Appendix A

Guidance Document on Strain-Based Design

Guidance Document on Strain-Based Design

1.0 Introduction

1.1 Scope

Strain-based design is appropriate where the stresses and strains exceed the proportional limit, and where the peak design loads will be reduced when the material strains.

Note: This guidance has been developed before the implementation of standards or recommended practices covering many aspects of strain-based design. Designers are cautioned that the onus to insure integrity of designs beyond yield remains on them. The information here, while it can provide limited guidance, should be supplemented by a good fundamental understanding of the physical phenomena involved and the application to the particular pipeline situation.

Commentary: Design codes and specifications for pipelines either provide limited coverage of cases where strain in the pipe is the appropriate design parameter (for instance, in API 1104) or integrate the coverage of these cases into a larger framework document (as in DNV 2000 or CSA Z662). This document is designed to provide guidance specific to pipeline design where strain is the appropriate design parameter.

Commentary: For designs where some plastic yielding of the pipeline material is expected, a strain-based design method may have major advantages. When strain and stress are not proportional, stress-based methods become very sensitive to details of the material stress-strain behavior and to any safety factors. Strain-based design avoids these problems.

Commentary: Strain-based design has proven applicability to offshore pipe laying, pipelines operating at high temperatures, pipelines in areas of soil movement, and arctic pipelines.

Commentary: For cases where the loading mode is load controlled, where a change in pipe shape will not change the loading, strain-based design is not usually applicable. For cases where the loading mode is displacement controlled, where the pipe could change shape to cause the loading to go to zero, strain-based design is applicable. There are intermediate cases where part of the loading is load controlled and part is displacement controlled, so that a change in pipe shape can change the loading, but not take it to zero. A simple model of the latter case is a vertical hanging pipe that stretches due to a weight placed at the bottom end and then is stretched additionally when the weight is bolted to a floor.

1.2 Principles

This document has paragraphs of three types: basics, notes, and commentary.

Basics are designed to provide the framework for pipeline strain-based design and to apply to all cases. Basics describe the underpinnings of strain-based design that are not expected to change with time or additional engineering data.

Notes are designed to provide technical information based upon current knowledge. As additional information becomes available, the specifics given in notes may need to be updated.

Commentary is designed to provide additional information, such as descriptions of procedures, examples of cases, references to the literature, or options in design.

Where specific descriptions of actions are provided, the verb “should” is used in provisions, “should” is used in notes, and “may” is used in the commentary.

1.3 Exclusions

Design information for pipelines is not included in the guidance document if it is the same both for pipe sections where strain-based design is applied and where it is not applied.

2.0 Causes of Strain

2.1 Pressure

Pressure should be assessed based upon the difference between the external and internal pressure. The sign of this difference may be important, that is, whether external pressure is higher, the external overpressure case, or internal pressure is higher, the internal overpressure case. Pressure loadings should be assumed to be load controlled, rather than displacement controlled, in the hoop direction.

2.2 Soil Movement

Note: Soil movement should generally be considered displacement controlled. However, situations are known where soil-induced loadings are load controlled or intermediate between load and displacement controlled.

2.3 Restrained Thermal Expansion

Thermal expansion will induce longitudinal mechanical compression strain in the pipe wall when the pipe ends is restrained. The mechanical compression strain due to restrained thermal expansion should be assumed to be displacement controlled, rather than load controlled.

Commentary: The description of restrained thermal expansion covers the situations that arise because the stress-free length of a pipe changes with its temperature. A temperature-compensated strain gage will measure strain in a pipe when the ends are restrained and the pipe is heated.

2.4 Bending to Conform to a Curved Surface

Bending strains in pipe against a curved surface should be assumed to be displacement controlled. Strain in bending may be determined by the curvature of the surface against which the pipe rests.

Commentary: Strains may be higher at areas where the pipe does not rest completely against the surface and these strains may be intermediate between load and displacement controlled.

2.5 Spanning

Pipeline areas that are not supported by the soil or other surrounding solid material must carry their own weight and the weight of any additional material on the pipe to a supported area. Transverse loads such as from wind, waves, or currents must also be carried to the supported points. All of these are normally described as primary loadings and are thus load controlled. Transverse loads can also excite resonant behavior, (vortex induced vibration, etc.) which is controlled neither by load or displacement alone, but by the energy of vibration.

