Care, Maintenance, and Inspection of Coiled Tubing

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Care, Maintenance, and Inspection of Coiled Tubing

1 Scope

This recommended practice covers the care, maintenance, and inspection of used low alloy carbon steel coiled tubing. Commonly manufactured coiled tubing outside diameters range from 25.4 mm (1.000 in.) to 88.9 mm (3.5 in.).

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API Specification 5ST, *Specification for Coiled Tubing*

ASTM A370 [1], *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*

H. Haga, K. Aoki, and T. Sato (1980a), Welding Phenomena and Welding Mechanisms in High Frequency Electric Resistance Welding—1st Report, *Welding Journal* 59(7), pp. 208–212

H. Haga, K. Aoki, and T. Sato (1980b), The Mechanisms of Formation of Weld Defects in High-Frequency Electric Resistance Welds, *Welding Journal* 59(7), pp. 103s–109s

For a list of other documents associated with this standard, see the Bibliography.

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purpose of this document, the following definitions apply.

3.1.1
Bauschinger Effect
A phenomenon that occurs in polycrystalline metals (including steel), that results in a decrease of the yield strength in one direction due to plastic deformation in another direction such as is caused by service loads, coiling, or straightening.

3.1.2
bed wrap
The wraps of coiled tubing that are adjacent to the cylindrical core of the shipping or usage reel.

3.1.3
cold work
Plastic deformation at such temperatures and rates that substantial increases occur in the strength and hardness of the metal.

NOTE Visible structural changes include changes in grain shape and, in some instances, mechanical twinning or banding.

3.1.4
critical weld(s)
Primary connections in coiled tubing where failure would jeopardize the safety of personnel or equipment and/or be detrimental to the integrity of the coiled tubing string or operation.

NOTE Critical welds include, but are not necessarily limited to, tube-to-tube girth joints and high-pressure end-fitting welds for union connections to swivel joints on coiled tubing reels.

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[1] ASTM International, 100 Barr Harbor Drive, West Conshohocken, Pennsylvania 19428, www.astm.org.

3.1.5
cycle
One complete bend and straightening event that the coiled tubing experiences during manufacture, operation, and use.

3.1.6
defect
An imperfection of sufficient magnitude to warrant rejection of a product or the part of the product containing the defect, according to an agreed specification.

3.1.7
diametral growth
The increase in tubing outside diameter observed following coiled tubular operations.

3.1.8
electro-discharge machining
EDM
Method for producing reference indicators for nondestructive testing (NDT) cut into part surface using the spark-erosion technique.

3.1.9
electromagnetic inspection
Either the generic term for all NDT performed using electromagnetic methods, such as eddy current and magnetic flux leakage, or the oilfield tubular inspection term for various combinations of eddy current and magnetic flux leakage inspections commonly performed on such tubulars.

3.1.10
flash (OD/ID)
A fin of metal formed at the sides of a weld when a small portion of metal is forced out between the edges of the forging or welding dies.

3.1.11
fleet angle
The angle at which the coiled tubing goes on to or comes off the storage reel measured from the adjacent tubing already on the reel.

3.1.12
fluorescent magnetic particle inspection
The magnetic particle inspection process employing a finely divided fluorescent ferromagnetic inspection medium that fluoresces when activated by ultraviolet light.

3.1.13
high frequency induction welding
A welding method in which metal is heated to softness by eddy currents and pressed together forming a continuous material without addition of filler metal.

3.1.14
image quality indicator
IQI
A reference standard for radiography.

3.1.15
lamination
An internal metal separation creating layers generally parallel to the surface.

3.1.16
Level I
A person trained to a written practice in the NDT methods employed in testing product but not necessarily capable of interpreting results.

3.1.17
Level II
A person trained to a written practice in the NDT methods employed in testing product, capable of interpreting procedures, results, procedures, and supervising Level I inspectors.

3.1.18
Level III
A person trained to a written practice in NDT methods employed in testing a product and capable of interpreting the results, writing test procedures, and qualifying and certifying Level I and Level II inspectors.

3.1.19
liquid penetrant inspection
An inspection process in which fluids are attracted into tight flaws by cohesive surface forces, partially leached out, and developed for visibility.

3.1.20
magnetic flux
Φ
The amount of magnetism, measured in Webers, or lines of magnetism.

3.1.21
magnetic flux leakage
MFL
An inspection process that consists of magnetizing a ferromagnetic product and detecting flaws using the magnetic flux they expel into the surrounding air.

3.1.22
magnetic induction
B
The amount of magnetism per unit of cross-sectional area (A), measured in Tesla (Weber/square meter), lines per square centimeter.

3.1.23
magnetic particle inspection/testing
MT
An inspection process that consists of magnetizing the material and applying a prepared magnetic powder that adheres along the lines of flux leakage.

3.1.24
magnetic permeability
The ratio of the magnetic induction to the intensity of the magnetizing field.

3.1.25
maximum outside diameter
D_{max}
The maximum outside diameter is the largest measured outside diameter at any location of the coiled tubing.

3.1.26
maximum permitted outside diameter
$D_{p,max}$
The maximum permitted outside diameter is the largest outside diameter that can be accepted on the job for which the coiled tubing will be used.

3.1.27
microhardness
Measurement of bulk hardness using a small load.

3.1.28
microhardness test
The average of three values taken at the measurement location, with obvious inaccurate readings repeated.

3.1.29
minimum outside diameter
D_{min}
The minimum outside diameter is the smallest measured outside diameter at any location of the coiled tubing.

3.1.30
minimum permitted outside diameter
$D_{p,min}$
The minimum permitted outside diameter is the smallest outside diameter that can be accepted on the job for which the coiling will be used.

3.1.31
nondestructive inspection
nondestructive testing
NDT
Evaluation of the tubular to detect any surface, internal, or concealed defects or flaws by using techniques that do not damage or destroy the product.

3.1.32
ovality
Difference in outside diameters of the tubular of a single cross section of the tubular.

3.1.33
penetrator
A weld seam defect that goes from inner or outer diameter into or through the weld.

3.1.34
radiography
A nondestructive test method in which high energy electromagnetic radiation (generally X-rays) are passed through an object and a shadow of variations within the product captured on film or digitally.

3.1.35
reeling
Transferring tubing or pipe from one reel to another.

3.1.36
reference indicator
A defined imperfection that is used for setting the sensitivity level of nondestructive evaluation equipment.

3.1.37
reference standard
A block or tube containing machined imperfections used as a base for comparison or for the standardization of inspection equipment.

3.1.38
sensitivity
The size of the smallest discontinuity detectable by a nondestructive test method with a reasonable signal-to-noise level.

3.1.39
skelp
The rolled steel sheet used in making of high-frequency induction welding or laser-welded tube.

3.1.40
spooling
The act of transferring tubing from one storage (shipping) reel (spool) to another by means of unwinding the payoff string and rewinding the take-up string.

3.1.41
ultrasonic inspection
A nondestructive method of inspection of a product for wall thickness or the presence (or absence) of imperfections or defects employing high-frequency sound.

3.1.42
ultrasonic shear waves
Short wavelength, high-frequency waves in which the energy flows in a direction perpendicular to the particle motion.

3.1.43
ultrasonic testing
UT
A nondestructive method of inspecting material by the use of high-frequency sound waves.

3.1.44
used coiled tubing
Coiled tubing that has passed from a storage reel past the injector into a well.

3.1.45
wiper ball
A compressible and disposable sponge ball that is propelled through the tubing to remove as much of the hydro test or other fluid as possible.

3.1.46
yield radius
The minimum radius above which, when coiled tubular product is wound upon a reel, it will not experience any plastic yield.

3.1.47
yoke
A device for magnetizing a small area of a ferromagnetic part surface so that magnetic particle inspection can be performed.

3.2 Acronyms and Abbreviations

AWS	American Welding Society
BHT	bottomhole temperature
BOP	blowout preventer
CWB	Canadian Welding Bureau
EC	environmental cracking
EDM	electro-discharge machining

EW	electric weld
FSH	full screen height
GTAW	gas tungsten arc welding
HAZ	heat-affected zone
HIC	hydrogen-induced cracking
IQI	image quality indicator
LCF	low cycle fatigue
MFL	magnetic flux leakage
mpy	mils per year (1 mil = 0.001 in.)
MT	magnetic particle inspection/testing
NDE	nondestructive examination
NDT	nondestructive testing
NORM	naturally occurring radioactive material
OEM	original equipment manufacture
PQR	procedure qualification record
PT	liquid penetrant testing
PWHT	postweld heat treatment
RT	radiographic testing
SG	specific gravity
SOHIC	stress-oriented hydrogen-induced cracking
SSC	sulphide stress cracking
TIG	tungsten inert gas
UT	ultrasonic testing
WPS	welding procedure specification

4 General Information

4.1 Applications of Coiled Tubing

4.1.1 General

Coiled carbon steel tubing can be used, but not limited to, the following applications.

4.1.2 Workstrings

Workstrings are specifically designed for servicing specific wells or specific fields but are often used in other wells and fields. Certain regions of workstrings may receive heavy bending and experience considerable fatigue. They may or may not contain means of communicating with tools attached to the end of the tubing, such as electric or fiber optic cables. They may be used to transport acids, liquid nitrogen, cement, and sand for well service operations.

4.1.3 Drill Strings

Coiled tubing drill strings are used with rotary bits that are driven by mud motors and bottomhole electric motors. The tubing itself does not rotate other than as a flexural response to the drilling operation.

4.1.4 Siphon and Velocity Strings

Siphon strings are introduced into wells in order to provide a channel for the introduction of fluids at pressure to the producing section of the well in order to raise well fluids to the surface inside the production tubing. Velocity strings are introduced into wells to restrict the annular flow area in wells that employ conventional tubing, thus promoting higher flow rates for the produced fluids. Such strings are not generally cycled in this mode of use. Older strings may be retired into this type of service.

4.1.5 Sucker Rod Systems

Coiled carbon steel tubing may be used as coiled sucker rods. In this application, the produced fluid flows up the bore of the coiled tubing.

4.2 Responsibility of the Purchaser

4.2.1 Purchaser Responsibility

It is the responsibility of the purchaser of the inspection, maintenance, and repair services to inquire if the companies employed to perform the work have quality systems in place to conform to this recommended practice. In this context, “system” is taken to mean the combination of equipment, equipment performance, operator training, and a quality system under which the company operates. The quality system should include written procedures for equipment operation and recalibration, operator training, and certification and should take as the model the requirements of API Q1 or the ISO 9000 series of quality standards.

4.2.2 Purchaser Access

4.2.2.1 Access to Quality System

The purchaser should have access to the quality system of the service provider and may perform periodic audits thereon for the purpose of qualifying or requalifying the service provider.

4.2.2.2 Access to Provider Facility

Upon agreement, the purchaser should have access to monitor the work of the provider, provided that the representative of the purchaser meet and comply with all the necessary safety standards in operation under the auspices of the provider and any legal and governmental requirements.

4.3 Naturally Occurring Radioactive Materials (NORMs)

Coiled tubing strings that have been in service in certain areas may develop a coating of NORM. The coiled tubing strings should be checked for the presence of NORM prior to performing the service work herein.

Guidelines for operations involving NORM on tubulars are provided in API E2.

Unless otherwise agreed between the owner of the coiled tubulars and the service provider, all work performed as services in this document shall be on coiled tubulars that have NORM in accordance with appropriate local regulations.

4.4 Properties of Coiled Tubing

Annex A provides information on coiled tubing properties.

5 Welding Coiled Tubing

5.1 General

Welds in coiled tubing are used for repair and modifications such as extending the length, removing damaged sections of the coiled tubing, or for attaching temporary or permanent end-fittings. Unlike welds in conventional process piping or tubing, tube-to-tube girth welds (butt welds) in coiled tubing are subjected to plastic bending cycles and therefore shall exhibit both sufficient strength and plasticity so as to provide acceptable low cycle fatigue (LCF) performance. Experience has shown that the LCF life may vary from 25 % to 75 % of the base tubing, depending upon the welding process used. Since the LCF life of these welds is highly dependent upon their welding procedure specification (WPS) and quality of workmanship, it is of critical importance to pay special attention to welding procedure control such as fit-up, edge preparation, filler metal selection, thermal cycle control, and dressing of the as-welded connection. This section is intended to provide guidelines to achieve sound welds in carbon steel coiled tubular operations with emphasis on achieving acceptable plastic bend fatigue performance.

Welders of coiled tubing manufactured to API 5ST should meet the requirements in Table 1.

Table 1—Welds with Filler Metal (Tube-to-Tube Weld)

Condition	Special Process
Weld	90° tube-to-tube weld
	Heat treatment of tube-to-tube weld
	NDT of tube-to-tube weld
Tube wall	NDT

This section is concerned only with welds in new and in-service coiled tubing involving tube-to-tube girth welds of equivalent or dissimilar CT strength grades, wall thicknesses and/or loading history, and welded end-fittings involving fillet weld connections between new or used CT and other heat-treatable high-strength low-alloy carbon steels.

Welding of corrosion-resistant alloy coiled tubing is outside the scope of this document. Joining by amorphous diffusion bonding is outside the scope of this document. If looking for additional information not identified in this document, refer to ASME *BPVC* Section IX.

5.2 Type of Welds Used in CT Products

5.2.1 Tube-to-Tube Welds

A tube-to-tube weld is a girth butt weld that joins two lengths of existing coiled tubing of equal outside diameter. The two ends to be joined are cut square, carefully aligned and welded from one side without backing around the circumference. The resulting weld is perpendicular to the coiled tubular string axis. Butt welds in coiled tubing should meet the requirements of API 5ST.

5.2.2 Coiled Tubing to Fitting Welds

End-fittings are welded to coiled tubing for connections to swivel joints on the CT reel and, in some cases, for attachment to bottomhole assemblies. Welding of fittings for swivel joint connections is generally performed at the coiled tubing manufacturer and is therefore governed by the specifications and quality control of the coiled tubing manufacturer. However, whenever slip on type fittings are involved, the use of two fillet welds in tandem is recommended.

Since fittings are generally made of different steel grades including air-hardenable alloys, a special WPS is required for these connections.

5.2.3 Flag Welds on Coiled Tubing

Flag welds are welds made around the tubing at certain positions specified by the operator. These welds may both reduce the fatigue life of that local section of the tubing, preferentially corrode in acid service, and are not recommended.

5.3 Welding Processes

Welding processes for coiled tubing usually entails both manual and mechanized (orbital) gas tungsten arc welding (GTAW) also referred to as tungsten inert gas (TIG). Manual GTAW is the most common welding process used for tube-to-tube connections. Orbital GTAW welding processes are also used for field welds but are less common due to their higher costs and more critical joint fit-up and specialized operator training requirements. However, made in carefully controlled conditions and with the repeatability and consistency of automation, the fatigue life of orbital GTAW welds can be expected to be about twice that of manual GTAW welds. Since the quality of manual welds is inherently more variable, orbital GTAW or other processes that result in more consistent and superior LCF performance are preferred for tube-to-tube welds.

Manual shielded metal arc is another process commonly used for welding coiled tubing products, but it is not recommended for tube-to-tube welds.

5.4 Welding Procedure and Qualification

5.4.1 General

All carbon steel coiled tubing welds should be performed only by qualified welders in accordance with a written WPS. A WPS may be qualified by a procedure qualification record (PQR). The coiled tubing service provider shall maintain a permanent file of all welding procedures, procedure-qualification test results and PQRs. Copies of all or parts of this file should be available upon request by customers of the service provider.

5.4.2 WPS

A WPS is a set of written instructions and welding parameters designed to enable the welder to make a sound weld. It consists of a WPS datasheet and a welding engineering standard. For a given welding process, the WPS provides detailed information on the following:

a) base material,

b) applicable standards and codes,

c) joint type,

d) thickness range,

e) edge preparation,

f) welding position and progression,

g) filler metal (consumable) classification and size,

h) welding wire feed speed (if applicable),

i) preheat and inter-pass temperatures,

j) postweld heat treatment (PWHT),

k) shielding gas type and flow rate,

l) electrical characteristics (polarity, amps, volts),

m) arc travel speed,

n) welding technique,

o) pass sequence,

p) PQR, and

q) other information that may be relevant.

A typical WPS format is given in a document for the preparation of tube-to-tube welds that has been published by the International Coiled Tubing Association (ICoTA) (see [39]) and is recommended for the detailed preparation of WPSs for coiled tubular strings.

WPSs should be prepared by a welding engineer with the guidance of [39], [45], [46], and [61].

5.4.3 Welding PQR

5.4.3.1 A PQR is a supporting document on test weld coupon results to verify that the weldment exhibits the required physical properties and desired material performance when welded according to a particular WPS datasheet. The PQR for coiled tubular welds should include the following:

a) yield and tensile strength,

b) ductility tests (% elongation, side bend tests),

c) micro and macro etch photography,

d) microhardness survey,

e) nondestructive examination (NDE), and

f) plastic bend fatigue testing (in the case of tube-to-tube welds).

5.4.3.2 In special circumstances such as low-temperature or corrosive environments, the following may also be required by the customer:

a) Charpy impact tests,

b) fracture toughness tests,

c) plastic bend cycle tests,

d) preferential corrosion resistance testing.

5.4.3.3 The PQR serves to qualify a given WPS. It is recommended that all coiled tubular welding be performed only with a pre-qualified WPS. All WPSs for critical welds in coiled tubing shall be pre-qualified by a PQR. A typical PQR format and record sheet is given in [39] and [61]. Qualification of welding procedures should be performed under the supervision of a welding engineer with the guidance of [39], [43], [45], and [61].

5.5 Tube-to-Tube Weld Procedure Specification

In addition to the requirements of [61] for the preparation of a WPS for tube-to-tube welds in coiled tubulars, special attention should be paid to the following aspects of preparing a girth weld connection in coiled tubing.

a) Tube End Preparation

Coiled tubing ends may be flame cut or rough sawn cut. Ends that have been flame cut should be cut back by mechanical means far enough to assure that any thermal effects from the flame cut are removed. At least 3 in. should be removed. Prior to welding groove or edge preparation, rough cut tubing ends should be cut square and perpendicular with the tubing axis using mechanical pipe cutters or similar tooling. The angular deviation from perpendicular should be checked at four locations or more with a straight edge. Should a surface be found that is more than $^{1}/_{32}$ in. from square, the tube end should be reworked until this criterion is satisfied.

Edge preparations (welding groove) should be located at least 3 in. from torch cut ends. The weld groove should be prepared in accordance with the pre-qualified WPS and welding engineering standards.

b) Internal Flash Removal

The electric resistance weld flash on the inside of both tubing ends to be joined should be tapered back with the inner tubing surface to a length of at least 1 in.

Appropriate tools that do not leave circumferential grinding marks or cause heat checking should be used to remove internal flash. Use of a pencil grinder for this operation may cause accidental gouging of the coiled tubing surface adjacent to the electric resistance weld seam. Grinding can also cause heat check defects that act as fatigue initiation cracks, especially in coiled tubing. The finished inside surfaces should not have any transverse scratch marks and shall be smooth to a surface roughness value of less or equal 60 μin. rms.

c) Demagnetization

Welding magnetized materials can cause problems with arc-blow, and result in weld defects. If necessary, demagnetization may be effected by application of appropriate direct or strong alternating coil fields for a distance of at least 3 ft (1 m) at each end to be welded. The use of the type of AC yokes used in magnetic particle inspection is not permitted.

The reading of a gauss-meter (Tesla-meter) probe held so as to measure the maximum value of the magnetic flux density emergent from either prepared end of the tube should be less than 5 Gauss at all points around the circumference of the end of the tubing. Demagnetization should be performed after all end preparation.

Demagnetization is generally required at location to be tube-to-tube welded, after coiled tubing have been inspected by electromagnetic methods.

d) Welding of Dissimilar Strength Grades

Coiled tubular strength grades are designated by their specified minimum yield strength in thousands of pounds per square inch (ksi). Coiled tubing strength grades within API 5ST include CT70, CT80, CT90, CT100, and CT110.

Tube-to-tube welds of dissimilar strength grades are permitted in coiled tubing provided that the welding is performed in accordance with a pre-qualified WPS. However, loss of LCF may occur depending on the degree of mismatch in local CT yield strength. (See 3.3.1 of [61].)

Tube-to-tube welds of dissimilar strength grades are not suggested for use in coiled tubing.

e) Welding Consumables

For elastically stressed weldments, filler metal welding wire for the TIG process is generally specified by AWS A5.18 and AWS A5.28 in which the ultimate tensile strength of the filler metal is matched with that of the base metal. For plastically strained girth welds in coiled tubing performed with the orbital TIG process, research has shown [45] that improved LCF life can be obtained by matching the tensile strength of the filler metal with the specified minimum yield strength of the coiled tubing. The increased LCF life is achieved at the expense of a small (10 %) loss in axial yield strength capacity of the tube-to-tube welded connection.

Under-matching of filler metal with coiled tubing tensile strength is not recommended for manual TIG tube-to-tube welds because the benefits of more uniform plastic strain distribution across the weld joint is offset by the nonflush internal weld profile typically obtained with manual welding.

f) Welding Technique and Pass Sequence

Multi-pass stringer beads are recommended for tube-to-tube girth welds because they result in a lower heat input and grain refinement of previously deposited weld beads. Orbital TIG welding is capable of depositing extremely small stringer beads and weld metal layers that result in a grain size of similar magnitude as the coiled tubing base material. Welding stops and starts should be staggered from layer to layer.

g) Preheat and Inter-pass Temperature

Tube-to-tube welding of coiled tubing steels performed at room temperature, typically 21 °C (70 °F), or higher generally does not require preheating to preclude hydrogen-induced cold cracking. At lower ambient temperatures, preheating to 10 °C (50 °F) for a distance of at least 3 in. from the weld edge preparation is recommended. When welding in ambient temperatures of less than 0 °C (32 °F), the coiled tubing ends should be preheated to 36.5 °C (100 °F) for a distance of at least 3 in.

Inter-pass temperatures shall be controlled to the maximum permitted by the WPS to preclude excessive loss of yield strength in the deposited weld metal or heat-affected zone (HAZ). Inter-pass temperatures can be limited by allowing the weldment to cool between successive weld bead deposits or with the use of chill blocks.

