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## A REVIEW OF THE TIME DEPENDENT BEHAVIOUR OF LINE PIPE STEEL

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### ABSTRACT

It is good practice to reduce the pressure in a pipeline prior to inspecting damage. One of the purposes of this pressure reduction is to prevent a 'time dependent failure' whilst inspecting the damage. The EPRG (European Pipeline Research Group) guidelines for the assessment of mechanical damage recommend that the internal pressure be reduced to 85 percent of the pressure at the time of damage to prevent time dependent failures. The PRC I (Pipeline Research Council International) Pipeline Repair Manual recommends a pressure reduction to 80 percent of the pressure at the time of damage.

Failures that occur under a constant load are time dependent failures. This means that a defect in a pipeline could fail sometime after the damage was caused, even though there has been no increase in the applied load, or an active growth mechanism such as corrosion or fatigue. They have been observed during hydrostatic test hold periods, during operation and under laboratory conditions. Failures under constant load occur because plastic deformation occurs in the material surrounding a defect subject to a load, and because plasticity is time dependent.

Time dependent behaviour is relevant to: (1) the safe working practices in the vicinity of a damaged pipeline, (2) pressure reversals, (3) the margin between the operating pressure and the hydrostatic test pressure, and (4) the minimum duration of a hydrotest.

The results of experimental and analytical studies of time dependent behaviour reported in the published literature are reviewed in this paper, to understand the background to the above recommended pressure reductions.

This paper is based on the findings of the Pipeline Defect Assessment Manual (PDAM) project, a Joint Industry Project sponsored by sixteen international oil and gas companies<sup>1</sup>.

### 1. INTRODUCTION

Defects in line pipe materials can fail when held at a constant load below the straight -off to failure load (see Fig. 1). This is because ductile materials can exhibit time dependent behaviour. The implication of this time dependent behaviour is that a damaged pipeline can fail sometime after the time that the damage was caused, even though there has been no subsequent increase in the applied loads (and no fatigue or environmentally assisted defect growth mechanism).

Evidence of time dependent behaviour is given by failures during the hydrostatic test hold period and pressure reversals. Time dependent behaviour has been observed at room temperature in small scale fracture mechanics test specimens held at constant loads. Time dependent behaviour has also been observed in full scale burst tests of part -wall defects (machined slots and gouges) in undented and dented pipe. There is a load threshold for time dependent behaviour; sustained loads below a certain percentage of the straight -off failure pressure will not cause a time dependent behaviour.

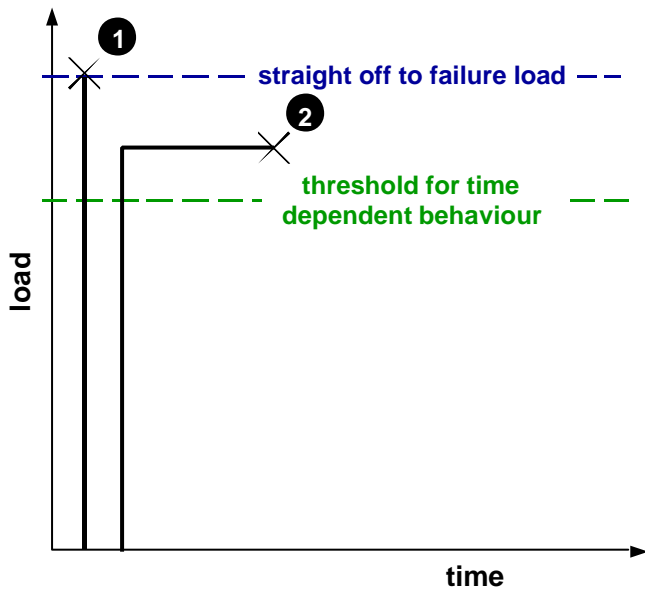
A defect in a pipe that has not failed immediately may be on, or near to, the point of failure, and could fail after some period of time has elapsed, due to time dependent effects. Prior to inspecting a damaged section of pipeline, the severity of the damage is unknown. Consequently, it is necessary to take steps to prevent the possibility of a time dependent failure, thereby allowing safe access to the damage site for inspection and assessment. Time dependent behaviour is load dependent.

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<sup>1</sup> 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 Total.

Therefore, failures under constant load conditions can be avoided by reducing the applied load. An understanding of time dependent failures is relevant to determining the necessary pressure reduction to prevent a time dependent failure. It is also applicable to studies of the role of the hydrotest.

In this paper, the results of the small scale and full scale tests and other studies of time dependent behaviour are reviewed. This paper is based on the findings of a detailed literature review conducted during the development of PDAM [1-4].



Note:

1. Load straight to failure.
2. Load to some level below the straight-off to failure load and hold at a constant load until failure.

**Fig. 1 Straight-off to failure load and time dependent behaviour**

**NOMENCLATURE**

$J$	$J$ -integral	
$L_r$	ratio of applied load to yield load	
$L_r^{max}$	the maximum permitted value of plastic collapse)	$L_r$ (represents
$d$	crack tip opening displacement	
SMYS	specified minimum yield strength	

**DEFINITIONS**

The following terminology is used in this paper:

straight-off to failure load this is the load at failure when the load is applied in a continuously increasing (monotonic) manner (also referred to as the monotonic collapse load).

displacement control	the response of the structure is determined by the applied displacement.
load control	the response of the structure is determined by the applied load.
hold period	a period of time at a constant load (or constant displacement).
isochronous	occurring at equal time intervals; an isochronous stress-strain curve is a curve of the strain accumulated after a constant period of time, obtained by loading to a given load (stress) and holding the load constant.
viscoplasticity	the flow of matter by creep, a time dependent process.

**2. TIME DEPENDENT PLASTICITY**

Inelastic deformation is usually separated into three types: anelastic, plastic and creep. Anelastic deformation (or delayed elasticity) is not permanent and will recover with time<sup>2</sup>. Plastic and creep (or viscoplastic) deformation are permanent. Plastic deformation is time independent. Creep deformation is time dependent. Creep is described by viscoplasticity theory. Creep can occur over a wide range of temperatures; it is not restricted to high temperatures. However, at low temperatures creep occurs slowly (what appear to be time independent strains may be time dependent, if a sufficiently long period of time elapses). At high temperatures (above about 0.5 times the absolute melting point), metals show primary, secondary and tertiary stages of creep. During primary creep, the creep rate (or the viscoplastic strain rate) decreases with time. During secondary creep, or steady state creep, the creep rate is approximately constant. Tertiary creep is the final stage, associated with a rapid increase in the creep rate, and leads to fracture. At low temperatures (below about 0.4 times the absolute melting point), metals show primary creep and negligible secondary creep.

At high temperatures, isochronous stress-strain curves will show a decrease in strength as time increases. At low temperatures, isochronous stress-strain curves reach a steady level, illustrated by the static stress-strain curve in Fig. 2.

The term 'time dependent plasticity' is not rigorous; plastic deformation is time independent. It is used here as a convenient shorthand to describe a low temperature creep process involving primary (or logarithmic) creep.

Large inelastic deformation and ductile fracture are time dependent in ductile engineering alloys at room temperature. A defect in a ductile material fails due to some combination of plastic flow and ductile crack growth (the contribution of the latter decreases as the material toughness increases). The

<sup>2</sup> Anelastic strain is treated in the framework of viscoelasticity theory. It is difficult to detect in metals, and is mentioned only for completeness.

stresses in the remaining ligament of a defect in a ductile material that is close to failure are at or above yield.

In relatively ductile materials, such as line pipe steels, constant loads can cause a form of creep deformation, due to the effect of time (strain rate) on the yield and work hardening characteristics of the steel, which govern plastic collapse and time dependent crack growth. The stress-strain characteristics of line pipe steels are strain rate dependent (see Fig. 2), as can be illustrated in isochronous stress-strain tests [5]. The steady state response is that achieved when loading at an infinitely slow strain rate, or after holding at a constant stress (or displacement) for a long period of time. Time dependent straining (an increase in the strain with time) occurs under load control. Time dependent stressing (a decrease in the stress with time), also known as relaxation, occurs under displacement control. Strain rate sensitivity and time dependent straining lead to time dependent ductile failures, as illustrated in Fig. 3.

Time dependent plasticity can occur at temperatures well below the creep range in ductile materials. This time dependent behaviour is sometimes referred to as cold creep. In general, failure is only found to occur if the sustained loads are greater than 90 percent of the monotonic collapse load [6]. Below this value some stable crack growth can occur which does not lead to failure [6]. Ductile tearing is not a prerequisite for time dependent behaviour, but it is time dependent. Time dependent failure only occurs under load controlled conditions, when the net section (remaining ligament) has yielded.

