Date of Issue: July 2007
Affected Publication: API Standard 1104, *Welding of Pipelines and Related Facilities*, October 2005.

ERRATA/ADDENDUM

Please insert the following changes to Std 1104:

Section 3.2.2, *Change:*

"**branch weld:** The completed weld joining a branch pipe or branch fitting to a run pipe."

to

"**branch weld:** The completed groove and/or fillet weld joining a set on or set in branch pipe or a set on or set in branch fitting to a run pipe."

Please replace Appendix A with the following attachment:

APPENDIX A—ALTERNATIVE ACCEPTANCE STANDARDS FOR GIRTH WELDS

A.1 General

The acceptance standards given in Section 9 are based on empirical criteria for workmanship and place primary importance on imperfection length. Such criteria have provided an excellent record of reliability in pipeline service for many years. The use of fracture mechanics analysis and fitness-for-purpose criteria for determining acceptance criteria is an alternative method and incorporates the evaluation of both imperfection height and imperfection length. Typically, but not always, the fitness-for-purpose criteria provide more generous allowable imperfection length. Additional qualification tests, stress analysis, and inspection are required to use the fitness-for-purpose criteria. Performing analysis based on the principles of fitness-for-purpose is alternatively termed engineering critical assessment, or ECA.

The fitness-for-purpose criteria in the prior versions of this appendix required a minimum CTOD toughness of either 0.005 or 0.010 in. and were independent of any higher values of fracture toughness. Improvements in welding consumables and with more precise welding procedures, especially, with the increased use of mechanized welding devices have resulted in higher and more uniform toughness and ductility in most welds. At the same time, toughness values below 0.005 in. have been observed, particularly with more stringent notching procedures of CTOD specimens than those in the prior versions of this appendix. Welds with toughness below 0.005 in. have shown to perform adequately when the acceptance criteria are properly adjusted to account for the lower toughness. The acceptance criteria are revised so that they are commensurate with the measured toughness and applied load levels.

This appendix includes three options for the determination of acceptance limits of planar imperfections. In numerical order, the options are increasingly complex in application but offer wider range of applicability. Option 1 provides the simplest methodology. Option 2 allows for the full utilization of the toughness of the materials thus providing a more accurate criterion but requires more calculation. The first two options were developed with a single set of underlying procedures but are limited to applications with a low to moderate fatigue loading as described in A.2.2.1[7]. Option 3 is provided primarily for those cases where fatigue loading exceeds the limit established for the first two options. Option 3 is not prescriptive and its consistency could be significantly less than Options 1 and 2. Option 3 should only be exercised, when necessary, by skilled practitioners with demonstrated knowledge of fracture mechanics and pipeline load analysis. With these three options this current revision of the appendix should provide a more complete approach to determine inspection and acceptance limits for imperfections.

It is usually impractical to qualify individual pipeline welds for the alternative acceptance limits after a defect under Section 9 is detected, because destructive testing is required to establish the required mechanical properties for the welding procedure under consideration.

This appendix provides procedures to determine the maximum allowable imperfection sizes. It does not prevent the use of Section 9 for determining imperfection acceptance limits for any weld. Use of this appendix is completely at the company's option.

In this appendix, the use of the phrase imperfection acceptance limits and other phrases containing the word imperfection is not intended to imply a defective condition or any lack of weld integrity. All welds contain certain features variously described as artifacts, imperfections, discontinuities, or flaws. These terms are widely accepted and used interchangeably. The primary purpose of this appendix is to define, on the basis of a technical analysis, the effect of various types, sizes, and shapes of such anomalies on the suitability of the whole weld for a specific service.

This use of this appendix is restricted to the following conditions:

- Circumferential welds between pipes of equal nominal wall thickness.
- Nondestructive inspection performed for essentially all welds.
- No gross weld strength undermatching, see A.3.2.1.
- Maximum axial design stress no greater than the specified minimum yield strength (SMYS).
- Maximum axial design strain no greater than 0.5%.
- Welds in pump and compressor stations, repair welds, fittings and valves in the main line are excluded.

A.2 Stress Analysis

A.2.1 AXIAL DESIGN STRESS

To use this appendix, a stress analysis shall be performed to determine the maximum axial design stresses to which the girth welds may be subjected to during construction and operation. The stress analysis shall include stresses during pipeline installation and stresses induced by operational and environmental conditions. These stresses may reach their peak values at different times. The maximum axial design stress is the max-

[7]Wang, Y.-Y. and Liu, M., "A Comprehensive Update in the Evaluation of Pipeline Weld Defects," U.S. DOT Agreement No. DTRS56-03-T-0008, PRCI Contract No. PR-276-04503, Draft report to DOT and PRCI, November 2004.

imum total axial stress at any given time during the design life of the pipeline[8].

A.2.2 CYCLIC STRESS

A.2.2.1 Analysis

The cyclic stress analysis shall include the determination of the predicted fatigue spectrum to which the pipeline will be exposed over its design life. This spectrum shall include but is not limited to stresses imposed by hydrostatic testing, operation pressure, installation stresses, and where applicable, thermal, seismic, and subsidence stresses. The spectrum should consist of several cyclic axial stress levels and the number of cycles applicable to each. If the stress levels vary from cycle to cycle, a suitable counting method, such as the rainflow method, should be used to determine cyclic stress levels and cycle count[9].

The fatigue spectrum severity, S^*, is computed from the following equation:

$$S^* = N_1(\Delta\sigma_1)^3 + N_2(\Delta\sigma_2)^3 + \ldots$$
$$N_i(\Delta\sigma i)^3 + \ldots + N_k(\Delta\sigma_k)^3 \quad \text{(A–1)}$$

where

S^* = spectrum severity,
N_i = number of cycles at the ith cyclic stress level,
$\Delta\sigma_i$ = ith cyclic stress range, in kips per square in.,
k = total number of cyclic stress levels,
i = number ith cyclic stress, from 1 to k.

If the spectrum severity is less than 5×10^6, and if the use of "steel in-air" crack growth curves, such as those defined in Table 4, BS 7910:1999, is appropriate, Options 1 and 2 acceptance criteria (A.5.1.2 and A.5.1.3) may be applied without any further fatigue analysis[10]. If the spectrum severity exceeds 5×10^6, and/ or in-air crack growth curves are not applicable, Options 1 and 2 may be used with further analysis, or Option 3 procedures may be applied.

[8]For consistency with the computation of material's flow stress in this appendix, stress-strain relations based on minimum specified values are recommended when converting axial strains to axial stresses. Using actual stress-strain relations may result in the overestimation of the applied load level, as the flow stress is computed from the minimum specified values, e.g., see A.5.1.2.

[9]For an example of the use of the rainflow method, see N.E. Dowling, "Fatigue Failure Predictions for Complicated Stress-Strain Histories," *Journal of Materials*, March 1972, Volume 7, Number 1, pp. 71 – 87.

[10]The implied safety factor in the fatigue spectrum severity limit for Options 1 and 2 varies, depending on, e.g., the pipe wall thickness and distribution of fatigue spectrum. For a wide range of onshore and offshore pipeline scenarios, the spectrum severity limit is estimated to provide a safety factor of more than 2 or 5 on cycles when the fatigue growth rates are based on mean +2 standard deviation or mean values of BS 7910:1999 (Table 4, $R > 0.5$), respectively.

