf{... 14}$$

$$M = \begin{cases} \sqrt{1 + 0.6275\left(\dfrac{L}{\sqrt{Dt}}\right)^2 - 0.003375\left(\dfrac{L}{\sqrt{Dt}}\right)^4} & \text{for} \quad \left(\dfrac{L}{\sqrt{Dt}}\right)^2 \leq 50.0 \\ 0.032\left(\dfrac{L}{\sqrt{Dt}}\right)^2 + 3.3 & \text{for} \quad \left(\dfrac{L}{\sqrt{Dt}}\right)^2 > 50.0 \end{cases} \qquad \textbf{... 15}$$

The RSTRENG method is based on an iterative algorithm, and was developed to allow the actual (river bottom) profile of a corrosion defect to be considered, thereby giving more accurate predictions of the failure pressure of the corrosion defect. In most cases, although not all, RSTRENG predicts a minimum failure pressure that is less than the value predicted using the exact area, total length method[36]. The modified B31G method, including RSTRENG, has been validated against 86 burst tests on pipe containing real corrosion defects[36].

Line Pipe Corrosion Group Sponsored Project

New methods for the assessment of corrosion defects under internal pressure loading have been developed through a Group Sponsored Project, undertaken by BG Technology (formerly British Gas). Over 70 full scale tests on single, interacting and complex shaped (pits in patches) machined defects (to simulate corrosion), and a large number of three-dimensional, non-linear, elastic plastic finite element analyses were carried out in the course of the development and validation of the assessment methods[38,39].

The project produced guidance for the assessment of single defects and interacting defects, and a method for assessing the actual shape of a corrosion defect (i.e. using a river bottom profile). The underlying failure model has the same form as the original Battelle part wall failure criterion (as used in the B31G and modified B31G methods), but the geometry correction factor (i.e. the Folias factor) has been modified. In addition, the flow stress has been defined in terms of the ultimate tensile strength of the line pipe steel, rather then in terms of the yield strength. The use of the ultimate tensile strength is based on an analytical model of the ultimate pressure of a fully restrained pipe containing long corrosion patches[5] and the results of the tests and analyses conducted during the project, and is consistent with failure controlled by plastic flow.

The single defect equation is given by

$$s_q = \bar{s}\left[\frac{1 - \dfrac{d}{t}}{1 - \dfrac{d}{t}\dfrac{1}{Q}}\right] \qquad \textbf{... 16}$$

where

$$Q = \sqrt{1 + 0.31\left(\frac{L}{\sqrt{Dt}}\right)^2} \qquad \textbf{... 17}$$

$$\bar{s} = 0.9 s_U \qquad \textbf{... 18}$$

The method for taking into account the actual profile of the corrosion defect is, like RSTRENG, an iterative procedure, but is based on the principle of considering the actual profile as a collection of 'pits' within 'patches'. The corrosion defect is divided into a number of depth increments, and modelled as an idealised 'patch' containing a number of idealised 'pits'. The assessment method determines whether the defect behaves as a single irregular 'patch', or whether local 'pits' within the patch dominate. Potential interaction between the pits is also assessed. The failure pressure is taken as the minimum failure pressure from the analysis of all of the depth increments.

The methods developed from this project, together with those from a DNV project (see below), have been incorporated into a DNV Recommended Practice, RP-F101[40,41][5].

DNV Joint Industry Project

A Joint Industry Project undertaken by Det Norske Veritas (DNV) has also produced guidelines for the assessment of corrosion defects, considering axial and bending loads in addition to internal pressure[42]. In the course of the project, 12 full scale tests on axial and circumferential single defects subjected to internal pressure, and axial and bending loads were carried out, together with a large number of three-dimensional, non-linear, elastic plastic finite element analyses[43].

Guidance was developed for assessing single corrosion defects under both internal pressure and combined loading. In addition, a probabilistic calibration exercise was undertaken to produce partial safety factors to be used with the assessment method. The intention of providing partial safety factors, rather than a single safety factor, was to give a more consistent level of safety over a wide range of defect sizes and pipeline geometries.