Time dependent plasticity and sub critical crack growth are believed to explain the phenomena of pressure reversals (failure at a given pressure having previously survived a higher pressure) and failures after being held at a constant pressure for a given time. Only failures associated with a constant applied load are considered here because they are directly relevant to the issue of the pressure reduction required to avoid time dependent failures.

Direct evidence for time dependent behaviour in line pipe steels is given by failures during the hydrostatic test hold period<sup>3,4</sup>. In the US, earlier experience of hydrostatic testing indicates that 50% of failures occurred during initial pressurisation, 18% in the next four hours and 16% in the final 19 hours [7]. The experience of British Gas is similar; out of 165 failures that occurred during testing to the nominal yield strength, 100 occurred during the 24 hour hold [10]; some hydrotest failures occurred after a period of approximately 15

hours [7]. Time dependent failures have been observed experimentally after as long as a year [11], and anecdotal evidence suggests that longer time periods have been observed during operation (but note that other time dependent degradation mechanisms may have been at play, so such observations should be treated with caution).

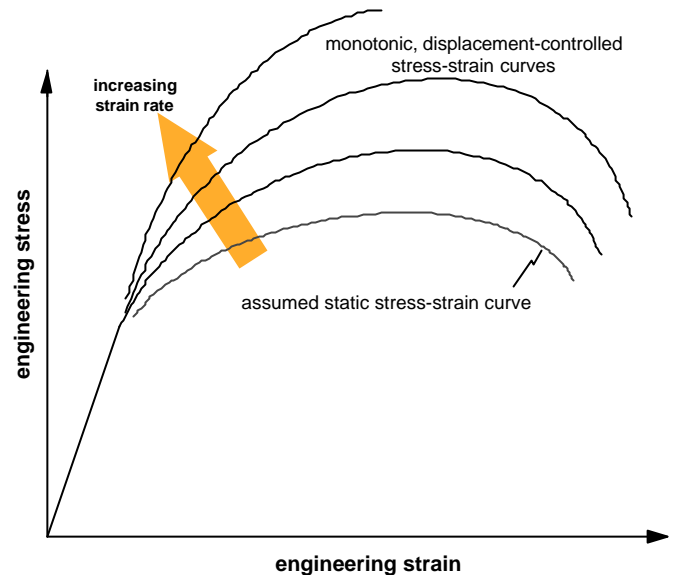


Fig. 2 Monotonic displacement-controlled stress-strain curves as a function of strain rate

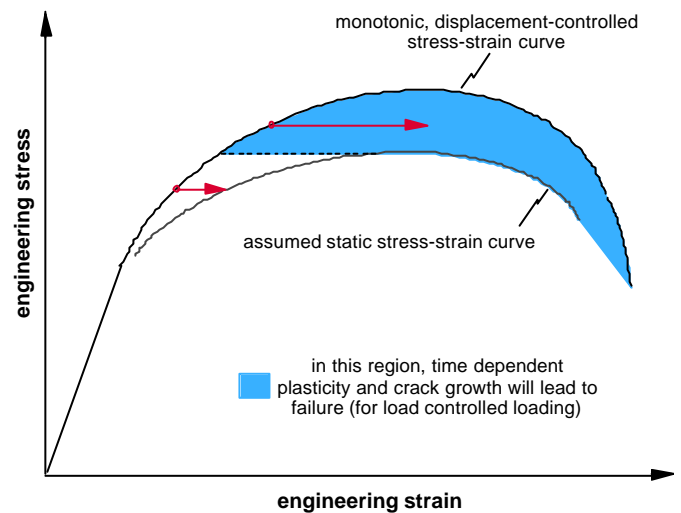


Fig. 3 Time dependent plasticity leading to time dependent failure (after Garwood (1986) [18])

Full scale tests on pipe specimens with strain gauges attached to the pipe adjacent to, or opposite, a defect have shown a creep type effect during constant pressure hold periods [12]. Other tests have shown that ductile tearing followed by stable crack growth can occur at the defect as the

<sup>3</sup> The original practice adopted in the U.S. by gas transmission pipeline operators was a 24 hour hold period at the maximum pressure [7]. The U.S. DOT Pipeline Safety Regulations specify a hold period of at least 8 hours [8]. IGE/TD/1, a design code for gas transmission pipelines, specifies a hold period of 24 hours at the hydrotest pressure [9].

<sup>4</sup> It should be noted that the hydrotest does not perfectly represent constant load conditions; fluctuations in load can occur due to changes in temperature, expansion of the pipe and subsequent 'topping up' of the pressure, etc.

pipe is pressurised to failure [11,13] and when a defect is held at a constant pressure [10-12].

The mechanism of time dependent behaviour has been studied through a number of controlled small scale tests, see section 3. Battelle and British Gas have carried out full scale tests in which defects in line pipe were held at constant loads until failure to investigate time dependent behaviour, see section 4. The results of these tests give an empirical threshold for time dependent behaviour.

### 3. TIME DEPENDENT BEHAVIOUR IN SMALL SCALE TEST SPECIMENS

Time dependence under constant loads has been observed in the testing of fracture mechanics test specimens [14-18] and in the testing of standard tensile specimens at room temperature [19], demonstrating that the processes leading to ductile fracture are time dependent. Experiments are reported in the following:

Green and Knott (1975) [14]  
Schulze and Fuhlrott (1980) [15]  
Tsuru and Garwood (1979) [16]  
Ingham and Morland (1983) [17]  
Garwood (1986) [18]

The small scale tests on tensile and fracture mechanics test specimens give an insight into the causes of time dependent behaviour:

1. Time dependent effects are only significant under load controlled conditions. Under displacement control the effects are negligible [16,18].
2. Time dependent behaviour is only relevant to ductile materials under conditions of net section yielding (i.e. the onset of general yielding of the structure), where the final fracture is controlled by plastic collapse. Time dependent crack growth would not be expected under conditions of contained yielding, where the plastic zone at the crack tip is contained within an elastic stress field [16-18].
3. Time dependent effects observed experimentally are considered to be due to the strain rate sensitivity of the material (i.e. they can be explained by viscoplasticity theories in terms of the total strain and overstress) [16,17,19].
4. There is a load threshold for time dependent behaviour.
5. An empirical limit for unstable time dependent behaviour, based on small scale test results, is that the constant load at the initiation of crack growth is within 10 percent of the collapse load [17,18].
6. The threshold for time dependent behaviour is strain rate dependent [17].

### 3.1 VISCOPLASTICITY

The results of the various tests on tensile specimens and fracture mechanics test specimens support the theory proposed by Tsuru and Garwood (1979) [16] (and also stated elsewhere [17,19]) that time dependent behaviour can be explained by viscoplasticity theories that predict the existence of an equilibrium stress-strain curve corresponding to truly static conditions, and predict increasing stress levels (for a given strain level) with increasing loading rate (see Fig. 2). Time dependent behaviour is then explained in terms of the total strain and the overstress associated with an increase in the loading rate [16-18]. If a specimen is loaded at 'conventional' loading rates to a specified load (displacement) and the load is then held constant, time dependent behaviour (i.e. increasing crack growth or displacement with time) will be observed if the specified load (displacement) is greater than a threshold value for time dependent behaviour. The time dependent behaviour will cease when the displacement reaches the corresponding point on the equilibrium load-displacement curve. If the constant load is greater than the maximum load on the equilibrium load-displacement curve, then failure will eventually occur due to time dependent behaviour (see Fig. 3).

The role of viscoplasticity is supported by the finite element analysis of compact tension specimen loaded through small scale yielding into the large scale yielding regime [20]. The results of the analysis show that for strain rate-controlled fracture (i.e. plastic collapse), crack growth could be initiated at some time subsequent to the attainment of a maximum load, if the load is held at a constant level. Little et al. (1984) suggest that this type of behaviour would be most likely to be observed under load control conditions because this promotes time dependent straining, whereas time dependent stressing (relaxation) is promoted under displacement control [20].

### 3.2 DUCTILE CRACK GROWTH

Some small scale fracture mechanics tests have shown time dependent behaviour when the crack tip opening displacement,  $d$  (or  $J$ -integral), is greater than the value for the initiation of crack growth,  $d_0$  [14] (note that instability in ductile materials occurs at a value of  $d$  greater than  $d_0$ ). Other tests have indicated an increasing crack tip opening displacement with time when the initial value was less than  $d_0$  [15,18]. Time dependent effects have been observed in blunt notched specimens as well as in fatigue pre-cracked specimens, the crack initiation occurring during the load hold period [18]. This has led to the conclusion that the threshold for time dependent behaviour is not connected with the initiation of crack growth [18], which is consistent with it being caused by time dependent plasticity.