2.6 Primary Loadings

Note: Strain-based methods are not generally applicable to primary loading, that is, load-controlled situations. However, there are many individual instances where a limiting strain will be more appropriate. One example would be a pipeline spanning between two supports and deforming under its weight. This normally load-controlled situation may be more appropriate to assess based on strain, if at a given strain the pipe will be supported at an intermediate point. Another example is fatigue cycles that exceed the yield strength of the pipe material, for which strain range is a better measure of the damage incurred by a fatigue cycle than is stress range.

3.0 Design Limits

3.1 Maximum Strain

3.1.1 Tension

Commentary: Designs would not be expected to attempt to use strains in excess of half the tensile elongation from a tensile test on the base pipe material.

Commentary: The maximum strain limit may be set to a value near 10% (0.1) for many pipeline steels. Lower or higher values have been observed to be appropriate based upon the plastic properties of the material. Strain localization will usually increase the local maximum strain limit at the same time that it increases local strain.

3.1.2 Compression

Commentary: Compressive strains well in excess of the yield value would only be expected in combination with other deformation mechanisms such as plastic shear and buckling. Limits on maximum compressive strains may be most appropriately defined in relation to the deformation mechanism, although limits on maximum strain may be used to achieve this goal.

3.2 Global Compressive Strain

Pipe sections subject to dominant primary loads in global axial compression should be designed to prevent longitudinal collapse buckling.

Pipe sections subject to dominant secondary loads in global axial compression should be designed with account for global buckling in combination with other failure modes.

Note: Pipe sections subject to loading that is intermediate between load control and displacement control in global axial compression should be designed to limit global buckling strains and account for global buckling in combination with other failure modes.

Note: Other failure modes to be assessed should include local buckling, fracture, ductile failure, and cyclic failure modes such as fatigue and ratcheting.

Commentary: Global in this section describes a loading situation that relates to the entire pipe cross section and extends over several pipe diameters in length.

3.2.1 Lateral

The limits on the position of the pipeline after any lateral buckling that is allowed within the design should be determined and the position shown to be acceptable.

3.2.2 Upward

Where upward buckling will significantly reduce the resistance to additional loading modes, restrictions on global compressive strain should be defined.

3.3 Local Compressive Strain

Pipe sections subjected to axial compressive strain should be designed to avoid failure by local buckling of the pipe wall.

> **Note:** For situations where primary loads dominate behavior, but strain-based methods are appropriate, the allowable strain should be determined based upon the ultimate longitudinal compressive strain. The ultimate longitudinal compressive strain may be determined based on equations available in standards, such as DNV 2000.

Equations are also available in DNV 2000 for the case of longitudinal compressive strain combined with external overpressure.

Alternatively, the ultimate longitudinal compressive strain may be determined by analysis methods or physical tests that take into account internal and external pressure, welds and weld residual stresses, and the pipe stress-strain behavior.

Note: For situations where secondary loads dominate behavior, the allowable strain should be in excess of that for primary loads. The amount of this excess should be determined by analysis or physical testing techniques that can account for post-buckling behavior.

Note: For situations that are dominated by behavior intermediate between load and displacement controlled, the allowable strain may be determined based upon the ultimate longitudinal compressive strain. Alternatively, the allowable strain may be in excess of that for primary loads. The amount of this excess should be determined by analysis or physical testing techniques that can account for post-buckling behavior. The assessment must include the effect of the loss of stiffness in the buckled region on the loading system.

Note: Allowable strain should be determined from ultimate compressive longitudinal strain by multiplying by an appropriate resistance strain factor, such as those described in the factors of safety section.

Commentary: The equations for design compressive strain in DNV 2000 are limited to D/t of 45. Some comparisons have been made where the same equation forms are applied to higher D/t. The general forms appear to be appropriate up to D/t of above 90, but the effect of hoop stress from internal overpressure is significantly overestimated, as shown by test results collected by Dorey et al. 2000. Mohr has proposed that a better fit can be obtained by modifying the pressure term.

Commentary: The excess in allowable strain above that for primary loads would not be expected to be more than 0.015 (1.5%) for secondary loading based on tests and models of common pipeline steels. Values determined in tests can be used to shift this expectation, but should be based upon an appropriate ratio of primary to secondary loading for the service conditions of interest.

3.3.1 Elastic Local Buckling

Note: Elastic local buckling should be checked as a possible mode of failure when D/t >50.

3.3.2 Elastic-Plastic Local Buckling

Note: Methods for assessment of buckling should account for all buckling modes, as has been done by techniques in current standards, such as DNV 2000 and API 1111.