The methods developed from this project, together with those from a BG project (see above), have been incorporated into a DNV Recommended Practice, RP-F101[5].

GIRTH WELDS

Pipeline girth welds have a good operating record and are not a major cause of pipeline failures[4,44]. However, defects are sometimes detected during service, and they require assessment. Additionally, operators may wish to set different defect acceptance levels (based on fitness-for-purpose, rather than workmanship limits) at the construction stage of their pipeline.

Girth welds are fabricated to stringent standards (e.g. API 1104, BSI 4515, CSA Z184). These standards contain acceptance levels for defects based on workmanship considerations and fitness for purpose criteria. A review conducted on behalf of the European Pipeline Research Group (EPRG) highlighted the wide differences in girth weld

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[5] The methods developed during this project are being incorporated into a PRC*I* study of the assessment of corrosion defects.

acceptance levels (both the workmanship limits and the fitness for purpose criteria) in various company and national pipeline welding codes[45]. Workmanship standards are, by their nature, subjective so differences are not surprising. Fitness for purpose criteria are based on structural analysis and should result in more consistent limits. However, different approaches have been adopted in the various standards, giving rise to different limits[45].

The workmanship standards require the repair of non-planar defects such as slag and porosity which are generally accepted as innocuous[46,47], although they may mask the presence of more serious planar flaws. Many planar defects are also considered to be unacceptable, despite full scale tests which show high failure stresses even under the most severe loadings at low temperatures[44,48].

In the absence of universally accepted defect acceptance criteria and the stringent requirements in standards regarding otherwise innocuous defects, the EPRG produced a set of independent guidelines for the assessment of girth weld defects[49]. The guidelines consist of three tiers. Tier 1 is workmanship limits, derived from existing welding standards. The Tier 2 limits are semi-empirical, the workmanship limits are extended based on the results of wide plate tests. For both Tier 1 and Tier 2 a minimum Charpy impact energy is specified. The Tier 3 limits are also semi-empirical and were derived using fitness for purpose failure criteria and validated by full scale tests. A minimum Charpy impact energy and a minimum CTOD (crack tip opening displacement) toughness are required for Tier 3.

The EPRG guidelines can be used on new pipelines (to set weld defect acceptance levels), and can be applied to the assessment of defects in existing pipelines. The reader is directed towards these guidelines and their background literature[49].

For girth welds and defects outside the scope of the EPRG guidelines, more advanced assessment methods are available (e.g. BS 7910[2]).

CONSTRUCTING DEFECT ASSESSMENT CURVES

The basic equations for assessing defects can be used to construct defect acceptance curves.

Figure 2 shows such curves. The maximum depth and length of a number of part-wall metal loss defects (square points) that have been detected in a pipeline are plotted. Equation 2 is used to construct two assessment curves. The first one calculates the failure stress of defects in the pipeline at the maximum operating pressure (MAOP), and the other curve shows the size of defects that would fail at the pre-service hydrotest pressure.

As can be seen, two defects are predicted to fail at the MAOP. These defects would need to be repaired immediately. The hydrotest pressures is used as an acceptance criterion, i.e. any defect that has a failure pressure greater that the hydrotest pressure is acceptable. Any defect with a lower failure stress, but one above the failure stress at MAOP, needs to be reassessed using more sophisticated methods, or more accurate defect measurements obtained, or repaired. The plot can be used to prioritise the repair of the defects.

These type of plots can be constructed for gouges, corrosion (taking into account corrosion growth), etc..