### 3.3 TIME

The length of time at the constant load before failure occurs has not been quantified. It is expected that it would depend upon the proximity of the load to the straight-off to failure load and the initial loading rate. Considering all of the various tests

reported above, the longest time to failure when held at a constant load was about 72 hours [ 15]; other specimens were held for up to 1450 hours and did not fail, although some time dependent behaviour, an increase in the load line displacement, was observed.

#### 4. TESTS ON THE LONG TERM STABILITY OF PIPELINE DEFECTS

There has been a large body of research work, much of it undertaken by Battelle in the 1960s and 70s, investigating the effect of hydrotesting on the behaviour of pipeline defects and in particular, the effect of high level hydrotesting (i.e. testing to circa 100% SMYS) and the effect of the hydrotest hold period [11,21-23]. Subsequently, there was additional research, mostly conducted by Battelle and British Gas (now Advantica, part of National Grid Transco), on the long term stability of defects in pipelines [10,11,24-29]. Two types of defect have been considered:

1. Defects in undented pipe.
2. Defects in dented pipe.

The studies of time dependent behaviour in full scale tests of defects in pipelines are limited to longitudinally orientated defects (cracks, machined notches or gouges) subject to internal pressure. However, time dependent behaviour is not limited to any particular defect type, orientation or load, as demonstrated by the small scale tests, and, in principle, the results from the full scale tests can be generalised.

The experimental work has shown that sustained loads and high pressure loads can cause pipeline defects to extend prior to failure and to fail below the straight-off to failure pressure, due to time dependent plasticity [ 10,11,22,24-26]. Work at Battelle has also demonstrated that stable crack growth can be observed in defects loaded to 86 percent of their failure pressure [ 24-26]. Observations and conclusions from the various experimental studies of part-wall defects in circular pipe and of dents and 'gouges' are summarised below. The results of the full scale tests are generally consistent with those of the small scale tests.

##### 4.1 DEFECTS IN UNDATED PIPE

The tests considered in detail here, by Battelle and British Gas, are those in which the long term stability of part-wall defects when held at constant pressure below the straight-off to failure pressure, has been investigated directly (i.e. a defect has been held at a constant pressure until failure, or until the test was terminated). Tests in which sub-critical crack growth has been investigated are not considered here and neither are tests designed to investigate pressure reversals.

Battelle has carried out a number of experimental studies (burst tests) of the long term stability of part-wall defects in line pipe, in which the defects were held at some pressure below the straight-off to failure pressure until either failure occurred or the test was terminated [11,21,22]. All of the defects were machined V-shaped notches. British Gas has also undertaken a number of

tests, but these were limited to small scale notch-bend tests of specimens of line pipe [10].

Battelle (1968) [21]	3 vessel tests
Battelle (1969, 1980) [11,22]	12 vessel tests
Battelle (1980) [11]	8 vessel tests
British Gas (1991) [10]	a number of small scale notch-bend tests <sup>5</sup>

1. Full scale tests carried out by Battelle on part-wall defects (machined V-shaped notches) in undented pipe, indicate that the threshold for time dependent behaviour is between 92 and 95 percent of the monotonic collapse load (see Fig. 4 and Fig. 5)<sup>6</sup> [11,22].
2. Based on the corrected Battelle tests (see Fig. 5)<sup>7</sup>, Kiefner et al. (1980), concluded that the threshold was approximately 95 percent of the monotonic collapse load [11].
3. Based on further studies of the effect of the hydrotest and sustained loads, Kiefner et al. (1980) concluded that defects loaded to within circa 14 percent of their straight-off to failure pressure would exhibit some degree of stable crack growth, the extension increased as the failure load was approached, and that there appeared to be a threshold of constant service pressure (approximately 92 percent of the test pressure), below which remaining defects in the pipeline will survive indefinitely, when the failure mode is ductile [11].
4. Notched bend specimen tests, carried out by British Gas, showed failures within a 24 hour period occurring for constant pressure loads of between 93 and 96 percent of the straight-off failure pressure (see Fig. 10) [13].
5. Fearnough and Jones (1978) suggested that time dependent failures can largely be accounted for by time dependent yielding, and concluded that a 5 percent adjustment to the failure stress would generally account for the time dependent behaviour of sub-critical part-wall defects (not associated with a gross geometric discontinuity) [12].
6. The other small scale tests (see section 3) indicate a threshold between 90 and 95 percent.

Therefore, for part-wall defects in undented pipe, a threshold for time dependent behaviour of 90 percent of the straight-off to failure load is proposed as a lower bound to both small scale and full scale test data.

<sup>5</sup> Limited test details are reported.

<sup>6</sup> Note that the y-axis scale is greatly expanded in these figures.

<sup>7</sup> The effect of the hold time is small and can be masked by local differences in wall thickness, yield strength and flaw geometry. To account for these effects, strain gauge data was used to calculate 'corrected' pressures. The premise of the correction was that, whilst the differences in failure pressure are obscured by local differences, the pressure-strain curves should be identical for 'identical' defects [ 11,22].

The small scale test data and analyses described previously indicate that time dependent failures can be attributed to time dependent plasticity. The Battelle and British Gas full scale test data provides empirical evidence for a load threshold for time dependent behaviour. The test data from which to determine the threshold for time dependent behaviour is limited. Only a limited range of pipeline geometry, grade, toughness and, in terms of type and size, of pipeline defects have been tested.

The constant load tests demonstrate experimental scatter. Some of this can be attributed to the repeatability of the straight-off to failure pressure, due to the variation of pipeline geometry and material properties within and between lengths of pipe (even from the same batch and heat). The effect of this scatter is illustrated in a comparison of the results of Battelle tests shown in Fig. 4 and Fig. 5, where the failure pressure has been ‘corrected’ in the latter to account for such differences.

The failure of a defect in ductile line pipe occurs as a result of plastic flow and stable ductile crack growth. Consequently, stable crack growth at some load prior to failure has been commonly observed in tests of sharp part-wall and through-wall defects when the load is monotonically increased to failure. The threshold for the initiation of stable crack growth does not necessarily correspond to the threshold for time dependent behaviour (the latter could be higher or lower, as has been observed in the tests discussed here). Plastic flow and stable crack growth demonstrate time dependent behaviour because they depend upon the stress-strain characteristics of the material.

The results of the tests do not indicate a time threshold for time dependent behaviour. The longest time to failure in the tests of defects in undented pipe held at constant load was approximately 23 hours [11,22], and in tests of defects in dented pipe (see below) it was approximately 40 hours [27,28]. In a series of eight simulated long term service tests of vessels containing part-wall defects conducted by Battelle, failures occurred after several months at a constant load [11]. There is limited anecdotal evidence that failures in the field have occurred after several years. Consequently, it cannot be assumed that there is a time threshold for time dependent behaviour; a visco-plastic model of time dependent behaviour implies that failures at a constant load could occur after a significant period of time has elapsed, if the load threshold is exceeded.

#### 4.2 DEFECTS IN DENTED PIPE

Both British Gas [27-29] and Battelle [24] have also carried out experimental studies of the long term stability of part-wall defects in smooth dents. A dent under internal pressure is a source of high stresses and strains. A defect in the dent is an additional source of stress concentration. The combined structure behaves in a complex and unstable manner. A dent is pushed outward by internal pressure. This movement induces bending stresses in the defect; the large stresses and strains due to the general rotation promote tearing of the defect

through the remaining ligament. Consequently, the time dependent behaviour of a dent and ‘gouge’ defect is more complicated than that of a defect in undented pipe. The tests referred to below are primarily those in which time dependent behaviour has been studied by holding the pressure constant at some level below the straight-off to failure pressure, but reference is also made to sub-critical crack growth and the change in dent depth with time.

In all of the British Gas tests and two of the Battelle tests the ‘gouge’ was a machined V-shaped notch, and the damage was introduced at zero pressure. Hopkins et al. (1983) refer to tests of denting rings containing gouges with sub-surface cracking carried out by British Gas [28], but no details are given.