When welding to other than CT alloys, refer to the appropriate WPS for preheating requirements. Preheat and inter-pass temperatures should be determined with the use of thermal crayons or similar means.

h) PWHT

While many welds are supplied in coiled tubing manufactured from grades ASTM A606 or A607 modified steels without PWHT, cases arise where PWHT is employed. This should be controlled by the WPS.

5.6 Tube to End-fitting WPS

5.6.1 General

Separate pre-qualified weld procedure specifications are required for end-fittings to coiled tubing weld joints. Welding of end-fittings to coiled tubing generally involves dissimilar alloys and the use of fillet welds in a lap joint configuration. Hence there is no welding groove preparation or EW flash removal requirement.

5.6.2 Preheat and Inter-pass Temperature (End-fittings)

Depending on the steel grade used for coiled tubing end-fittings, preheating and control of maximum inter-pass temperature may be required as specified on the appropriate WPS. If preheating is necessary, it should be applied separately to the end-fitting before mating with the coiled tubing for welding.

5.6.3 PWHT (End-fittings)

Because PWHT is detrimental to ASTM A606/607 modified coiled tubing steels and once joined together, end-fittings cannot be selectively heat-treated without affecting the coiled tubing, end-fitting materials should be selected such that PWHT is not required. Commonly used fittings made from air-hardenable alloys, e.g. 4130/4140 steels, should be wrapped in a thermal blanket to slow cool the weldment to 93.5 °C (200 °F) before removing the blanket. The PWHT should be defined in the WPS.

5.7 Qualifying Weld Procedure Specifications

The basic PQR requirements are given in [39] and [61]. It is not necessary to individually qualify every coiled tubing weld. A WPS incorporating a number of varying welding parameters can be qualified by a single PQR. Re-qualification of a WPS is required only when one or more of essential variables have been changed. For tube-to-tube coiled tubing welds, these variables are defined in Table 3.1 of [61].

In addition to the requirements of [61], the following PQR testing and essential variables shall apply to welds in coiled tubing.

a) Mechanized Welding Process

   A separate PQR shall be prepared for either the manual or orbital GTAW process.

b) Tensile Testing

   Tensile testing of full body coiled tubing test specimen shall be performed in accordance with the 1 % pre-strain method described in H. Haga et al. (1980a, 1980b).

c) Hardness Testing

   Hardness measurements for tube-to-tube, pipe-to-pipe, and end-fitting welds should be made for the deposited weld metal, HAZ, and base metal. For field tube-to-tube welds, measurements are made with a portable field hardness tester. For coiled tubing, all readings shall be below the maximum specified for the grade, when new.

d) Tube-to-Tube PQR

   When weldments in coiled tubulars are designed to function in fatigue cycling operations, qualifications may include low cycle plastic fatigue bend testing of multiple welded connections along with multiple samples of the parent coiled tubing.

   Testing for the qualification of tube-to-tube welds shall include low cycle plastic bend fatigue testing of the welded connection. Generally, the working fatigue life of manual tube-to-tube welds in coiled tubing is in the range of one quarter to one third of the working life of the coiled tubular. For orbital TIG welds, a working life roughly equal to one half of the coiled tubular can be expected. Acceptable ultra-low cycle fatigue life of tube-to-tube welds in coiled tubing is a matter of tubing string management and/or agreement between customer and coiled tubing service provider.

5.8 Welder and Welding Operator Qualification

Welding of steel coiled tubing requires welders and welding operators with advanced qualifications and specialized training.

A welder performance test is required to verify that the welder is capable of following the written procedure specifications and producing a coiled tubular weld with the same quality expected from the PQR test results. The welder shall also demonstrate periodically that proficiency in welding coiled tubing has been maintained. For coiled tubing, reference should be used as a guide for re-qualification of welders.

In addition to performance evaluation, the coiled tubing welder shall have a clear understanding of the critical factors that affect the integrity of the weld. Often it is the correct fit-up, edge-preparation, weld dressing, and general quality of workmanship that determines the success or failure of a coiled tubular weld.

Section 4 of [61] should be consulted for qualification and re-qualification requirements of welders engaged in performing coiled tubing welds. In addition to these requirements, the following shall apply.

a) Tube-to-Tube Qualifying Tests

   To qualify, a welder or operator shall produce at least three consecutive girth welds in full body coiled tubular specimens and welding positions representative of actual welding conditions. Acceptance of these test welds is generally determined by radiographic or shear wave ultrasonic examination for volumetric defects, and liquid penetrant or wet fluorescent magnetic particle testing for accessible surface defects.

b) Disqualification

   If the test in 5.8 a) fails to meet the specified requirements, the welder or operator may make one only additional qualification weld. If this re-test fails, the welder or operator is disqualified from performing any tube-to-tube girth welds in coiled tubing until the welder has satisfactorily completed additional training.

c) Welding Engineering Standards

   All coiled tubing welds should be performed in accordance with a consistent set of welding engineering standards. Each welding fabricator or service organization may have their own proprietary welding standards. Welding fabricators that are certified by the American Welding Society (AWS) or the Canadian Welding Bureau (CWB), for example, are required to adhere to welding standards that are approved by these licensing authorities. At minimum, welding engineering standards for coiled tubing welds should include the following.

d) Alignment and Fit-up

   Proper alignment and fit-up of the weld groove preparation is critical for tube-to-tube joints for maximum LCF performance. This requires a welding fixture that is capable of rigidly securing both tubing sections to be joined, usually in the horizontal (5G) position. Welding fixtures shall not impose excessive axial restraint on the tubing so as to preclude high shrinkage stresses upon cooling of the weldment. Any rigid clamping for the tubing sections should be applied as far away from the faying surfaces (edge preparation) as possible.

   The two ends to be welded should be straight for a minimum of 3 ft. Axial alignment may be checked by the use of a straight edge placed so that it straddles equally each side of the weld and adjusting the position of the tubing clamps so that no more than $^{3}/_{32}$ in. of air gap is observed at either end of the straight edge.

   Where possible, the tubing ends should be aligned with the electric resistance weld seam offset to avoid states of high and localized triaxial stress at the intersection with girth welds.

e) Tubing Diameter

Only coiled tubing and pipe of the same outside diameter shall be welded together. The mismatch across outside diameters should not exceed 0.010 in. To achieve the desired outside diameter alignment, where possible the tubing may be rotated within the clamps in order to produce the minimum OD misalignment, as measured at four places around the proposed weld. Consideration should be given to cutting back the tubing until the mismatch is minimized.

An effective mismatch in tubing ID can also occur for tubing of equal wall thickness due to differences in ovality of the two mating tubing sections. The permitted step change in ID shall not exceed 10 % of the nominal wall thickness.

f) Wall Thickness

Wherever possible, the wall thickness of mating coiled tubing sections should be equal; however, variation in wall thickness should not exceed 5 % of the specified wall thickness. Whenever this is not possible, the owner of the tubing should be cautioned that the fatigue life of the proposed weld will be significantly reduced.

g) Tubing Ovality

Excessive out-of-roundness or ovality of the tubing cross section should be removed. This is especially critical for orbital TIG welding. Restoring the tubing to a near circular cross section is best accomplished with a special coiled tubular product circularizer. Alternatively, it may be possible to cut back the tubing until a more acceptable cross-section geometry for welding is found.

Maximum tubing wall offset due to tubing ovality should be limited to 0.010 in. Where this is not possible, a test should be performed on tube-to-tube welds in excessively ovalized coiled tubing, to determine its LCF performance. At minimum, the owner of the tubing string should be cautioned that the fatigue life of the completed weldment may be unacceptably low.

h) Surface Preparation and Cleaning (Before Welding)

LCF testing of tube-to-tube welds has shown a high sensitivity to the surface finish quality, cleanliness, and/or loss of wall section of the prepared surfaces from weld groove and flash removal operations. Transverse (circumferential) grinding or filing marks are particularly conducive to fatigue crack initiation. Similarly, local heat checks from contact of high-speed grinders with inner wall surfaces can act as hot spots for fatigue crack initiation. Great care shall therefore be taken to avoid surface damage from excessive filing, grinding, or gouging and to prevent other forms of mechanical damage to the inner tubing surfaces.

Surfaces prepared for welding should be free of filings and other debris. Both tubing ends should be cleaned with an emery cloth, wire brush, or similar means to remove rust and scale for approximately 6 in. from the edge preparation. Prior to welding, these surfaces shall be cleaned with denatured alcohol or similar quick evaporating solvents to remove all hydrocarbons and other contaminants that may provide a source of hydrogen atoms.

During welding, completed passes shall be cleaned by wire brush or grinding to sound metal prior to depositing successive weld beads.

i) Weld Profile and Dressing (After Welding)

The outer surface of tube-to-tube welds should be dressed flush with the coiled tubular outside diameter by removing the weld reinforcement (crown) prior to the performance of ultrasonic or radiographic NDE. Similar to the precautions to be taken in preparing the internal surfaces, great care shall also be taken to prevent damage to the outer surfaces or wall thinning by excessive grinding or filing. Transverse or circumferential grinding marks shall be removed by draw filing in the axial or longitudinal direction followed by sanding with emery cloth to obtain a smooth finish. All weld spatter, if encountered, shall be removed. Weld spatter is an indication of improper welding conditions such as lack of gas shielding or improper arc current/voltage characteristics and shall be rectified.

Root pass penetration should be kept to a minimum. In the ideal case, which is generally achievable only with the orbital GTAW process, the root pass profile would be flush with the inner tubing surface. No undercut is permitted.

Fillet weld profiles shall ensure sufficient throat thickness for strength requirements and avoid undercuts and excessive convexity. The requirements of acceptable fillet weld profiles specified in AWS or CWB should apply to fillet welds in coiled tubulars and end-fittings.

j) Welding Habitat

Because gas metal arc welding processes such as TIG are sensitive to strong cross winds (that interfere with the shielding gas stream), rain, and snow, a suitable habitat is required to protect both the weldment and welder from inclement weather conditions.

k) Chill Blocks

Because coiled tubing steels are generally heat-treated alloys, the heat input from welding may reduce the yield strength of the HAZ, typically by 5 % to 10 %, with the greater loss being attributed to manual TIG welding. To avoid this loss, local heat sinks or “chill blocks” fabricated from a copper alloy may be used. Since chill blocks are not readily accommodated by orbital welding equipment, some loss of yield strength in the HAZ will occur. Alternatively, coiled tubing welds performed without chill blocks may be placed in service provided allowance is made for appropriate weld joint efficiency as determined from PQR tensile tests.

When used, chill blocks should be placed sufficiently far from the welding arc to preclude weld metal contamination with copper. The location, size, and auxiliary cooling method of chill blocks should be included in the WPS.

5.9 Inspection of Coiled Tubular Welds

5.9.1 General

NDE for imperfections or defects of coiled tubing welds, particularly critical welds, is indispensable to ensure the integrity and expected material performance of the weld joint. However, the extent of NDE to be performed on any particular coiled tubular weld is a matter of agreement between the coiled tubular provider and customer. NDE of coiled tubing welds entails one or all of the following: visual inspection, liquid dye penetrant (PT), magnetic particle inspection (MT), ultrasonic testing (UT), and radiographic testing (RT).

5.9.2 NDE of Tube-to-Tube Welds

Tube-to-tube welds should be inspected visually both with the naked eye for gross imperfections or defects and with the aid of a magnifying glass to ensure the absence of transverse (circumferential) grinding or filing marks. A short straight edge should be used to ensure a flush weld profile.

At least UT or RT for NDE of tube-to-tube and pipe-to-pipe joints should be applied for through-thickness inspection of the weld. It is recommended that both RT and UT be used in conjunction because one method can generally identify flaws that may be undetected by the other. Ultrasonic inspections should include measurements of local wall thickness variations for at least 3 in. on either side of the girth joint.

By agreement between the coiled tubular service provider and customer, NDE of tube-to-tube or pipe-to-pipe welds may include hardness survey measurements across the weld to confirm conformance with PQR requirements.

5.9.3 NDE of Coiled Tubulars to End-fitting Welds

Coiled tubular end-fittings using fillet welds should be inspected visually for gross flaws or defects, undercut, sufficient leg size, sufficient throat, and weld profile. MT or PT should be used to inspect for surface or near-surface cracks, respectively.

Since it is generally difficult to perform ultrasonic inspection on fillet welds, end-fitting welds should be examined by radiographic methods.

By mutual agreement between the coiled tubing service provider and customer, NDE of end-fitting welds may include hardness survey measurements to confirm conformance with PQR requirements.

5.9.4 Engineering Critical Analysis

The quantitative results obtained from a particular NDE method shall be evaluated against a specified code or standard. There are currently no generally accepted and published codes or standards against which indications obtained by NDE for tube-to-tube welds in coiled tubing girth joints can be evaluated.

It is recommended that the NDE results be subjected to an engineering critical analysis in order to decide whether to accept, reject or repair the coiled tubular weld. The engineering critical analysis may be facilitated with reference to acceptance standards and criteria published in ASME *BPVC* Section IX and/or API 1104.

Ongoing research, supported by the coiled tubing industry, is in progress to quantify the effects of surface damage on LCF of coiled tubulars including welded girth joints. Wherever available, these results should be used as a guideline for the engineering critical analysis.

Whatever codes, standards, or engineering critical analysis methodology is to be used is a matter of mutual agreement between the coiled tubing service provider and customer.

5.9.5 Local Coiled Tubing Weld and Grind Repairs

Research has shown [48] that local weld repairs of any imperfections found in coiled tubing or coiled tubing weld areas are ineffective with respect to ultra-low cycle fatigue performance. Therefore, any defects in tube-to-tube or pipe-to-pipe welds should not be ground out and repaired with local spot welding techniques. Defective welds should be completely removed and the tubular prepared for re-welding.

The same research has shown, however, that minor surface imperfections can be repaired by grinding a smooth and shallow crater that does not appreciably reduce the wall thickness. A measurable recovery in LCF life that is lost due to the presence of the original defect could be realized. It was shown that the net fatigue life corresponds, in general, to that of a coiled tubing string of wall thickness equivalent to that of the reduced wall from the grind repair. Surface defects may therefore be removed from the coiled tubular weldment by gentle grinding to an agreed minimum wall thickness. See 9.21.

5.10 Field Management of Coiled Tubular Welds

5.10.1 Coiled Tubular Weld Identification and Location

Welds in coiled tubulars represent inhomogeneity in the tubing string. Tube-to-tube girth welds have reduced LCF life compared to the base tubing and provide potential sites for preferential corrosion attack [46]. The loading history for each weld should be monitored accurately to preclude undesirable string failures associated with the weld joint.

Documentation should be maintained to identify the weld, welder or welding operator, and welding sub-contractor. The weld identification would include, but not be limited to, the date, location, conditions of welding environment, CT string identification, remaining fatigue life, and WPS and PQR numbers used to perform the repair weld. This is best accomplished with the aid of computer management programs.

If possible, tube-to-tube welds should be located in sections of the tubing string that are subjected to the least amount of bend fatigue loading.

5.10.2 Weld Failure Investigations

The weld identification will assist in any post failure investigations. Root cause(s) identified in any weld failure investigation should be used to modify WPS datasheets, upgrade welder training and/or qualification requirements, or help rectify deficiency(s) in any aspects of the welding operation that can be related to the root cause(s) of weld failure.

To maintain ongoing quality and tube-to-tube weld performance and improve the statistical basis on which allowable working cycles are based, one CT service company removes all tube-to-tube welds after a specified number of fatigue cycles and rejoins the string with a similar repair weld. Two adjacent sections of approximately 7 ft (2.13 m) are removed prior to rejoining, one containing the girth weld and the other consisting of bare tubing. The remaining LCF life obtained from each tubing section is compared and recorded for ongoing quality and performance monitoring of tube-to-tube repair welds.

5.10.3 Safety and Operational Considerations

Due attention shall be paid to all safety considerations associated with all aspects of coiled tubing welding operations. Section 6 of [61] should be made for more detailed discussions of coiled tubing welding safety.

To achieve the desired coiled tubular weld performance and quality, it is essential that the welder or welding operator be granted sufficient time to perform quality workmanship without excess duress or undue pressures that are inherent in periods of downtime.

5.11 Welds in CT Product for Sour Service

Sour environments can result in sulphide stress cracking (SSC) in tube-to-tube welds. Manual tube-to-tube girth welds are not recommended for coiled tubing operations involving sour wells. Orbital TIG and other automatic or semi-automatic welding processes may be used to perform repair welding in sour service coiled tubing other than under-balanced drilling operations, provided that the welding is performed in accordance with a qualified WPS.

5.12 Butt Welds and Fittings

5.12.1 Tube-to-Tube Butt Welds

Coiled tubing may be supplied with tube-to-tube butt welds that are manufactured to written procedures. The ability of these welds to sustain bend cycle loading is generally substantially less than that of the tube itself. The classification of coiled tubing as CT70–CT110 is not affected by the presence of tube-to-tube welds.

5.12.2 End-fittings

Many strings of coiled tubing are supplied with an end-fitting that is manufactured from a different steel than the tubing itself. Such fittings are applied to written welding procedures and inspected nondestructively when cold. Special fittings are required for high pressure and for sour service work.

6 Corrosion—Effects and Mitigation in Steel Coiled Tubing

6.1 General

In-service steel coiled tubing often corrodes between jobs, generally due to lack of protection or improper protection. The coiled tubing may also corrode during actual service jobs due to exposure to wellbore fluids and materials or the local environment. Various forms of corrosion can have such detrimental effects as reduced axial load capacity, reduced pressure integrity (collapse and burst), reduced fatigue life, and an increase in susceptibility to sudden and unexpected premature failures. This section outlines types of corrosion mechanisms found in coiled tubulars and remedies for corrosion mitigation.

6.2 General Comments

The following are considerations for CT corrosion.

a) Safe and successful completion of coiled tubing service tasks and maximization of string life may be assisted by good storage habits and good pre- and post-job maintenance practices that minimize corrosion.

b) Exposure of unprotected coiled tubing to humid atmospheres produces iron oxides (rust) that can interfere with proper functioning of the injector gripper blocks and wellhead stripper and promote pitting of the steel coiled tubing.

c) Internal pitting corrosion can be caused by aqueous fluids left inside the tube after a job. It is extremely difficult to remove all fluids with wiper balls since some fluid will always stick to the wall of the tubing and run back down to the lowest level under gravity. Small pools of fluid form that can be highly corrosive.

d) The potential for steel coiled tubing problems increases with lack of utilization if the tubing is not properly protected during storage.

e) The operator should be aware of the nature of the downhole and flowline conditions and take appropriate measures. For example, if H_2S is expected, some higher strength steel coiled tubing may be inappropriate or stress-cracking inhibitors may be required.

f) Effective inventory management should be employed to ensure that tubulars are kept in service as much as possible, and their condition monitored at regular intervals.

g) Such procedures may vary depending upon location.

6.3 Corrosion and Environmental Cracking (EC) of Coiled Tubing

6.3.1 General

Corrosion damage and stress corrosion cracking together account for a major portion of reported carbon steel coiled tubing field failures, particularly when the interaction with other failure modes such as fatigue (e.g. corrosion fatigue), overloads (e.g. wall thinning), and manufacturing (e.g. localized attack in welds) are taken into account. Because of the complexity of variables involved, systematic derating of coiled tubing serviceability in corrosive service is often arbitrary and difficult, even when using full-length NDE. Therefore, this section provides only guidelines and best practices, which are likely to decrease the risk of steel coiled tubing failures in corrosive environments.

6.3.2 Corrosion

Types of corrosion damage applicable to coiled tubing are listed below.

a) General Corrosion

This manifests as uniform wall thinning of the coiled tubing. Though not common in coiled tubing operations involving short-duration exposures (<30 hours), wall-thinning corrosion is accelerated by the degree of cold work and the extent of galvanic coupling of the coiled tubing to more passive corrosion-resistant materials downhole.

General corrosion may be accelerated along the seam weld line in the region where the grain flow is preferentially toward the ID or OD of the tube.

b) Galvanic Corrosion

Like general corrosion, galvanic corrosion is not a problem for use of steel coiled tubing on wells containing low alloy steel components. It can be a serious problem when low-alloy carbon steel coiled tubing is used in corrosive wells containing corrosion-resistant alloys, such as duplex stainless steels, nickel-based super alloys, and titanium alloys. For such wells, electrochemical contact of the coiled tubing with the corrosion-resistant alloys in the presence of poorly inhibited well fluids, workover fluids, or acids can result in accelerated corrosion of the coiled tubing. The more passive alloy will increase the wall thinning of the more anodic carbon steel coiled tubing.

For example, 2205 duplex steel and alloy 718 have been shown to increase the corrosion rates of 4130 steels by up to 50 % in 25 % NaCl + 1.0 psi H_2S + 1200 psi CO_2 at 200 °C (392 °F) and by up to 400 % in 12 ppg $CaCl_2$ + 400 psi CO_2 packer fluid at 177 °C to 200 °C (350 °F to 392 °F). Such effects shall be minimized when designing coiled tubing jobs for corrosion-resistant alloy wells by use of inhibition, by limiting the duration of the exposure (<30 hours), or by using thicker wall coiled tubing.

c) Atmospheric and Filiform Corrosion

Coiled tubulars stored with remnant fluids in the ID, splashed fluid on the OD, or in areas of high humidity and warm climate with aerated conditions can suffer accelerated corrosion on the OD (rust) and localized randomly distributed corrosion streaks on the ID (filiform). Filiform corrosion appears as streaks of long, narrow pits.

Time-of-wetness is also a critical variable. Wetness is generally greater on the inside wraps than on the outer wraps of a spool. Fluids trapped in the inner wraps due to condensation with temperature changes can result in permanent wetness of the inner wraps. Condensing water solutions may contain carbon dioxide CO_2, forming carbonic acid, and certain chlorides, sulphates, and sulphides. Condensation may also occur inside the coiled tubing, washing salts from the ID to the bottom of the wrap under gravity.

Elimination of aqueous fluids from the tubing ID will eliminate filiform corrosion.

Sulphur compounds are a major cause of increased corrosion in industrial areas.

The ID corrosion manifests as sharp and narrow pits that grow deep within a short time during storage or transit and could result in leaks.

To minimize damage due to internal corrosion, during storage or transit, coiled tubing strings should be displaced with an inhibitor and blown dry with inert gas and seal capped. Various vapor corrosion inhibitors are commercially available for providing protection during storage and transoceanic shipments.