A.2.2.2 Environmental Effects on Fatigue

The enlargement of weld imperfections due to fatigue is a function of stress intensity, cycles of loading, imperfection size, and the environment at the crack tip. In the absence of contaminating elements, oil and hydrocarbons are considered no worse than air. Water, brine, and aqueous solutions that contain CO_2 or H_2S may, however, increase the growth rate. It is normal for minor amounts of these components to be present in nominally noncorrosive pipelines. When the concentration of either CO_2 or H_2S exceeds typical historical levels experienced in noncorrosive pipelines, this appendix shall not be used, unless evidence exists that the proposed levels do not result in acceleration of fatigue crack growth or adequate corrosion inhibition is applied. The effects of environment on fatigue crack growth external to the pipe at girth welds are normally mitigated by external coating and cathodic protection and do not limit the use of this appendix.

A.2.3 SUSTAINED-LOAD CRACKING

Certain environments may enhance imperfection growth in service at sustained load or induce brittleness in the material surrounding the imperfection to the point that an otherwise dormant imperfection becomes critical. These environments typically contain H_2S but may contain strong hydroxides, nitrates, or carbonates. When these materials are present inside the pipe, a minimum threshold stress shall be established, and this appendix shall not be used if the calculated stress exceeds the threshold value. With respect to H_2S service, the definition of such service shall be that given in NACE MR0175. Although external exposure to carbonates and nitrates in the soil has been shown to produce stress corrosion cracking (SCC) in a small number of cases, the cracking is normally axial and is associated with circumferential stress rather than axial stress. However, circumferential SCC failures may occur at locations where longitudinal stresses have increased over the life of the pipeline, e.g., at overbends above unstable slopes.

The frequency and severity of SCC can be mitigated by the use of proper coating and proper cathodic protection. The use of this appendix is not precluded when direct exposure to the aggressive environment is prevented by a coating designed to resist the environment.

A.2.4 DYNAMIC LOADING

The stress analysis shall include consideration of potential dynamic loading on girth welds, such as loads from closure of check valves. This appendix does not apply to welds strained at a strain rate greater than 10^{-3} second (a stress rate of 30 kips per sq. in. per second for steel).

A.2.5 RESIDUAL STRESS

The effects of welding residual stress are accounted for by specifying minimum CTOD toughness and Charpy energy and by incorporating appropriate safety factor in Options 1 and 2 procedures (A.5.1.2 and A.5.1.3). The determination of residual stress is not required under these conditions. The effects of residual stress shall be evaluated for all time-dependent failure mechanisms, such as fatigue.

A.3 Welding Procedure

A.3.1 GENERAL

The controls of the variables necessary to ensure an acceptable level of fracture toughness in a welding procedure are more stringent than those controlling welding procedures without minimum toughness requirements. An appropriate quality control program shall be established to ensure welding is performed within the parameters of the qualified welding procedure. Qualification of welding procedures to be used with this appendix shall be in accordance with Section 5 or 12 of this standard, with the additional mechanical property testing in accordance with A.3.2.

Any change in the essential variables specified below shall require re-qualification of the welding procedure:

a. A change in the welding process, mode of arc transfer, or method of application.
b. A change in the grade or manufacturing process of the pipe material or a basic change in the chemical composition or processing.
c. A major change in joint design (e.g., from U groove to V groove). Minor changes in the angle of bevel or the land of the welding groove that do not yield a change in the range of qualified heat input are not essential variables.
d. A change in position from roll to fixed, or vice versa.
e. A change in the nominal qualified wall thickness of more than ± 0.125 in.
f. A change in the size, type, or heat number of filler metal, including a change of manufacturer, even within an AWS classification. A change of heat number of the same consumable can be qualified by a single nominal weld that is tested for weld tensile (A.3.2.1), weld Charpy (A.3.2.2) and weld CTOD (A.3.2.3).
g. An increase in the time between the completion of the root bead and the start of the second bead.
h. A change in direction (e.g., from vertical downhill to vertical uphill, or vice versa).
i. A change from one shielding gas to another or from one mixture of gases to a different mixture.
j. A change in the nominal qualified flow rate of shielding gas of more than ±10%.
k. A change in the shielding flux, including a change in manufacturer within an AWS classification.
l. A change in the type of current (AC or DC), or polarity.
m. A change in the requirements for pre-heat temperature.
n. A change in the interpass temperature[11], if the interpass temperature is lower than the minimum interpass temperature recorded during the procedure qualification test, or if the interpass temperature is 45°F (25°C) higher than the maximum interpass temperature recorded during the procedure qualification test.
o. A change in the requirements for post-weld heat treatment or addition or deletion of a requirement for post-weld heat treatment.
p. A change in the nominal pipe outside diameter more than –0.25D or +0.5D, where D is the pipe outside diameter of procedure qualification welds.
q. A change of more than ±10% from the nominal heat input range recorded for each weld pass during the procedure qualification.

Note: The heat input may be calculated from the following equation:

$$J = 60VA/S \tag{A–2}$$

where

J = heat input (in joules per in.),
V = welding arc voltage (volt),
A = welding current (amp),
S = welding arc speed (in. per minute).

A.3.2 MECHANICAL PROPERTY TESTING

A.3.2.1 Weld Tensile Properties

A.3.2.1.1 Specimen Preparation and Testing

The test specimens are of rectangular cross-section with reduced width at the mid-length. The specimens shall be prepared in accordance with the requirements of Figure A-1. The weld reinforcement does not need to be removed. The ends of the specimens shall be sufficient for the grips.

A.3.2.1.2 Requirements

a. The tensile strength shall be equal or greater than the specified minimum tensile strength of the pipe, and
b. The specimen should not fail in the weld. Gross weld strength under matching that may result in preferential straining of the weld shall be avoided[12].

A.3.2.2 Charpy Impact Energy

A.3.2.2.1 Specimen Preparation

Charpy V-notch impact test specimens shall be prepared with their lengths parallel to the pipe axis. The largest size specimens permitted by the pipe wall thickness should be used. The thickness of subsized specimens should have at least 80% of the wall thickness. Six specimens shall be removed from each of the following positions: 12, 6, and 3 or 9 o'clock.

[11]The temperature at a location near the start position of the welding arc(s) recorded immediately before initiating consecutive pass or passes (multi-arc processes).

[12]An example of assessing weld strength undermatching is given in Wang, Y.-Y., Liu, M., Horsley, D., and Bauman G., "A Tiered Approach to Girth Weld Defect Acceptance Criteria for Stress-Based Design of Pipelines," 6th International Pipeline Conference, Paper No. IPC2006-10491, September 25-29, 2006, Calgary, Alberta, Canada.

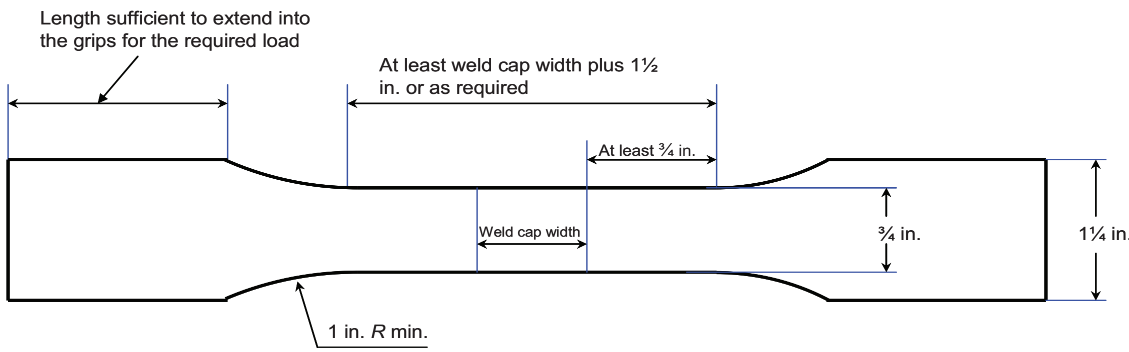


Figure A-1—Top View (Width in Circumferential Direction) of the Tensile Test Specimen