British Gas (1982, 1983) [27,29]	21 ring tests (dent then notch)
British Gas (1983) [28]	6 ring tests (dent then notch)
Battelle (1986) [24]	2 vessel tests (notch then dent)
Battelle (1986) [24]	2 dynamic <sup>8</sup> vessel tests (damaged introduced at pressure)

1. The Battelle constant load tests on dents and ‘gouges’ are not conclusive regarding the threshold for time dependent behaviour, but do indicate that the behaviour of dented pipe is more complex than that of undented pipe.
2. The British Gas tests on dented rings containing machined slots indicate a threshold of 85 percent of the straight-off to failure pressure (see Fig. 6) [27,29]. It is reported that similar results were observed in dents containing simulated gouges with sub-surface cracking [29]. Jones and Hopkins (1983) concluded that dents with associated defects are susceptible to time dependent behaviour and that failures can occur after a period of time at sustained pressures of at least 85 percent of the straight-off to failure pressure [27,29].

The threshold for time dependent behaviour for a defect in a dent is lower than that for a defect not in a dent. There are no other published data, and the range of the test data is limited. Nevertheless, a threshold for time dependent behaviour of 85 percent of the straight-off to failure load for a defect in a dent has been adopted in industry guidance, see below.

In one of the Battelle tests of a machined notch in a dent held at a constant pressure, crack growth (in terms of electric potential) and dent depth were measured during the test; these plots are shown in Fig. 7 and Fig. 8, respectively [24]. The data indicate the outward movement of the dent under increasing

<sup>8</sup> The dent and gouge were introduced simultaneously under dynamic loading conditions (as opposed to quasi-static) in order to simulate damage caused by excavation equipment.

internal pressure, and stable crack growth prior to failure, some at constant pressure, but most when the pressure is increased. Stable crack growth was observed from about 70 to 95 percent of the failure pressure of a similar defect pressurised straight to failure [24]. Consequently, Maxey (1986) concluded that if combined dent and gouges were found in a pipeline then, prior to a detailed inspection, the pipeline pressure should be reduced to 67 percent of the pressure in the pipeline at the time the damage was discovered [24,25].

British Gas also investigated the stages of crack growth during the outward movement of a dent containing a gouge with subsurface cracking under internal pressure [28]. A record of one such test, in which failure occurred after holding the pressure at 94 percent of the straight-off failure pressure for 14.5 hours is reproduced in Fig. 9 [27,28]. The dent moved out continuously during the hold period, accompanied by a similar displacement of the clip gauge (mounted on the edge of the gouge).

#### 4.3 THE EFFECT OF TOUGHNESS

Time dependent behaviour is a consequence of time dependent plasticity. The toughness of the line pipe steel will affect the time dependent behaviour, because it determines whether the fracture is ductile or brittle.

British Gas conducted a series of small scale tests to investigate the relative contribution of crack extension (ductile crack growth) and plasticity on time dependent behaviour in line pipe steels [10]. It was concluded that time dependent failures could be explained by the effect on the tensile properties rather than crack growth [10]. In low toughness line pipe steels there was a small contribution from ductile crack growth. These observations are generally consistent with the results of other small scale tests (see above), from which it can be concluded that time dependent behaviour is not connected with the initiation of crack growth, and that it is entirely due to the strain rate sensitivity of the material.

Time dependent behaviour will only occur in ductile steels; failure occurs due to ductile fracture, involving some combination of plastic flow and ductile tearing. The plastic zone around a defect in a ductile material is much larger than in a brittle material, and net section yielding (yielding throughout the remaining ligament) can occur, leading to unconstrained plasticity. In brittle materials any crack instability is associated with the onset of failure. Plastic deformation does not play a significant role in brittle fracture; the plastic zone is small and surrounded by elastic material. Strain based time dependent behaviour would not be expected in brittle materials. It could be hypothesised that in a less ductile material, the time to failure at a constant load would be expected to be shorter and the threshold load (expressed as a percentage of the straight-off to failure load), above which time dependent failure is observed, would be expected to be higher (but note that, for a given geometry and defect size the straight-off to failure load will be

lower in a lower toughness material). However, there is little experimental evidence to prove this hypothesis.

#### 4.4 THE EFFECT OF STRAIN RATE

The threshold for time dependent behaviour is dependent on the strain rate during loading, as can be seen from examination of Fig. 2 and Fig. 3.

The loading rates are not quoted for any of the full scale tests. It can only be assumed that they are 'conventional' loading rates. An indication of what this figure might be is given in a description of the testing procedure for the Battelle burst tests of machined through-wall and part wall defects; the specimens were pressurised straight away to failure at a steady rate not exceeding 20 psig.min<sup>-1</sup> [30]. A threshold would be non-conservative when applied to loading rates significantly higher than that used to derive it.

### 5. THEORETICAL DESCRIPTIONS OF TIME DEPENDENT BEHAVIOUR

Theoretical considerations indicate that time dependent behaviour is only relevant under conditions of net section yielding, and then only if the load is above a certain threshold value. Therefore, in principle, a criterion for determining whether a defect of a given size may exhibit time dependent behaviour could be devised, based on the fact that time dependent behaviour will not occur if the remaining ligament has not yielded. It would, of course be more difficult to analyse a defect in a dent, because such defects are geometrically unstable and there is plasticity in the dented area.

A framework for the analysis of time dependent behaviour is given in R6 [6], a document originally developed for applications in the nuclear industry, that gives detailed guidance for the application of fracture mechanics to structures containing defects (R6 is similar to the more widely known BS 7910 [31]). A theoretical treatment of the time dependent behaviour of defects in pipelines has been proposed by Leis et al. (1991) [32] at Battelle (under the sponsorship of the Pipeline Research Council International (PRCI)), and implemented in the Ductile Flaw Growth Model (DFGM).

#### 5.1 R6

R6 indicates that time dependent fracture can occur under sustained loads (load control) approaching and in excess of general yield [6]. The ratio of the reference stress (the stress in the net section) to the yield strength is defined in R6 as  $L_r$ . General yielding (net section yielding) corresponds to  $L_r$  greater than unity. In ferritic steels, the effect of a sustained load is considered negligible when  $L_r$  is less than 90 percent of the straight-off to failure load (defined in R6 as  $L_r^{max}$ ), i.e. when the applied load is less than 90 percent of the plastic collapse load. For austenitic steels, it is indicated that the effect of sustained loads can be neglected when  $L_r$  is less than 65 percent of  $L_r^{max}$  (this limit is based on a lower bound to test data for which  $0.6L_r$  was about 1.1).



A method is given for analysing time dependent behaviour using time -dependent plastic strain data (isochronous stress - strain data or constant stress creep curves at the relevant temperature are required). The approach described in R6 is similar to that implemented in the DFGM.

Note that the latest edition of R6 (revision 4) has modified the guidance for analysing time dependent behaviour, based on new test data, and indicates that the effect is negligible when  $L_r$  is less than or equal to unity  $\beta$ 3].

## 5.2 THE DUCTILE FLAW GROWTH MODEL (DFGM)

The DFGM was originally developed to assess flaw growth during hydrotesting [32]; it is a revised and updated form of the original NG-18 equations developed by Battelle in the 1960s and 70s [30,34]. The DFGM, and its implementation in PAFFC (Pipeline Axial Flaw Failure Criterion) is more accurate than the original Battelle failure criterion because it accounts for the stable crack growth that occurs in ductile materials and it is a better model of 'flow stress' and 'toughness' dependent failure mechanisms [32,35,36].

Ductile crack growth in line pipe materials, considered to occur because of plasticity effects during loading or time dependent effects during the hold period, is assumed to be  $J$ -integral controlled, i.e.  $J$ -tearing theory is used<sup>9</sup>. The use of  $J$  theory is intended to account for both time dependent plasticity and crack growth (initiation, stable growth and then instability). Time dependent behaviour has been implemented through time-marching a (time independent) deformation theory of plasticity model of the material behaviour. This means that time dependence is accounted for by incrementing time in steps (i.e. discrete) and the  $J$ -integral is calculated using a constitutive model appropriate to that time step, i.e. incrementing a time independent model over time using appropriate material data. The time dependence in the DFGM comes from the change in the stress-strain response of the material with time.

In the course of the development and validation of the DFGM, a large number of material tests were carried out in order to obtain the necessary data to characterise the response of the material [5]. These tests included isochronous stress -strain tests under monotonic loading to simulate time dependent flow behaviour. The time dependent values of a stress -strain curve were obtained by fitting coefficients of the Ramberg -Osgood equation to the experimentally derived isochronous stress-strain curves. The DFGM describes both time dependent plasticity and strain rate dependent behaviour.

The DFGM has been used to analyse the time dependent failure of part -wall defects and has been used to explain the occurrence of pressure reversals and the time dependent failure of defects under sustained loading  $\beta$ 7].

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<sup>9</sup> Although based on  $J$ - $R$  curve material data, the DFGM also incorporates a semi-empirical correlation between the  $J$  integral and  $J$ - $R$  curves and the upper shelf Charpy impact energy and tensile properties.