If the tubing is being placed in storage or not in use, an inhibitor should be utilized. This should be done as quickly as possible at completion of job. Ideally this process would take place during the last run out of the hole, where possible.

d) Pitting and Crevice Corrosion

Pitting and crevice corrosion of coiled tubing occurs primarily in hot acidic environments (low pH) and gets worse with increasing temperature. It can also occur in aerated brines under atmospheric conditions. These are more common forms of coiled tubing corrosion damage than general corrosion and result in leaks or premature fatigue life loss. Some forms of pitting can represent a more severe form of corrosion than uniform metal loss. This is due to extensive localized wall loss that may compromise the integrity of the string.

Effective inhibition is a necessary control for such damage, even for short-duration jobs, as pit depths are not reliably monitored during service. Also crevices formed by poor contact at seals, downhole connectors, or other downhole tools should be avoided.

High flow rates, such as those that occur in velocity strings or coiled tubing completions, may increase pitting rates.

e) Marine Corrosion

Corrosion of coiled tubing occurs through contact with marine salts, primarily sodium chloride (NaCl), but also with potassium (K^+) magnesium (Mg^{++}), calcium (Ca^{++}), and sulphate (SO_4^{--}) ions. Chloride salts are hygroscopic, and the chloride ion promotes pitting in carbon steels. Once pitting is established, penetration into the steel can occur at more accelerated rates. It has been observed that steel will corrode 12 times faster when located 24.4 m (80 ft) from the coastline than when it is located 244 m (800 ft) from the coastline due to the level of marine salts that are present at the two locations. Note, however, that sea-salt can be found at great distances from a sea coastline, typically 160 km (100 mi) inland, and can descend as both a dry dust and in rain-fall. Time of wetness becomes a critical factor in determining the level of corrosion caused in such circumstances. Salt tends to increase time-of-wetness by absorbing water at lower humidity.

6.4 Effects of Corrosion on Coiled Tubing Serviceability

6.4.1 Material loss due to the various forms of corrosion described above has several specific detrimental effects such as:

a) reduced usable strength of coiled tubing due to wall thinning and pits,

b) reduced pressure integrity—collapse, burst, and yield,

c) reduced service cycles due to corrosion fatigue,

d) increased susceptibility to premature fracture due to corrosion and pits acting as initiators for H_2S and/or CO_2 related stress corrosion cracks, and/or

e) reduced service life in deviated wells due to increased erosion-corrosion.

6.4.2 Corrosion and rust on the OD surface have the following undesirable effects:

a) poorer seal at the stripper and blowout preventers (BOPs),

b) deterioration of the tubing surface weakens the mechanical integrity and provides sites for subsequent corrosion following exposure to wellbore or treatment fluids,

c) elastomers used in well pressure control equipment may be damaged or rendered less effective by a rough tubing surface,

d) accumulated rust or scale can affect the depth measurement and tubing monitoring equipment, and/or

e) the snubbing force required to run the tubing through the stripper on a high-pressure well may be significantly increased by a rough tubing surface.

6.5 Corrosive Fluids in Coiled Tubing Service

Specific considerations for various fluids are as follows.

a) Production Fluids

In production fluids with acid gases (H_2S + CO_2), the pH of the aqueous phase can be very low. For temperatures of 68 °F to 212 °F, pH » 3.4 at PH_2S + PCO_2 = 0.147 ksi; pH » 3.0 at PH_2S + PCO_2 = 1.47 ksi, and pH » 5.0 at PH_2S + PCO_2 = 0.147 psi. Production water containing brines increase the corrosivity of production fluids. Multiphase fluids as well as fluid velocity are also critical considerations, particularly in the use of coiled tubing for production or velocity strings.

b) Workover and Completion Fluids

Brines used in workovers and completions increase corrosivity as temperature increases from 49 °C (120 °F) to 204 °C (400 °F). The effect increases with the specific gravity (SG) of the brine and the degree of aeration. For example, at 102 °C (216 °F), NaCl brine with SG = 1.05 corrodes low alloy steel at the rate of <5 mpy after 8 hours exposure when deaerated, but under aerated conditions, the corrosion rate can be up to 40 mpy.

Similarly, a high density brine such as $CaBr_2$-$ZnBr_2$, SG = 2.3, can produce a corrosion rate of » 25 mpy at 149 °C (300 °F), while $CaCl_2$-$CaBr_2$, SG = 1.45, produces a corrosion rate of <10 mpy at 149 °C (300 °F).

c) Acidizing Fluids

Stimulation and well cleanout acids used in coiled tubing jobs require special care to avoid aeration. Corrosion rates can increase by up to 5 to 7x due to aeration. The most danger of aeration occurs due to exposure of coiled tubing to air between coiled tubing runs, and between job locations, even though the acids used are deaerated. Spent acids are also more corrosive than fresh acids due to oxygen pickup as well as deterioration of the inhibitor. When acid cleanouts are enhanced with gas, such as during nitrified acid descaling, increased corrosion rates and loss of inhibitor effectiveness can result due to more turbulence and slug behavior of the acid inside the tubing.

6.6 Environmental Cracking

6.6.1 General

Coiled tubing strength and reliability can be seriously reduced by exposure to wet hydrogen sulfide (H_2S). Hydrogen sulfide is noncorrosive in the absence of moisture, so the risk of corrosion or cracking in dry gas wells containing H_2S is low. However, a highly corrosive environment occurs when moisture in present and this may affect coiled tubing integrity. Generally speaking, $H_2S + Fe + H_2O = FeS_x + 2H + H_2O$.

The released hydrogen atoms may enter the steel matrix and cause various forms of hydrogen-related damage, including hydrogen blistering and various forms of hydrogen cracking including hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC), surface fissuring, and SSC. Hydrogen in the steel matrix may also cause embrittlement that can reduce steel ductility, promote brittle fracture, and potentially reduce fatigue life in CT. Higher strength CT is, of course, more susceptible to EC than lower strength CT. The industry has learned through years of experience and by laboratory testing that the primary environmental variables related to cracking of coiled tubing in H_2S containing aqueous fluids are the *in situ* pH of the water phase and H_2S partial pressure. Low pH (more acidic) and high H_2S partial pressure increase the likelihood of EC of CT. Coiled tubing cracking in wet H_2S environments may manifest itself in different ways, depending on the environmental severity, duration of exposure, steel and weld metallurgy, strength, chemistry, heat treatment, residual stress, pre-existing mechanical damage or cold work, and prevalent service stress.

It is recommended that users check the sour service properties of coiled tubing prior to use.

The service life for tubing used in sour service can be drastically reduced to about one-third of the service life in nonsour applications.

It is recommended that field repairs are not performed on materials that will be used in sour service.

6.6.2 Hydrogen Blistering

Surface bumps are caused by accumulated molecular hydrogen, which forms elongated subsurface voids. The molecular hydrogen is from coalescence of atomic hydrogen generated during corrosion, which diffuses into the steel. Blistering is independent of applied stress. Susceptibility increases with increase in content of nonmetallic inclusions (manganese sulfide), banded microstructure, and pre-existing delaminations in the steel. This damage is more common in lower strength coiled tubing grades (CT70). Control is achieved through selection of coiled tubing metallurgy and/or the use of corrosion inhibition.

6.6.3 HIC

HIC is similar to blistering but exists only subsurface and joins in a through-wall direction in a stepwise pattern to result in failure of the coiled tubing. HIC is principally responsible for axial (longitudinal) failures of coiled tubing, loss of burst and collapse properties, and is independent of the prevalent operating stress. HIC is common (but not exclusively) with moderate to high-strength coiled tubing grades (CT80 and above) and with coiled tubing that contains pre-existing mechanical damage or severe cold work. Control is achieved by: (1) limiting % Mn (<1.2 %), % S, and % C in the coiled tubing; (2) limiting the microhardness within the segregation bands in the coiled tubing to 300 VHN; and (3) limiting hydrogen absorption by using corrosion inhibition.

6.6.4 SOHIC

SOHIC is like HIC except that the HIC cracks are shorter in length, are stacked rather than stepped in the through-wall direction, and are oriented and propagate in response to the prevalent applied and/or residual stresses. Unlike HIC, inclusion stringers are not required initiation sites, rather grain boundaries, segregation bands, and in-homogeneities in the microstructure can initiate SOHIC cracks. Though measures that control HIC are beneficial for control of SOHIC, weld residual stress and operating stress are critical factors and should together be kept to << 80 % of specified yield strength.

6.6.5 Surface Fissuring

Surface fissures are cracks initiated as SSC by wet H_2S corrosion, but only penetrate the coiled tubing wall to about 5 mils (0.13 mm) deep, and the root gets blunted by corrosion. Surface fissuring manifests itself as shallow parallel surfaces that are perpendicular to the applied tensile loading. This type of cracking is influenced by the residual and operating stresses in the coiled tubing string, as well as surface cold work, and can occur in the ID or OD of the coiled tubing. The cracking can also occur selectively along welds in the coiled tubing.

6.6.6 Sulfide Stress Cracking

SSC is the most severe form of hydrogen-related cracking and results in brittle failure caused by applied or residual stresses along with significant hydrogen absorption from wet H_2S corrosion. High-strength coiled tubing grades are generally more susceptible to SSC than lower strength grades. And laboratory testing has shown [44] that the welds (seam weld, bias weld, and especially butt welds) are more susceptible to SSC than the parent metal or body of the CT. The amount of strain cycling (LCF) to which the CT has been subjected before H_2S exposure is also a factor but may not be significant until over 50 % utilization has occurred [44]. Another study [59] concluded that based on transverse SSC tests conducted at 50 % to 100 % of the specified minimum yield strength, no increase in susceptibility to SSC was observed with cyclic cold work.

Figure 1 of [44] shows the “No SSC Zone” and “SSC Zone” for CT90 with respect to the two main environmental conditions: (1) *in situ* pH of the water phase and (2) H_2S partial pressure. This figure indicates that CT operated in Domains 1 and 2 environments are unlikely to fail by SSC whereas SSC susceptibility is high in Domain 3 environments. The area of uncertainty in Figure 1 is where test laboratory samples exhibited surface fissuring.

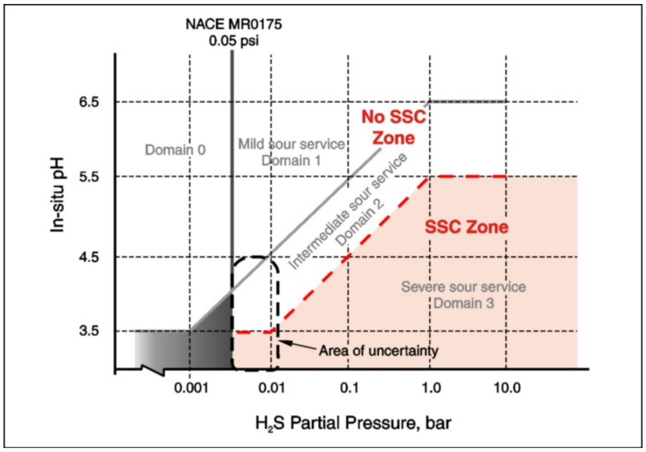


Figure 1—SSC Zoning (Excluding Tube-to-Tube Welds)

6.7 Specific Guidelines to Reduce the Risk of Coiled Tubing Environmental Cracking Failures in Wet Sour Wells

Use of coiled tubing in sour wells requires special care due to the factors discussed above. Some specific guidelines to reduce risk of EC are as follows.

a) Always know the environment in which the CT may be operated. Control of the environment to which the coil tubing may be exposed may be necessary by, for example, introducing a brine to the wellbore and/or adding a chemical inhibitor. For additional protection, swab the OD of the coiled tubing with an appropriate inhibitor. Be aware that acid, which has an extremely low pH, mixed with H_2S downhole will significantly increase cracking susceptibility of the coiled tubing. Also, note that H_2S in brine, with or without CO_2, is more corrosive than H_2S in oil.

b) Hardness and strength of the coiled tubing are obviously important parameters with respect to susceptibility of EC. However, be aware that used low-strength CT may contain OD mechanical surface damage (and therefore increasing local hardness), which therefore increases EC susceptibility.

c) Tube-to-tube (butt) welds are more susceptible to SSC than bias welds or seam welds. Use of coiled tubing field tube-to-tube welds for sour service should be avoided if possible. If the use of tube-to-tube welds is necessary, then minimize cycling of tube-to-tube welds.

d) Consider full-body NDE after significant H_2S exposure(s). H_2S can degrade the tubing (surface fissuring, for example), leading to pinholes at a later date. Hydrostatic pressure testing should be performed to assure pressure integrity.

e) If full-body NDE is not available, it is recommended to perform a careful visual inspection of the coiled tubing outside diameter after the first 10 cycles when used in continuous H_2S service or in numerous acidizing or sour gas well jobs.

f) Hydrogen bake-out treatments [e.g. 150 °C (300 °F) for 48 hours] may be performed after an extended duration of service in a sour well to extend the life of the coiled tubing string. The effectiveness of this treatment depends on whether there has been irreversible hydrogen damage to the coiled tubing.

g) End connectors induce mechanical damage, which makes the coiled tubing more vulnerable to EC. It is recommended to cut off connector damaged portions after exposure to sour wells.

h) Wet H_2S assisted damage of coiled tubing can be cumulative with respect to fatigue damage. Therefore, coiled tubing that has accumulated significant cycles in a sour well, e.g. during cleanouts and workovers, will be more degraded than coiled tubing used continuously, e.g. velocity string, in a sour well and should therefore be derated.

6.8 Corrosion Related to Inserts

Coiled tubing may be supplied with wireline or other inserts. Wireline, for example, may be pumped into the coiled tubing on the reel, and some water may remain inside the coiled tubing. Fluids trapped next to wireline or other insert may cause internal corrosion.

If tubing with wireline is to stand for any length of time, the insert should be removed from the tubing. The inside surface tubing should then be wiped with wiper balls to remove most of the fluid, and the inside surface of the tubing should then be passivated and dried with dry, warm nitrogen.

Where possible, wireline should only be re-inserted into coiled tubing strings immediately prior to performing service work with the tubing. It is also common practice to apply internal corrosion inhibitor after the wireline injection and displace with nitrogen.

7 String Protection

7.1 Protection for Coiled Tubing

7.1.1 Nitrogen Purge

To assist with preserving coiled tubing after use, it is recommended to displace internal fluids with wiper plugs and nitrogen. The volume (V_N) of nitrogen to be used may be calculated from:

$$V_N = L \pi d^2 / 96 \quad (1)$$

where

V_N is the volume of nitrogen (ft^3);

L is the length of coiled tubing (ft);

d is the maximum ID (in.).

The minimum recommended amount of nitrogen for displacement is two times the internal string volume. Additionally, the amount of water vapor in the nitrogen passing out of the tubing may be measured with a relative humidity meter to be compared to the dryness of nitrogen going in.

When purging is finished, the tube ends should be capped or plugged.

7.1.2 Freeze-proofing and Internal Protection

Tubing shipped to colder locations should be flushed with anti-freeze. Tubing that will be stored for a long period after shipment should be internally protected by coating the internal surface with an appropriate coating.

This may be accomplished by entrapping a slug of the coating fluid between wiper pigs and blowing it through the tubing on the storage reel.

7.1.3 External Coatings

Coiled tubing may be coated with a nonpermanent external coating. These coatings may be washed from or evaporate from the surface over a period of time or during trans-shipment.

7.1.4 Wrapping and Crating

Tubing outer wraps may be protected by wrapping with plastic sheet and by adding slats around the outer edges of the shipping reel. Reels should be supplied with anti-movement attachments for shipment.

In cases where the shipping reel is to be lifted on to a boat or an offshore rig, it may be necessary to certify the lifting device and the reel lifting points.

7.1.5 Storage Prior to Use

Prior to use, coiled tubing should be stored under cover wherever possible. If a positive pressure is applied inside the tube, the gauge should be checked at regular intervals and the inert gas replenished if necessary.

7.2 Coiled Tubular Reel Dimension Effects

7.2.1 Yield Radius (R_Y) and Reel Dimensions

During manufacture, inspection, testing, removal of imperfections, coating, and while in use, coiled tubing strings are moved from one reel to another and suffer from ultra-low cycle fatigue during these operations. As the tubing is bent onto the reel, it is bent past the yield radius, which is defined by:

$$R_Y = (E/S_y)(D/2) \tag{2}$$

where

R_Y is the yield radius (in.);

E is Young's Modulus for material (lb/in.^{2});

S_y is the specified yield strength of material (lb/in.^{2});

D is the specified OD of tubing (in.).

Annex C compares yield radii (R_Y), shipping spool core radii (R_S), tubing reel core radii (R_{REEL}), and tubing guide arch radii (R_{TGA}) for various coiled tubing sizes. It is recommended that the smallest reel core diameter not be less than 40 times the diameter of the tubing.

7.2.2 Value of Young's Modulus

Values for Young's modulus (E) for steel coiled tubular materials have been found in the range 27×10^6 to 32×10^6 psi. A value of 30×10^6 psi is commonly used, but care should be taken in determining a value for used coiled tubing.

8 Inspection

8.1 Used Coiled Tubulars

Used coiled tubing is tubing that has been at least once over the CT unit guide arch and into the well. Changes in length, diameter, and wall thickness may introduce the following additional items when working with used coiled tubing.

a) Outside Diameter of Used Coiled Tubing

Maximum ($D_{p,max}$) and minimum ($D_{p,min}$) permitted outside diameters for used coiled tubing are determined by injector considerations and shall be agreed upon during contract review prior to the performance of an inspection or coiled tubing job.

In order to perform the computation, the average diameter (D_{av}) is computed using Equation (3) from a minimum of four diameter readings (D_1, D_2, D_3, and D_4) as shown in Figure A.1, at approximately 90° intervals around the tubing, and averaged. For example:

$$D_{av} = (D_1 + D_2 + D_3 + D_4)/4 \quad (3)$$

where

D_{av} is the calculated average diameter for used coiled tubing (in.);

D_1, D_2, D_3, and D_4 are four approximately equidistant outside diameter measurements (AA, BB, CC, and DD in Figure A.1) made at the same location along the tube and include the values of D_{max} and D_{min}.

The D_{av} is rounded to the closest 0.001 in.

b) Wall Thickness of Used Coiled Tubing

The minimum remaining wall thickness of used coiled tubing should be determined in contract review prior to inspection of the string. Measuring techniques for wall thickness are given in 9.7 and 9.8.

The average wall thickness ($t_{av,s}$) for used coiled tubing is computed from four or more wall thickness measurements that are made with a suitably calibrated gauge at roughly equal intervals around the tubing, with no measurements made that could be construed as including a contribution from internal flash. The average wall thickness is computed by:

$$t_{av,s} = (\Sigma t_i)/n \quad (4)$$

where

$t_{av,s}$ is the calculated average wall thickness for used coiled tubing (in.);

t_i are the wall thickness readings, which include t_m (the minimum wall thickness reading), taken at approximately equidistant locations around the circumference of the tubing at the same axial location (in.);

n is the number of readings taken around the tubing.

For t_i, measurements should not be made to the cap of any internal flash that may be present. The average wall thickness is rounded to the closest 0.001 in.

c) Pipe Metal Cross-sectional Area for Used Coiled Tubing ($A_{m,s}$)

The pipe metal cross-sectional area for used coiled tubing is computed from measurements made on the diameter and wall thickness in accordance with the techniques in 9.5.

The computed pipe metal cross-sectional area is calculated by (see A.2.2 for an example calculation):

$$A_{m,s} = \pi t_{av,s}(D_{av,s} - t_{av,s}) \quad (5)$$

The cross-sectional area of the tubing material is reported to the nearest 0.0001 in.^{2}.

d) Length of Used Coiled Tubing

Because of cycling, hanging under its own weight, and pulling during service, the tubing generally stretches and true lengths of tube sections between skelp-end welds may change during use. Pieces are also removed for various string maintenance operations.

The length of coiled tubing is measured by mechanical counters that depend upon contact between the tubular and a wheel (or wheels) in the counter. In cases where several counters are employed, the largest reading may be taken.

As a used string changes length, results from accurate length measurements, an inspection for the location of skelp-end and tube-to-tube welds may be used to update the as-manufactured locations of these welds.

Length measurements shall be recorded to the nearest 30 cm (1 ft).

8.2 Drifting of Used Coiled Tubing

8.2.1 Used coiled tubing should be drift tested whenever a reduction in ID that is detrimental to the required performance and functionality is suspected. Reasons for drifting used CT may include the following.

a) The coiled tubing is suspected of containing high internal flash.

b) The coiled tubing is suspected of containing sections of high ovality.

c) The coiled tubing is suspected of containing dents or excessively crimped areas caused by prior operations with the tubing.

d) Tube-to-tube welds have been placed in the tubing and a check for a minimum internal diameter is required.

e) The coiled tubing has been pulled excessively and may have “necked.”

f) When required by the end-user or owner of the CT.

g) After pumping solid laden fluids or cement.

8.2.2 A tool of known diameter is passed down the tubing. Passage of a drift ball through tubing in a reel at the surface does not always indicate that a tool of a known outside diameter will pass down the tubing. Under these circumstances the operator should check that the tubing, when installed, will pass the tool.

Either steel or nylon drift balls may be employed.

a) Drifting of Used Coiled Tubing with Cylindrical Drift

In order to determine that a tool will pass through an installed coiled tubular, the operator should drift the tubing with a drift that has a diameter and a length that both exceed those of the tool to be used.

b) Relationship of Weld Flash and Drift Ball

Annex C, Table C.2 shows the relation between standard drift balls (column 3) and the inside bore of the coiled tubing (column 4).

c) Area Covered by Drift Ball

Column 5 of Table C.2 shows the ratio of the cross section of the drift ball to the flow area of the tubing, calculated from $(d_{ball}/d)^2$ and expressed in percent. Figure 2 provides an illustration.

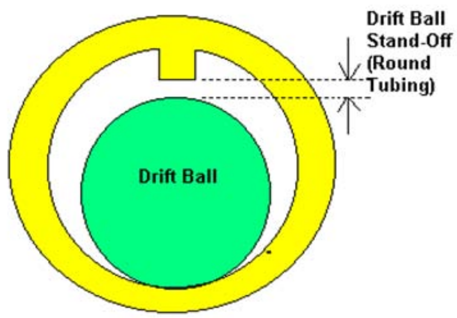


Figure 2—Drift-ball Standoff in Perfectly Round Coiled Tubing

8.3 Drift Ball Standoff for Flash-free Coiled Tubing ($S_{R,O}$)

8.3.1 General

The smallest standoff between the specified gauge ball and the distance across the inner diameter of the tubing at the location of the flash is given in column 6 of Table C.2.