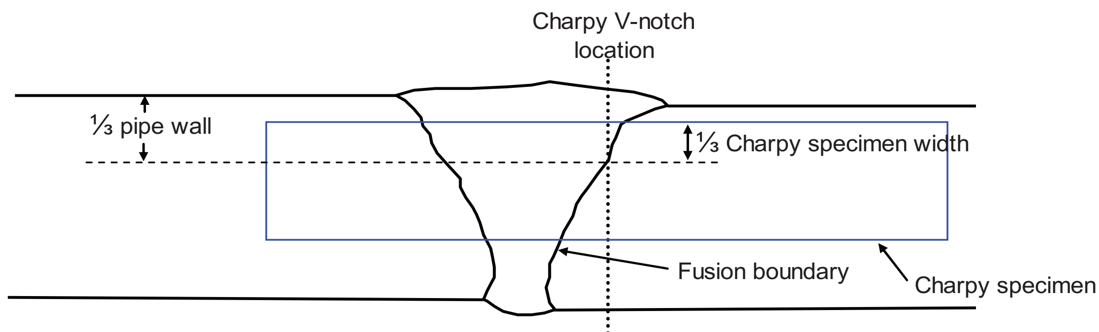


Figure A-2—Charpy Specimen and V-Notch Location for the HAZ Impact Testing

For each of these positions, three specimens shall have the V-notch placed in the weld centerline; and the other three shall have the V-notch placed in the HAZ such that the V-notch intersects the fusion boundary at the $^1/_3$ pipe wall location from the pipe OD. The location of the Charpy specimen relative to the pipe wall is shown in Figure A-2.

A.3.2.2.2 Testing

The test shall be performed at the minimum design temperature in accordance with the requirements of ASTM E 23.

A.3.2.2.3 Requirements

The minimum and averaged Charpy impact energy shall be greater than 22 ft-lbs (30 J) and 30 ft-lbs (40 J) for each notch location, respectively. The shear area should be 50% or greater.

A.3.2.3 Fracture Toughness Testing

A.3.2.3.1 General

To use the alternative acceptance criteria, the fracture toughness of the weld shall be determined by testing in accordance with BS 7448: Part 2, as supplemented by this appendix.

A.3.2.3.2 Specimen Preparation

The preferred test piece (B × 2B) shall be used. As shown in Figure A-3, the specimen should be oriented so that its length is parallel to the pipe axis and its width is in the circumferential direction; thus, the crack-tip line is oriented in the through-thickness direction. The specimen thickness (see Figure A-4) should be equal to the pipe thickness less the minimum amount of milling and grinding necessary to produce a specimen with the prescribed rectangular cross section and surface finish from a curved pipe segment. The weld reinforcement shall be removed. The specimen should be etched after initial preparation to reveal the weld deposit and the geometry of the heat-affected zone. For weld-metal tests, the notch and fatigue crack tip should be located at the center of the weld and completely in weld metal (see Figure A-5).

For the HAZ tests, the fatigue precracks shall be aimed to intersect the largest unrefined coarse grain HAZ regions within the central 70% of the specimen thickness (see Figure A-6). Each of the three HAZ specimens should be aimed at different coarse grained regions within the central 70%. If there are fewer than three such regions in the central 70%, then multiple specimens may be aimed at the same region. Multiple specimen sampling of the cap pass coarse grain HAZ should be avoided. No more than one specimen should be devoted to the cap pass HAZ. To identify coarse grain HAZ regions, it may be useful to conduct a microhardness survey to locate the coarsest HAZ regions that have undergone the least amount of tempering by subsequent weld passes.

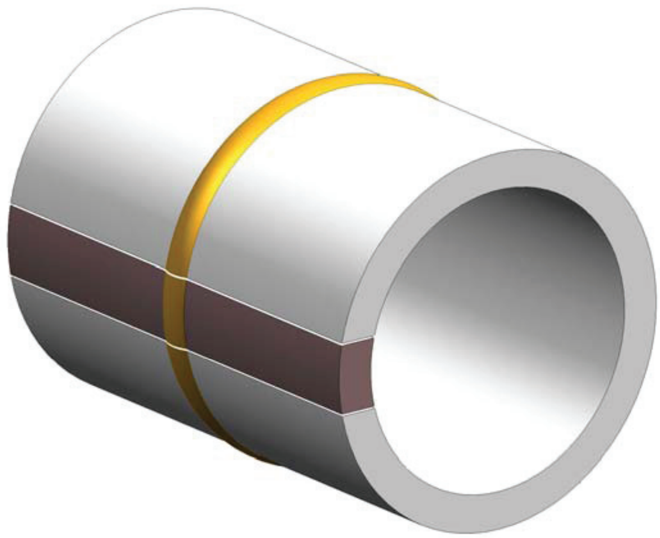


Figure A-3—Location of CTOD Test Specimens

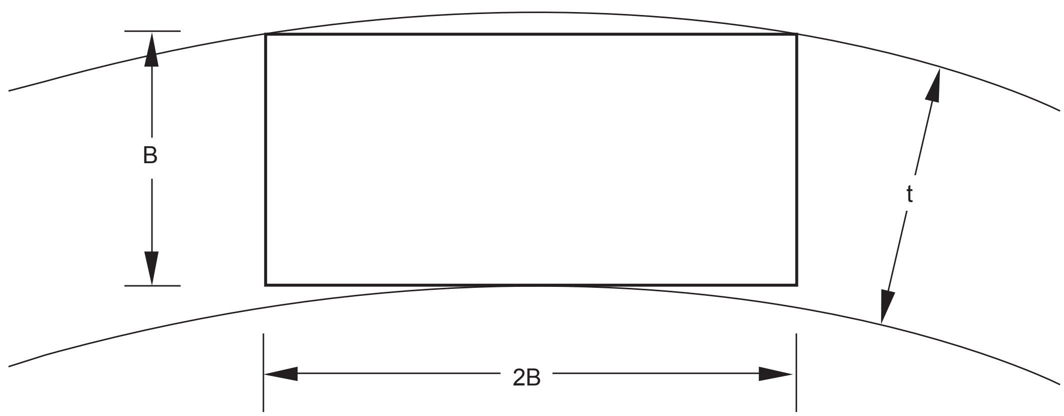


Figure A-4—Machining Objective for CTOD Test Specimen with Respect to Pipe Wall

A.3.2.3.3 CTOD Toughness Testing

For each welding procedure, both the weld metal and the heat-affected zone shall be tested. Each test (of weld metal or heat-affected zone) shall consist of at least three valid specimen tests performed at or below the minimum design temperature. The three specimens shall consist of one each from the nominal 12, 3 or 9, and 6 o'clock positions on the test weld and should be permanently marked to identify the original position.