## 6. THE PRESSURE TEST LEVEL, THE HOLD PERIOD AND 'PRESSURE REVERSALS'

The time dependent behaviour of defects in line pipe steels has implications for the level and duration of hydrostatic testing.

As a pipeline is pressurised to the test pressure at the start of a hydrotest, some defects, above a certain critical size for initiation, will grow in size due to stable ductile crack growth and plastic flow. During the hold period, some defects will continue to grow in size due to time dependent plasticity. Depending upon the material properties and the size of the defect, the defect may fail. This behaviour has led to discussions about whether a long hold period could impair the integrity of the pipeline. Practical experience of 24 hour hold periods indicates that very few failures occur in the final hours of the test [ 7]. An experimental study of the effect of the hydrostatic test hold period on the surviving defect population carried by British Gas concluded that the largest surviving defect after the 24 hour hold period is smaller than that after the initial loading, indicating that the longer hold period has a beneficial effect [10,12]. A theoretical examination of the hydrotest by Battelle, based on predictions using the DFGM, has suggested that a maximum test pressure of 1 hour duration, followed by a hold time at a reduced pressure (greater than or equal to 1.1 times the operating pressure) (as a leak test), appears to be the best for pipeline applications [ 37]. The conclusions from these two studies are contradictory, but note that there is no comparative study of the two cases in the published literature.

A pressure reversal is where a defect in a pipeline survives pressurisation to a certain level, only to fail upon subsequent pressurisation to a lower pressure. Pressure reversals during hydrotesting are generally limited to less than 5 percent below the test pressure [ 23]<sup>10</sup>. A review, by Battelle, of the service experience of a large number of pipelines suggested that the minimum test pressure should be at least 1.1 times the design pressure to prevent possible time dependent failures of surviving defects in service [21]. Subsequent studies, discussed above, indicate a threshold of the order of 90 to 95 percent of the straight -off to failure pressure. Therefore, it is generally accepted that the minimum test pressure should be at least 1.1 times the design pressure, to avoid pressure reversals due to time dependent plasticity. Note that pressure reversals are caused by both time dependent behaviour and sub -critical crack growth; the latter is generally the more significant effect, particularly in the larger reversals. Large pressure reversals are

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<sup>10</sup> The largest published pressure reversal during hydrotesting was 62 percent, and occurred in an old (low frequency) ERW pipeline in the USA [23]. Low frequency ERW seam welds were often plagued with defects and had very poor material properties. Large pressure reversals have also been introduced in the laboratory; Barkov (1972) reported a reversal of 17 percent [38] and Hopkins and Jones (1992) reported one of 39 percent [39].

very rare, and where they have occurred it has been due to an unusual combination of factors.

## **7. SAFE WORKING ADJACENT TO A DAMAGED PIPELINE**

The implication of time dependent behaviour is that a defect in a pipeline may fail sometime after it has been introduced, in the absence of a defect growth mechanism such as fatigue or corrosion. The theoretical and experimental work reviewed above indicates that there is a load threshold for time dependent behaviour, but it provides no information on the time threshold.

Working in the vicinity of a damaged pipeline is a potentially hazardous operation. Health, safety and environmental considerations need to be addressed, including such details as the conditions at the site, and the consequences of a failure.

Considering the defect, two situations can be envisaged: (1) the severity of the defect is known (e.g. the defect has been found from an intelligent pig run), and (2) the severity of the (suspected) defect is unknown. Note that even when excavating to inspect a 'known' defect, something unexpected may be revealed.

It is generally considered to be good practice to reduce the pressure in a pipeline prior to excavating and inspecting the damage. The primary reason for this pressure reduction is to prevent a possible time dependent failure. Excavating a pipeline will also change the loads; a pressure reduction can compensate for any significant increase in the external loads. The pressure in a pipeline is not constant, pressure surges can occur for a variety of different reasons; a pressure reduction can compensate for any surges during the duration of the excavation and inspection of the damaged pipeline.

Some repair methods require a pressure reduction prior to their installation.

## **8. INDUSTRY GUIDANCE**

Guidance on pressure reductions to avoid a time dependent failure during the excavation of a damaged pipeline is given by the EPRG [40-42] and the PRCI [43]. There is very little information in the published literature that refers to the practices adopted by specific pipeline companies, although the procedures adopted by National Grid Transco (formerly British Gas), in their widely known document BGC/PS/P11, been described by Pallan (1988) [44].

Transco and the EPRG recommend a pressure reduction to 85 percent of the pressure at the time the damage was introduced into the pipeline (or the maximum pressure that the damage has experienced since it was introduced, if higher) prior to excavation. The PRCI pipeline repair manual recommends a pressure reduction to 80 percent of the pressure at the time of damage. The background to these different recommendations can be traced back to the studies of time dependent behaviour, and the role of the hydrotest, as summarised below.

### **8.1 PRC/Pipeline Repair Manual**

A pipeline repair manual has been developed by Kiefner et al. (1994) under the auspices of the Pipeline Research Council International (formerly the Pipeline Research Committee of the American Gas Association) [43]. This manual includes a section on the response to the discovery of an anomaly or a defect. The manual states that a pressure reduction to a level of 80 percent of the pressure which exists at the time the defect or anomaly is discovered provides a minimum level of confidence that the defect or anomaly will not fail during the course of its examination or repair. The stated rationale for this pressure reduction is that an anomaly or defect for which little, if any, information is available, may be on the verge of failure. The reduction to 80 percent of the pressure at the time of damage is recommended in cases of defects discovered unexpectedly, in response to an on line inspection run (when it is not possible to establish with confidence the significance of any defects), and when leaks are detected during a leakage survey.

The reduction to 80 percent of the pressure at the time of damage is based on the criterion for the maximum operating pressure in a pipeline stated in ASME B31.4, ASME B31.8, and the U.S. DOT Pipeline Safety Regulations [8,45-47]. A regulated pipeline cannot be operated at more than 80 percent of its test pressure. Lowering the operating pressure to 80 percent of its actual current value creates the same margin of safety as that if a hydrotest to 1.25 times the operating pressure. The safety margin of 1.25 was derived from a study by Battelle of the role of the hydrotest, which considered time dependent behaviour and pressure reversals [21,22]. The U.S. Pipeline Safety Regulations require that the operating pressure must be at a safe level during a repair operation (§192.713(b)), and that repairs are made in a safe manner (§195.422(b)) [8].

The reduction to 80 percent of the pressure at the time of damage, i.e. a 20 percent reduction, is greater than the 15 percent reduction that follows from the experimental studies of time dependent behaviour of dents and gouges, and therefore is conservative with respect to this empirical threshold.

### **8.2 EPRG Guidelines for the Assessment of Mechanical Damage**

The EPRG (European Pipeline Research Group) has developed guidelines for the assessment of mechanical damage [40-42]. These guidelines recommend a pressure reduction of 15 percent of the maximum operating pressure experienced by the defect since the damage occurred. This pressure drop should be maintained until either the defect has been repaired or assessed.

It is indicated that information on time dependent failures is limited, but that failures in the field have occurred up to five years after damage was introduced [41]. The EPRG make reference to the work by British Gas [12,27,28], The Welding Institute [16], and Battelle [11,24] (as discussed above), and highlight the conclusions of this work indicating an approximate

5 percent threshold for part-wall defects and 15 percent threshold for dent and gouge defects. It is noted that the Battelle work on dent and gouges (of which there are only four tests) indicated stable crack growth from approximate 70 percent of the straight-off to failure pressure. It is suggested that the steels tested were of low toughness compared to modern line pipe [41]<sup>11</sup>. It is further suggested by the EPRG that in the Battelle tests significant crack growth did not occur until the pressure was in excess of 85 percent of the straight-off to failure pressure (this is based on an interpretation of Figure 10 from Maxey (1986) (reproduced in Fig. 7); note that 85 percent of the straight-off to failure pressure is approximately 1062 psi). Based on this reanalysis of the Battelle data, the EPRG concluded that the tests are consistent with the 15 percent pressure reduction recommended by Jones and Hopkins (1983) [41]. This conclusion is supported by the studies that have indicated that time dependent behaviour is not dependent on crack initiation [10].

### 8.3 National Grid Transco

The National Grid Transco (formerly British Gas) document BGC/PS/P11 gives procedures to be adopted in the event that damage is detected in any of its transmission pipelines. The procedures have been described by Pallan (1988) [44]. Damage to a pipeline is categorised on the basis of its severity (the damage categories are superficial, moderate, severe and extreme<sup>12</sup>). The required actions depend upon the damage category. Pressure reductions are specified to ensure that it is safe to excavate and examine the damage to the pipeline, whilst minimising the possibility of a major gas supply failure.