This column is calculated for the worst case of a permitted internal flash column of 0.5 mm (0.020 in.).

8.3.2 Standoff for Round Tubing with Internal Flash Present (S_R)

The standoff for a drift ball for perfectly round tubing with the maximum permitted internal flash present is illustrated in Figure 3 and calculated by:

$$S_R = D - 2t - \mathrm{MFH} \tag{6}$$

where

D is the specified OD (in.);

t is the specified wall thickness (in.);

MFH is the maximum flash height (in.).

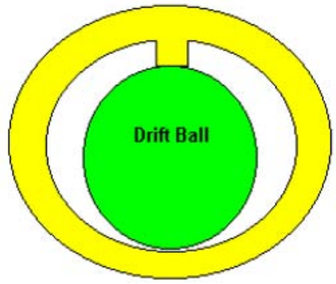


Figure 3—Drift-ball in Ovalled Coiled Tubing

8.3.3 The Minimum Opening at the Minimum Inside Diameter With Flash Present (Λ)

In columns 11 and 14 of Table C.2, the minimum opening between with the internal flash located at the minimum diameter is computed, based upon 2 % and 5 % ovality. The minimum opening is calculated by:

$$\Lambda = D_{\text{min}}(X\ \%\ \text{Ovality}) - 2t - \text{MFH} \quad (7)$$

where

$D_{\text{min}}(X\ \%\ \text{Ovality})$	is the minimum OD at a specified location with a specified ovality (in.);
t	is the specified wall thickness (in.);
MFH	is the maximum flash height (in.).

8.4 Pressure Testing of Used Strings

Hydrostatic testing is recommended after butt weld repair and immediately prior to using the tubing. The test pressure should not exceed the calculated value from:

$$P = 1.60\ f_{\text{service}}\ S_{\text{y}}\ t_{\text{service}}/D \quad (8)$$

where

P	hydrostatic test pressure (psig), rounded to the nearest 100 psi;
f_{service}	function of maximum anticipated circulating pressure (ranges from 1 to 1.25);
S_{y}	specified minimum yield strength (psig);
t_{service}	minimum wall thickness of the thinnest wall section of the tubing on the spool as determined by measurement (in.);
D	specified OD (in.).

The value of f_{service} should be determined and may depend upon the category of service and the minimum wall thickness of the tubular. The test should be in accordance with API 5ST.

Pressure testing after welding should be tested to pressure of original parent string.

8.5 Imperfections in Coiled Tubing

The detection of imperfections depends partially upon the design and sensitivity of the inspection equipment and partially upon the training and experience of the inspector. Understanding and correctly classifying detected imperfections so that they can be removed prior to growth to critical proportion or their effect upon the local fatigue value can be calculated is crucial to effective tubular operation.

The relative frequency of occurrence depends partially upon the training of the user of the coiled tubing to avoid adding imperfections during daily operations.

Annex D shows typical service-induced imperfections.

Many imperfections are dependent upon the coiled tubing rig type, the fluids employed and produced, locations where and how the tubing is stored, and the service pressures used. Those manufacturing imperfections and defects that escape detection during mill inspection will be present during the tubing's service life and could lead to premature failure. The following problems and imperfections have been noted in coiled tubing.

a) Internal and External Pitting

   CT external corrosion is most often related to its exposure to wellbore, completion, and/or workover fluids without inhibition. Recommended forms of corrosion inhibition for coiled tubing are given in Section 7.

   1) Residual Fluids Left Inside New Tubing from Manufacture and Transportation

      These may be detected during early inspections at regular intervals corresponding to the 6 o'clock positions of the tubing on the storage reel. Thus, as-manufactured coiled tubing that may be left sitting for long periods may corrode at these locations, even when back-filled with nitrogen. Such corrosion will often be in the form of pitting. The corroded area might be relatively small, as only a small, elliptically shaped pool may form from the fluid that moves down the tubing wall under gravity.

   2) Residual Fluids Left in the Tube from Performing Coiled Tubing Operations

      Such fluids may be strong acids and brines used in well operations (e.g. HCl, KCl), dilute acids from insufficient washing of the tubing, and seawater from the washing process in offshore operations. Thus, used steel coiled tubing that may be left sitting for long periods may corrode even when back-filled with nitrogen. Such corrosion will often be in the form of pitting located at the 6 o'clock position while the tubing is stored. The corroded area might be relatively small and such areas may ultimately crack under the residual tensile force in the tubing wall.

      External pitting is often caused by the same means as the internal pitting, since the same fluids may be involved. External pitting is also caused by fluids that collect in the crevices that are created between the wraps of the coiled tubing, and may become increasingly severe toward the inner wraps. Tubing left in the rain may have corrosive fluids or dried salts re-dissolving from the outer wraps and settling nearer to the inner wraps where the humidity remains high and evaporation may be slow. Elongated rows of pits have also been observed that resulted from corrosion between the tubing and sides of the storage reel.

      In hang-off applications, the pitting types that are commonly found in oilfield tubing should be anticipated.

b) Reduction of Wall Thickness of Coiled Tubing

   For the purpose of this document, six forms of wall thinning occur as follows.

   1) General Corrosion

      General corrosion occurs from leaving the pipe wall in a corrosive environment such as acid stimulation and may be either uniform around the pipe wall or localized to certain areas.

2) General Erosion

General erosion in coiled tubing is caused by abrasive materials in the fluids that are being pumped through and around the coiled tubing. These are typically sand-ladened fluids and drill cuttings.

3) Localized Abrasion

When tubing is rubbed against the side of the well, the OD will wear locally. This may occur due to pulling the tubing against the casing or formation in deviated wells, or because of the natural bend in the tubing, or well tubing or casing, and has been observed at regular intervals due to the buckling that may occur when tubing is pushed into deviated and horizontal wells.

4) Gouges

Metal may be removed from the outer surface of the tubing in several ways. Larger diameters of tubing may exhibit some shallow “chafing” that is caused by contact with the sides of the storage reel. Hanging up against hard objects either in the well or any part of the rig's mechanical system may gouge the tubing. Gouging may range from quite shallow elongated longitudinal scratch-like marks to deep regions of wall loss at which substantial volumes of metal are removed.

5) Overstretched Conditions

Wall reduction may occur as “necking,” indicating that crystal slip planes in the carbon steel coiled tubing steel have moved against each other from their initial positions and that the section of tubing has been taken past its yield strength.

6) Wall Thinning from Ballooning

When tubing is maintained at or close to its yield point, the tubing may balloon and a small amount of elongation occurs that results in some thinning of the wall.

c) Damage to Coiled Tubing from Surface Handling Equipment

1) Gripper Block Damage

Various forms of gripper blocks in the tubing injection system may leave small marks over 360° of the circumference of the outer tubing surface, which may locally increase the hardness and cause indentations.

2) Injector Ring Damage

Other forms of gripping the tubing during injection include tight rings. These may indent the tubing.

3) Alignment Between the Pack-off and Guide Arch

There should be no axial misalignment between the tubing guide arch and the top of the injector, or between the bottom of the injector and the BOP stack, or there is the possibility of buckling the tubing on the way into the hole.

4) Spooling Damage

When one section of the tubing is moved against the adjacent wrap or against the sides of the reel (either shipping reel or storage reel), transverse chafing may occur as the two metal components move relative to each other. This is most likely to occur where there is: (1) a high “fleet angle” between the coiled tubing going on or coming off the reel and the wraps on the reel and (2) when the tubing is being wound too tightly against the next wrap or the side of the reel. This type of damage can be minimized by use of the following.

i) Distance Adjustment

Increasing the distance from the pay-off reel to the level-wind and take-up reels and performing the reeling operation slowly.

ii) Tubing Lubrication

Outer surface lubrication with a suitable lubricant can lower the sliding friction between the tubing wraps and the reels and thereby reduce the possibility of this type of damage.

iii) Spoke Dents

A second form of damage occurs when winding low-strength tubing on to open-sided reels with spokes. Dents may occur in the tubing where they press up against the side of the spokes.

d) Ultra-low Bend Cycle Fatigue

1) Fatigue

Coiled tubing is plastically deformed both when it is bent over the reel and the tubing guide arch and when it is straightened again. This plastic deformation results in cumulative and regressive changes in the material. Most fatigue in coiled tubing operations occurs at the reel and guide arch; some occurs due to tensile overload in the well. This is classed as ultra-low cycle fatigue. The fatigue that is created by reeling and passage over the guide arch may be predicted and used as part of a successful derating program. Section 11 outlines fatigue measurements.

Fatigue damage per cycle is greater at a higher number of cycles undergone than at a lower number of cycles. Thus, more damage is accumulated in later cycles of the tubing into and out of a well than in earlier cycles. The accumulated fatigue in coiled tubing may result in the problems that are outlined below and may be accelerated by the presence of imperfections in the tubing. A fatigue test cycle performed for a test is different than a field coiled tubing use cycle or trip. There are three test cycles per one trip in and out of the hole. Care should be taken when reviewing fatigue data and using the information for tracking the life of a coiled tubing string.

2) Fatigue Cracking

Ultra-low cycle fatigue eventually leads to the formation of micro-cracking. Under continued cycling, fatigue cracks propagate through the tube wall until it is breached. In cases of high pressure, the crack may propagate rapidly around the circumference of the tubing, possibly causing the pipe to part. Fatigue cracking may also preferentially begin at the bases of transversely oriented damage to the pipe surfaces, including transverse cuts, inner and outer surface pits, outer surface gouges, and other damage.

3) Shape and Diameter Changes

Cyclic bending leads to changes in shape and diameter, which may also lead to changes in mechanical properties, notably tensile and yield strength, and collapse resistance. Thinning and ovalling can lead to potential problems with surface equipment. Observations regarding diametrical changes in coiled tubing are as follows.

i) Coiled tubing diameter increases as the tubing is fatigue cycled by bending under internal pressure with increasing change per cycle as the number of cycles rises.

ii) Diameter growth rate increases with internal pressure.

iii) Large diameter coiled tubing grows relatively more quickly than smaller diameter coiled tubing as a percentage of its specified diameter.

iv) Thinner coiled tubing of the same diameter grows more rapidly than thicker coiled tubing.

v) Higher yield strength coiled tubing shows less diametrical growth than lower grades.

vi) Smaller bending radii leads to more rapid growth of the outside diameter.

vii) Mechanical limitations placed on the outside diameter by the rig may cause situations where the effective life of specific sections of the tubing at higher pressures may be only a fraction of the available fatigue life.

viii) For ovality, a typical operation limit is $\Theta = 5$ %. However, measurements should be made on the bushings of the stripper of the rig, which are made of brass and have an internal diameter that is slightly larger than the specified outside diameter of the coiled tubing.

ix) During diametrical growth, a redistribution of the material also occurs with the top and bottom walls tending to thin more rapidly than the sides.

x) Surface rippling sometimes occurs with cycled pressured tubing on the “top” surface with a typical period of twice the diameter of the tube. This rippling typically occurs late in the life of the tubing.

e) Reduction of Yield Strength

Reduction of yield strength commonly occurs during the first few cycles of the coiled tubing and continues throughout cycling, and thus those factors affected by yield strength should be considered relatively early in the life of the use of the coiled tubing. The tendency is for the yield strength to lower rapidly and then to stabilize, but no rules have been presented for an accurate assessment of the stabilized yield strength. The loss of yield strength is commonly referred to as the Bauschinger Effect. Combinations of ovality and reduction of yield strength may lead to severe lowering of the collapse pressure.

f) Loss of Elongation

The minimum initial elongation of new tubulars is defined in API 5ST as:

$$e = kA^{0.2}/U^{0.9} \tag{9}$$

where

e is elongation;

A is the measured cross-sectional area of the tubing when as-manufactured (in.^{2});

U is the ultimate tensile strength of the tubing (psi);

k is the constant for the grade of steel tubing.

Elongation is measured during initial tensile testing and reported. This is a maximum value for the section of tubing between the skelp-end welds. In the case of coiled tubing, plastic deformation during cycling results in lowered values of the elongation as measured by a tensile test as the tubing life is consumed.

g) Accumulated Lengthening

Coiled tubing may elongate as it is run into and out of a well even though the axial load is far smaller than the maximum allowable tension. Such elongation affects depth measurement, tubing diameter, and wall thickness.

h) Splitting

Splitting occurs where the wall has thinned and where the resulting material is pressure cycled. Some typical examples are:

1) the tube has been abraded locally against the side of the well and then cycled under pressure,

2) the tube has been worn thin and is then vibrated, or

3) embrittlement of coiled tubing has been found to lead to splits.

i) Imperfections

Details of certain imperfections associated with steel tubing that is manufactured by the electric weld method are provided in API 5T1. The following types of defects and imperfections have been noted as resulting in performance variations of used coiled tubing.

1) Penetrators

Penetrators are oxides of some of the elements in the steel that are drawn down into the “V” of the weld area as the two edges of the plate are forced together at high temperature. They may originate from either surface and a physical open defect may or may not occur. They may or may not pass from one tube surface to the other. They may survive the mill hydrostatic test.

2) Pinholes

A pinhole is a pathway through the tube wall at the seam weld line and may be only a few thousandths of an inch long. Such defects typically do not pass hydrostatic testing but could enlarge under cycling, pressure, and acid ingress. See API 5T1.

3) Partially Open Seams

Incompletely fused longitudinal weld seams, notably those located at the inner surface, may survive the hydrostatic test but will enlarge under cycling and attack by acid. Such imperfections lead to “pinhole” leaks.

4) Material Imperfections

Typical material imperfections include surface pits, inclusions, laminations, and segregations within the steel. Inclusions may have remained spherical or become elongated during the strip rolling process. They may contain refractory materials or be undissolved materials such as manganese sulphide. Such imperfections lower the cycling ability of the tubing and provide sites for ingress of hydrogen and crack initiation.

5) Physical Properties

Since physical properties are measured only at mill stops and the ends of strings of coiled tubing, the possibility exists for certain regions in the string to possess out-of-specification initial physical properties such as yield strength, tensile strength, elongation, or hardness.

6) Skelp-end Weld Imperfections

Welds may contain undetected imperfections such as small two-dimensional weld line cracks and certain other conditions such sanding marks. These conditions may lead to poor performance under cyclic loading.

7) Tube-to-Tube Weld Imperfections

Where tube-to-tube welds are permitted and typical weld flaws that survive NDE are also possible. These might include small weld cracks inside the metal or open to the inner diameter, porosity, unacceptable hardness, transverse grind marks from weld preparation, and sanding marks from poor finishing of the outside diameter that may not be detected by NDE.

8.6 Mechanical Testing Procedures for Used Coiled Tubing

The following mechanical testing procedures are available while evaluating sections of coiled tubing.

a) Outside Diameter Measurement

The measured values should include the maximum (D_{max}) and minimum (D_{min}) diameters. Ovality should be computed.

b) Wall Thickness Measurement

Wall thickness should be measured as needed but in reduced-wall sections the extent of the wall loss should be recorded both in angular extent and minimum remaining wall. Wall thickness measurements taken from the outside diameter may be inaccurate if the material has a pitted inner surface.

c) Hardness Testing

Hardness testing of the outer surface should be performed as needed with an anvil-type hardness tester that employs the Rockwell B and C scales. Either laboratory or field testers may be used. Hardness testing should be performed on all field butt welds at regular intervals around the weld after dressing. Test indentations should be conducted on the weld metal, the HAZs, and the tubing wall. Curvature corrections for small-diameter tubing should be applied where necessary. See ASTM E18.

d) Microhardness Testing

Microhardness testing should be performed with the indenter parallel to the axis of the tube. Readings should be sufficiently far from the surfaces or imperfections so as to be unaffected by the surface. Readings may be taken on Knoop scale microhardness testers and converted to the appropriate Rockwell values on the B or C scale.

e) Instrument Check

All hardness and microhardness readings should be taken after checking the instrument against a known standard. The hardness of the standard shall be within 5 Rockwell C units of the readings to be taken.

f) Tensile Test

1) Type of Specimen

For determining the axial loading capacity of in-service coiled tubing, tensile tests may be taken on machined strip tensile or full body specimens. Since the local tensile properties of in-service tubing generally vary with angular position of the CT cross section at a given axial location in the CT string, standard ASTM A370 strip tensile specimens shall be removed and tested from each of the four quadrants of the tubing cross section. If insufficient material is available to test four quadrants of the tubing, the maximum number possible of standard strip tensile specimens shall be used. The effective tensile properties for the CT string shall be calculated as the average values obtained from the individual strip tensile tests. In the event that the average value for either the yield or tensile strength is greater than the mill certificate value of the tubing in the as-milled condition, the corresponding value from the mill certificate shall govern.

2) Full Body Tensile Testing

Full body tensile testing shall be conducted in accordance with the "pre-straining" test procedure described in [39]. In this procedure, the specimen is subjected to an initial strain of between 0.8 % and 1 % in order to straighten the sample and relieve prior hysteresis. Because any difference in cross-sectional areas between specified and measured values can lead to an error in the measured yield and tensile strengths, the cross-sectional area shall be measured as accurately as possible. In the event that the average value for either the yield or tensile strength is greater than the mill certificate value of the tubing in the as-milled condition, the corresponding value from the mill certificate shall govern. Note that the "pre-straining" tensile testing procedure for obtaining the yield strength of full body specimens does not apply for collapse pressure calculations of in-service CT.

g) Fatigue Test

In some cases it is possible to estimate the remaining fatigue life of coiled tubing by the use of a fatigue machine. This may occur when an isolated imperfection is under evaluation after removal from the tubing and it is suspected that there is a considerable amount of fatigue life left in the remaining sections of the string such that repair by addition of a tube-to-tube weld or a connector would return the tubing to service.

9 Nondestructive Inspection and Testing of Used Coiled Tubing

9.1 General

9.1.1 The methods outlined in this section are recommended for NDT and inspection of used coiled tubing and represent good practice; other methods and techniques that can produce equivalent results in monitoring the degradation of the tubing are acceptable. They should be performed only after any coating, oil, rust, or cement on the outside surface has been removed by brushing, washing, or wiping. If the pipe is brushed with wire brushes, then the brushing action should be such as to leave no transverse marks on the pipe outside surface.

API 5A5 is useful in setting up a quality program for the equipment used in the inspection of used ferromagnetic steel coiled tubing. All NDE should be performed to written procedures and a written record of the results made.

9.1.2 In this section, the following are presented.

a) The test equipment quality assurance, including its calibration and standardization requirements.

b) The minimum qualifications for inspection personnel employed in the inspection of new and used coiled tubular product.

c) Recommendations for test equipment and re-standardization intervals.

9.1.3 The following nondestructive inspection methods are appropriate to coiled tubing.

a) X-radiography (RT) of skelp-end and tube-to-tube welds, and the tube body wall (ASTM E94).

b) MT of skelp-end and tube-to-tube welds, fitting welds, and areas in which imperfections are detected (see ASTM E709).

c) PT of skelp-end and tube-to-tube welds, fitting welds, and areas in which imperfections are detected (ASTM E164).

d) Electromagnetic [magnetic flux and magnetic flux leakage (MFL)] inspections of new and used coiled tubing strings (ASTM E570).

e) Ultrasonic compression wave inspection for wall thickness measurement.

f) Ultrasonic shear wave inspection of tube-to-tube butt welds.

g) Ultrasonic shear wave inspection of skelp-end welds in tube form.

h) Ultrasonic (compression and shear) inspection of indications found during tubing inspection.

9.2 Test Equipment

All test equipment should be placed under a formalized calibration and recalibration scheme designed to maintain that equipment in a calibrated condition. If test equipment whose calibration or verification is required under the provisions of this recommended practice, is subjected to unusual or severe conditions, sufficient to make its accuracy questionable, recalibration or recertification should be performed before further use of the equipment. Recommended maximum intervals between recalibration and/or recertification are given in Table 2.

Table 2—Recommended Maximum Intervals Between Recalibration/Recertification

Item	Maximum Interval	Verification
In-house Reference Material		
Caliper test blocks	1 year	Master standard
Ultrasonic thickness reference standards	1 year	Master standard
Magnetic yoke (DC) test block	5 years	Certified weigh scale accurate to <0.1 lb
Magnetic yoke (AC) test block	5 years	Certified weigh scale accurate to <0.1 lb
Radiographic reference standards	5 years	Certified metrology
Electromagnetic inspection reference standards	2 years	Written testimony of test flaw dimensions
Equipment		
Digital caliper	4 months	Certified caliper test blocks
Mechanical pit and other depth gauge	4 months	Certified test blocks
Length measurement device	6 months	To OEM
Magnetic yoke (DC)	4 months	Certified 40 lb weight
Certified 40 lb weight	4 months	Certified 10 lb weight
Ultraviolet lamp	After turning on	Ultraviolet Intensity at inspected surface
Ultraviolet light meter	6 months	To OEM
Ultrasonic thickness gauge	6 months	Meet ASTM E797 and API 5A5
Ultrasonic flaw detector	6 months	Meet ASTM E317
Ammeter on any unit	4 months	To OEM
Electromagnetic inspection unit coil polarity	6 months	API 5A5
White light meter	1 year	To OEM

9.3 Qualification of Nondestructive Inspection Personnel

9.3.1 Written Standard Inspection Procedures

The NDT techniques employed during evaluation of the tubing should be performed to written standard procedures, which refer to this practice or to accepted national or international standards.

9.3.2 Qualification and Certification of Inspection Personnel

Companies performing nondestructive inspection of coiled tubing should qualify and certify their inspection personnel to a written practice. All personnel performing nondestructive inspection of coiled tubing should be qualified and certified to a national standard (such as ASNT SNT-TC-1A and ANSI/ASNT CP-189), by the company performing the inspections. Under such a certification scheme, generally operated under a Level III, the inspector may be certified at Level I or Level II. In the event that the inspector performing the inspection task is Level I, the inspection task should be overseen by a Level II in the same inspection technology. Inspection personnel should be qualified and certified in all the inspection technologies that they perform.

Qualification also includes standardized eye examinations at defined intervals.

9.3.3 Requirements for Certification

The inspector should be competent at each level in the general theory of the examination method, the practical aspects of operating the inspection equipment, and the specifications and recommended practices that govern the decision-making process with regard to imperfection and defect removal and the need to remove certain sections of tubing.