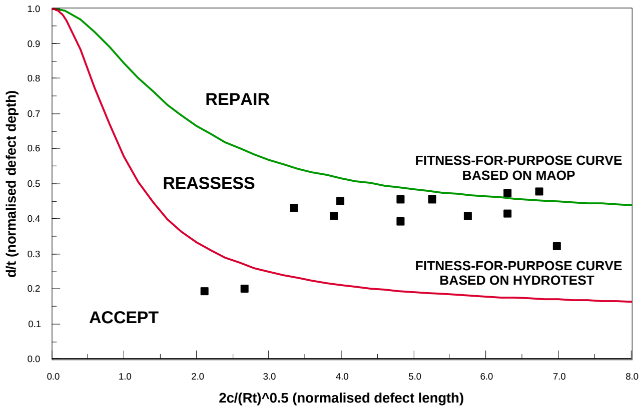

Figure 2 - Example of a Defect Assessment Curve

THE WAY AHEAD- AN INDUSTRY INITIATIVE

The information presented in this paper is drawn from the results of a study of the published literature on the assessment of defects in pipelines by Andrew Palmer and Associates, for BG Technology, BP and Total Oil Marine. The literature review was not a critical review, and the methods were not analysed in detail; it simply reported the contents of the literature. The large amount of published test data was not reviewed. Based upon this review, a Pipeline Defect Assessment Manual (Version One) was developed. The manual summarised many of the available fitness-for-purpose methods, in a simple and systematic format, and addressed most types of defect that may be found in a pipeline.

The next phase of the study is being sponsored by thirteen international oil and gas companies and regulatory authorities. The intention of this Joint Industry Project is to produce the Pipeline Defect Assessment Manual (Version Two), based upon a comprehensive, critical and authoritative review of available pipeline defect assessment methods. Included in the critical literature review will be a compilation of all of the published full-scale test data used in the development and validation of existing defect assessment methods. The full-scale test data is being used to assess the inherent accuracy of the defect assessment methods, and to identify the ‘best’ methods (considering relevance, accuracy and ease of use).

The Pipeline Defect Assessment Manual (Version Two) will collate and present the ‘best’ methods in simple terms, define the necessary input data, give the limitations of the method, and define an appropriate factor of safety to account for the model uncertainty. The manual will provide the written text, the methods, recipes for application, acceptance charts and simple examples. Simple electronic workbooks will also be developed and supplied with the manual to permit quick implementation of the ‘best practice’ methods.

The Pipeline Defect Assessment Manual (Version Two) will be available to its sponsors in March 2001.