It is stated that, prior to excavating the pipeline, the pressure must be prevented from exceeding the pressure at the time of damage, and it is recommended that the pressure is reduced to 85 percent of the pressure at the time of damage. Subsequent to the excavation, if on the basis of a visual inspection the damage appears to be more than superficial, the pressure must be reduced to 85 percent of the pressure at the time of damage or a pressure corresponding to a hoop stress of 30% SMYS (whichever is the lower).

If the damage is being excavated based on the results of an intelligent pig run, and the damage is categorised as severe or extreme, based on the intelligent pig report, then the pressure must be reduced to the lower of 85 percent of the pressure at the time of damage or a pressure corresponding to a hoop stress of 30% SMYS.

Further pressure reductions are required if, upon excavation and inspection, the damage is categorised as extreme.

The pressure reduction to 85 percent of the pressure at the time of damage is based on the experimental studies of time

dependent behaviour of pipeline defects, specifically dents and gouges, carried out by British Gas and Battelle (and described above). The 30% SMYS figure is based on full scale tests on part-wall and through-wall defects that have shown that it is very unlikely that a part-wall defect will fail as a rupture at this stress level [48]. Therefore, whilst the reduction to 85 percent of the pressure at the time of damage is related to time dependent failure, the reduction to a hoop stress of 30% SMYS is based on consideration of the consequences of a failure.

## 9. CONCLUSIONS

1. Ductile materials can exhibit time dependent plasticity well below the creep range. If a defective structure is held at a constant load, failure can occur at a stress level that is below the straight-off to failure load of the defective structure. Time dependent effects observed experimentally are considered to be due to the strain rate sensitivity of the material; they can be explained by viscoplasticity theories in terms of the total strain and overstress.
2. Time dependent failures are limited to load controlled conditions and under conditions of net section yielding (i.e. the onset of yielding of the remaining ligament).
3. Failures under constant load conditions can be avoided by reducing the applied load.
4. An empirical threshold based on small scale test results indicates that time dependent failures will only occur when the sustained loads are in excess of 90 percent of the monotonic (straight-off) plastic collapse load.
5. Full scale tests on part-wall defects (machined slots) in line pipe carried out by Battelle and British Gas have shown that failures can occur after a period of time at sustained pressures at or above 92 percent of the straight-off to failure pressure.
6. Tests on dented rings containing machined notches or simulated gouges carried out by British Gas have shown that failures can occur after a period of time at sustained pressures at or above 85 percent of the straight-off to failure pressure.
7. Pressure reductions prior to excavating and inspecting a damaged pipeline are recommended in the EPRG Guidelines for Assessing Mechanical Damage and in the PRCI Pipeline Repair Manual. The recommendations are based on studies of the time dependent behaviour of defects in pipelines.

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## REFERENCES

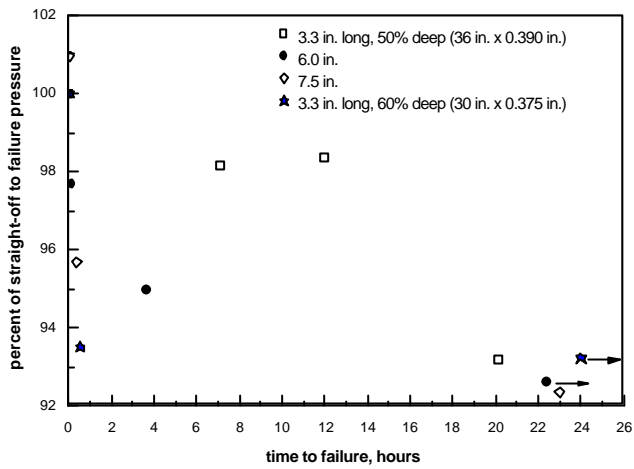
1. Cosham, A., Hopkins, P., 2002, "The Pipeline Defect Assessment Manual," IPC02 -27067, Proceedings of IPC 2002, International Pipeline Conference, American Society of Mechanical Engineers, Calgary, Alberta, Canada.

<sup>11</sup> The DWTT transition temperature (defined by a shear area of 85 percent) of the line pipe was +45°F (7.2°C) [24].

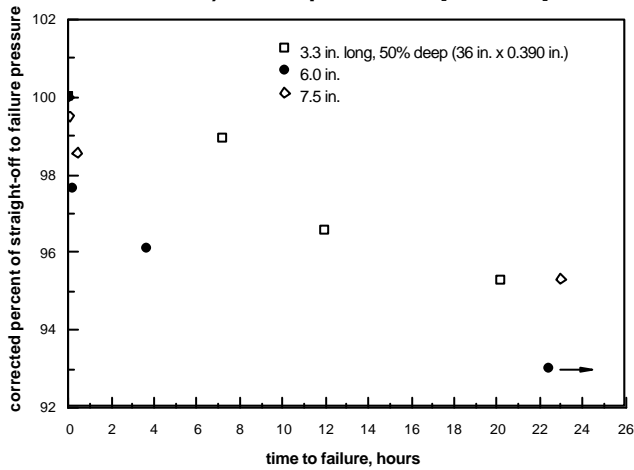
<sup>12</sup> The difference between the severe and extreme damage categories is whether the damage is predicted to fail as a leak or as a rupture.