9.4 Light Levels

9.4.1 Light Level for Visual Inspection

Where visual inspection is performed, the ambient light level should be a minimum of 50 foot-candles (500 lux), with 100 % of the surface covered by the inspection at the same level of illumination. Mirror systems may also be used in order to aid coverage around the pipe surface. When lights are used for illumination, they should be directed toward the pipe surface and not toward the observer.

9.4.2 Type of Illumination for Visual Inspection

Broad daylight, light from mercury tubes, and mono-chromatic light from high-intensity single element lamps provide the best forms of illumination. When measuring ambient light levels, the nature of the light in relation to the acceptable band of the light meter employed should be born in mind and where necessary accounted for.

9.4.3 Measurement of Light Levels

Direct daylight conditions do not require a check of surface illumination. For night and enclosed facility lighting, the below practices should be followed.

a) Diffused light levels at the surfaces being inspected should be a minimum of 50 foot-candles (500 lux).

b) Illumination should be checked once every 4 months. The check should be recorded in a log with the date, the reading, and the initials of the person who performed the check. This record should be available on site. Illumination should be checked whenever lighting fixtures change position or intensity relative to surfaces being inspected.

9.5 Visual and Dimensional Inspection

9.5.1 Visual Inspection

Visual inspection requires observation of 10 % of the outside surface of the tube in the amount of light required. Visual inspection identifies gross imperfections on the outside surface. When further evaluation is necessary for acceptance of a visual indication, other methods such as MT, PT, and UT should be used to locate imperfections and also to ensure complete removal or repairable defects after removal.

Visual inspection may also involve the use of contact with the outside surface of the pipe by hand in order to feel the presence of certain imperfections. When this is performed, care shall be taken to avoid injury from slivers and sharp edges. Gloves are typically worn.

9.5.2 Dimensional Inspection

Dimensional inspection is limited to the following.

a) Outside Diameter Measurement

   The outside diameter should be measured with a caliper or a micrometer at a minimum of four locations around the test location on the tubing (A-A, B-B, C-C, D-D in Figure A.1 or Figure E.1) and the results (D_1, D_2, D_3, and D_m) recorded to the nearest 0.001 in.

   The contact areas of the caliper or micrometer should be flat. Pointed contact areas should not be used for diameter measurements.

b) Wall Thickness Measurements

   The wall thickness should be measured with an ultrasonic compression wave gauge at a minimum of four locations around the test location on the tubing (C-C, D-D in Figure A.1) and the results recorded to the nearest 0.001 in. If an imperfection is removed at a specific location, one measurement (t_m) should be at the thinnest remaining wall at that location.

c) Outside Surface Imperfection Depth Measurement

   Where the outside surface contains a high density of imperfections, such as scratches or shallow pits, and removal is not feasible, then the depth of typical imperfections may be reported.

d) Outside Surface Imperfection Removal and Remaining Wall Measurement

   Isolated outside surface imperfections may be removed with a file and sand paper to a remaining wall thickness (measured by compression wave ultrasonics) determined in contract review. When imperfections are removed, the surface of the tubing should be contoured for at least 3 in. axially on either side of the imperfection location and at least 1 in. radially on either side of the imperfection location. Computation is limited to the following.

   1) Ovality

      The appropriate formula may be used for the computation of ovality at the inspection locations.

   2) Cross-sectional Area Computation

      The cross-sectional area (A') of the steel of the tubing may be computed from the relation of:

$$A' = \pi t_{av} (D_{av} - t_{av}) \quad (10)$$

where

t_{av} = $(t_1 + t_2 + t_3 + t_m)/4$ (using four wall readings as an example only), rounded to the nearest 0.001 in.;

D_{av} = $(D_1 + D_2 + D_3 + D_m)/4$, rounded to the nearest 0.001 in.

A' is computed to the nearest 0.0001 in.^{2}

The calculated value of A may be used with the specified or measured yield and tensile strengths for the product in order to determine axial loads.

9.5.3 Frequency of Visual and Dimensional Inspections Along the Tubing

As agreed on the purchase order, the tubing should be inspected visually for either 100 % of the length of the tube or at stated intervals [e.g. 30.5 m (100 ft), 76.3 m (250 ft), 152.5 m, (500 ft), 305 m (1000 ft)]. All tube-to-tube welds should be inspected.

Should more localized inspections be specified, then the length of pipe that is to be inspected on either side of the length marker should also be specified on the purchase order [e.g. 3 m (10 ft)].

When such an inspection is ordered, the owner should realize that the entire pipe surface is not inspected.

9.5.4 Reporting for Visual and Dimensional Inspection

Form E.1 provides a typical form for visual and dimensional inspection of a coiled tubular. A completed inspection report should be signed by the certified inspector.

9.6 Length

9.6.1 Requirements for Length Measuring Devices

Measurement of length may be made by wheeled (or other) systems that should be accurate to 1 % of the length of the tube. Counters should be reversible in that when inspection devices are used, an accurate location of noteworthy locations is always possible. Where length-measuring devices feed signals into computers, provision should be made for removal of sections of tube records from the string record.

9.6.2 Length Records

Length should be measured from a convenient point in the vicinity of the bed wrap end of the coiled tubular or recorded as if the measurement had been made from such a location (called the length reference point). This is essential when comparing inspection results with subsequent runs. Measurements made from the downhole end of the coiled tubing should be converted to measurements made from the reference point as soon as possible after the end of the inspection. Lengths should be recorded to the nearest 30 cm (1 ft).

NOTE The pipe may stretch due to tensile loading during operations and such benchmarks as skelp-end and tube-to-tube welds may appear to have moved between successive inspections.

9.7 Wall Thickness Measurement Using Ultrasonic Compression Waves

Except at places where the wall thickness is readily accessible to measurement by calipers, the wall thickness should be measured with compression wave ultrasonics. When evaluation of the inside surface of the tubing is to be performed, a 0.8 mm ($^1/_{32}$ in.) flat bottomed hole at least 12.7 mm (0.50 in.) from the front surface of a parallel surface test block should be detectable. In order to perform these measurements, the following protocol should be performed using a compression gauge (having a digital or oscilloscope readout) with an operating frequency in the range 5 MHz to 10 MHz and a focused transducer with the diameter of the transducer wear plate is less than 0.375 in.

a) Reference Standard

Select a reference standard with the same outside diameter as the tube to be measured and manufactured from steel of similar acoustic velocity and attenuation properties to the material being inspected. Steel from material of the same grade is acceptable. Flat reference standards should not be used.

b) Coupling Gel

Select a relatively thick coupling gel since the outside surface of the tube may be relatively rough and require a thick coupling to provide the correct amount of contact between the face of the transducer and the pipe surface.

c) Standardization of Ultrasonic Compression Wave Gauge

Prior to use, to minimize error due to temperature differences, the standard(s) should be exposed to the same ambient temperature as the material for 30 minutes or more. Standardize the gauge on a wall thickness on the reference standard that is at least 0.64 mm (0.025 in.) thinner than the specified wall thickness and on a second standard thickness that is at least 0.65 mm (0.025 in.) thicker than the specified wall thickness of the tube wall to be measured. The gauge accuracy should be within 0.025 mm (0.001 in.) of the standard's thickness. In order to do this, place coupling gel on the standard and place the dividing line of the ultrasonic transducer perpendicular to the axis of the reference standard.

d) Measurement on Tubing

Remove all dirt and rust from the tubing surface, place coupling gel on the tubing at the location to be measured, and place the transducer's dividing line perpendicular to the tube axis. If the reading lies between the two standardization values then the value measured is as accurate as can be measured with the compression wave gauge.

e) Measurements on Tapered or Corroded Strings

If the tubing wall reading falls outside the original standardization values, as may occur when working with tapered strings, re-standardize the ultrasonic gauge using the appropriate wall thickness intervals on the reference standard attempting to span the wall to be measured by the standard values.

f) Internal Flash

Unless attempting to measure internal flash height, avoid taking initial wall measurements into the flash wherever possible. Note also that during the manufacturing process there is a tendency for the wall to thicken on either side of the flash column. If an assessment of internal flash height is required, the reading at the flash location will not be as accurate as the reading in an area away from the flash. Note that the internal flash column often undulates in height over relatively short distances.

g) Wall Thickness Measurement in the Presence of Pitting

With an uneven pitted outside surface, it is essential that the gel fill the space between the transducer wear plate and the tubing. Small pits (if any) on the ID that do not reflect enough ultrasound to affect the shape of the returned echo from the inside wall will not be detected. Larger pits that reflect sufficient ultrasound to move the echo toward the transducer will be detected although the true wall thickness reading may lie between the remaining wall at the base of the pit and the ambient wall thickness.

h) Wall Thickness Measurement in Tapered String Skelp-end Welds

Commonly used ultrasonic gauges should experience no difficulty in measuring the change in wall thickness in passing from the low side to the high side of the wall at a tapered skelp-end weld.

This change is relatively gradual and should occur over 76 mm to 102 mm (3 in. to 4 in.). The change in wall thickness over the angled skelp-end weld may cause some ovality in the tube at this point. The inspector should be particularly diligent in measuring the wall thickness at tapered skelp-end welds in tube form in order to determine the remaining wall in regions that may have originally been oval (i.e. originally ovalled welds may have worn into a more round condition due to metal loss).

9.8 Wall Thickness Measurement Using Electromagnetic and Gamma Ray Methods

9.8.1 Gamma Ray Measurement Technique

Wall thickness may be measured by rotating a gamma ray source around the tubing while it is passing axially though an inspection unit. Inaccuracies may occur due to the possibility of off-centering of the tubing in the bore of the inspection unit. When this method is selected, the coverage of the gauge will generally be relatively low.

9.8.2 Magnetic Measurement Technique

9.8.2.1 Technique Description

Wall thickness is measured for the full length of the tube by a magnetic method, which employs a ring or rings of solid state magnetic sensors at a certain stand off from the pipe wall. In this technique, the pipe wall is magnetized longitudinally, and the sensors measure the effect of tube wall thickness on distortion of the magnetizing field in the air outside of the tube wall.

NOTE The thicker the wall, the lower the magnetic field at the sensor location.

9.8.2.2 Coverage

The measured thickness is an average of a relatively large area of tube wall immediately beneath each sensor, and is thus not a "spot" measurement in the manner that ultrasonic compression wave measurements are considered to be "spot" measurements. However, the method provides the necessary sensitivity to detect and measure wall loss areas over lengths as small as roughly 51 mm (2.0 in.).

9.8.2.3 Effect of Saturation Flux Density (B_s)

This method depends upon the constancy of the magnetic saturation flux density along the tube for its accuracy and may therefore yield incorrect readings at skelp-end welds or heavily worked areas, where the changes in magnetic permeability from the skelp-end weld process affect the local saturation flux density in an unknown manner.

9.8.2.4 Spot Ultrasound readings

Variations in the magnetic wall readings average over small wall thickness changes in the tube and therefore should not be expected to agree with ultrasonic compression wave readings taken on pits or in heavily pitted areas. In the same manner, single ultrasonic compression wave readings taken in such areas should be treated with caution when attempting to obtain a single value for "wall thickness."

9.8.3 Standardization of Wall Measurement

Wall thickness systems should be standardized prior to the commencement of each inspection on a suitable reference standard as follows.

a) Reference Standard (Electromagnetic Method)

For a section of tube that contains an elongated wall thickness section that is within 0.13 mm (0.005 in.) thickness of the maximum specified wall of the tube to be inspected, the reference standard should contain a region of 10 % wall thickness loss of the specified wall thickness. This area should be at least one-eighth of the circumference of the tubing and should be at least 6 in. long at full depth.

For concerns with sensitivity to magnetic flux level, due to the potential for the effect of variation in the saturation flux density (B_s) with grade, when inspecting the reference standard should be manufactured from the same grade if possible.

b) Reference Standard (Gamma Ray Method)

The instrument may be standardized with a flat test block or with a tube section that exhibits a wall variation of at least 10 % of the specified wall thickness of the tube around the circumference.

9.8.4 Presentation of Wall Thickness Data

The wall data may be presented on as many or as few wall thickness information channels as are needed to determine parameters of importance. These may be any of the following.

a) Minimum wall thickness detected from single sensor readings.

b) Minimum wall thickness measured over one sector or quadrant of the tubing surface.

c) Average wall thickness measured over one sector or quadrant of the tubing surface.

d) Average wall thickness measured around the full 360° of the tube.

However, coiled tubing inspection systems should present the minimum wall thickness detected by electromagnetic methods over at a minimum of 90° of the circumference of the tube.

NOTE The wall thickness measured in these techniques is not the minimum wall thickness at the bases of small pits but rather a value recorded over a finite volume of the tubing.

9.9 Transverse Imperfection Detection by Electromagnetic Methods

9.9.1 Transverse Imperfection Detection Technique

When the active longitudinal magnetic flux in the tube wall encounters a transverse or three-dimensional imperfection, magnetic flux is forced out of the tube wall into the surrounding air and into the vicinity of the sensors. The relative amount of this MFL that is diverted by an imperfection depends on the dimensions and orientation of the flaw to the field direction.

Because of the wide variety of imperfection types, which can divert magnetic flux, it is not generally possible to use signal amplitude to determine flaw depth unambiguously. However, general trends in signal amplitude do indicate that, under favorable circumstances, larger signals do occur from deeper flaws. Therefore, it is not always possible to determine whether the origin of a signal is a sharp crack, a round-bottomed pit, or that the location of the imperfection is on either wall of the tube or is located mid-wall. With these considerations, in order to set baseline sensitivity for MFL, the channels are standardized with an appropriate standard.

9.9.2 Standardization for Imperfection Channels

The electromagnetic flaw channel system should be standardized prior to the commencement of each inspection on a suitable reference standard. The reference standard should be selected to have wall thickness that is within 0.005 in. in thickness of the specified wall of the thicker end of the tube to be inspected and should have the following reference indicators placed in its surfaces.

a) Transverse Crack Simulation

The reference indicators for transverse crack simulation should be as follows.

1) One transverse electro-discharge machining (EDM) reference notch placed in the outside surface of the tube to depth minimum 10 % of the specified wall, with a tolerance of −0/+0.05 mm (+0.002 in.), maximum length 6.4 mm (0.250 in.) long, and the maximum width should not exceed 0.50 mm (0.020 in.). If a 10 % notch is selected, its minimum depth should be 0.38 mm (0.015 in.)

2) A through-drilled hole [maximum diameter 1.6 mm ($^{1}/_{16}$ in.)] may also be used.

NOTE Certain equipment may require deeper reference indicators in order to provide an acceptable reference signal.

b) Pit Simulation

The reference indicator for pit simulation should be one spherical indentation drilled or electro-discharge machined in the outside surface of the reference standard with a 6.4 mm (0.25 in.) radius to a depth of 10 % of the specified wall thickness of the material.

Reference indicators should be placed at least 610 mm (24 in.) from the ends of the standard and at least 305 mm (12 in.) away from other reference indicators or from any sources of magnetic noise in the reference standard.

9.10 Longitudinal Imperfection Detection

9.10.1 Longitudinal Imperfection Detection Techniques

Longitudinal imperfections may be detected by the application of eddy currents that encircle the tubing or rotating magnetic poles around the tubing. Penetration of the eddy currents into the tube wall is aided by a high magnetic field induced in the tube wall.

Because of the wide variety of types of longitudinal imperfections, it is not generally possible to determine the flaw depth unambiguously. However, general trends in signal amplitude do indicate that under favorable circumstances larger signals do occur from deeper imperfections. With these considerations and in order to set baseline sensitivity for this inspection, the channel(s) are standardized with an appropriate reference standard.

9.10.2 Eddy Current Systems

Standardization of eddy current systems should be performed by setting signal response to a 25.4 mm (1 in.) long through-wall cut of maximum width 0.5 mm (0.020 in.) in material of the same outside diameter and wall thickness. Use of a through-drilled hole can also be used for standardization. Reference ASTM E309.

9.10.3 Circumferential Magnetizing Systems

Standardization of rotating magnetic pole equipment should be performed using a reference standard as follows (as determined during contract review).

a) A 12.7 mm (0.50 in.) long minimum, 10 % deep outer surface EDM notch with a tolerance of −0/+0.05 mm (0.002 in.), with the maximum width not exceeding 0.5 mm (0.020 in.). If a 10 % notch is selected, its minimum depth should be 0.38 mm (0.015 in.).

b) A through-drilled hole (maximum diameter 1.6 mm ($^{1}/_{16}$ in.).

NOTE Certain equipment may require deeper reference indicators in order to provide an acceptable reference signal.

9.11 Ovality Measurement

9.11.1 Ovality Measurement Technique(s)

Ovality is measured using the following techniques.

a) Mechanical Method

In certain equipment, signals from the spring-loaded shoes that are used for other inspections are processed electronically to measure the ovality of the tube at the point of inspection.

b) Electromagnetic Method

In other equipment, the tubing is passed centrally through a ring of standoff measurement sensors that operate using high-frequency eddy currents. The signals from suitable sensors are processed electronically to read diameter increases and decreases and to compute ovality.

9.11.2 Standardization of Ovality Channel(s)

The sensor system should be standardized to the outside diameter of a tube of the same specified diameter as the tube to be inspected. The standardization tube should minimally contain a ring groove that is machined axially with the tube axis to a depth of 10 % of the tube wall. This permits the wall thickness standardization sample to be used as a standard for the ovality standardization. The instrument may also be standardized with tubes of the same diameter as the tube to be inspected and of known ovality.

9.12 Prove-up of Indications

9.12.1 General

9.12.1.1 Signals from automated full-length inspection devices should be re-investigated for imperfection type and severity.

9.12.1.2 The following measurements should be taken at all locations at which prove-up is performed.

a) Diameter measurement should be made at a minimum of four orientations with respect to the seam and an ovality computation performed.

b) Wall thickness measurement should be made with a calibrated ultrasonic gauge.

9.12.1.3 The general state of the tubing outside diameter wall should be noted by the following:

a) low depth pitting of average depth 5 % of the specified wall or 0.13 mm (0.005 in.),

b) medium depth pitting of average depth up to 10 % of the specified wall,

c) large depth pitting of average depth up to 15 % of the specified wall,

d) longitudinal gouges,

e) injector ring and other marks from rig damage,

f) transverse scratches from spooling,

g) ovality in excess of 2 %,

h) open seams,

i) cracked skelp-end welds,

j) ballooning and necking, and

k) any other as agreed.

If no visual indications are found, the area may be inspected with at least one technique that is sensitive to two-dimensional imperfections (e.g. magnetic particle inspection).

Where indications possibly originate from the inner surface, certain signs may provide the origin. For example, if indications occur regularly at π × the diameter of the storage reel, then internal storage corrosion may be a possible cause. Other regularly spaced OD indications may indicate problems associated with the injector.

9.12.2 Signals Exceeding Threshold

All signals that exceed a predetermined threshold as determined by the operational procedures for the inspection equipment or customer specification for inspection, whichever is appropriate, should be further evaluated.

9.12.3 Signals Not Exceeding Threshold

The inspector may evaluate signals that do not exceed threshold.

9.12.4 Pit Depth Measurement

Pit depths are measured using a calibrated pit gauge after light cleaning of the OD surface with sandpaper and removal of material from the base of the pit.

9.12.5 Measurement of Depth of Gouges and Other Indentations

The surface of the tubing may be dressed to remove metal that has been raised from the wall. Any extraneous material in the base of the imperfection shall be removed.

9.13 Magnetic Particle Inspection

9.13.1 General

Magnetic particle inspection should be performed on coiled tubular surfaces as a check for outside surface imperfections (typically planar) in the tube and tube-to-tube welds. Magnetic particle inspection should also be performed on the welds between coiled tubing and on any welded fittings.

9.13.2 Application for Magnetic Particle Inspection

Magnetic particle inspection may be performed on prepared surfaces and should always be used in order to check that an imperfection that is detected by a liquid penetrant inspection (if employed) or an earlier magnetic particle inspection has been fully removed.

Magnetization may be performed with an AC or DC yoke. In this method, 100 % of the surface is scanned at least twice with the yoke field being applied in two roughly perpendicular directions. The legs of the yoke should touch the part on either side of the inspected area. The most sensitive area is the central one-third of the area between the legs of the yoke. Particles should be applied while the magnetic field is active.

Because of the thin-walled nature of coiled tubing, cracks originating at the ID surface and not completely through the wall may be detected with a DC yoke and wet or dry particles.

9.13.3 Dry Magnetic Particles

Dry particles should be finely ground and exhibit a high contrast with the inspected surface. The particle mixture should consist of different sized particles, with at least 75 % by weight being finer than 100 ASTM sieve size and a minimum of 15 % by weight finer than 325 ASTM sieve size. The particle mixture should not contain contaminates such as moisture, dirt, sand, etc.

As a supplementary practice, there may be a particle manufacturer's batch or lot check of particles for high magnetic permeability and low retentivity. Dry magnetic particles should be used once only.

9.13.4 Wet Magnetic Particle Inspection

9.13.4.1 Fluorescent Particles

Particles and carrier solution should meet the requirements of ASTM E709 with the bath concentration being checked prior to the beginning of the inspection and at least once each 24 hours. In many circumstances, the sensitivity of the technique is higher than the dry particle technique.

9.13.4.2 Ultraviolet Light Intensity

While performing wet fluorescent magnetic particle intensity, the intensity of the ultraviolet light should be at least 20 watts per square meter (2000 μW/cm^2) at the inspected surface.

9.14 X-radiography of Tube-to-Tube Welds or Other Sections

9.14.1 General Requirements

When radiography is required, x-radiography should be performed at specified locations. For tube-to-tube welds, radiography should only be performed after all weld spatter has been removed and the outside surface of the weld has been dressed to final acceptable dimensions.

9.14.2 Local Site Regulations

The following may apply to local sites.

a) When x-radiography is required at an inspection facility under the control of the inspection company, the company (as agreed) should be responsible for meeting all local requirements pertaining to radiation safety.

b) When x-radiography is required at a field location under the control of the owner or operator, the owner or operator (as agreed) should be responsible for ensuring that the inspection company meets all local requirements pertaining to radiation safety.

c) All persons performing x-radiography should have completed a documented course in radiation safety that has been approved by local authorities.