After testing, particular attention should be given to the validity criteria of 12.4.1 of BS 7448: Part 2; these criteria deal with the geometry of the fatigue crack front. For this appendix, the appropriate value of CTOD shall be δ_c, δ_u, or δ_m. (These are mutually-exclusive terms defined in BS 7448: Part 2 that describe the three possible and mutually-exclusive outcomes of the test. The value of δ_i [CTOD at initiation of stable crack growth] has no significance with regard to this appendix and need not be measured.) When δ_m applies, care should be taken to measure from the point of first attainment of maximum load. "Pop in cracking" must be considered the controlling event if any load drop occurs. The test report shall include all items specified in Section 13 of BS 7448: Part 2. Particular attention should be given to reporting the position of the test specimen in the qualification weld and to distinguishing whether the reported CTOD value represents δ_c, δ_u, or δ_m. The test report shall also include a legible copy of the load-displacement record and a record of the appearance of the fracture surfaces; the latter requirement can be satisfied

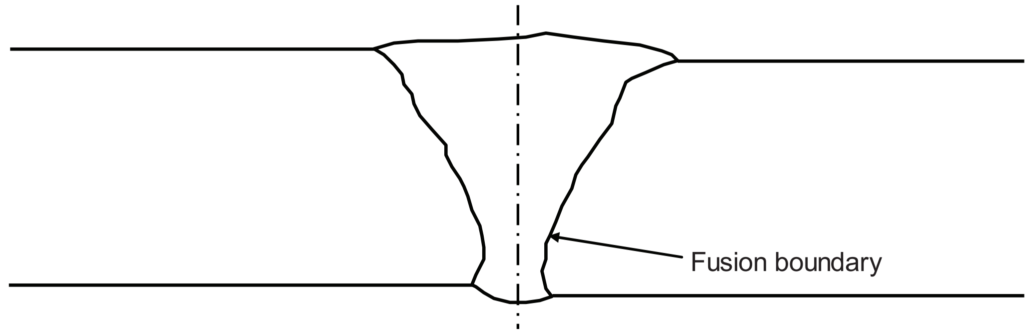


Figure A-5—Location of Notch for Weld-Metal Specimen

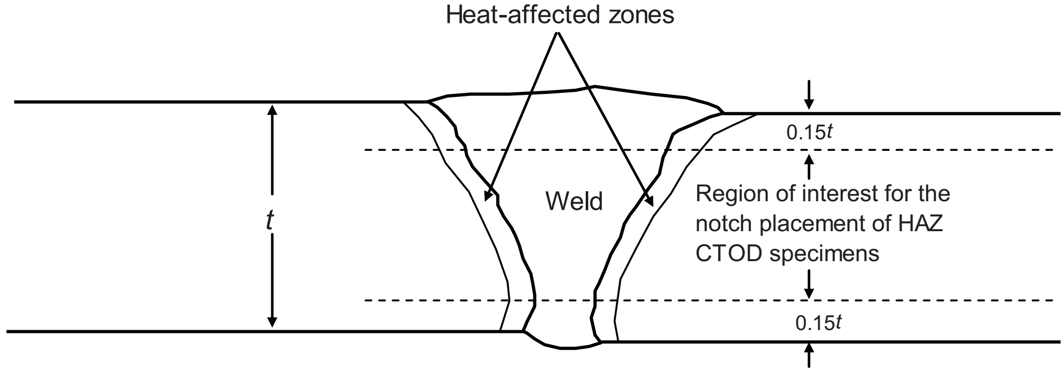


Figure A-6—Location of Notch for Heat-Affected Zone Specimen

by a clear photograph of one or both fracture surfaces or by retaining one or both fracture surfaces (properly preserved and identified) for direct observation.

A.3.2.3.4 Re-Testing

Re-testing is permitted on a one-to-one basis only when any of the following conditions exist:

a. Specimens are incorrectly machined.
b. The fatigue crack front fails to meet the straightness requirements.
c. Substantial weld imperfections adjacent to the crack front are observed upon the fracture of the specimen.

A.3.2.3.5 Requirements

The minimum CTOD value of all six specimens shall be greater than 0.002 in. (0.05 mm) to use this appendix.

A.4 Qualification of Welders

Welders shall be qualified in accordance with Section 6. For mechanized welding, each operator shall be qualified in accordance with 12.6.

A.5 Inspection and Acceptable Limits

A.5.1 PLANAR IMPERFECTIONS

The length and height of an imperfection, and its depth below the surface, must be established by appropriate nondestructive inspection techniques or otherwise justified before a decision to accept or reject can be made. Conventional radiography, as described in 11.1, is adequate for measuring imperfection length but is insufficient for determining height, particularly for planar imperfections such as cracks, lack of fusion, undercutting, and some types of lack of penetration. The use of ultrasonic techniques, radiographic techniques that employ densitometers or comparative visual reference standards, acoustic imaging, inherent imperfection-size limitations due to weld-pass geometry, or any other technique for determining imperfection height is acceptable, provided the technique's accuracy has been established (e.g., see 11.4.4 for AUT) and any potential inaccuracy is included in the measurement; i.e., the determination of imperfection height shall be conservative. The use of conventional radiography (see 11.1) to identify imperfections that require height measurement by other means is acceptable.

A.5.1.1 Structure of the Procedures to Determine the Maximum Acceptable Imperfection Size

The procedures to determine the maximum acceptable planar imperfection size are given in three options. Option 1 is a simplified approach in graphical format. It relies on theoretically sound and experimentally validated plastic collapse criteria, and has been modified by the Option 2 approach when appropriate. Option 2 is in the form of a failure assessment diagram, or FAD. The FAD format allows the simultaneous consideration of brittle fracture, plastic collapse, and the interaction between those two failure modes (elastic-plastic fracture). Options 1 and 2 are limited to pipelines with limited fatigue loads as specified in A.2.2. Option 3 permits the use of validated fitness-for-purpose procedures when the cyclic loading exceeds the spectrum requirements of Options 1 and 2.

The Option 1 procedures are limited to CTOD toughness equal or greater than 0.004 in. (0.10 mm). The Options 2 and 3 procedures may be applied at any CTOD toughness level greater than the minimum required value of 0.002 in. (0.05 mm).

The basis of the Options 1 and 2 procedures places no limit on pipe diameter or diameter to wall thickness ratio (D/t ratio). Theoretical validation has shown that the procedures are valid for $D/t \geq 10$.

Line pipes with ultra-high Y/T ratio ($Y/T > 0.95$) are often associated with low uniform strain (engineering strain at ultimate tensile stress) and low ductility. Additional testing and validation may be necessary to use the alternative acceptance criteria in this appendix.

A.5.1.2 Determination of Acceptable Imperfection Size by Option 1

Two sets of acceptance criteria are given, depending on the CTOD toughness value.

When the CTOD toughness is equal to or greater than 0.010 in. (0.25 mm), the maximum acceptable imperfection size is given in Figure A-7 at various load levels (P_r). If the load level is not given in Figure A-7, the maximum acceptable imperfection size can be obtained by interpolating the adjacent curves or by taking the value of the next higher load level.

When the CTOD toughness is equal to or greater than 0.004 in. (0.10 mm) and less than 0.010 in. (0.25 mm), the maximum acceptable imperfection size is given in Figure A-8.

The acceptable imperfection size may be more limiting than that from the Option 2 procedure as the limits in Figure A-7 and Figure A-8 were calibrated to a CTOD toughness of 0.010 in. (0.25 mm) and 0.004 in. (0.10 mm), respectively.

The total imperfection length shall be no greater than 12.5% of the pipe circumference. The maximum imperfection height shall be no greater than 50% of the pipe wall thickness.

The allowable height of the buried imperfections is treated the same as the allowable height of the surface-breaking imperfections.

The built-in safety factor in the acceptable imperfection size can accommodate certain amount of undersizing of imperfection height without negatively impacting weld integrity. The assumed height uncertainty is the lesser of 0.060 in. (1.5 mm) and 8% of pipe wall thickness. No reduction in allowable imperfection size is necessary if the allowance for inspection (alternatively termed inspection error) is better than the assumed height uncertainty.

The allowable imperfection height shall be reduced by the difference between the allowance for inspection and the assumed height uncertainty if the above condition cannot be met[13].