2. Cosham, A., Hopkins, P., 2003, "The Effect of Dents in Pipelines, Guidance in the Pipeline Defect Assessment Manual," Proceedings of ICPVT -10 International Council for Pressure Vessel Technology, Vienna, Austria.
3. Cosham, A., Hopkins, P., 2004, "An Overview of the Pipeline Defect Assessment Manual," Volume III, Proceedings of the Fourth International Pipeline Technology Conference, Oostende, Belgium, R. Denys, Ed., Scientific Surveys Ltd., pp. 1487-1502.
4. Cosham, A., Hopkins, P., 2004, "The Assessment of Corrosion in Pipelines, Guidance in the Pipeline Defect Assessment Manual (PDAM)," Pipeline Pigging and Integrity Management Conference, Amsterdam, The Netherlands.
5. Leis, B. N., Brust, F. W., 1990, "Ductile Fracture Properties of Selected Line -Pipe Steels," Topical Report to the Line Pipe Research Supervisory Committee of the Pipeline Research Committee of the American Gas Association, NG -18 Report No. 183, SI Task 1.7/1.8-84, Battelle.
6. British Energy, 2001, "Assessment of the Integrity of Structures Containing Defects," R/H/R6, Revision 3, Barnwood, Gloucestershire.
7. Jones, D. G., 1992, "Notes on the Philosophy and History of Pressure Testing," IMechE Seminar on Developments in Pressure Vessel Technology, London.
8. Anon., Pipeline Safety Code of Federal Regulations (CFR) Title 49 Part 186 -199, Office of Pipeline Safety, Research and Special Programs Administration, Department of Transportation, October 1, 2003.
9. IGE/TD/1 Edition 4: 2000, Steel Pipelines for High Pressure Gas Transmission, Recommendations on Transmission and Distribution Practice, Institution of Gas Engineers, Communication 1670, 2001.
10. Fearnough, G. D., Hopkins, P., and Jones, D. G., 1991, "The Effect of the Hydrostatic Test Hold Period on Defect Behaviour and Surviving Defect Population," 8<sup>th</sup> EPRG/AGA Joint Technical Meeting on Line Pipe Research, Paris.
11. Kiefner, J. F., Maxey, W. A., and Eiber, R. J., 1980, "A Study of the Causes of Failure of Defects that have survived a Prior Hydrostatic Test, Final Report to Pipeline Research Committee of American Gas Association, Report NG-18, No. 111.
12. Fearnough, G. D., Jones, D. G., 1978, "An Approach to Defect Tolerance in Pipelines," IMechE Conference on Defect Tolerance of Pressure Vessels.
13. Fearnough, G. D., Lees, G. M., Lowes, J. M., and Weiner, R. T., 1971, "The Role of Stable Ductile Crack Growth in the Failure of Structures," IMechE Conference on Practical Applications of Fracture Mechanics to Pressure Vessel Technology, London.
14. Green, G., Knott, J. F., 1975, "On Effects of Thickness of Ductile Crack Growth in Mild Steel," Journal Mechs. Phys. Solids, **23**, pp. 167 to 183.
15. Schulze, H. D., Fuhlrott, H., 1980, "Stable Crack Growth and Variation of Crack Opening Displacement of Pre-Cracked Specimens under Sustained Load," International Journal of Pressure Vessels and Piping, **8**, pp. 131-142.
16. Tsuru, S., Garwood, S. J., 1979, "Some Aspects of the Time Dependent Ductile Fracture of Line Pipe Steels," Proceedings of Third Conference on Mechanical Behaviour of Materials, **3**, Cambridge, UK, pp. 519 to 528.
17. Ingham, T., Morland, E., 1983, "Influence of Time -Dependent Plasticity on Elastic -Plastic Fracture Toughness," Elastic -Plastic Fracture, Second Symposium, Volume I - Inelastic Crack Analysis, ASTM STP 803 (Eds. C.F. Shih and J.P.Gudas), pp. I-721-I-746.
18. Garwood, S. J., 1986, "Time Dependent Ductile Crack Extension in A533B Class 1 Steel," Nuclear Engineering and Design, **91**, pp. 179-206.
19. Krempl, E., Lu, H., 1984, "The Rate (Time) - Dependence of Ductile Fracture at Room Temperature," Engineering Fracture Mechanics, **20**, pp. 629 to 632.
20. Little, M. M., Krempl, E., and Shih, C. F., 1984, "Viscoplastic Analysis of a Compact Tension Specimen in Mode I Loading," Engineering Fracture Mechanics, **20**, pp. 633-653.
21. Duffy, A. R., McClure, G. M., Maxey, W. A., and Atterbury, T. J., 1968, "Study of the Feasibility of Basing Natural Gas Pipeline Operating Pressure on Hydrostatic Test Pressure," Final Report to the American Gas Association, AGA Catalogue No. L30050, Battelle Memorial Institute.
22. Duffy, A. R., 1969, "Hydrostatic Testing," 4<sup>th</sup> Symposium on Line Pipe Research, Dallas, Texas.
23. Eiber, R. J., 1974, "Hydrostatic Testing," 5<sup>th</sup> Symposium on Linepipe Research.
24. Maxey, W. A., 1986, "Outside Force Defect Behaviour," Report to Line Pipe Research Supervisory Committee of the PRC of the AGA, NG-18 Report No. 162.
25. Maxey, W. A., 1986, "Outside Force Defect Behaviour," 7<sup>th</sup> Symposium on Line Pipe Research, Houston, Texas.
26. Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., 1971, "Recent Research on Flaw Behaviour During Hydrostatic Testing," AGA Operating Section Transmission Conference, Texas.
27. Jones, D. G., 1982, "The Significance of Mechanical Damage in Pipelines," 3R International, 21, Jahrgang, Heft.
28. Hopkins, P., Jones, D. G., and Clyne, A. C., 1983, "Recent Studies of the Significance of Mechanical Damage in Pipelines," The American Gas Association and European Pipeline Research Group Research Seminar V, San Francisco, USA.
29. Jones, D. G., Hopkins, P., 1983, "The Influence of Mechanical Damage on Transmission Pipeline Integrity," IGU 1983 International Gas Research Conference, London.
30. Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., 1973, "The Failure Stress Levels of Flaws in Pressurized Cylinders," ASTM STP 536, American Society for Testing and Materials, Philadelphia, pp. 461-481.
31. Anon; "Guide on methods for assessing the acceptability of flaws in fusion welded structures," BS 7910 : 1999, Incorporating Amendment No. 1, British Standards Institution, London, UK, 1999.
32. Leis, B. N., Brust, F. W., and Scott, P. M., 1991, "Development and Validation of a Ductile Flaw Growth Analysis for Gas

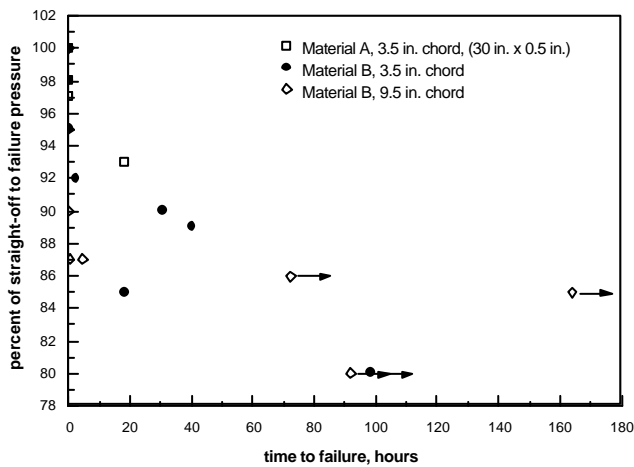
- Transmission Line Pipe,” Final Report to A.G.A. NG-18, Catalog No. L51543.
33. Ainsworth, B., 2003, “Recent Assessments of Defects in Nuclear Power Plant,” IMechE Seminar on Fitness -For-Service of Pressure Equipment and Pipelines, Institution of Mechanical Engineers, London.
  34. Maxey, W. A., Kiefner, J. F., Eiber, R. J., and Duffy, A. R., 1972, Ductile Fracture Initiation, Propagation and Arrest in Cylindrical Pressure Vessels, ASTM STP 514.
  35. Leis, B. N., Ghadiali, N. D., 1994, “Pipe Axial Flaw Failure Criteria - PAFFC,” Version 1.0 Users Manual and Software, Topical Report to A.G.A. NG-18, Catalog No. L51720.
  36. Anon., “NEB Report of the Public Inquiry Stress Corrosion Cracking on Canadian Oil and Gas Pipelines,” MH-2-95, National Energy Board, Canada, November 1996.
  37. Leis, B. N., 1993, “New Insights into Hydrostatic Testing and Retesting,” Proceedings of the 1993 American Gas Association Operating Section, AGA Catalogue No. X59707, pp. 532-543.
  38. Barkow, A. G., 1972, “Don’t Bet on a Pit,” Materials Protection and Performance, Vol. 11 (10), pp. 11-17.
  39. Hopkins, P., Jones, D. G., 1992, “A Study of the Behaviour of Long and Complex -Shaped Corrosion in Transmission Pipelines,” Proceedings of Eleventh International Conference on Offshore Mechanics and Arctic Engineering (OMAE 1992), American Society of Mechanical Engineers, Calgary, Canada.
  40. Roovers, P., Bood, R., Galli, M., Marewski, U., Steiner, M., and Zaréa, M., 2000, “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, R. Denys, Ed., Elsevier Science, pp. 405-425.
  41. Bood, R., Galli, M., Marewski, U., Roovers, P., Steiner, M., and Zaréa, M., 1999, “EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage (Part 1),” 3R International, pp. 739-744.
  42. Bood, R., Galli, M., Marewski, U., Roovers, P., Steiner, M., and Zaréa, M., 1999, “EPRG Methods for Assessing the Tolerance and Resistance of Pipelines to External Damage (Part 2),” 3R International, pp. 806-811.
  43. Kiefner, J. F., Bruce, W. A., and Stephens, D. R., 1994, “Pipeline Repair Manual,” Final Report to Line Pipe Research Supervisory Committee of the PRC of the AGA, Contract No. PR -218-9307, Catalogue No. L51716.
  44. Pallan, W., 1988, “Transmission Pipeline Repair,” The Pipeline Journal, **102**.
  45. Anon., Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids, ASME Code For Pressure Piping, B31, ASME B31.4 – 2002 Edition (Revision of ASME B31.4 – 1998), American Society of Mechanical Engineers, New York, NY, USA, 2002.
  46. Anon., Gas Transmission and Distribution Piping Systems, ASME Code For Pressure Piping, B31, ASME B31.8 – 1999 Edition (Revision of ASME B31.8 – 1995) incorporating ASME B31.8a-2000 addenda, American Society of Mechanical Engineers, New York, NY, USA, 2000.
  47. Private Communication with John F Kiefner, 2003.
  48. Fearnough, G. D., 1990, “Pipeline Safety,” Proceedings of the Pipeline Technology Conference, Oostende, Belgium.