Commentary: Several modes of buckling have been observed in pipes under test conditions. Assessments for local wrinkle formation may need to check all applicable modes, such as outward, inward, and diamond. Where the capacity is determined by ovalization as at small D/t and the excess capacity for secondary loading is being assessed, buckling by additional modes may need be checked.

3.4 Plastic Ovalization

Ovalization of the pipe cross section should be limited in design to prevent section collapse and allow the unhindered passage of internal inspection devices.

Note: Ovalization deformation should be limited so that the minimum diameter does not shrink to the extent that the passage of internal inspection devices is hindered. A simple limit may be a minimum diameter with a reduction of 3% from the design inner diameter.

Commentary: Combinations of cyclic bending loading and internal pressure can result in ovalization deformation with an increase in average diameter. These conditions may allow greater ovalization deformation while still allowing passage of internal inspection devices.

Note: Ovalization deformation should be limited to prevent section collapse under external pressure.

Commentary: A simple limit on ovalization for external pressure may be set at ovalization deformation of 0.03 (3%) measured as the difference between the maximum and minimum diameters divided by the average of these diameters. Simple estimates can also be made comparing the diameter difference to the original diameter.

3.5 Global Tensile Strain

Pipe sections in global axial tension shall be designed to prevent ductile failure.

Note: Global axial tension strain should be limited to no more than half the material's uniaxial tensile elongation to failure in a tensile test.

Commentary: Global in the context of axial tension strain can describe cases where only part of the pipe cross section is in tension. It may be appropriate to average the tension strain over a length equivalent to two pipe diameters.

3.6 Local Tensile Strain

Pipe sections subject to local axial or hoop tensile strain shall be designed to prevent brittle fracture and ductile failure.

Note: Local tensile strain should be limited to no more than the material's uniaxial tensile elongation to failure in a tensile test.

Commentary: Under appropriate conditions of constraint, such as around crack tips, local tensile strains have been observed to considerably exceed the uniaxial tensile elongation to failure. Such areas can be considered in design using engineering critical assessment (ECA) methods.

Commentary: Local in the context of tension strain may normally be interpreted based on length dimensions from 0.5 to 5 mm. This size range is chosen to be smaller than individual weld passes, but significantly larger than the individual grains that make up the materials. High strains at sharp stress concentrations or cracks may be better interpreted within the context of an ECA.

Commentary: Brittle fracture is prevented by limiting the possible combinations of fracture toughness, applied tension stress, local geometry, and flaw size. Limiting the range of application to steel pipelines places implicit limits on each of these parameters. Thus, it is often sufficient to place additional requirements on only one or two of these parameters to limit the combinations to those that avoid brittle fracture. Alternatively, information correlated to these parameters may be required, such as Charpy V-notch test impact energy, which is correlated to fracture toughness.

Commentary: Ductile failure is prevented by limiting the possible combinations of fracture toughness, applied tension stress, applied tension strain, local material stress-strain behavior, local geometry, and flaw size.

Note: When strains in excess of the yield strain are included in design, an ECA should be completed.

3.7 Ratcheting

Note: Pipe sections subjected to multiple cycles of plastic deformation should be designed to avoid a ratcheting failure. The pipe section should meet limits on accumulated strain during the initial cycles and shall be elastic on further cycles of loading.

Commentary: Pipe sections with plastic strain histories including both tensile and compressive plastic strain, but in unequal amounts, may be susceptible to ratcheting failure when the strain difference accumulates. Pipe sections with plastic strain histories including both tensile and compressive plastic strain and hoop stress due to internal or external pressure may be susceptible to ratcheting failure when the strain accumulates in the hoop direction, causing ovalization deformation or diameter change.

Commentary: Resistance to ratcheting may be partly determined by changes to the material-stress-strain behavior during cyclic loading. Steels with a yield plateau tend to lose this plateau and have lower yield strength during cyclic loading, provided the cycles are applied rapidly enough. Stainless steels, including 13% Cr materials, tend to exhibit cyclic hardening.

Commentary: Ratcheting may also occur due to cyclic deformation of the pipe in combination with accumulating changes to the material supporting the pipe. Upheaval creep has been observed in North Sea buried pipelines where the soil supporting the pipe fills in underneath the pipe during periods when the pipe has an upward deflection cycle.

3.8 Fatigue under a Load Spectrum

Commentary: Fatigue loading spectra can include stress ranges where the maximum stress of the cycle exceeds the tensile yield strength of the material. Fatigue for these cycles may be assessed based upon the strain range rather than the stress range.