A.5.1.2.1 Computation of the Load Level P_r

It is necessary to determine material's flow stress in order to obtain the load level P_r. The flow stress is the averaged value of the specified minimum yield strength (SMYS) and specified minimum tensile strength (SMTS). Alternatively the flow stress of API 5L Grade X52 to X80 may be conservatively estimated as,

$$\sigma_f = \sigma_y\left[1 + \left(\frac{21.75}{\sigma_y}\right)^{2.30}\right] \qquad \text{(A–3)}$$

where the pipe grade, σ_y, is in the unit of ksi. The load level, P_r, is given as,

$$P_r = \frac{\sigma_a}{\sigma_f} \qquad \text{(A–4)}$$

A.5.1.2.2 Example of Option 1 Application

The following is an example for performing an ECA with the Option 1 methodology. A 24 in. outside diameter (OD) pipeline with a nominal wall thickness (WT) of 0.50 in. with the grade of API 5L X70 is considered. After reviewing sections A.1 and A.2 of this appendix and consulting with the project's engineer (as required) it is understood that the maximum axial design stress is 61.5 ksi. Weld test data conducted per the requirements of the appendix indicate that the minimum CTOD value is 0.011 in. These parameters are summarized as follows:

Pipe OD:	24 in.
Pipe WT:	0.500 in.
SMYS:	70 ksi
SMTS:	82 ksi
CTOD:	0.011 in.
σ_a:	61.5 ksi
Allowance for inspection:	0.050 in.

The following steps detail the ECA computation.

[13]See example problem in A.5.1.2.2.

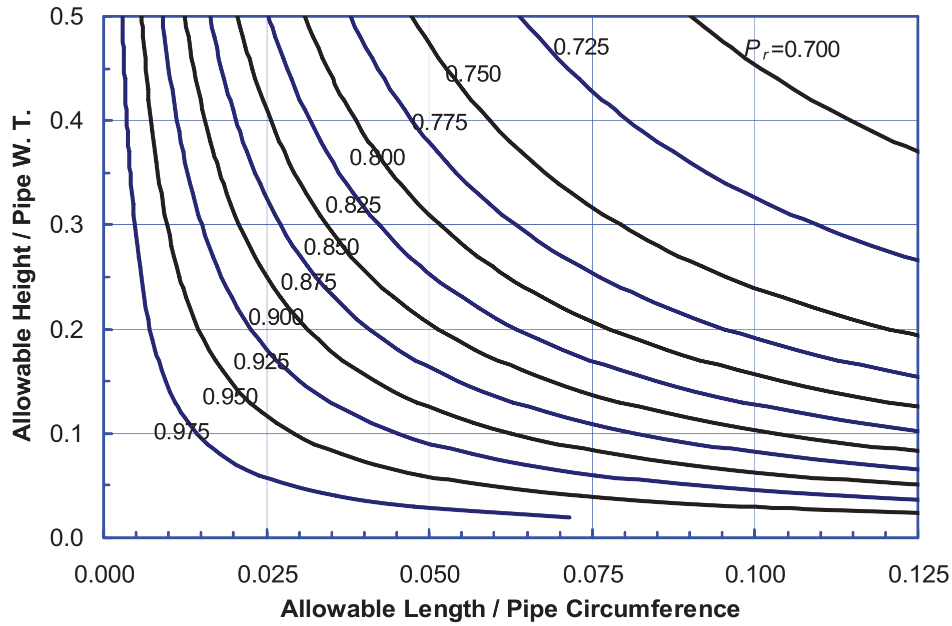


Figure A-7—Option 1 Imperfection Limits for CTOD ≥ 0.010 in. (0.25mm)

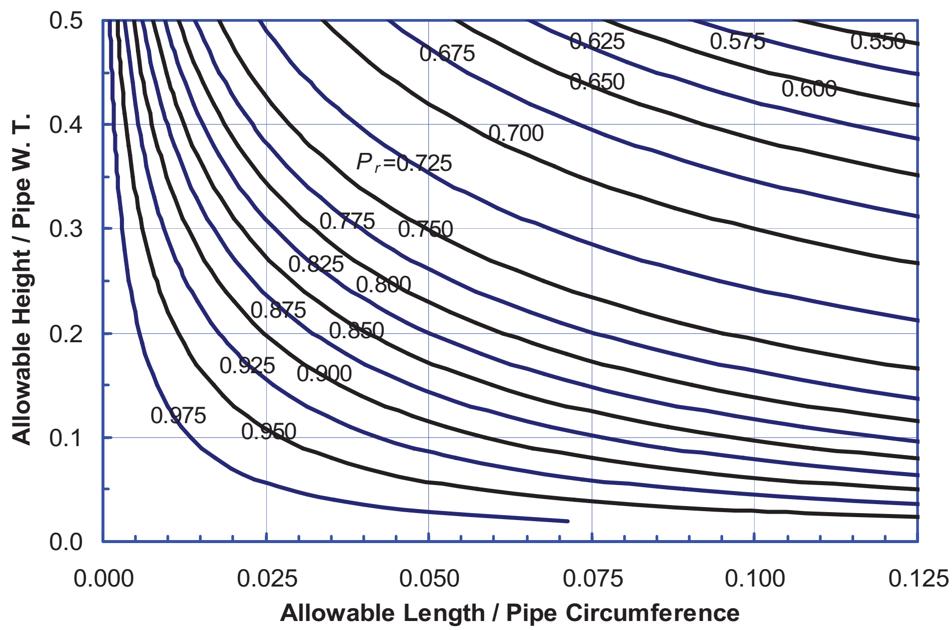


Figure A-8—Option 1 Imperfection Limits for 0.004 in. (0.10 mm) ≤ CTOD < 0.010 in. (0.25 mm)

Step 1, Determine flow stress

Determine the flow stress with Eq. A-3 by substituting the 70 ksi for σ_y,

$$\sigma_f = 70\left[1 + \left(\frac{21.75}{70}\right)^{2.30}\right] = 74.76$$

Note that for this example the flow stress can alternatively be determined as the averaged value of SMYS and SMTS, or in this case 76 ksi, a value very close to the value derived using Eq. A-3.

Step 2, Determine applied load level

The load level P_r is now calculated by inserting the aforementioned values for σ_a and σ_f,

$$P_r = \frac{\sigma_a}{\sigma_f} = \frac{61.5}{74.76} = 0.823$$

Step 3, Determine initial allowable imperfection size

Figure 7 is utilized for determining the initial allowable imperfection size (CTOD ≥ 0.010 in. or 0.25 mm). The curve of $P_r = 0.825$ in the figure is now used for the interpolations. The allowable imperfection size is tabulated in Table 1 and shown in Figure 9.

The allowable height quantities, shown in the second column of Table 1, are derived by multiplying the Allowable Height/Pipe WT value by the wall thickness which in this example is 0.500 in. Similarly, the Allowable Length is calculated by multiplying the Allowable Length/Pipe Circumference quantity by the pipe circumference (π × OD) or 3.14 × 24 in.

Step 4, Determine height adjustment

Assumed height uncertainty = lesser of 8% WT and 0.060 in. = 0.040 in. (1.02 mm).

Allowance for inspection (i.e., inspection error) = 0.050 in. (1.27 mm).

Imperfect height adjustment = allowance for inspection – assumed height uncertainty = 0.050 – 0.040 = 0.010 in. (0.25 mm).

Table A-1—Initial Allowable Imperfection Size for $P_r = 0.825$

Allowable Height/Pipe WT	Allowable Height (in.)	Allowable Length/Pipe Circumference	Allowable Length (in.)
0.5	0.25	0.025	1.9
0.4	0.2	0.032	2.4
0.3	0.15	0.042	3.2
0.2	0.1	0.063	4.8
0.1	0.05	0.128	9.7

Step 5, Produce final acceptance table

The results of the ECA should be tabulated in a user-friendly format. Table 2 suggests an operator-friendly format for this ECA example. However, a project with a heavier wall thickness may have more rows in a similar table[14].