9.14.3 X-radiography Locations

X-radiography may be conducted at the following locations.

a) Tube-to-tube welds—new and existing tube-to-tube welds should be radiographed for 100 % of the weld.

b) Other locations—at the owner's request or as deemed necessary by the inspector, x-radiography should be conducted.

9.14.4 Imaging Requirements

Film should be fine grained, and both film and digital imaging systems should be capable of detecting a number 2T hole in a number 10 ASTM hole-type image quality indicator (IQI).

9.14.5 Film Image Requirements

All film or digital recording media should clearly indicate the following:

a) whether a film side or source side IQI is employed; and if a film side IQI is used, a lead letter F should be used and placed on the IQI,

b) image of the essential hole in the appropriate IQI,

c) date the radiograph was taken, and

d) mark of the radiographer.

9.15 Radiographic Procedures

9.15.1 Straight Shots

For all coiled tubular radiography, three radiographs should be taken with the beam at two radial locations that are separated by 60° with the center of the beam at 60° to the axis of the tubing.

9.15.2 Elliptical Shots

For radiography of tube-to-tube welds in coiled tubulars, two radiographs should be taken with the beam at two radial locations that are separated by 90° with the center of the beam passing through the plane of the weld at an angle so that the shadow of the weld on the film is elliptical.

9.15.3 Radiographic Energy

The radiographic voltage should be in the region 100 kV to 200 kV and the time of exposure should be adjusted to provide a density on the film of 2 to 3 H and D density.

9.15.4 Geometric Unsharpness

The dimensions of the X-ray system should be such that the geometric unsharpness is no greater than 0.5 mm (0.02 in.) for material thickness of less than or equal to 50.8 mm (2.0 in.).

9.15.5 IQIs

The inspection system should be able to detect a 2T hole in a No. 10 ASTM hole-type IQI or equivalent type of IQI. A smaller size IQI may be used provided radiographic sensitivity is maintained.

9.15.6 Accept and Reject Criteria

Acceptable film should exhibit none of the following:

a) streaks, stains, and scratches,

b) internal penetration,

c) undercut,

d) cracks, or

e) lack of fusion.

In the case of coiled tubing, there should be no porosity. In the case of coiled line pipe, there should be no images of porosity larger than the diameter of the image of the essential hole and no more than two such images in each 152 mm (6 in.) length of weld.

9.16 Ultrasonic Inspection of Tube Welds and Other Tube Sections

9.16.1 General

The following areas of coiled tubing may be inspected using ultrasonic shear waves: seam welds, skelp-end welds in strip form, tube-to-tube butt welds, and suspect sections of the tubing wall.

9.16.2 Equipment Requirements

9.16.2.1 Shear Wave Flaw Detector

A modern flaw detector with an analog or digital screen capable of generating and detecting ultrasound in the frequency range 2.25 MHz to 10 MHz and a time base capable of exhibiting 25 mm to 64 mm (1.0 in. to 2.5 in.) on the screen should be used. Phased array systems may be used.

9.16.2.2 Transducer

An ultrasonic transducer of diameter 6.4 mm to 12.7 mm (0.25 in. to 0.50 in.) and capable of vibration between 2.25 MHz to 10 MHz should be used. The transducer may be focused. Phased array transducers may be used.

9.16.2.3 Wedges

Wedges should be contoured for the outside diameter of the tubing to be evaluated and be capable of sound entry angles from 45° to 70° into the part. Flat wedges should not be used on curved surfaces.

9.16.2.4 Seam Weld Inspection

For flash-free tubing, the sound should enter the tubing outside surface at approximately 45°. Where flash remains inside the tubing, an appropriate angle shall be selected that avoids reflections from the internal flash column. Contouring the wedge to aim the center of the sound beam at $^{2}/_{3}$ to $^{3}/_{4}$ of the thickness of the tube wall from the OD surface has proved effective in scanning for seam weld imperfections.

9.16.2.5 Tube-to-Tube Weld

It is recommended that a high sound entry angle be employed so as to minimize reflections from the inner weld bead.

9.16.3 Reference Standards

The following apply to reference standards for ultrasonic inspection of seam weld lines and skelp-end weld lines.

a) For skelp-end welds in strip form, see API 5ST.

b) When inspecting tubing, the reference standard should be a section of tubing of the same diameter and wall thickness as the tubing to be evaluated with the following test imperfections.

    i) One internal surface electro-discharge machined notch of maximum depth 10 % of the specified wall thickness. The test imperfection should be perpendicular to the expected direction of the imperfection(s) and of length not exceeding 9.5 mm (0.375 in.).

ii) One radially drilled 1.6 mm ($^1/_{16}$ in.) diameter through-drilled hole should be used to determine the location of the ID and OD of the tube on the baseline of the ultrasonic test instrument.

9.17 Ultrasonic Inspection of Seam Weld Area

9.17.1 Weld Line

Care should be taken when inspecting the seam weld with the internal flash present. This flash can create large reflections that might obscure weld line imperfections and imperfections within $^1/_8$ in. on either side of the weld line.

9.17.2 Inspection

The inspection equipment should be standardized on the appropriate a reference standard. In order to do this, the signal from the test imperfection may be set at a convenient height on the screen [such as 80 % full screen height (FSH)]. Inspection on the tubing may be performed at additional gain and the weld area should be isonified from both sides.

Where possible, inspection should be performed to the procedures of the API 5UE.

9.17.3 Acceptance Criteria

No imperfections in the seam weld line and for 3.2 mm ($^1/_8$ in.) on either side of the weld line are permitted.

9.18 Ultrasonic Inspection of Skelp-end Welds

9.18.1 Presence of Internal Flash

Care should be taken when inspecting the skelp-end weld with the internal flash from the seam weld present. This flash can create large reflections that might obscure skelp-end weld line imperfections.

9.18.2 Inspection

The inspection system should be standardized using the reference standard. In order to do this, the signal from the test imperfection may be set at a convenient height on the screen (such as 80% FSH). Inspection of the tubing may be performed at additional gain and the weld should be isonified from both sides.

9.18.3 Acceptance Criteria

No imperfections in the skelp-end weld line or in the region scanned on either side of the weld line are permitted.

9.19 Ultrasonic Inspection of Tube-to-Tube and Pipe-to-Pipe Butt Welds

9.19.1 Presence of Internal Weld Crown

Care should be taken when inspecting the butt weld with the internal flash present. This flash can create large reflections that might obscure imperfections, and imperfections within 0.125 in. on either side of the weld line.

9.19.2 Inspection

The inspection system should be standardized using a reference standard. In order to do this, the signal from the test imperfection may be set at a convenient height on the screen (such as 80 % FSH). Inspection of the weld and the tubing for roughly 2 in. on either side may be performed at additional gain and the weld should be isonified from both sides.

9.19.3 Acceptance Criteria

The weld should not contain the following:

a) porosity and other three-dimensional imperfections of any size,

b) cracks and other two-dimensional imperfections of any size,

c) lack of fusion, and

d) large internal surface weld crown that would not permit the passage of a gauge ball.

9.20 Liquid Penetrant Inspection

9.20.1 Applications of Liquid Penetrant Inspection

Typical applications include the outside surface of coiled tubulars and welds (butt welds, fitting welds) for planar imperfections that are open to the surface (e.g. cracks). Magnetic particle inspection is preferred.

9.20.2 Preparation for Liquid Penetrant Inspection

Liquid penetrant inspection may be performed on surfaces of coiled tubing that have been swabbed or lightly brushed clean, without sanding or filing. When inspecting welds, the surface to be inspected should be free of weld spatter, but un-ground since surface grinding may be responsible for closing up surface breaking imperfections that might otherwise give a liquid penetrant indication.

9.20.3 Performance of Liquid Penetrant Inspection

The inspection should be performed at a temperature within the temperature range of the liquid penetrant components specified by the manufacturer of those components. The weld should have been at room temperature for at least 1 hour.

A second liquid penetrant inspection after imperfection removal is not advised. The imperfection removal process may close the mouth of a tight imperfection, and the bottom of a tight imperfection may already be full of penetrant from the prior imperfection.

9.21 Removal of Surface Imperfections

9.21.1 General

Surface imperfections with a transverse component should be completely removed. Complete removal of sharp-bottomed imperfections should be checked with a technique such as magnetic particle inspection.

It may not be necessary to remove very shallow surface imperfections such as scratches, dents, and impressions within 5 % t (where t refers to actual wall thickness).

9.21.2 Removal Procedure

The imperfections should be removed by making longitudinal (axial) stokes with a file or belt sander so that the finished length of the removal area is at least two times the diameter of the tube. A very smooth final profile is required with no abrupt thickness changes. Once the imperfection has been roughly removed, the entire area should be finished by polishing with increasingly finer emery cloth. Polishing should commence with 180 to 240 grade cloth and should finish with 400 to 600 grade cloth, leaving an area with a roughness of not more than 0.008 m (32 μin.) rms. The length of the removal area should be at least twice the diameter of the tubing and the location of the removal area should be noted.

10 Assessment of Coiled Tubing

10.1 General

This section discusses the use of the results from the application of theoretical fatigue models as well as destructive and nondestructive evaluations to assess the condition of local sections of carbon steel coiled tubing. The appropriateness of the further use of coiled tubing or localized sections thereof may be assessed for future use as described in this section.

10.2 Fatigue Life and Fatigue Management of Coiled Tubing

Ultra-low cycle fatigue life of new coiled tubing based on laboratory testing and in the absence of corrosion and damage to the tubing typically follows the curve shown in Figure 4. Figure 4 illustrates the experimental results (cycles to failure at each pressure, average of 5 samples/tests) of fatigue cycling samples of 31.8 mm (1.25 in.) diameter grade CT-100 coiled tubing over a 1220 mm (48 in.) radius on a fatigue testing machine with internal pressures from 0 to 68.95 MPa (10,000 psi). The general trend is for the cycles to failure to rise initially with internal pressure and then to fall gradually above a certain internal pressure. Minimum bend radius and the internal pressure inside the tubing are thus critical parameters in ultra-low cycle fatigue life. A fatigue test cycle performed for a test is different from a field coiled tubing use cycle or trip. There are three test cycles per one trip in and out of the hole, and they generally happen over different bending radii on the reel and goose neck than the bending radii used in fatigue testing. Care should be taken when reviewing fatigue data and using the information for tracking the life of a coiled tubing string.

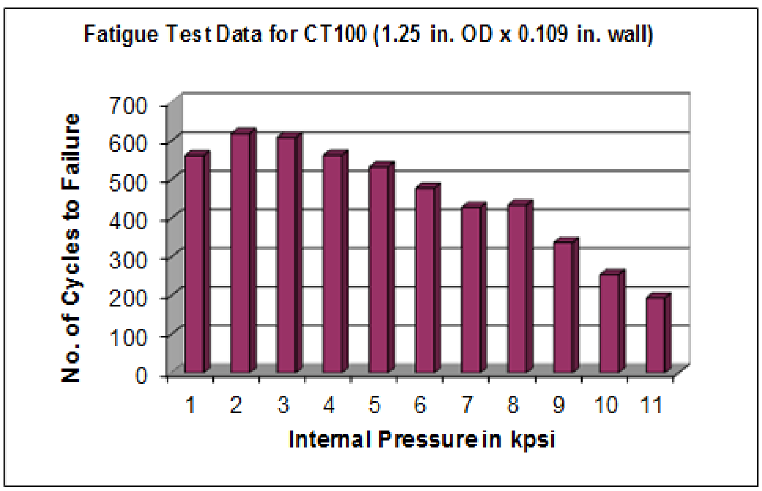


Figure 4—Cycles to Failure for CT-100 (1.25 in. × 0.109 in.)

Fatigue life of new coiled tubing generally decreases under the following circumstances:

a) as tubing OD increases,

b) as wall thickness decreases,

c) as bend radii decrease,

d) as internal pressure increases above a low pressure value,

e) at skelp-end welds, or

f) at tube-to-tube welds.

For the same tubing dimensions, ultra-low cycle fatigue life also differs between the grades of low alloy steel coiled tubing.

In coiled tubing operations, two generally different bend radii are encountered: (1) the reel radius and (2) the guide arch radius. Maximizing these radii prolongs the cycle life of the tubing in the absence of corrosion, surface damage, and other imperfections.

The ultra-low cycle fatigue life may be severely reduced by the presence of ovality, necking, stretching, corrosion, and tubing surface damage.

10.3 Theoretical Calculated Fatigue Life

It is good operational practice to employ computer programs that have been written to model the general shape of the curve in Figure 4 based upon measurements made on the coiled tubing steels. Such programs compute the following.

a) The cycles to initiation of a fatigue crack on a bend cycling machine with and without an outer surface imperfection present.

b) The cycles to initiation of a fatigue crack in the rig situation, with and without an outer surface imperfection present, using the bend radii of the reel and the guide arch.

c) The cycles to failure of the tubing wall on a bend cycling machine with and without an outer surface imperfection present.

d) The cycles to failure of the tubing wall in the rig situation, with and without an outer surface imperfection present, using the bend radii of the reel and the guide arch.

e) The theoretical remaining ultra-low cycle fatigue life in short lengths of the tubing based upon accumulated fatigue in each length.

Fatigue models permit deratings for skelp-end and tube-to-tube welds, and with outer surface imperfections, based upon experimental results. In the case of such imperfections, the depth, width, and length of the imperfection shall be measured and used in the program.

10.4 Review of String Records

The combination of fatigue modeling and the results of destructive and nondestructive examinations are used to assess coiled tubing strings. Theoretical fatigue life and nondestructive test reports should be reviewed by the owner and the inspector prior to determination of the future use of the string.

Where possible, local sections may also be tested for tensile properties since they may have changed from prior use.

10.5 Examples of Effective Repair on Coiled Tubing

The following are examples of typical repairs conducted on used coiled tubing. In all cases, the record for the string should be updated before the string is returned to service. The location of a skelp-end weld should be used as a fixed point when updating the string record since pieces may be removed from both ends and central sections of a string during its service life.

a) Removal of Heavily Pitted Sections

   A length of tubing is removed from an area that is heavily pitted, fatigued, heavily ovalled, ballooned, or necked, and the balance is joined by a tube-to-tube-weld or a section of similar length of the same grade is added in. The string record should then be updated with the new section (if added) and the fatigue life derating for the new tube-to-tube weld. Removal of the bottom end of the string may move the heavily cycled locations along the remaining string and bring material that has not previously been off the reel into service.

b) Replacement of Tail Section

After removal, a section of new or higher-class tail section of the same grade is added with a certified tube-to-tube weld. The string record should then be updated with the new section and the fatigue life derating for the new tube-to-tube weld.

c) Removal of Bed Wrap

A section of bed wrap that has suffered severe (e.g. >15 % t) wall loss due to bed wrap corrosion, while the rest of the string is acceptable, has the bed wrap section removed. In some areas, a thick coating of corrosion-resistant material is applied to the new bed wrap section. The string record should then be updated.

d) Replacement of Bed Wrap Section

A length of tubing of the same grade is used to replace a removed bed wrap section, using a certified tube-to-tube weld. In some areas, a thick coating of corrosion mitigation material is applied to the new bed wrap section. The string record should then be updated with the new section and the fatigue life derating for the new tube-to-tube weld.

e) Replacement of Tube-to-Tube Weld

A tube-to-tube weld that is considered to be (a) uncertified, (b) of uncertain origin, and (c) close to the end of its life is removed and replaced by a certified weld. The string record should then be updated with the new weld and its fatigue life derating as for a new tube-to-tube weld in the same grade material.

f) Tube Wall Erosion

The general wall thickness of a 50 ft section of tubing was reduced over at least one-eighth of the circumference by more than 15 % t due to wear or erosion. At this location, the reduced cross-sectional area would reduce the load-bearing capacity and the collapse resistance of the string. The section is replaced by a certified tube-to-tube weld so that the remaining wall across weld is as close to the specified wall as possible. The string record should then be updated with the new weld and the fatigue life derating for the new tube-to-tube weld.

g) Joining Strings

Acceptable parts of two or more existing strings of the same grade are joined with certified tube-to-tube-welds in order to construct one string. The string record should then be updated with the new weld(s) and the fatigue life derating for a new tube-to-tube weld in the same grade material.

h) Reversing Strings

Strings have been reversed so as to spread fatigue accumulation.

10.6 Record Keeping

The following records should be kept following maintenance, repair, and servicing of coiled tubing strings.

a) Original material grade.

b) Heat number of each strip, including any sections added to a string.

c) Original yield strength and tensile strength for each strip section of the tube.

d) Skelp-end weld locations.

e) Tube-to-tube weld location(s).

f) Locations of repaired areas and minimum walls (when new).

g) Locations of ovality in excess of 2 %.

h) Maximum and minimum outside diameter.

i) Updated theoretical ultra-low cycle fatigue life model.

j) Classification of string.

11 Coil Tubing Fatigue Testing and Equipment

11.1 Objectives of Full-scale Coiled Tubing Fatigue Testing

11.1.1 Cyclic bending strains imposed on coiled tubing during routine use lead to the inevitable development of fatigue cracking and the need to monitor the service history of strings throughout their service life. The fatigue behavior of coiled tubing is known to be influenced by (1) the magnitude of the bending strain imposed by wrapping on or off of the spool or guide arch (gooseneck) and (2) the internal pressure at the time of the wrapping or unwrapping event.

11.1.2 Fatigue test machines have been developed and used to obtain repeatable fatigue data using pressurized segments of full-scale coiled tubing. Tests are conducted by applying a constant internal pressure to the sample and alternately bending the tubing over two mandrels: (1) one straight and (2) the other with a fixed radius of curvature. Cycles are counted until a loss of internal pressure results from a fatigue crack growing through the wall thickness. The primary data resulting from the test are the cycles to failure and diametral growth. Other important data include ovality, crack location (e.g. tension or compression side), and crack size. The crack location information can be important relative to the location of the longitudinal weld seam. The crack size is important to note the potential for parting of the tubing should failure occur at high internal pressures.

11.1.3 The objectives of this section are (1) define a standard fatigue machine, (2) define a standard fatigue testing procedure, and (3) define a minimum acceptable data set to characterize the fatigue behavior of a particular coiled tubing material grade.

11.1.4 The size (i.e. length) of the fatigue crack should be routinely measured since it could be a forewarning of a possible parting of the CT string under tensile loading when in service. Larger fatigue cracks can be obtained under high internal pressures and/or higher strength CT for which the fracture toughness is insufficient to arrest the crack and limit its growth to true “pinhole” dimensions.

11.2 Recommended Standard Fatigue Testing Machine

Figure 5 illustrates the most recently developed “beer-pump” style fatigue testing concept that has been accepted by the CT industry and is now proposed as the standard fatigue technique for samples up to 88.9 mm (3.5 in.) in diameter. The new machines are designed to make it easier and faster to load samples and change bending radius mandrels. Data generated on the earlier machines are still considered valid, so long as the sample is fully wrapped to the ends of the bending mandrel with each cycle.

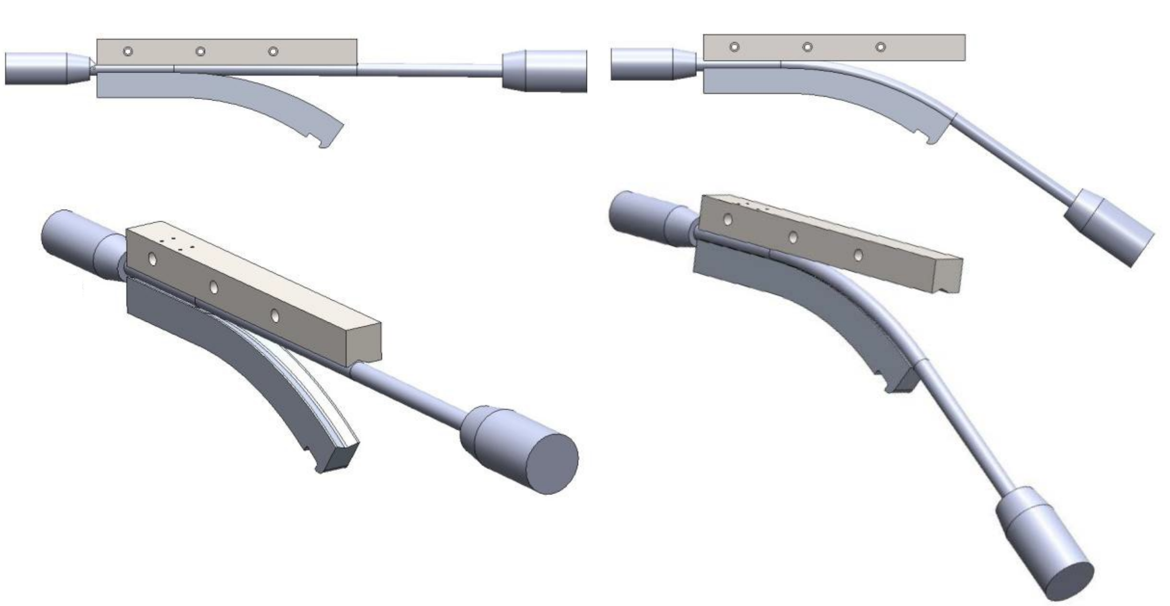


Figure 5—The Standard Bending Machine Concept

Since cantilevered systems clamp the samples between the curved and straight forms, samples do not rotate during testing. This is considered to be more severe in general than the deformation seen by tubing in the field, since tubing rotates intermittently on actual coiled tubing units. Intermittent rotation has been shown to more uniformly distribute bending strains and thus fatigue damage development around the circumference, rather than concentrating maximum bending strains on opposing sides of the tubing. The exception to this is the case in the field where tubing rotates 180° in between each trip in and out of the well, doubling the bending strain associated with spool curvature.