Commentary: The number of strain cycles to failure may be assessed according to a two-part curve from ABS 2001. These curves are derived from the original X curve from AWS D1.1:1972 as described by Marshall (1992) and written below with N as the number of strain cycles and $\Delta\varepsilon$ as the range of cyclic strains:

$$\begin{gathered} \Delta\varepsilon = 0.055N^{-0.4} \;\; for\ \Delta\varepsilon \geq 0.002 \\ \text{and} \\ \Delta\varepsilon = 0.016N^{-0.25} \;\; for\ \Delta\varepsilon < 0.002 \end{gathered} \tag{2}$$

Commentary: The above two-part curve is based on strain ranges adjacent to the weld that include geometrical concentrations of strain, but do not include concentrations of strain due to the weld cap or root profile or welding imperfections.

Commentary: Local strain concentrations due to buckling would need to be included in the $\Delta\varepsilon$ to account for cases where buckling occurs on the compression part of the cycle. Strain concentrations from buckling may be expected to be large enough to severely reduce the allowable number of fatigue cycles.

Commentary: Fatigue cycles may act in combination with other loads, such as pressure, to cause increasing ovalization.

3.9 Concentration of Strain

Note: Strain concentrations at changes of section thickness, changes of material grade, transitions to attachments, transitions in coating thickness, and localized areas of transverse loading should be accounted for in assessments of allowable strains, both in tension and compression.

Commentary: Plastic strain may also be concentrated by differences in strength between the base and weld metal.

Commentary: Strain may be locally concentrated by the shape of the weld itself, as at the edge of the cap or root surface. Such concentrations act over a small fraction of the pipe wall thickness and are not normally assessed using strain concentration factors across the full wall thickness. Instead, weld magnification factors are used to assess imperfections that are within the area of the stress concentration, such as weld toe surface flaws, during fracture assessment. Weld magnification factors may be found in BS 7910.

Commentary: Plastic strain may be further concentrated when loading is present in other directions. For instance, hoop stress from internal overpressure may allow further concentration of strains in low-strength girth welds or weld heat-affected zones (HAZs).

Commentary: Plastic strain may be concentrated in low-strength HAZs when these regions are positioned to allow shear bands to form during deformation. HAZs of lower strength than the base metal have been observed in X-80 and X-100 grades of pipeline steel. For common welding parameters, such as bevel angle of 30 degrees or below and heat input to limit the visible HAZ width to 3 mm, shear bands are only expected to be able to form within the HAZ for thicknesses of less than 12 mm.

Commentary: Internal pressure may increase the strain concentration due to other geometrical factors, such as misalignment across girth welds, above the product of the strain concentration effects for pressure and misalignment taken individually.

3.10 Accumulated Plastic Strain

Note: Accumulated plastic strain is the sum of the plastic strain increments in the strain history, irrespective of sign and direction. The plastic strain increment is the largest amount of plastic strain reached for each part of the history where plastic strain occurs. The accumulated plastic strain need not include strains induced during linepipe manufacture.

Commentary: Accumulated plastic strain sums the absolute value of both the positive (tensile) and the negative (compressive) plastic strains that may occur at successive parts of the strain history. Accumulated plastic strain is commonly used in the determination of the effect of reeling where cyclic bending plastic strain is counted for the multiple cycles within a reeling/unreeling cycle.

Commentary: Accumulated plastic strain is a relatively severe combination of strain that will not be appropriate to all types of cycles.

4.0 Factors of Safety

Commentary: Factors of safety may be chosen based upon the uncertainty of the design information, the likelihood of the strain event, and the consequences of failure by the mode contemplated. Strain events with annual probabilities below 1 in 10,000 over the pipeline service lifetime may appropriately be assessed with lower safety factors.

Commentary: Safety factors on strain for buckling failure modes may be applied based upon a table from DNV 2000 and provided in a simplified version below.

Resistance Strain Factor	**Safety Class**		
	Low	**Normal**	**High**
Supplementary requirement U	2.0	2.5	3.3
No supplementary requirement	2.1	2.6	3.5

This table uses safety classes as defined in the following sections. The reduction in safety factors for supplementary requirement U are based upon testing indicating that the pipes used exceed the standard minimum yield strength (SMYS) in the transverse direction by at least 3%.

Commentary: Safety factors on strain, parameters within the ECA, and flaw size for tension failure modes may be coordinated so that overall resistance to these modes is maintained. Where the safety factor is applied on strain alone, the value of this factor may be compared to those in the table below and the safety classes defined in the following sections.