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REFERENCES

1. HOPKINS,P., HASWELL,J.; *The Practical Assessment Methods for Application to UK Gas Transmission Pipelines*, The Institute of Materials 2nd Griffith Conference, Sheffield, UK, September 1995.
2. ANON; *Guide on methods for assessing the acceptability of flaws in fusion welded structures*, BS 7910 : 1999, British Standards Institute, London, UK, 1999.
3. BOLT,R., OWEN,R.W.; *Recent Trends in Gas Pipeline Incidents (1970-1997): a report by the European Gas pipeline Incidents data Group (EGIG)*, Paper C571/032/99, Ageing Pipelines, Optimising the Management and Operation: Low Pressure - High Pressure, IMechE Conference Transactions 1999-8 (C571), Institution of Mechanical Engineers, Newcastle upon Tyne, UK, 11-13 October 1999.
4. HOPKINS,P.; *Ensuring the Safe Operation of Older Pipelines*, International Pipeline and Offshore Contractors Association, 28th Convention, Acapulco, Mexico, September 1994.
5. STEWART,G., KLEVER,F.J., and RITCHIE,D.; *An Analytical Model to Predict the Burst Capacity of Pipelines*, Vol. V. Pipeline Technology, International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1994), American Society of Mechanical Engineers, 1994, pp. 177-188.
6. KIEFNER,J.F., *Fracture Initiation*, Paper G, 4th Symposium on Linepipe Research, AGA, Dallas, Texas, 1969.
7. KIEFNER,J.F., MAXEY,W.A., EIBER,R.J., and DUFFY,A.R.; *The Failure Stress Levels of Flaws in Pressurised Cylinders*, ASTM STP 536, American Society for Testing and Materials, Philadelphia, 1973, pp. 461-481.
8. SHANNON,R.W.E.; *Failure Behaviour of Line Pipe Defects*, International Journal of Pressure Vessels and Piping, Vol. 2, No. 3, 1974, pp. 243-255.
9. KASTNER,W., ROHRICH,E., SCHMITT,W., and STEINBUCH,R.; *Critical Crack Sizes In Ductile Piping*, International Journal of Pressure Vessels and Piping, Vol. 9, 1981, pp 197-219.
10. BELANOS,S.P., RYAN,R.S.; *Dents in Pipe*, Oil and Gas Journal, Vol. 56, pp 155-161, November 1958.
11. EIBER,R.J., MAXEY,W.A., BERT,C.W., and McCLURE,G.M.; *The Effects of Dents on the Failure Characteristics of Linepipe*, Battelle Columbus Laboratories, NG18, Report No. 125, May, 1981.
12. JONES,D.G.; *The Significance of Mechanical Damage in Pipelines*, 3R International, 21, Jahrgang, Heft, 7, July 1982.
13. WANG,K.C., SMITH,E.D., *The Effect of Mechanical Damage on Fracture Initiation in Linepipe: Part I - Dents*, Canadian Centre for Mineral and Energy Technology (CANMET), Canada, Report ERP/PMRL 82-11 (TR), January 1982.
14. HOPKINS,P., JONES,D.G., CLYNE,A.C.; *The Significance of Dents and Defects in Transmission Pipelines*, Paper C376/049, Proceedings of International Conference on Pipework, Engineering and Operation, Institution of Mechanical Engineers, London, February 1989.
15. HOPKINS,P., CORDER,I. and CORBIN,P.; *The Resistance of Gas Transmission Pipelines to Mechanical Damage*, Paper VIII-3, International Conference on Pipeline Reliability, Calgary, Canada, June 1992.
16. KIEFNER,J.F., ALEXANDER,C.R., and FOWLER,J.R., *Repair of Dents Containing Minor Scratches*, Paper 9, 9th Symposium on Line Pipe Research, Pipeline Research Committee of the American Gas Association, Houston, Texas, 1996.
17. ALEXANDER,C.R., KIEFNER,J.F.; *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines*, Final Report to The American Petroleum Institute, Stress Engineering Services, Inc., and Kiefner and Associates, Inc., 10 October 1997, API Publication 1156, First Edition, November 1997.
18. BJØRNØY,O.H., RENGÅRD,O., FREDHEIM,S., and BRUCE,P.; *Residual Strength of Dented Pipelines, DNV Test Results*, Tenth International Conference on Offshore and Polar Engineering (ISOPE 2000), Seattle, USA, 28 May - 2 June 2000.
19. ROOVERS,P., BOOD,R., GALLI,M., MAREWSKI,U., STEINER,M., and ZARÉA,M.; *EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage*, Pipeline Technology, Volume II, Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium, 21-24 May 2000, R. Denys, Ed., Elsevier Science, 2000, pp. 405-425.
20. ROSENFELD,M.J.; *Investigations of Dent Rerounding Behaviour*, Volume 1, Proceedings of Second International Pipeline Conference, IPC-98, Calgary, Canada, American Society of Mechanical Engineers, 1998, pp. 299-307.
21. FOWLER,J.R., ALEXANDER,C.R., KOVACH,P.J. and CONNELLY,L.M.; *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges, and Dents with Welds*, AGA Pipeline Research Committee, Report PR-201-927 and PR-201-9324, June 1994.