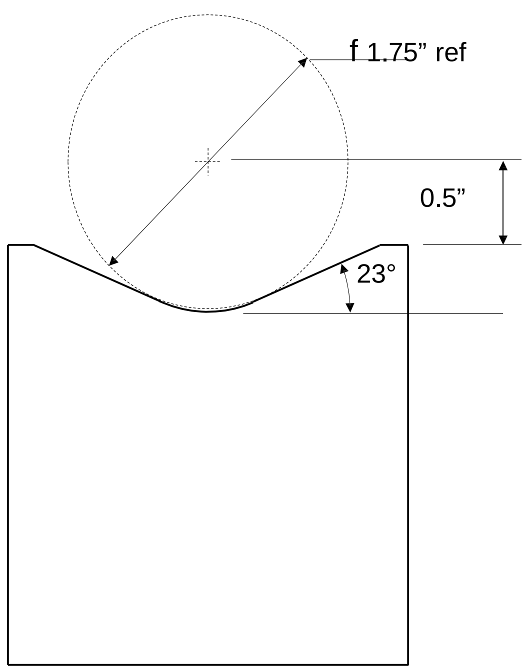


Figure 6—Profile of the Straight and Curved Mandrels

The profile used for straight and curved forms is depicted in Figure 6. The overall size of the curved forms is based on a reference tubing diameter of 44.5 mm (1.75 in.) and a minimum gauge section arc length of 22 in. The nominal radius of curvature for a standard forms is imposed on the centroidal axis of a of 44.5 mm (1.75 in.) sample (depicted in Figure 7). The transition section can be a spiral to the gauge section radius or tangential constant radius of at least twice the gauge section radius of curvature. Tubes of diameters other than 44.5 mm (1.75 in.) have a slightly different radius of curvature (see Table 3).

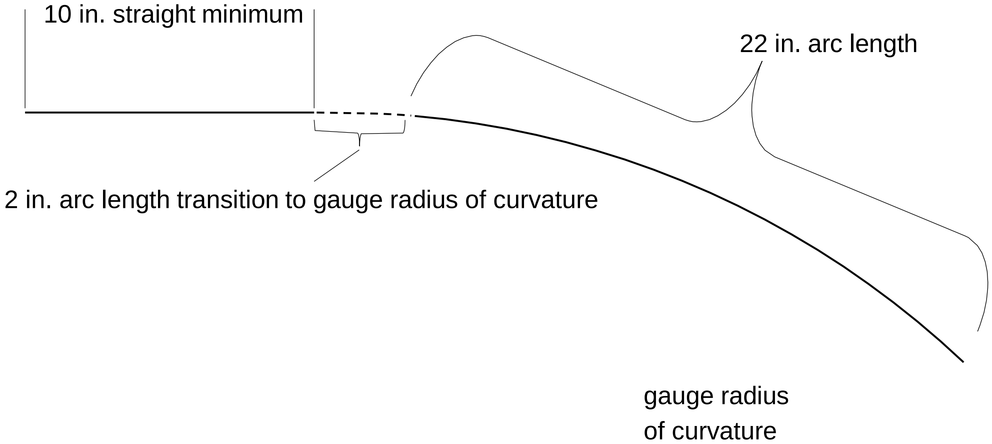


Figure 7—Curvature of a 1.75 in. Reference Tube Fully Wrapped onto a Standard Bending Form

Table 3—Actual Sample Radius of Curvature on a Standard Bending Form

Tube Diameter (in.)	Nominal Radius Block (in.)					
	32	48	60	72	96	102
0.75	31.457	47.457	59.457	71.457	95.457	101.457
1	31.593	47.593	59.593	71.593	95.593	101.593
1.25	31.728	47.728	59.728	71.728	95.728	101.728
1.5	31.864	47.864	59.864	71.864	95.864	101.864
1.75	32.000	48.000	60.000	72.000	96.000	102.000
2	32.136	48.136	60.136	72.136	96.136	102.136
2.375	32.339	48.339	60.339	72.339	96.339	102.339
2.875	32.611	48.611	60.611	72.611	96.611	102.611
3.5	32.951	48.951	60.951	72.951	96.951	102.951

11.3 Recommended Standard Coiled Tubing Fatigue Testing Procedure

11.3.1 Standard fatigue tests may be conducted on the following.

a) Samples that are free of transverse welds (factory bias or butt welds) or other structural discontinuities.

b) Samples that contain a factory skelp-end (bias) weld.

c) Samples that contain a factory butt weld.

For cases (a) and (b), the standard practice is to place the samples in the machine with the longitudinal weld seam oriented against the curved bending mandrel (i.e. at the intrados).

11.3.2 Data Collected During Fatigue Testing Process

The testing procedure itself (i.e. how samples are loaded into a machine, clamped, pressurized, etc.) is different on different machines, but the procedure should be fully documented to avoid discrepancies between operators. In order to evaluate data consistently from facility to facility, obtaining the following data is recommended for newly milled tubing or in-service samples (i.e. used CT).

a) Before Testing

1) A unique ID number for the sample.

2) The material grade and skelp manufacturer.

NOTE Various skelps within the same grade may exhibit different fatigue properties.

3) A strip identification number.

4) A string identification number.

5) Monotonic tensile properties (S_y, S_u, % EL, HRB, or HRC hardness).

i) S_y = measured yield strength taken close to the samples.

ii) S_u = ultimate tensile strength taken close to the samples.

iii) % EL = the percent elongation (where tests should be made on full body specimens).

iv) Hardness data should be as specified in API 5ST (e.g. taken on the Knoop or Vickers scales or nonstandard indenter loads and converted to HRB or HRC values).

6) Measured diameter across the tension-compression (T-C) axis to the nearest 0.001 in.

NOTE This is across the weld seam in a standard test.

7) Measured diameter across the neutral bending axis (N-A) to the nearest 0.001 in.

NOTE 1 This is perpendicular to the weld seam in a standard test.

NOTE 2 If the sample is oval prior to testing, measure the maximum and minimum diameters and load the sample into the machine with these as the N-A and T-C axes, respectively.

8) Measured wall thickness averaged over three locations (two within 0.25 in. of either side of the longitudinal weld seam and the third 180° from the weld seam) and reported to the nearest 0.001 in.

9) Nominal bending radius of curvature of the bend block.

10) Target internal pressure (measured and recorded throughout the test by the fatigue testing machine).

11) The orientation of the weld seam relative to the plane of the curved mandrel should be recorded.

NOTE For a standard test samples that are free of transverse welds (factory bias or butt welds) or other structural discontinuities and samples that contain a factory scalp end (bias weld), this will usually be 0° since the tubing is usually placed against the curved mandrel; however, existing curvature or ovality could prevent the sample from being placed into the machine in this manner.

When testing newly manufactured tubing, the specimens should be inspected for mechanical or corrosion damage that might affect the fatigue life. Corrosion damage may occur in newly milled tubing if it has been in storage for a while in corrosive environments.

b) During Testing

1) Document if water cooling is needed and used.

2) Maximum and minimum cycling rates for various tubing diameters.

3) Interruptions to the test routine.

4) Machine operators should observe written rules regarding personal safety.

c) After Testing

1) Number of cycles to failure (defined as loss of internal pressure).

2) Actual internal pressure, displayed or recorded on a computerized data acquisition system or strip chart recorder, averaged over the duration of the test and should not fluctuate more than 200 psi or 5 % of the target pressure, whichever is larger.

3) Final maximum measured diameter across the T-C axis.

4) Final maximum measured diameter across the N-A axis.

NOTE The maximum diameter is measured at the maximum ballooned region of the tubing, which is often near the failure site.

5) Longitudinal location of the failure site from the tangent point at the fixed end of the gauge section.

NOTE Over time this can reveal any tendency for the machine to exhibit a “sweet spot” where welds or other defects can be placed when examining their influence on fatigue.

6) Angular orientation of the failure site, relative to the curved mandrel.

NOTE For example, 0° means the crack occurred on the side in contact with the curved mandrel and 180° means the crack occurred opposite side in contact with the straight mandrel; failure can also occur at other locations around the circumference.

7) Crack Information.

NOTE This can include the length of the final crack, its origination site (inner or outer surface), its relation to a weld or defect, if applicable, or other observations.

Keeping a photograph of the failure site can be helpful over the long run at classifying failure mechanisms as a function of bending strain and hoop stress. Sectioning the failure and keeping it physically is a good practice in the event the data fall out of line with the trend exhibited by other samples of the same alloy.

An example datasheet is attached for recording data from an individual test (Annex E, Figure E.6).

11.4 Recommended Testing Matrices

11.4.1 For a particular grade of material, the more fatigue data generated the more reliably fatigue life parameters may be formulated for that material. A methodology for obtaining fatigue data for a particular grade of coiled tubing is described below from a minimum acceptable matrix that consists of 450 tests from the following.

— 3 diameters: minimum diameter, mid diameter, maximum diameter

— 2 wall thicknesses: min thickness, max thickness

— 3 bending radii: minimum (smallest core diameter), mid radius, maximum (largest gooseneck)

— 5 repeats of the above data

— 5 recommended pressure levels

With P1 = 50 psi to 200 psi (minimum system can control), P2 results in an average hoop stress = 7 % of nominal yield strength, P3 results in an average hoop stress = 30 % of nominal yield strength, P4 results in an average hoop stress = 45 % of nominal yield strength, and P5 results in an average hoop stress = 60 % of nominal yield strength.

Other methodologies exist and are valid approaches to obtain fatigue results for modeling. These include, but are not limited to, increased bending radii to cover a larger strain range and less testing, as long as a statistical confidence level is obtained.

11.4.2 It is recognized that some deviations could be required from either of these suggested testing strategies. For example, if the tubing is to be subjected to high-pressure work beyond the maximum recommended range, then data should be generated at and just above the anticipated field pressure levels.

11.4.3 A final recommendation is to supplement either of these matrices with a finite number of tests from each string produced (e.g. a low- and high-pressure test taken from each end of the string over the smallest bending radius experienced in the field). Such testing will note any discrepancies that may occur due to changes in the milling practices of the material suppliers or to different material from a new supplier.

11.4.4 Over time, should fatigue properties migrate away from those exhibited initially, the newer data should be used to replace the fatigue properties defined earlier.

11.5 Final Recommendations

It is the CT user's responsibility to ensure that adequate testing and test data are available to represent the fatigue strength under the most stringent conditions, including minimum bending radius, maximum hoop stress, and material integrity. It is well known that mechanical damage in the form of corrosion pits or HIC and hydrogen embrittlement from CT exposure to wet H_2S, scratches, nicks, cuts, dents, scrapes, etc. can drastically compromise the fatigue integrity of CT.

Annex A
(informative)

Coiled Tubing Properties

A.1 General

In order to understand the processes employed in care, maintenance, and inspection of used carbon steel coiled tubulars, the properties and testing of as-manufactured (new) steel coiled tubing are in this annex. Additional information on requirements for new coiled tubing are in API 5ST.

Definitions of measurements taken on coiled tubing and tables of standard wall thicknesses and capacities, along with an internal gauge table for round and ovalled materials, are provided.

This annex also contains information regarding problems that have been found to be associated with coiled tubulars.

A.2 Derived Quantities

A.2.1 Ovality of Coiled Tubulars

The ovality (Θ) of new coiled tubulars at any point can be calculated by:

$$\Theta = 2(D_{max} - D_{min})/(D_{max} + D_{min}) \qquad (A.1)$$

For new (round) tubing, the equations reduce to:

$$\Theta = (D_{max} - D_{min})/D \qquad (A.2)$$

where

D_{max} is the maximum outside diameter of tubular at a location;

D_{min} is the minimum outside diameter of tubular at the same location as D_{max};

D is the specified outside diameter.

For the ovality (Θ) as a percentage, multiply Equations (A.1) or (A.2) by 100.

These equations are used in order to separate ovality from dilation and where the tubing has either ballooned or necked.

A.2.2 Pipe Metal Cross-sectional Area

The pipe metal cross-sectional area (A_m) for new coiled tubing can be calculated from:

$$A_m = \pi(D^2 - d^2)/4 \qquad (A.3)$$

Using $d = D - 2t$, Equation (A.3) can be rewritten as:

$$A_m = \pi t_{av}(D_{av} - t_{av}) \qquad (A.4)$$

where

D_{av} is the average outside diameter;

t_{av} is the average wall thickness.

The average outside diameter (D_{av}) for the computation of the cross-sectional area value that is to be used for the determination of yield strength and tensile strength when testing full section samples may be computed as the average of D_{max} and D_{min} for new tubing. The result is reported to the nearest 0.001 in.

The average wall thickness (t_{av}) to be used in the computation of the cross-sectional area value that is used for the determination of both yield and tensile strength when testing full-section samples may be computed from a minimum of four equally spaced wall thickness measurements (t_1, t_2, t_3, t_4) taken with calipers or a suitably calibrated gauge as illustrated in Figure A.1.

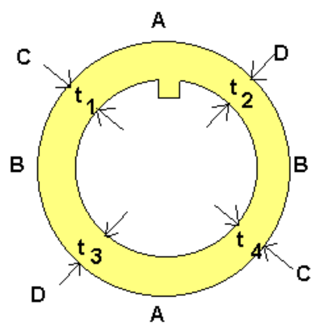


Figure A.1—Typical Measurement Locations for Coiled Tubing Outer Diameter and Wall Thickness Measurements (OD Readings at AA, BB, CC, and DD)

Using those measurements, an average wall thickness can be calculated using:

$$t_{av} = (t_1 + t_2 + t_3 + t_4)/4 \quad \text{(A.5)}$$

NOTE The result is reported to the nearest 0.001 in.

A.3 Yields

A.3.1 Pipe Body Yield Load

The pipe body yield load (L_y) for coiled tubing is the axial tension load in the absence of pressures or torque that produces a stress in the tube equal to the specified minimum yield strength (S_y) in tension and can be calculated by:

$$L_y = \pi \times t_{av} \times (D - t_{av}) \times S_y \quad \text{(A.6)}$$

NOTE The value of L_y is rounded to the nearest 45.4 kg (100 lb).

A.3.2 Internal Yield Pressure

The internal yield pressure (P_t) is defined as the internal pressure that produces a stress in the tubing equal to the specified minimum yield strength (S_y) based on the specified outside diameter and the minimum wall thickness and can be calculated by:

$$P_t = 2 \times S_y \times t_{min}/D \quad \text{(A.7)}$$

NOTE The value of P_t is rounded to the nearest 0.69 MPa (100 psi).

A.3.3 Torsional Yield Strength

Torsional yield strength (T_f) for coiled tubing is defined as the torque required to yield the coiled tubing in the absence of pressure or axial stress and can be calculated by:

$$T_f = S_y \times [D^4 - (D - 2t_{min})^4]/105.86 \times D \tag{A.8}$$

where

T_f is the torsional yield strength (lb-ft);

S_y is the specified yield strength (psi);

D is the specified outside diameter (in.);

t_{min} is the specified minimum wall thickness (in.).

NOTE The value of T_f is rounded to the nearest 135.6 m-N (100 ft-lb).

Annex B
(informative)

Collapse of Coiled Tubing

B.1 General

This annex takes information from API 5C7 (withdrawn) and discusses the collapse of coiled tubing. Coiled tubing collapses when excess pressure is applied from the outside surface. Formulae were originally developed to cover collapse of oilfield casing and tubing, based on statistical fits at the 95 % confidence level to tests performed on cylindrical tubular sections. The results of the original formulae developed are applied to coiled tubing and are based on known D/t_{min} ratios for coiled tubing. The value of t_{min} is that shown in Table B.1. The results for round tubing are then extended to include the effect of ovality using a correction developed by Timoshenko [60]. Table B.1 shows the results for 2 % and 5 % ovality.

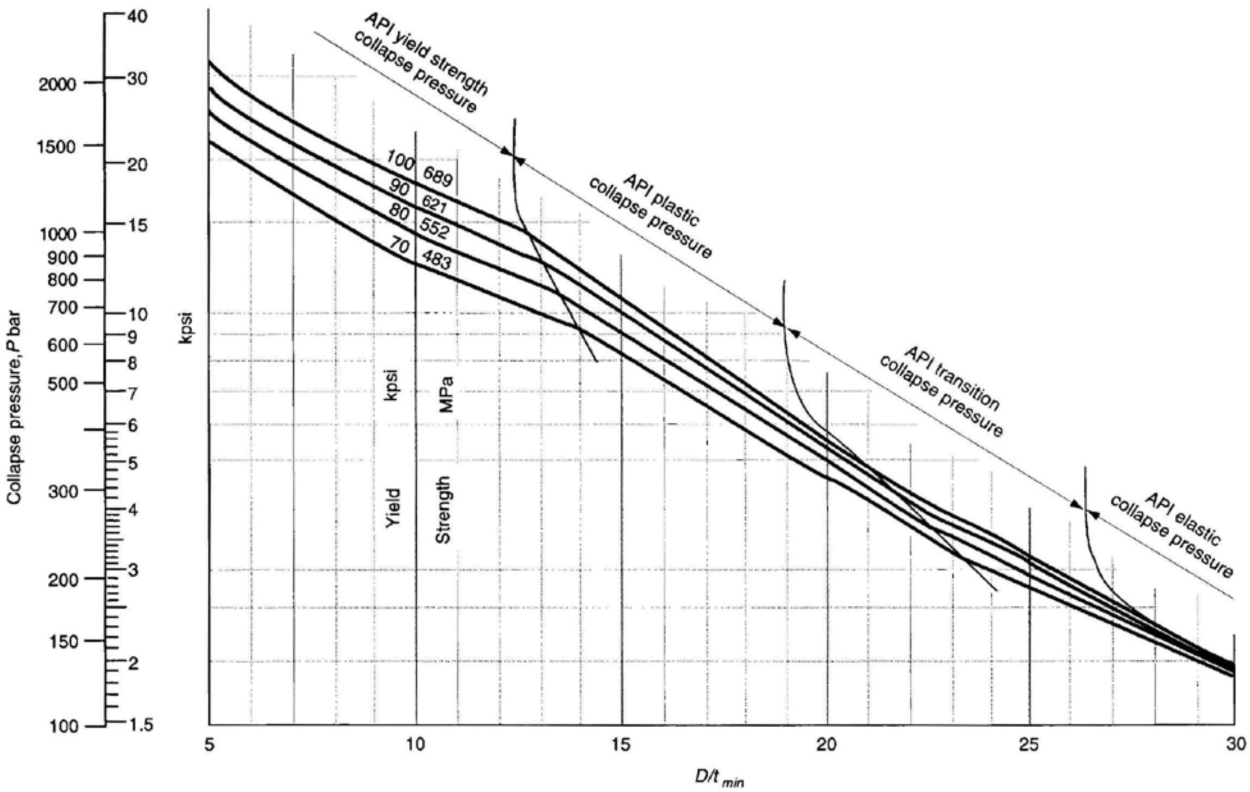
B.2 Collapse Pressure for As-manufactured Coiled Tubing

The collapse pressure for coiled tubing, in the absence of axial stress and internal pressure, P_c, for as-manufactured coiled tubing is calculated using the appropriate formulae from API 5C3, Sixth Edition, for elastic, yield strength, plastic, or transition collapse pressure using the specified outside diameter and the minimum wall thickness that determine the D/t_{min} ratio in the appropriate formula. Figure B.1 shows the collapse pressure for new, round coiled tubing for D/t_{min} ratios from 5 to 30 for grades CT70 to CT100.

Since roundness of coiled tubing is measured during the manufacturing process prior to spooling only at the ends, it is the responsibility of the user to determine the ovality of as-received and in-service coiled tubing. This is best performed during the first and subsequent nondestructive inspections performed on the tubing.

B.3 Collapse Pressure

Collapse pressure (P_c) in the absence of axial stress and internal pressure for new coiled tubing is calculated using the appropriate formula of API 5C3, Sixth Edition. If the coiled tubing D/t_{min} ratio is less than the D/t_{min} ratio as shown in Table 4, column 2 of API 5C3, Sixth Edition, then the collapse pressures may be estimated using Figure B.1 as a function of D/t_{min} and minimum yield strength, S_y. Collapse pressure tables where axial load is combined with external pressure, P, and tubing ovality are given below.



NOTE Not representative of coiled tubing in service conditions.

Figure B.1—Calculated Collapse Pressure Ratings for Various D/t_{min} Ratios of As-manufactured Coil Tubing

B.4 Used Coiled Tubing

B.4.1 Derating for Ovality

For coiled tubing in service, the tubing, or sections of it, should not be considered to be perfectly round unless it can be proved so by direct measurement. Working the tubing from reels and over guide arches increases the accumulated fatigue in the tubing wall—one result of which may be continued increase in ovality. Heavily cycled sections of lower strength coiled tubing are particularly prone to exhibiting ovality.

Table B.1 provided values for yield strength, plastic, transition, and elastic collapse regimes vs the various D/t_{min} ratios for new coiled tubing. Corrections factors should be used to estimate the collapse pressure for used tubing.

Warning—Care should be taken if and when applying the values given in Table B.1 to used tubing because of possible damage to the tubing and loss of yield strength from cycling.