Tension Strain Safety Factor	**Safety Class**		
	Low	**Normal**	**High**
Factor on strain	1.5	2	3

The safety factors are based on those used in engineering practice, for example the factor of 3 used on tensile strain for the Northstar pipeline, and the 1.5 factor used in a somewhat different context by the Appendix K of CSA Z662:1999.

Commentary: A safety factor on longitudinal strain related to pipe rotation, where this can be interpreted as a failure mode, may be applied. This may be appropriate during offshore S-lay of a pipeline with T-joints or other orientation-critical equipment. The safety factor on longitudinal strain may be chosen as 1.3.

Commentary: Safety factors on lifetime for fatigue assessment may be chosen based upon the table below and the safety classes defined in the following sections.

Fatigue Safety Factor	**Safety Class**		
	Low	**Normal**	**High**
Factor on lifetime	3	5	10

This safety factor accounts for the order in which cycles are applied and may be used in conjunction with other safety factors, such as those incorporated in the design S-N (stress range – cycles) or strain-range to cycles curves or in the crack growth rate. Crack growth rates may be assessed based on the mean plus two standard deviation growth rate for the material of interest or for a class of materials to which the material of interest belongs.

Commentary: Fatigue assessments may be preferred that use one fatigue safety factor for all of the cycles. That safety factor may be chosen based on the safety class applicable to the time the final stress range is applied.

4.1 Installation

Commentary: Installation may normally fall within safety class low. Exceptions may be needed to account for cases such as pressurized installation, installation within sensitive areas, or installation with high stored mechanical or potential energy.

Commentary: Designers may not normally wish to allow buckling strains in excess of the critical strain during the installation phase. Buckling and wrinkling during installation may reduce the margin of safety against several modes of failure during operation below levels expected in design.

4.2 Operation

Commentary: Operation conditions may fall into each of the safety classes depending upon the pipe contents. Pipes carrying water-based non-flammable fluids and non-toxic non-flammable gases in areas more than 500 m from offshore platforms and areas of frequent human activity may normally be placed in safety class low. Pipes carrying other materials may fall into safety class normal in these same regions. Adjacent to areas of frequent human activity or platforms, the pipes carrying water-based non-flammable fluids and non-toxic non-flammable gases may normally be placed in safety class normal. Pipes carrying other materials in these areas may normally be placed into safety class high.

5.0 Pipe Material Selection

5.1 Dimensions

Note: Pipe sections with accumulated plastic strain in excess of 2% in design should have dimensions of the pipe subjected to tighter tolerances and greater inspection. This should include testing every pipe for pipe end diameter and pipe end out of roundness. Pipe end matching should be practiced to limit wall misalignment across girth welds.

Commentary: Tight tolerances on pipe sections and measures to limit wall misalignment across girth welds may be applied to other conditions where limiting the stress concentration at girth welds is important, such as for risers under environmental fatigue loading.

5.2 Mechanical Properties

Note: Steel pipe sections with accumulated plastic strain in excess of 2% in design should have tensile properties of representative pipe material meet three criteria recommended by DNV 2000:

1. Measured yield strength minus SMYS of no more than 100 MPa
2. Measured yield strength to tensile strength ratio of no more than 0.85
3. Elongation equal to or exceeding 25%.

Commentary: All three of these recommendations may pose difficulties for pipe manufacturers, particularly for pipe grades above API 5L X65. It may be reasonable to choose values of these parameters appropriate to the steel grade being used. However, these values were chosen, within the small group of parameters commonly recorded, as ones appropriate to pipeline steels for which experience was available in reeled pipe, including API 5L X70.

Commentary: Strain-based design is able to use most effectively materials that have much plastic strain hardening as the strain increases past the yield strain. This stress-strain behavior is characteristic of the most common austenitic stainless steels. Carbon steels with lower yield strength, lower yield-tensile ratio, and higher elongation to failure are more likely to show this behavior. Alternatively, smoothly increasing stress-strain curves up to a given high strain level could be specified in agreement with the producer of the steel pipe.

5.3 Mechanical Properties after Strain-Aging Treatment

Note: Steel pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should have their mechanical properties tested after a strain-aging treatment, as required by DNV 2000. A strain-aging treatment should reach the design accumulated plastic strain through cycles of compressive and tensile strain and then follow with an artificial age at 250°C for 1 hr before additional mechanical testing. The mechanical test results should meet the requirements for the base pipe with the following exceptions:

1. Measured yield strength to tensile strength ratio of no more than 0.97
2. Elongation equal to or exceeding 15%.

Commentary: Requirements for strain-aging resistance tend to restrict the pipe material to pipe with improved local buckling resistance. Strain-age degradation is correlated to a sharp yield point and long yield plateau, while both of these are correlated with poor local buckling resistance.