Table A-2—Example Acceptance Table

Allowable Imperfection Height (in.)	Allowable Imperfection Length (in.)
0 to 0.05	8.0
0.05 to 0.15	3.0
0.15 to 0.24	1.9
> 0.24	0.0

[14]Further adjustments may be desirable, see Step 8 of A.5.1.3.2.

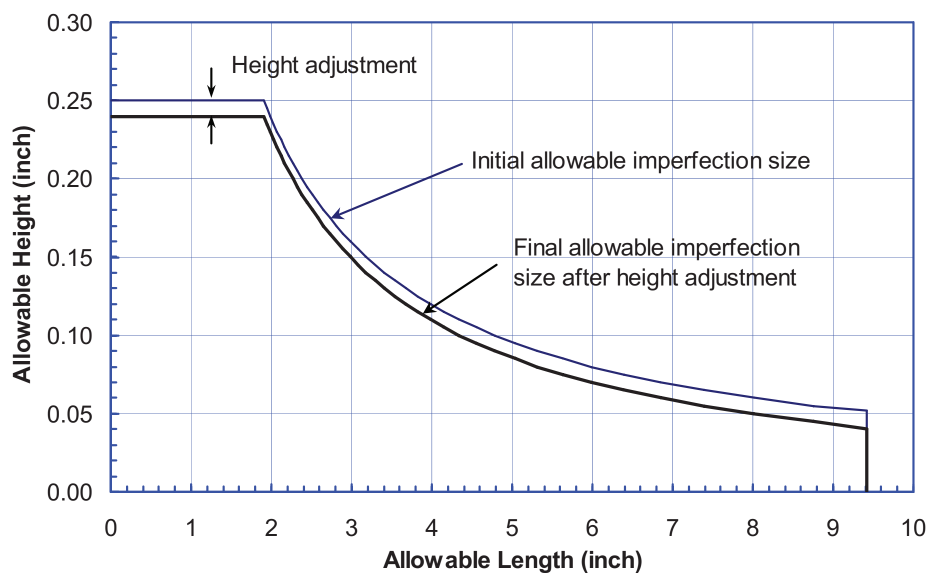


Figure A-9—Allowable Imperfection Size Curves Before and After Height Adjustment

A.5.1.3 Determination of Acceptable Imperfection Size by Option 2

A.5.1.3.1 Background

The underlining Option 2 procedure is the failure assessment diagram (FAD). There are three key components in the assessment in FAD format, see Figure A-10:

1. Failure assessment curve (FAC),
2. Stress or load ratio, S_r or L_r, and
3. Toughness ratio, K_r.

The FAC is a locus that defines the critical states in terms of the stress and toughness ratios. The stress ratio defines the likelihood of plastic collapse. The toughness ratio is the ratio of applied crack driving force over the material's fracture toughness. It defines the likelihood of brittle fracture.

The FAD approach is computationally complex. Proficiency and understanding of fracture mechanics is necessary to ensure the procedure is applied correctly. A validated computer program should greatly simplify the computation.

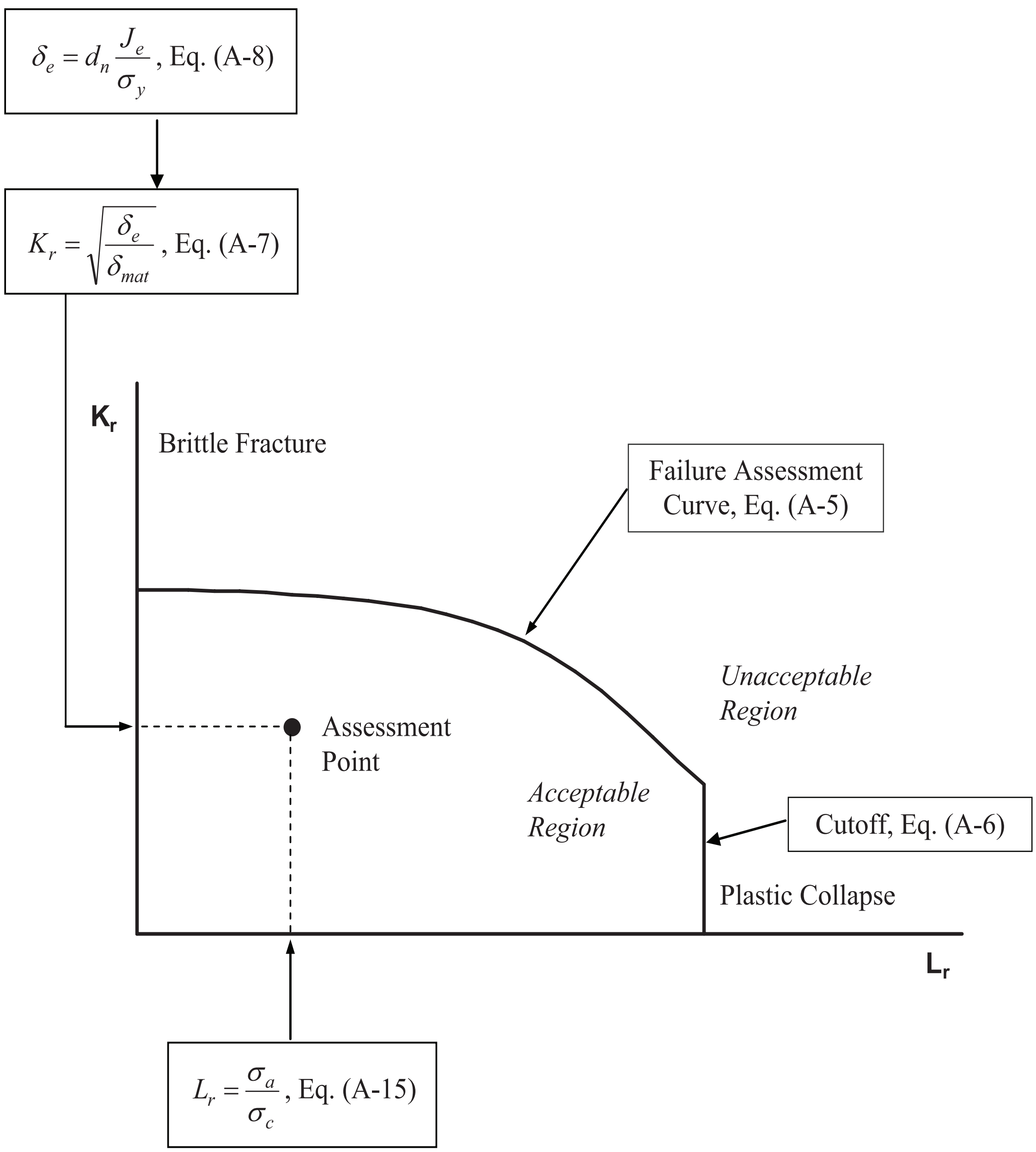


Figure A-10—Schematic Overview of the Option 2 Procedure

A.5.1.3.2 Determination of Critical Imperfection Size

The critical imperfection size can be computed iteratively using equations provided in A.5.1.3.3. The following steps may be followed:

1. Select an imperfection size as a start point. A reasonable start point is an imperfection with the maximum allowed height, $\eta = 0.5$, and a small imperfection length that represents the smallest imperfection length that the selected inspection methods can confidently detect.
2. Determine the assessment point in the FAD format in accordance with A.5.1.3.3.
3. If the assessment point falls inside the safe region, increase the imperfection length and repeat step 2.
4. If the assessment point falls outside the safe region, decrease the imperfection length and repeat step 2.
5. If the assessment point falls on the FAC:
   a. This represents a critical state with the combination of load, material property, and imperfection size. Make a note of the imperfection height and length.
   b. Reduce the imperfection height by a small increment, say $\Delta\eta = 0.05$. Start from the imperfection length determined in (a) and repeat step 2.
6. Make a table of critical imperfection height and length.
7. Apply a safety factor of 1.5 on the imperfection length to produce a draft table of the allowable imperfection height versus imperfection length.
8. Make necessary adjustment to the draft table to ensure detectability of the selected inspection methods[15] and sound welding practice[16]. Produce the final table of the allowable imperfection height versus imperfection length.