22. HOPE,A.D., VOERMANS,C.M., LAST,S., and TWADDLE,B.R.; *Mechanical Damage of Pipelines: Prediction of Fatigue Properties*, Proceedings of the 2nd International Pipeline Technology Conference, Oostende, Belgium, 11-14 September 1995, R. Denys, Ed., Elsevier, 1995.
23. MAYFIELD,M.E., MAXEY,W.A., and WILKOWSKI,G.M.; *Fracture Initiation Tolerance of Line Pipe*, Paper F, 6th Symposium on Line Pipe Research, American Gas Association, Houston, Texas, 1979.
24. WANG,K.C., SMITH,E.D., *The Effect of Mechanical Damage on Fracture Initiation in Linepipe: Part III - Gouge in a Dent*, Canadian Centre for Mineral and Energy Technology (CANMET), Canada, Report ERP/PMRL 85-69 (TR), December, 1985.
25. MAXEY,W.A.; *Outside Force Defect Behaviour*, Report to Linepipe Research Supervisory Committee of the Pipeline Research Committee of the American Gas Association, NG-18 Report No. 162, AGA Catalogue No. L51518, 1986.
26. SPIEKHOUT,J., GRESNIGT,A.M., KONING, C., and WILDSCHUT,H.; *Calculation Models for the Evaluation of the Resistance Against Mechanical Damage of Pipelines*, 3R International, 25. Jahrgang, Heft, pp 198-203, 4 April 1986.
27. HOPKINS,P.; *The Application of Fitness for Purpose Methods to Defects Detected in Offshore Transmission Pipelines*, Conference on Welding and Weld Performance in the Process Industry, London, UK, 27-28 April 1992.
28. BAI,Y., SONG,R.; *Fracture Assessment of Dented Pipes with Cracks and Reliability-Based Calibration of Safety Factor*, International Journal of Pressure Vessels and Piping, Vol. 74, 1997, pp. 221-229.
29. LEIS,B.N., BUBENIK,T.A., FRANCINI,R.B., NESTLEROTH,J.B., and DAVIS,R.J.; *Recent Developments in Avoiding, Detecting, and Assessing Severity of Mechanical Damage*, Pipeline Technology, Volume II, Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium, 21-24 May 2000, R. Denys, Ed., Elsevier Science, 2000, pp. 405-425.
30. HAGIWARA,N., MÉZÈIRE,Y., OGUCHI,N., ZARÉA,M., and CHAMPAVÈRE,R.; *Fatigue Behaviour of Steel Pipes Containing Idealised Flaws under Fluctuating Pressure*, JSME International Journal, Series A, Vol. 42, No. 4, 1999.
31. JONES,D.G., HOPKINS,P.; *The Influence of Mechanical Damage on Transmission Pipeline Integrity*, Paper A21, IGU 1983 International Gas Research Conference, London, UK, 13-16 June, 1983.
32. CHAMPAVÈRE,R., ZARÉA,M., and BATISSE,R.; *Fatigue Behaviour of Steel Pipes Containing Dent and Gouge Combinations*, Pipeline Technology, Volume II, Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium, 21-24 May 2000, R. Denys, Ed., Elsevier Science, 2000, pp. 103-117.
33. ANON; *Manual for Determining the Remaining Strength of Corroded Pipelines*, A Supplement to ASME B31 Code for Pressure Piping, ANSI/ASME B31G-1984, The American Society of Mechanical Engineers, New York, USA, 1984.
34. ANON; *Manual for Determining the Remaining Strength of Corroded Pipelines*, A Supplement to ASME B31 Code for Pressure Piping, ASME B31G-1991 (Revision of ANSI/ASME B31G-1984), The American Society of Mechanical Engineers, New York, USA, 1991.
35. KIEFNER,J.F., DUFFY,A.R.; *Criteria for Determining the Strength of Corroded Areas of Gas Transmission Lines*, AGA Operating Section on Transmission Conference, AGA, 1973.
36. KIEFNER,J.F., VIETH,P.H.; *A Modified Criterion for Evaluating the Strength of Corroded Pipe*, Final Report for Project PR 3-805 to the Pipeline Supervisory Committee of the American Gas Association, Battelle, Ohio, 1989.
37. ROSENFIELD,M.J., KIEFNER,J.F.; *Proposed Fitness for Purpose Appendix to the ASME B31 Code for Pressure Piping Section B31.8, Gas Transmission and Distribution Systems*, Final Report to the American Society of Mechanical Engineers, Kiefner and Associates, Inc., Worthington, Ohio, USA, January 1995.
38. KIRKWOOD,M.G., FU,B., VU,D., and BATTE,A.D.; *Assessing the Integrity of Corroded Linepipe - An Industry Initiative*, Advances in Subsea Pipeline Engineering and Technology (ASPECT'96), Aberdeen, UK, 27-28 November 1996, Society for Underwater Technology, 1996, pp. 55-68.
39. FU,B., BATTE,A.D.; *Advanced Methods for the Assessment of Corrosion in Linepipe*, Health and Safety Executive Summary Report, OTO 97-065, HSE Books, 1999.
40. BJØRNØY,O.H., FU,B., SIGURDSSON,G., CRAMER,E.H., and RITCHIE,D.; *Introduction and Background to DNV RP-F101 "Corroded Pipelines"*, International Conference on Offshore and Polar Engineering, ISOPE'99, Honolulu, USA, 1999.
41. ANON, *Corroded Pipelines*, DNV Recommended Practice RP-F101, Det Norske Veritas, 1999.
42. BJØRNØY,O.H., CRAMER,E.H., and SIGURDSSON,G.; *Probabilistic Calibrated Design Equation for Burst Strength Assessment of Corroded Pipes*, International Conference on Offshore and Polar Engineering, ISOPE'97, Honolulu, USA, 1997.
43. BJØRNØY,O.H., SIGURDSSON,G., and CRAMER,E.H.; *Residual Strength of Corroded Pipelines, DNV Test Results*, Tenth International Conference on Offshore and Polar Engineering (ISOPE 2000), Seattle, USA, 28 May - 2 June 2000.
44. HOPKINS,P., PISTONE,V., CLYNE,A.J.; *A Study Of The Behaviour Of Defects In Pipeline Girth Welds : The Work Of The European Pipeline Research Group*, Paper VI-3, Proceedings of an International Conference on Pipeline