5.4 Strength Variability

Note: Variability of pipe strength should be allowed for in design.

6.0 Girth Weld Material Selection

6.1 Mechanical Properties

Note: Weld metal should meet the minimum mechanical property requirements of the pipe base metal.

Commentary: There may be cases where weld metal that meets the base metal requirements cannot be used, such as when corrosion problems may occur at welds or when filler materials of that strength will give unacceptable risk of welding flaws. Under these conditions, strain concentrations at the weld area may cause locally large tensile plastic strains under the design conditions. Compensating increases in weld area toughness, decreases in allowable flaw size, or decreases in strain concentrations from other causes may be needed to reach the high strains without failure.

Note: The yield strength of the weld metal should be limited to no less than SMYS + 80 MPa and no more than SMYS + 250 MPa. The yield strength of the weld metal should be further limited for girth welds with accumulated plastic strain in excess of 2% in design to no more than SMYS + 200 MPa.

Commentary: Weld metal that has strength properties below the base metal requirements can accumulate local strain. Weld metal that greatly exceeds the base metal in strength may direct concentrated strain into the HAZ, most notably under conditions of local stress concentration in the weld area, such as by weld misalignment or local change in coating thickness. If local stress concentrations are minimized in design, girth welds of higher strength may be used. Weld metal that is higher than the base metal in strength can also increase allowable flaw sizes within the weld metal in an ECA.

6.2 Mechanical Properties after Strain-Aging Treatment

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 2% in design should have the weld mechanical properties tested after a strain-aging treatment.

6.3 Root Region Mechanical Properties

Commentary: Root regions may be welded with different filler metal from the majority of the weld to improve tie-in performance and resistance to cracking. This approach is common for manual procedures, but is not usually used for automatic welds.

6.4 Strength Variability

Note: Variability of strength of weld metal should be allowed for in design.

7.0 Fabrication and Installation

7.1 Matching of Diameter, Thickness, and Ovality Across Welds

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 2% in design should have the pipe ends matched across a girth weld so that “high-low” across the joint is limited to the lesser of 10% of wall thickness and 3 mm.

Commentary: Many applications may use tighter requirements on “high-low” to reduce the geometrical stress concentration around the girth weld area.

7.2 Matching of Mechanical Properties Across Welds

Note: Pipe sections including girth welds with accumulated plastic strain in excess of 0.02 (2%) in design should avoid larger differences in yield strength across the weld than necessary.

7.3 Pipeline External Coating

Note: Pipeline external coating should be designed to provide sufficient strain capacity so that the purposes of the applied coating are not compromised by the action of the design strains.

Commentary: Pipeline external coating systems may perform or combine functions of corrosion protection, thermal insulation, and mechanical protection. External coating systems may be designed to have linepipe coating and coating adjacent to pipe girth welds use different materials and layers. Consideration may be given to the strain capacity of the linepipe coating, the coating adjacent to girth welds, and the area where these two types of coating overlap. Coating applied for thermal insulation and the ends of such coating may be particular areas for examination.

Commentary: Tests of pipeline external coating for strain capacity may be completed on plate specimens.

7.4 Weight Coating

Note: Weight coating should be designed to provide sufficient strain capacity so that the purpose of the weight coat is not compromised by the action of the design strains.

Commentary: Weight coating, for instance with concrete, may be used to prevent buoyant rising of a pipe under external overpressure. Removal of long sections of weight coating may allow buoyancy forces to unacceptably change the configuration of the pipeline.

Commentary: Tests of weight coating strain capacity and the strain capacity of other types of coatings may be completed on plate specimens.

Commentary: Grooving of weight coating has been shown to be effective at increasing strain to failure.

7.5 Cathodic Protection Devices

Note: Cathodic protection devices should be designed so that connections to the pipeline provide sufficient strain capacity so that the cathodic protection system is not compromised by the action of the design strains.

Commentary: Cathodic protection devices need both the mechanical support of the pipeline and an electrical connection to the pipe steel.

Commentary: Cathodic protection potentials higher than normally used may charge hydrogen into the steel. This hydrogen may have the effect of embrittling the steel, particularly in regions that experience plastic strain.