The total imperfection length shall be no greater than 12.5% of the pipe circumference. The maximum imperfection height shall be no greater than 50% of the pipe wall thickness.

The allowable height of the buried imperfections is treated the same as the allowable height of the surface-breaking imperfections.

The built-in safety factor in the acceptable imperfection size can accommodate certain amount of undersizing of imperfection height without negatively impacting weld integrity. The assumed height uncertainty is the lesser of 0.060 in. (1.5 mm) and 8% of pipe wall thickness. No reduction in allowable imperfection size is necessary if the allowance for inspection is better than the assumed height uncertainty.

The allowable imperfection height shall be reduced by the difference between the allowance for inspection and the assumed height uncertainty if the above condition cannot be met.

[15]It is necessary to ensure that the smallest imperfection height and length could be reliably detected by the selected inspection method.

[16]For thick-walled pipes, the maximum allowable height of the 50% wall thickness could be a large value. The maximum allowable height may be reduced if such a large value is judged unnecessary by sound welding practice.

A.5.1.3.3 Determination of the Key Components in the FAD Procedure

Failure Assessment Curve (FAC)

The FAC is given as,

$$K_r = f(L_r) = (1 - 0.14L_r^2)[0.3 + 0.7\exp(-0.65L_r^6)] \qquad \text{(A–5)}$$

The cut-off of the FAC on the L_r axis is at,

$$L_r^{\text{cutoff}} = \sigma_f / \sigma_y \qquad \text{(A–6)}$$

where the flow stress σ_f is the averaged value of SMYS and SMTS, or alternatively determined by Eq. A-3.

Assessment Point, Toughness Ratio K_r

The toughness ratio K_r is given as,

$$K_r = \sqrt{\frac{\delta_e}{\delta_{mat}}} \qquad \text{(A–7)}$$

where δ_{mat} is the CTOD toughness of the material. The elastic component of the CTOD driving force, δ_e, may be computed as,

$$\delta_e = d_n \frac{J_e}{\sigma_y} \qquad \text{(A–8)}$$

The J to CTOD conversion factor, d_n, is estimated as,

$$d_n = 3.69\left(\frac{1}{n}\right)^2 - 3.19\left(\frac{1}{n}\right) + 0.882 \qquad \text{(A–9)}$$

where n is the strain hardening exponent in the following stress (σ) strain (ε) relation,

$$\varepsilon = \frac{\sigma}{E} + \left(0.005 - \frac{\sigma_y}{E}\right)\left(\frac{\sigma}{\sigma_y}\right)^n \qquad \text{(A–10)}$$

where E is Young's modulus.

The strain hardening exponent may be estimated from Y/T ratio,

$$n = \frac{\ln(\varepsilon_t / 0.005)}{\ln\{1/(Y/T)\}} \qquad \text{(A–11a)}$$

For ferretic material of API 5L grades X52 to X80, the Y/T ratio may be estimated as,

$$Y/T = \frac{1}{1 + 2\left(\frac{21.75}{\sigma_y}\right)^{2.30}} \qquad \text{(A–11b)}$$

and the uniform strain is estimated as,

$$\varepsilon_t = -0.00175\sigma_y + 0.22 \qquad \text{(A–11c)}$$

The pipe grade, σ_y, is in the unit of ksi in Eq. A-11.

The elastic J integral is given as,

$$J_e = \frac{K_1^2}{E/(1-\upsilon^2)} \text{ and} \qquad \text{(A–12)}$$

$$K_I = \sigma_a \sqrt{\pi a} F_b \qquad \text{(A–13)}$$

The parameter F_b is a function of pipe diameter ratio, α, and relative imperfection length, β, and relative imperfection height η,

$$F_b(\alpha,\beta,\eta) = \begin{cases} F_{b0}(\alpha,\beta,\eta) & \eta \geq 0.1 \text{ and } \beta \leq \dfrac{80}{\pi}\dfrac{\eta}{\alpha} \\ F_{b0}\left(\alpha, \beta = \dfrac{80}{\pi}\dfrac{\eta}{\alpha}, \eta\right) & \eta \geq 0.1 \text{ and } \beta > \dfrac{80}{\pi}\dfrac{\eta}{\alpha} \\ F_{b0}\left(\alpha, \beta = \dfrac{80}{\pi}\dfrac{0.1}{\alpha}, 0.1\right) & \eta < 0.1 \end{cases}$$

(A–14a)

where,

$$F_{b0}(\alpha,\beta,\eta) = \left(1.09 + 2.31\alpha^{0.791}\beta^{0.906}\eta^{0.983} + \frac{m_1}{\alpha\beta} + \alpha^{0.806}\beta m_2\right)$$

(A–14b)

$$m_1 = -0.00985 - 0.163\eta - 0.345\eta^2 \qquad \text{(A–14c)}$$

$$m_2 = -0.00416 - 2.18\eta + 0.155\eta^2 \qquad \text{(A–14d)}$$

Assessment Point, Stress Ratio L_r

The stress ratio L_r is given as,

$$L_r = \frac{\sigma_a}{\sigma_c} \qquad \text{(A–15)}$$

The plastic collapse stress is given as,

$$\sigma_c = \left[\frac{\pi}{4} + 385(0.05-\eta\beta)^{2.5}\right]\left[\cos\left(\frac{\eta\beta\pi}{2}\right) - \frac{\eta\sin(\beta\pi)}{2}\right]\sigma_y$$

$$\text{if } \eta\beta < 0.05 \qquad \text{(A–16a)}$$

$$\sigma_c = \frac{\pi}{4}\left[\cos\left(\frac{\eta\beta\pi}{2}\right) - \frac{\eta\sin(\beta\pi)}{2}\right]\sigma_y$$

$$\text{if } \eta\beta \geq 0.05 \qquad \text{(A–16b)}$$

A.5.1.4 Determination of Acceptable Imperfection Size by Option 3

A.5.1.4.1 General

In most offshore pipelines and flowlines, cyclic loading during construction and operation is present. The Option 3 procedures are permitted when significant imperfection growth is expected.

Subject to company approval, validated fitness-for-purpose procedures may be used to develop imperfection acceptance criteria. One of the most widely accepted procedures is BS 7910. The procedures shall be applied by well-qualified analysts/engineers who have the demonstrated command of the principles of fracture mechanics, pipeline welding, and NDT. Any selected procedure shall be taken as a whole in developing the acceptance criteria with appropriate considerations of safety factors. It should be recognized that the basic assumptions of various public-accessible assessment procedures may be different from those of Options 1 and 2. Mixing parts of different procedures is discouraged.

A.5.1.4.2 Fatigue Flaw Growth

Appropriate fatigue analysis shall be conducted to determine the starting flaw acceptance criteria. Various public-accessible procedures and software are available to determine the flaw growth (e.g., Section 8 of BS 7910). Static fracture resistance shall be checked for all peak loads during the entire fatigue loading spectrum. Available software programs may be used by skilled practitioners to conduct this fatigue analysis and check the static failure conditions during the entire application of the cyclic loads.

The allowable flaw size from Option 1 may be used as the starting flaw sizes for both buried and surface-breaking flaws. If the critical flaw size is reached or failure from static peak loads occurs prior to the end of the service life (with the appropriate design or safety factor), the starting flaw sizes need to be reduced. Care should be taken to select the appropriate flaw growth curves (da/dN curves) for the type of service. Tables 4 and 5 of BS 7910 provide guidance for selection of these curves, and Company may provide supplemental information used to generate flaw growth curves for different product conditions inside the pipe. For small *D/t* ratio pipes through-thickness stress is not uniform. Analyses from multiple initial flaw locations are necessary.