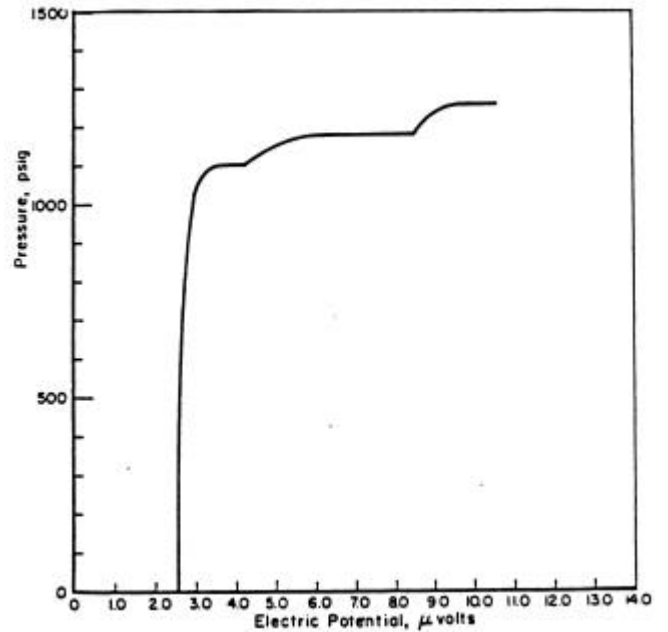
**Fig. 4 Battelle vessel tests on the long term stability of part-wall defects; based on uncorrected (as measured) failure pressures [11,21,22]**



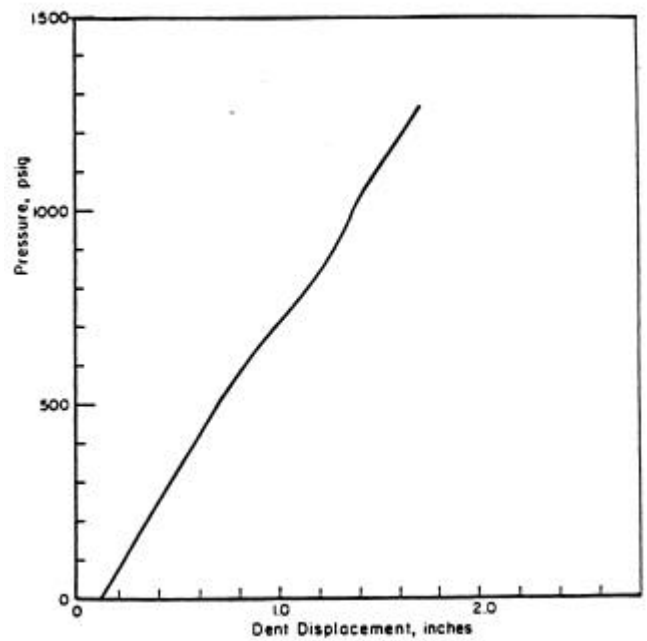
**Fig. 5 Battelle vessel tests on the long term stability of part-wall defects; based on corrected failure pressures [11,22]**



**Fig. 6 British Gas ring tests on long term stability of dented rings containing machined slots [27,28]**



**Fig. 7 Crack growth in a dent and gouge whilst held at during hold at constant pressure (Figure 10 from Maxey (1986) [24])**



**Fig. 8 Outward displacement of dent during pressurisation (Figure 11 from Maxey (1986) [24])**

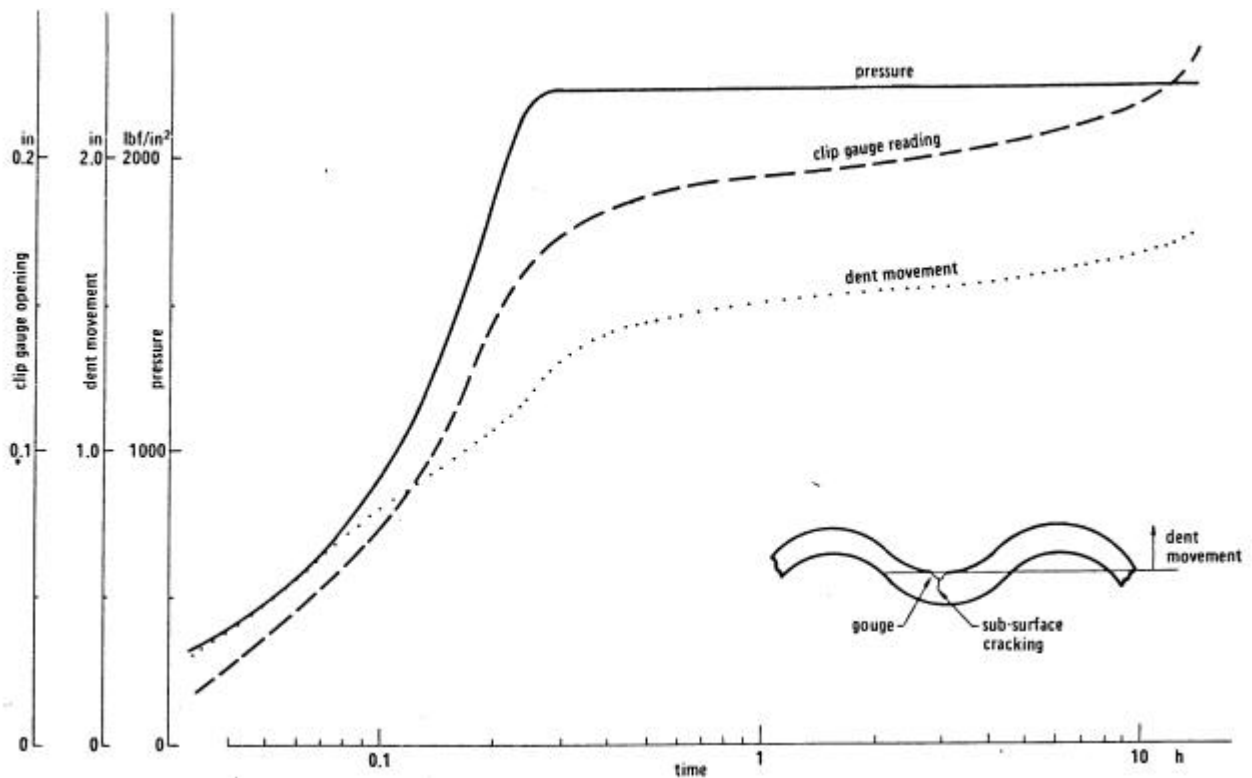


Fig. 9 Typical records from a stability test of a dented ring containing a gouge (Figure 6 from Jones (1982) [27])

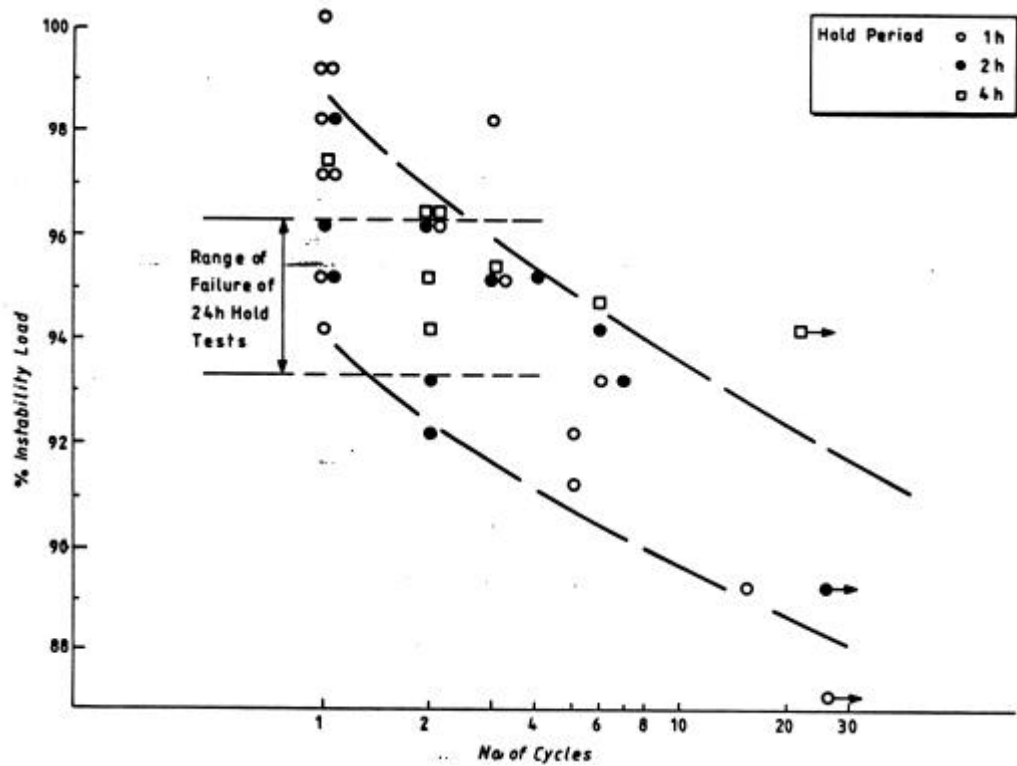


Fig. 10 Effect of hold time and cycling on failure below instability load (straight-off to failure load) (Fig. 1 from Fearnough et al. (1991) [10])