7.6 Prevention of Pipe Rotation

Note: Pipe that has been bent with plastic deformation may have a tendency to rotate around its axis under subsequent bending loadings. Pipe configurations where such rotations would be detrimental should be assessed to demonstrate that any rotations are limited to an acceptable range.

Commentary: Pipe rotation has been recognized in offshore S-lay where plastic strain is induced in bending on the stinger. The suspended span between the stinger and seabed touchdown has low torsional resistance, so the pipe can rotate to place the compression side of the pipe from the stinger bend on the compression side of the bend near the sea floor.

Commentary: Rotations may be detrimental to fittings, such as T’s, Y’s, and elbows, to valves, and to connections to corrosion protection systems.

7.7 Dents and Gouges

Commentary: Dents and gouges should only be left in place under rare circumstances; doing so, in general, is associated with a risk of fatigue or other subsequent failures. Dents and gouges from installation or during operation may be assessed using strain concentration factors. Strain concentrations may be assessed both at the deepest point and at the edge of the dent or gouge. Reduction of dent depth due to internal pressure may be considered.

8.0 Inspection

8.1 Methods

Note: Girth welds in pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should be inspected with 100% automated ultrasonic testing. Exceptions may require materials and design with unusually high resistance to failure under plastic tension strain.

Commentary: Girth welds in pipe sections with plastic strain in excess of 0.005 (0.5%) may require replacement of the manual ultrasonic inspection with an automated ultrasonic inspection to achieve reliable detection capabilities for the smaller flaws that result from ECA determination of acceptance criteria.

Commentary: Radiographic inspection may supplement the information from other inspection techniques. However, since it has limited measurement capability in the pipe wall through-thickness direction, it is not usually directly connected to an ECA of girth-welded pipelines.

8.2 Acceptance Criteria

Note: Girth welds in pipe sections with accumulated plastic strain in excess of 0.02 (2%) in design should be rejected and repaired or replaced if a flaw or flaws exceeds the allowable flaw size determined in the ECA.

Commentary: Inspection acceptance criteria for strains below 0.005 (0.5%) may be obtained from the applicable sections of many standards, such as API 1104 Appendix A and CSA Z662:1999.

Commentary: Inspection acceptance criteria for use with strains intermediate between 0.005 and 0.02 (0.5 and 2%) may be determined based upon an ECA, or based upon a generic ECA of a more severe case.

Commentary: The acceptance criteria may need to be reduced from those determined by the ECA to account for the variability of sizing with the inspection technique and procedures.

Commentary: Inspection may not be effective when the allowable flaw size is below that where the inspection technique can detect flaws more than 95% of the time. Change of the inspection method or procedures may be needed to achieve the desired detection capability. Alternatively, inputs to the ECA may be changed so that the resulting allowable flaw size can be reliably detected by the inspection method.

9.0 ECA

9.1 Simple Methods Appropriate to Low Strains

Methods available in widely distributed codes and standards applicable to pipelines cover cases of tensile strain up to the yield strain of 0.005 (0.5%). These methods provide for determining acceptable combinations of fracture toughness, applied tension stress, local geometry, and flaw size.

Note: Methods described in API 1104 Appendix A, CSA Z662:1999, the EPRG Guidelines, and BS 7910 (all levels) are applicable.

9.2 Intermediate Strain Methods

ECA methods used when strains in design are in excess of the yield strain shall be appropriate to the level of strain.

Note: Methods described in BS 7910 are designed primarily for load-controlled situations. Options are described for use in displacement-controlled situations. These options should be used for conditions that are defined to be displacement controlled rather than load controlled or intermediate between the two.

Commentary: The methods in BS 7910 are modifications to methods that use stress as a primary variable. There are methods available that use crack-tip opening displacement (CTOD) and strain as primary parameters, as in Anderson (1985) and Fukijubo et al. (1991). The results from such methods may be compared with those from BS 7910.

9.3 Accumulated High Strain Methods

Commentary: ECA methods for accumulated plastic strain in excess of 0.02 (2%) have not been widely validated. An example reported by Hoo Fatt and Wang can be compared to testing reported by Pisarski et al. for a single cycle. It is reasonable to believe that these cases may be assessed conservatively by a displacement-controlled assessment using the tension part of the accumulated plastic strain as though it were the monotonic plastic strain of a single partial cycle, and similarly for the compression part.