A.5.1.4.3 Inspection Error and Safety Factor on Allowable Imperfect Size

The allowable flaw height shall be reduced by the inspection error extracted from NDT qualification results of qualified inspection system/procedure/operator for the specific project or project with similar material and welding procedure.

A.5.1.5 Transverse Planar Imperfections

Transverse planar imperfections that are indicative of improper welding process or improper execution of welding process shall be repaired or removed. The height of the stacked imperfections from weld starts and stops shall not exceed 50% of the wall thickness.

A.5.2 ACCEPTABLE LIMITS OF VOLUMETRIC IMPERFECTIONS

Buried volumetric imperfections, such as slag or porosity, contained in material with high fracture toughness are much less likely to cause failure than planar imperfections. These imperfections may be treated and evaluated as planar imperfections or by the simplified method of Table 3. Surface-breaking imperfections, and buried imperfections that are recategorized as surface-breaking by the imperfection interaction rules, shall be treated and evaluated as planar imperfections. The minimum CTOD toughness and Charpy impact energy requirements are applicable regardless how the imperfections are evaluated.

Table A-3—Acceptance Limits for Buried Volumetric Imperfections

Imperfection Type	Height or Width	Length
Porosity	Lesser of $t/4$ or 0.25 in.	Less of $t/4$ or 0.25 in.
Slag	Lesser of $t/4$ or 0.25 in.	$4t$

A.5.3 ARC BURNS

Arc burns may occur on the internal or external surface of the pipe as a result of inadvertent arc strikes or improper grounding. They generally appear as a pit or cavity visible to the eye or as a dense area on the radiograph. The cavity may be surrounded by a hard heat-affected zone that may be of lower toughness than the base material or the weld deposit.

The acceptance limits for unrepaired arc burns are given in Table 4 and are based on the premise that the heat-affected zone has zero toughness but that any planar imperfection originating within the heat-affected zone is blunted at the edge of the zone. Substantial data indicate that the total depth of the arc burn, including the heat-affected zone, is less than half the width of the burn.

Table A-4—Acceptable Limits for Unrepaired Arc Burns

Measured Dimension	Acceptance Limit
Width	Lesser of t or $^5/_{16}$ in.
Length (any direction)	Lesser of t or $^5/_{16}$ in.
Depth (to bottom of crater)	$^1/_{16}$ in.

Arc burns that contain cracks visible to the eye or on conventional radiographs are not covered by this appendix and shall be repaired or removed.

A.5.4 IMPERFECTION INTERACTION

If adjacent imperfections are close enough, they may behave as single larger imperfections. Figure A-11 shall be used to determine whether interaction exists. If it does, the effective imperfection sizes shown in Figure A-11 shall be computed and the acceptability of the effective imperfection shall be evaluated by the applicable acceptance criteria. If a repair is indicated, any interacting imperfections shall be repaired in accordance with A.7.

A.6 Record

The type, location, and dimensions of all imperfections accepted in accordance with this appendix shall be recorded on suitable forms. This record shall be filed with the radiographs or other records of nondestructive tests of the pipeline.

A.7 Repairs

Any imperfections that are not acceptable under the provisions of this appendix shall be repaired or removed in accordance with Sections 9 and 10.

A.8 Nomenclature[17]

a = imperfection height (in. or mm).

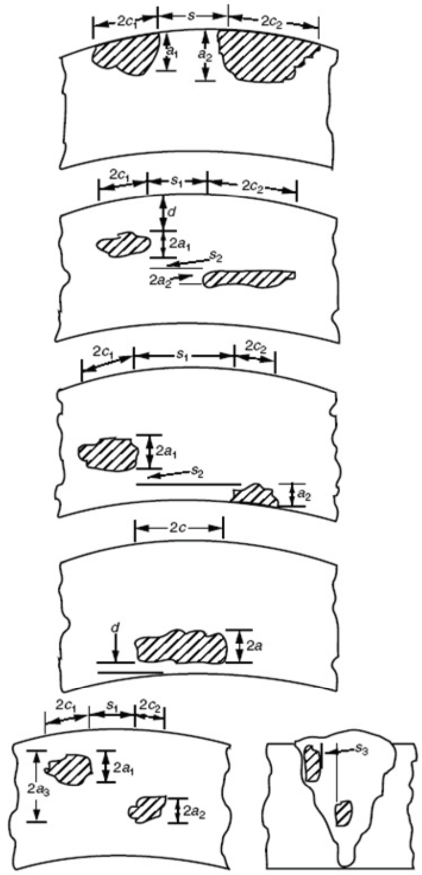
c = imperfection half length (in. or mm).

D = pipe outer diameter (in. or mm).

d_n = J integral to CTOD conversion factor (unitless).

E = Young's modulus (ksi or MPa).

[17]The units shown here are for illustrative purposes. It is necessary to ensure consistent units are used for all computations. Some equations, e.g., Eqs. A–3 and A–11, must use specified units.



Case	Interaction exists if	If interaction exists, effective imperfection size is
Case 1	$s < 2c_1$ $(c_1 < c_2)$ $(a_1 < a_2)$	$a_e = a_2$ $2c_e = 2c_1 + s + 2c_2$
Case 2	$s_1 < 2c_1$ and $s_2 < a_1 + a_2$ $(c_1 < c_2)$	$2a_e = 2a_1 + s_2 + 2a_2$ $2c_e = 2c_1 + s_1 + 2c_2$
Case 3	$s_1 < 2c_1$ and $s_2 < a_1 + a_2$ $(c_1 < c_2)$	$a_e = 2a_1 + s_2 + a_2$ $2c_e = 2c_1 + s_1 + 2c_2$
Case 4	$d < a$	$a_e = d + 2a$ $2c_e = 2c$
Case 5	$s_1 < 2c_1$ and $s_3 < 2a_1$ $(c_1 < c_2)$ $(a_1 < a_2)$	$2a_e = 2a_3$ $2c_e = 2c_1 + s_1 + 2c_2$

Figure 11—Criteria for Evaluation of Imperfection Interaction

J_e = elastic part of J integral (ksi in. or MPa mm).

K_I = stress intensity factor (ksi (in.)$^{1/2}$ or MPa (mm)$^{1/2}$).

K_r = toughness ratio in FAD format (unit-less).

L_r = stress ratio in FAD format (unit-less).

L_r^{cutoff} = cutoff stress ratio in FAD format (unit-less).

n = strain hardening exponent (unit-less).

P_r = normalized applied stress or load level, $P_r = \sigma_a / \sigma_f$ (unit-less).

t = pipe wall thickness (in. or mm).

α = ratio of pipe diameter to wall thickness, $\alpha = D/t$ (unit-less).

β = ration of imperfection length to pipe circumference, $\beta = 2c/\pi D$, (unit-less).

δ_e = elastic art of CTOD (in. or mm).

δ_{mat} = CTOD toughness (in. or mm).

t = nominal pipe wall thickness.

η = ratio of imperfection height to pipe wall thickness, $\eta = a/t$, (unit-less).

ν = Poisson's ratio (unit-less).

σ_a = maximum axial design stress (ksi or MPa).

σ_c = plastic collapse stress (ksi or MPa).

σ_f = flow stress of the pipe material (ksi or MPa).

σ_t, T = ultimate tensile strength of the pipe material, or UTS, (ksi or MPa).

σ_y, Y = specified minimum yield strength of the pipe material, or SMYS, (ksi or MPa).

ε_t = uniform strain (unit-less).