Reliability, CANMET, R. W. Revie, and K. C. Wang, Eds., Calgary, Alberta, Canada, 2-5 June 1992, pp. VI-3-1-VI-3-16.

45. ROODBERGEN,A., DENYS,R.; *Limitations Of Fitness For Purpose Assessments Of Pipeline Girth Welds*, International Conference Pipeline Technology, AIM, Rome, Italy, 1987.
46. McDONALD,K., HOPKINS,P.; *The Significance Of Embedded Non-Planar Defects In Transmission Pipeline Girth Welds-Part 1*, Pipes & Pipelines International, Vol. 40, No. 2, March-April, 1995, pp. 37-38.
47. McDONALD,K., HOPKINS,P.; *The Significance Of Embedded Non-Planar Defects In Transmission Pipeline Girth Welds-Part 2*, Pipes & Pipelines International, Vol. 40, No. 3, May-June, 1995, pp. 29-37.
48. CLYNE,A.J., JONES,D.G.; *The Integrity Of Transmission Pipelines Containing Circumferential Girth Weld Defects*, Proceedings of the Second International Pipeline Technology Conference, Volume II, Oostende, Belgium, 11-14 September 1995, R. Denys, Ed., Elsevier, 1995, pp. 299-314.
49. KNAUF,G., HOPKINS,P.; *The EPRG Guidelines on the Assessment of Defects in Transmission Pipeline Girth Welds*, 3R International, 35, Jahrgang, Heft, 10-11/1996, pp. 620-624.

Table 1 - Major Causes of Failures in Pipeline Systems[4]

COUNTRY	MAJOR CAUSE OF FAILURE	FAILURE RATE (per 1000 km year)
USA (onshore gas)	External Interference	0.16
USA (offshore gas)	Corrosion	0.70
USA (onshore and offshore oil)	External Interference	0.56
Western Europe (onshore gas)	External Interference	0.60
Western Europe (onshore oil)	Corrosion	0.80
Hungary (onshore gas)	Girth Weld Defects	0.10
Poland (onshore gas)	Corrosion	0.08
CIS (onshore gas)	Construction/Material Defect	0.33
Czechoslovakia (onshore gas)	Construction/Material Defect	0.13

Table 2 - Older Girth Welds in a Transmission System[1]

GIRTH WELDS	% UNACCEPTABLE TO CURRENT CODES
Fabricated before 1968	70
Fabricated between 1968 and 1972	10
Fabricated after 1972	0