9.4 Pressure Effects

Commentary: Internal pressure may reduce the allowable flaw size from an ECA of a girth weld even though the primary stresses from pressure are parallel to the weld and the planar imperfection. Pressure tends to localize strains in areas of low strength, around imperfections or around changes of section. The ECA should account for this effect of pressure.

Commentary: The internal pressure stresses also modify constraint around the girth weld imperfection. The need to account for pressure-induced constraint change may be avoided by testing for fracture toughness with a specimen that exceeds the maximum constraint to be observed in service. Single edge notch bending (SENB) specimens can be expected to provide sufficient constraint. Relatively lower constraint specimens such as single edge notch tension (SENT) specimens may be used, as they have been for qualification of un-pressurized girth welds for reeling, as described in DNV-RP-F108. It should be demonstrated that the constraint in the specimen exceeds the maximum constraint observed in service.

9.5 Temperature Effects

Commentary: ECA may be completed using the minimum design temperature and the maximum strain history. It may be more appropriate to partition the strains into different temperature groups and assess based on several minimum temperatures.

10.0 Full-Scale Testing

Note: Representative full-scale testing should be completed for cases with accumulated plastic strain in excess of 0.02 (2%). This testing should be designed to demonstrate sufficient resistance to unstable fracture under the design conditions.

Commentary: Full-scale tests may be performed to demonstrate pipe resistance to one or more of the failure modes described above, or to account for other possible pipe performance issues (coatings, etc.). The design of such tests should recognize that not all failure modes will be tested with the same safety factors during any individual test.

Commentary: Full-scale testing may need to include multiple modes of loading to provide a representative comparison of relative risks between different modes of failure. For instance, comparison of fracture risk from the tension side and buckling risk from the compression side would require a representative balance between the bending and axial strains on the overall pipe cross section.

Commentary: Testing specifically designed for checking unstable fracture resistance may need to be designed with additional efforts to avoid other failure modes while achieving the required strain at the defect being tested. An example of such testing can be found in Berge et al. (2001). This may involve adding additional axial loading, increasing internal pressure, or spreading the localized loading that occurs on the compression side.

Commentary: Modeling of full-scale tests may be appropriate to predict behavior when designing the test or to understand the behavior observed in the test.

11.0 References

1. API RP 1111 “Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design)”, American Petroleum Institute (1998).
2. DNV 2000, DNV-OS-F101 Submarine Pipeline Systems, det Norske Veritas (2000).
3. CSA Z662 Oil and Gas Pipeline Systems, Canadian Standards Association (1999).
4. Dorey, A. B., Murray, D. W., and Cheng, J.J.R., “An Experimental Evaluation of Critical Buckling Strain Criteria”, *2000 International Pipeline Conference*, Vol. 1, pp. 71-80 (2000).
5. API 1104, Welding of Pipelines and Related Facilities, Nineteenth Edition, American Petroleum Institute (1999).
6. BS 7910:2005, “Guide on Methods for Assessing the Acceptability of Flaws in Metallic Structures”, British Standards Institution (2005).
7. Anderson, T. L., “Elastic-Plastic Fracture Assessment Based on CTOD”, Report 276/1985, The Welding Institute, Cambridge, U.K. (1985).
8. Fukijubo, M., Berge, S., and Moan, T., “CTOD Estimates of Surface Cracked Wide Plates in Bending II, Level 3 CTOD method”, *Engineering Fracture Mechanics*, Vol. 40, pp. 641-651 (1991).
9. Berge, S., Igland, R., and Mainçon, P. “Full Scale Fracture Tests of Girth Welds in X65 Pipeline – Strain Based Fracture Assessment”, *2001 Offshore Mechanics and Arctic Engineering Conference*, Rio de Janeiro (2001).
10. Knauf, G. and 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.
11. Hoo Fatt, M. S. and Wang, Z. B., Fracture of Ductile Pipelines Subjected to Bending and Reverse Bending Loads, *ASME Journal of Offshore Mechanics and Arctic Engineering*, Vol. 120, pp. 184-190 (1998).

12. Pisarski, H. G., Phaal, R., Hadley, L. and Francis, R., Integrity of Steel Pipe during Reeling, *1994 Offshore Mechanics and Arctic Engineering Conference*, Houston, TX (1994).

13. Marshall, P. W., *Design of Welded Tubular Connections: Basis and Use of AWS Code Provisions*, Developments in Civil Engineering, Elsevier (1992).

14. DNV-RP-F108, Fracture Control for Pipeline Installation Methods Introducing Cyclic Plastic Strain, det Norske Veritas, (2006).