Table B.1—Collapse Values for API 5ST Coiled Tubing Grades

Specified				Specified Minimum Yield Strength														
				70,000 psi					80,000 psi					90,000 psi				
Outside Diameter	Wall Thickness	Min Wall	Ratio	Ovality $(D_{max} - D_{min})/D$														
D	t	t_{min}	D/t_{min}	0	0.02		0.05		0	0.02		0.05		0	0.02		0.05	
(in.)	(in.)	(in.)		Tensile Load					Tensile Load					Tensile Load				
				L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2
				Collapse Pressure, psi														
				P_c	P_{co}	P	P_{co}	P_{co}	P_c	P_{co}	P	P_{co}	P_c	P_c	P_{co}	P	P_{co}	P_c
0.750	0.080	0.075	10.000	12,600	8290	5670	6250	4280	14,400	9470	6480	7140	4890	16,200	10,660	7300	8040	5500
0.750	0.083	0.078	9.615	13,050	8710	5960	6610	4520	14,910	9950	6810	7550	5170	16,770	11,190	7660	8490	5810
0.750	0.087	0.082	9.146	13,630	9260	6340	7080	4850	15,580	10,580	7240	8090	5540	17,530	11,910	8150	9100	6230
0.750	0.095	0.090	8.333	14,780	10,380	7100	8050	5510	16,900	11,860	8120	9200	6300	19,010	13,350	9140	10,350	7080
0.750	0.102	0.097	7.732	15,760	11,360	7770	8910	6100	18,020	12,990	8890	10,180	6970	20,270	14,610	10,000	11,460	7840
0.750	0.109	0.104	7.212	16,720	12,340	8450	9780	6690	19,110	14,110	9660	11,180	7650	21,500	15,870	10,860	12,580	8610
0.750	0.118	0.110	6.818	17,520	13,180	9020	10,540	7210	20,020	15,060	10,310	12,040	8240	22,530	16,950	11,600	13,550	9270
0.750	0.125	0.117	6.410	18,430	14,150	9680	11,430	7820	21,070	16,180	11,070	13,060	8940	23,700	18,200	12,460	14,690	10,050
1.000	0.075	0.070	14.286	8730	5150	3520	3690	2530	9910	5870	4020	4210	2880	10,850	6530	4470	4690	3210
1.000	0.080	0.075	13.333	9710	5740	3930	4140	2830	11,100	6560	4490	4730	3240	12,250	7320	5010	5290	3620
1.000	0.083	0.078	12.821	10,070	6040	4130	4380	3000	11,510	6900	4720	5010	3430	12,940	7760	5310	5630	3850
1.000	0.087	0.082	12.195	10,540	6440	4410	4710	3220	12,040	7360	5040	5380	3680	13,550	8280	5670	6060	4150
1.000	0.095	0.090	11.111	11,470	7260	4970	5390	3690	13,100	8290	5670	6150	4210	14,740	9330	6390	6920	4740
1.000	0.102	0.097	10.309	12,260	7980	5460	5990	4100	14,010	9120	6240	6840	4680	15,770	10,260	7020	7700	5270
1.000	0.109	0.104	9.615	13,050	8710	5960	6610	4520	14,910	9950	6810	7550	5170	16,770	11,190	7660	8490	5810
1.000	0.118	0.110	9.091	13,710	9330	6390	7140	4890	15,660	10,660	7300	8160	5580	17,620	12,000	8210	9180	6280
1.000	0.125	0.117	8.547	14,460	10,060	6890	7770	5320	16,530	11,500	7870	8890	6080	18,600	12,940	8860	10,000	6840
1.000	0.134	0.126	7.937	15,420	11,010	7540	8600	5890	17,620	12,580	8610	9830	6730	19,820	14,160	9690	11,060	7570
1.250	0.075	0.070	17.857	5930	3550	2430	2500	1710	6470	3970	2720	2820	1930	6940	4370	2990	3110	2130
1.250	0.080	0.075	16.667	6780	4010	2740	2840	1940	7450	4510	3090	3200	2190	8060	4980	3410	3550	2430
1.250	0.087	0.082	15.244	7970	4670	3200	3320	2270	8830	5270	3610	3760	2570	9620	5840	4000	4180	2860
1.250	0.095	0.090	13.889	9330	5440	3720	3900	2670	10,400	6150	4210	4420	3030	11,410	6840	4680	4930	3370
1.250	0.102	0.097	12.887	10,020	6000	4110	4350	2980	11,450	6860	4700	4970	3400	12,880	7710	5280	5590	3830
1.250	0.109	0.104	12.019	10,680	6560	4490	4810	3290	12,200	7500	5130	5500	3760	13,730	8440	5780	6190	4240
1.250	0.118	0.110	11.364	11,240	7050	4830	5220	3570	12,840	8060	5520	5960	4080	14,450	9070	6210	6710	4590
1.250	0.125	0.117	10.684	11,880	7630	5220	5690	3890	13,570	8720	5970	6510	4460	15,270	9810	6710	7320	5010
1.250	0.134	0.126	9.921	12,690	8370	5730	6320	4330	14,500	9570	6550	7220	4940	16,320	10,770	7370	8130	5560
1.250	0.145	0.137	9.124	13,660	9290	6360	7100	4860	15,610	10,610	7260	8120	5560	17,570	11,940	8170	9140	6260
1.250	0.156	0.148	8.446	14,610	10,210	6990	7900	5410	16,700	11,670	7990	9030	6180	18,790	13,130	8990	10,160	6950
1.250	0.175	0.167	7.485	16,210	11,810	8080	9310	6370	18,520	13,500	9240	10,640	7280	20,840	15,190	10,400	11,970	8190

Specified		Min Wall	Ratio	Specified Minimum Yield Strength														
				70,000 psi					80,000 psi					90,000 psi				
				Ovality $(D_{max} - D_{min})/D$														
Outside Diameter	Wall Thickness	Min Wall	Ratio	0	0.02		0.05		0	0.02		0.05		0	0.02		0.05	
				Tensile Load					Tensile Load					Tensile Load				
D (in.)	t (in.)	t_{min} (in.)	D/t_{min}	L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2
				Collapse Pressure, psi														
				P_c	P_{co}	P	P_{co}	P_{co}	P_c	P_{co}	P	P_{co}	P_c	P_c	P_{co}	P	P_{co}	P_c
1.500	0.087	0.082	18.293	5650	3400	2330	2390	1640	6140	3800	2600	2690	1840	6570	4170	2850	2970	2030
1.500	0.095	0.090	16.667	6780	4010	2740	2840	1940	7450	4510	3090	3200	2190	8060	4980	3410	3550	2430
1.500	0.102	0.097	15.464	7770	4560	3120	3240	2220	8600	5140	3520	3660	2500	9360	5700	3900	4070	2790
1.500	0.109	0.104	14.423	8760	5110	3500	3650	2500	9740	5780	3960	4140	2830	10,670	6420	4390	4610	3160
1.500	0.118	0.113	13.274	9750	5770	3950	4170	2850	11,150	6600	4520	4760	3260	12,340	7370	5040	5330	3650
1.500	0.125	0.120	12.500	10,300	6240	4270	4550	3110	11,780	7130	4880	5200	3560	13,250	8020	5490	5850	4000
1.500	0.134	0.129	11.628	11,000	6850	4690	5050	3460	12,580	7830	5360	5770	3950	14,150	8810	6030	6490	4440
1.500	0.145	0.140	10.714	11,850	7600	5200	5670	3880	13,540	8690	5950	6480	4440	15,230	9770	6690	7290	4990
1.500	0.156	0.151	9.934	12,670	8360	5720	6310	4320	14,490	9550	6540	7210	4930	16,300	10,750	7360	8110	5550
1.500	0.175	0.170	8.824	14,070	9680	6630	7440	5090	16,080	11,060	7570	8500	5820	18,090	12,450	8520	9570	6550
1.500	0.188	0.183	8.197	15,000	10,590	7250	8230	5630	17,140	12,100	8280	9410	6440	19,280	13,620	9320	10,580	7240
1.500	0.204	0.199	7.538	16,110	11,710	8010	9220	6310	18,410	13,380	9160	10,540	7210	20,710	15,060	10,310	11,860	8120
1.750	0.095	0.090	19.444	4960	3030	2070	2130	1460	5340	3370	2310	2390	1640	5660	3670	2510	2620	1790
1.750	0.102	0.097	18.041	5810	3490	2390	2460	1680	6330	3900	2670	2760	1890	6780	4280	2930	3050	2090
1.750	0.109	0.104	16.827	6660	3950	2700	2790	1910	7310	4430	3030	3140	2150	7900	4890	3350	3490	2390
1.750	0.118	0.110	15.909	7390	4350	2980	3080	2110	8150	4890	3350	3480	2380	8860	5420	3710	3870	2650
1.750	0.125	0.117	14.957	8240	4820	3300	3430	2350	9130	5440	3720	3880	2660	9970	6040	4130	4330	2960
1.750	0.134	0.126	13.889	9330	5440	3720	3900	2670	10,400	6150	4210	4420	3030	11,410	6840	4680	4930	3370
1.750	0.145	0.137	12.774	10,100	6070	4150	4410	3020	11,550	6940	4750	5040	3450	12,990	7800	5340	5660	3870
1.750	0.156	0.148	11.824	10,840	6700	4590	4930	3370	12,390	7660	5240	5630	3850	13,940	8620	5900	6330	4330
1.750	0.175	0.167	10.479	12,090	7820	5350	5850	4000	13,810	8930	6110	6690	4580	15,540	10,050	6880	7520	5150
1.750	0.188	0.176	9.943	12,660	8350	5710	6300	4310	14,470	9540	6530	7200	4930	16,280	10,730	7340	8100	5540
1.750	0.204	0.192	9.115	13,670	9300	6370	7110	4870	15,630	10,630	7280	8130	5560	17,580	11,960	8190	9150	6260
1.750	0.224	0.212	8.255	14,910	10,500	7190	8150	5580	17,030	12,000	8210	9320	6380	19,160	13,500	9240	10,480	7170
1.750	0.250	0.238	7.353	16,450	12,060	8250	9530	6520	18,800	13,790	9440	10,900	7460	21,150	15,510	10,620	12,260	8390
2.000	0.109	0.104	19.231	5080	3100	2120	2180	1490	5480	3440	2350	2440	1670	5820	3760	2570	2680	1830
2.000	0.118	0.110	18.182	5720	3440	2350	2420	1660	6220	3840	2630	2720	1860	6660	4210	2880	3010	2060
2.000	0.125	0.117	17.094	6460	3840	2630	2710	1850	7080	4310	2950	3050	2090	7640	4750	3250	3390	2320
2.000	0.134	0.126	15.873	7420	4360	2980	3090	2110	8190	4910	3360	3500	2400	8900	5440	3720	3890	2660
2.000	0.145	0.137	14.599	8590	5020	3440	3580	2450	9540	5660	3870	4050	2770	10,430	6290	4300	4520	3090
2.000	0.156	0.148	13.514	9590	5640	3860	4060	2780	10,890	6430	4400	4630	3170	11,970	7160	4900	5170	3540
2.000	0.175	0.167	11.976	10,710	6590	4510	4840	3310	12,240	7530	5150	5530	3780	13,770	8480	5800	6220	4260
2.000	0.188	0.176	11.364	11,240	7050	4830	5220	3570	12,840	8060	5520	5960	4080	14,450	9070	6210	6710	4590
2.000	0.204	0.192	10.417	12,150	7870	5390	5900	4040	13,890	9000	6160	6750	4620	15,620	10,120	6930	7590	5190
2.000	0.224	0.212	9.434	13,270	8910	6100	6780	4640	15,160	10,190	6970	7750	5300	17,060	11,460	7840	8720	5970
2.000	0.250	0.238	8.403	14,680	10,280	7040	7960	5450	16,770	11,740	8040	9090	6220	18,870	13,210	9040	10,230	7000
2.000	0.276	0.271	7.380	16,400	12,010	8220	9490	6500	18,740	13,720	9390	10,840	7420	21,090	15,440	10,570	12,200	8350
2.000	0.281	0.266	7.519	16,140	11,750	8040	9250	6330	18,450	13,430	9190	10,570	7230	20,760	15,100	10,330	11,900	8140

Specified				Specified Minimum Yield Strength														
				70,000 psi					80,000 psi					90,000 psi				
				Ovality $(D_{max} - D_{min})/D$														
Outside Diameter D (in.)	Wall Thickness t (in.)	Min Wall t_{min} (in.)	Ratio D/t_{min}	0	0.02		0.05		0	0.02		0.05		0	0.02		0.05	
				Tensile Load					Tensile Load					Tensile Load				
				L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2	L=0	L=0	L=L_y/2	L=0	L=L_y/2
				Collapse Pressure, psi														
				P_c	P_{co}	P	P_{co}	P_{co}	P_c	P_{co}	P	P_{co}	P_c	P_c	P_{co}	P	P_{co}	P_c
2.375	0.109	0.104	22.837	3330	2170	1490	1530	1050	3470	2350	1610	1690	1160	3760	2580	1770	1870	1280
2.375	0.118	0.110	21.591	3870	2450	1680	1730	1180	4090	2690	1840	1920	1310	4230	2880	1970	2080	1420
2.375	0.125	0.117	20.299	4500	2790	1910	1960	1340	4810	3080	2110	2190	1500	5060	3340	2290	2400	1640
2.375	0.134	0.126	18.849	5300	3220	2200	2260	1550	5740	3580	2450	2540	1740	6110	3920	2680	2800	1920
2.375	0.145	0.137	17.336	6290	3750	2570	2640	1810	6880	4200	2870	2980	2040	7410	4620	3160	3300	2260
2.375	0.156	0.148	16.047	7270	4280	2930	3030	2070	8020	4820	3300	3430	2350	8700	5330	3650	3810	2610
2.375	0.175	0.167	14.222	8970	5230	3580	3740	2560	9980	5910	4040	4240	2900	10,940	6580	4500	4730	3240
2.375	0.188	0.176	13.494	9610	5650	3870	4070	2790	10,510	6340	4340	4580	3130	12,000	7180	4910	5180	3550
2.375	0.204	0.192	12.370	10,400	6320	4330	4620	3160	11,890	7230	4950	5280	3610	13,380	8130	5560	5940	4070
2.375	0.224	0.212	11.203	11,380	7180	4910	5320	3640	13,010	8210	5620	6080	4160	14,630	9230	6320	6840	4680
2.375	0.250	0.238	9.979	12,620	8310	5690	6270	4290	14,430	9500	6500	7170	4910	16,230	10,680	7310	8060	5520
2.375	0.276	0.261	9.100	13,690	9320	6380	7130	4880	15,650	10,650	7290	8150	5580	17,610	11,980	8200	9170	6280
2.375	0.281	0.266	8.929	13,920	9540	6530	7320	5010	15,910	10,900	7460	8370	5730	17,900	12,270	8400	9410	6440
2.375	0.300	0.285	8.333	14,780	10,380	7100	8050	5510	16,900	11,860	8120	9200	6300	19,010	13,350	9140	10,350	7080
2.625	0.145	0.137	19.161	5120	3120	2140	2190	1500	5530	3470	2370	2460	1680	5870	3790	2590	2700	1850
2.625	0.146	0.148	17.736	6010	3600	2460	2530	1730	6560	4020	2750	2850	1950	7040	4420	3030	3150	2160
2.625	0.175	0.167	15.719	7550	4440	3040	3150	2160	8340	5000	3420	3560	2440	9070	5530	3780	3960	2710
2.625	0.188	0.176	14.915	8280	4840	3310	3450	2360	9180	5460	3740	3900	2670	10,030	6070	4150	4350	2980
2.625	0.204	0.192	13.672	9570	5570	3810	4000	2740	10,680	6310	4320	4540	3110	11,730	7020	4800	5060	3460
2.625	0.224	0.212	12.382	10,390	6320	4330	4610	3160	11,880	7220	4940	5270	3610	13,360	8120	5560	5930	4060
2.625	0.250	0.238	11.029	11,540	7320	5010	5440	3720	13,190	8370	5730	6220	4260	14,840	9420	6450	7000	4790
2.625	0.276	0.261	10.057	12,540	8230	5630	6200	4240	14,330	9410	6440	7090	4850	16,120	10,580	7240	7970	5450
2.625	0.281	0.266	9.868	12,750	8430	5770	6370	4360	14,570	9630	6590	7280	4980	16,390	10,830	7410	8190	5610
2.625	0.300	0.285	9.211	13,550	9180	6280	7010	4800	15,490	10,490	7180	8010	5480	17,420	11,800	8080	9020	6170
2.875	0.125	0.117	24.573	2830	1870	1280	1330	910	2650	1890	1290	1390	950	3190	2220	1520	1610	1100
2.875	0.134	0.126	22.817	3340	2170	1490	1540	1050	3480	2350	1610	1690	1160	3760	2590	1770	1870	1280
2.875	0.145	0.137	20.985	4160	2610	1790	1840	1260	4420	2870	1960	2040	1400	4600	3090	2110	2220	1520
2.875	0.156	0.148	19.426	4970	3040	2080	2140	1460	5360	3370	2310	2390	1640	5670	3680	2520	2630	1800
2.875	0.175	0.167	17.216	6370	3790	2590	2680	1830	6980	4250	2910	3010	2060	7520	4680	3200	3340	2290
2.875	0.188	0.180	15.972	7330	4320	2960	3060	2090	8090	4860	3330	3460	2370	8790	5380	3680	3840	2630
2.875	0.204	0.196	14.668	8520	4980	3410	3550	2430	9460	5620	3850	4020	2750	10,340	6240	4270	4480	3070
2.875	0.224	0.216	13.310	9730	5750	3940	4150	2840	11,120	6570	4500	4740	3240	12,290	7340	5020	5300	3630
2.875	0.250	0.242	11.880	10,790	6660	4560	4890	3350	12,330	7610	5210	5590	3830	13,880	8570	5870	6290	4300

Specified Outside Diameter D (in.)	Specified Wall Thickness t (in.)	Min Wall t_{min} (in.)	Ratio D/t_{min}	70,000 psi, Ovality 0, L=0, P_c	70,000 psi, Ovality 0.02, L=0, P_{co}	70,000 psi, Ovality 0.02, $L=L_y/2$, P	70,000 psi, Ovality 0.05, L=0, P_{co}	70,000 psi, Ovality 0.05, $L=L_y/2$, P_{co}	80,000 psi, Ovality 0, L=0, P_c	80,000 psi, Ovality 0.02, L=0, P_{co}	80,000 psi, Ovality 0.02, $L=L_y/2$, P	80,000 psi, Ovality 0.05, L=0, P_{co}	80,000 psi, Ovality 0.05, $L=L_y/2$, P_c	90,000 psi, Ovality 0, L=0, P_c	90,000 psi, Ovality 0.02, L=0, P_{co}	90,000 psi, Ovality 0.02, $L=L_y/2$, P	90,000 psi, Ovality 0.05, L=0, P_{co}	90,000 psi, Ovality 0.05, $L=L_y/2$, P_c
				Specified Minimum Yield Strength / Ovality $(D_{max} - D_{min})/D$ / Tensile Load / Collapse Pressure, psi														
3.250	0.145	0.137	23.723	3030	2000	1370	1420	970	2860	2030	1390	1490	1020	3460	2390	1640	1730	1180
3.250	0.156	0.148	21.959	3710	2370	1620	1670	1140	3900	2580	1770	1850	1270	4070	2780	1900	2020	1380
3.250	0.175	0.167	19.461	4950	3030	2070	2130	1460	5330	3360	2300	2380	1630	5650	3660	2500	2620	1790
3.250	0.188	0.176	18.466	5540	3340	2290	2350	1610	6010	3730	2550	2640	1810	6420	4080	2790	2910	1990
3.250	0.204	0.192	16.927	6580	3910	2680	2760	1890	7220	4380	3000	3110	2130	7800	4840	3310	3450	2360
3.250	0.224	0.212	15.330	7890	4630	3170	3290	2250	8730	5210	3570	3720	2550	9520	5780	3960	4140	2830
3.250	0.250	0.238	13.655	9500	5560	3810	4000	2740	10,700	6320	4330	4550	3110	11,750	7040	4820	5070	3470
3.250	0.276	0.261	12.452	10,340	6270	4290	4570	3130	11,820	7170	4910	5230	3580	13,290	8060	5520	5880	4020
3.250	0.271	0.266	12.218	10,520	6430	4400	4700	3220	12,020	7340	5020	5370	3680	13,530	8260	5650	6040	4130
3.250	0.300	0.285	11.404	11,200	7020	4800	5190	3550	12,800	8020	5490	5930	4060	14,400	9030	6180	6670	4570
3.500	0.156	0.148	23.649	3050	2010	1380	1430	980	2880	2050	1400	1500	1030	3480	2410	1650	1740	1190
3.500	0.175	0.167	20.958	4170	2610	1790	1840	1260	4430	2870	1960	2050	1400	4620	3100	2120	2230	1530
3.500	0.188	0.180	19.444	4960	3030	2070	2130	1460	5340	3370	2310	2390	1640	5660	3670	2510	2620	1790
3.500	0.204	0.196	17.857	5930	3550	2430	2500	1710	6470	3970	2720	2820	1930	6940	4370	2990	3110	2130
3.500	0.224	0.216	16.204	7140	4210	2880	2980	2040	7870	4740	3240	3370	2310	8540	5240	3590	3740	2560
3.500	0.250	0.242	14.463	8720	5090	3480	3640	2490	9700	5750	3940	4120	2820	10,610	6390	4370	4590	3140
3.500	0.281	0.273	12.821	10,070	6040	4130	4380	3000	11,510	6900	4720	5010	3430	12,940	7760	5310	5630	3850
3.500	0.300	0.292	11.986	10,710	6590	4510	4830	3310	12,230	7530	5150	5520	3780	13,760	8470	5800	6210	4250

NOTE 1 Collapse pressure for round CT (Ovality = 0) is the yield strength, plastic, or transition collapse pressure from API 5C3, Fifth Edition.

NOTE 2 Collapse pressure for oval CT is the API value for round tubing, combined with the solution by S. Timoshenko, *Strength of Materials, Part 2*, Van Nostrand, 1954.

NOTE 3 Listed collapse pressures are given for a safety factor = 1. The operating pressure should be reduced by the appropriate SF.

B.4.2 Initial Recommendation

One suggested recommendation is that when coiled tubing is first put in use, lower strength coiled tubing (CT70) should immediately be considered as possessing a minimum of 2 % ovality and higher strength coiled tubing (CT80 to CT110) should be considered as having 1 % ovality. The collapse values using these percentages are substantially lower than those for perfectly round tubing.

B.4.3 Collapse Pressure for Standard Grades

For standard coiled tubing sizes and material grades, collapse pressures at 2 % and 5 % ovality are given in Table B.1 (see columns headed 0.02 and 0.05). When using ovalities other than these values, Equations (B.1) to (B.3) should be used to predict the collapse derating of the tubing. In these equations, the effect of ovality is shown in the "g" term.

$$P_{co} = g - (g^2 - f)^{1/2} \quad \text{(B.1)}$$

where

$$g = S_y/[(D/t_{min}) - 1] + (P_c/4)[2 + 3(D/t_{min}) \times (D_{max} - D_{min})/D] \quad \text{(B.2)}$$

$$f = 2\, S_y P_c/(D/t_{min} - 1) \quad \text{(B.3)}$$

and

S_y is the specified minimum yield strength (psi);

P_c is the collapse pressure (psi) for round tubing determined using the procedure defined in the first paragraph of this section (see API 5C3, Sixth Edition);

P_{co} is the collapse pressure for ovalled coiled tubing (psi);

D_{max} is the section maximum outside diameter (in.);

D_{min} is the section minimum outside diameter (in.);

D is the specified outside diameter;

t_{min} is the minimum specified wall thickness.

For the purpose of these computations, ovality is defined as $\Theta = (D_{max} - D_{min})/D$.

The owner of the tubing may wish to derate each section of tubing by a specific factor that accounts for the maximum value of the measured ovality in that section.

B.5 Effect of Loading on Collapse Resistance

When tensile loading (L) or torque (Γ) is combined with external pressure (P_o), the effect is accounted for with the introduction of full safety factors (SF) and can be calculated by:

$$(1/\mathrm{SF})^{4/3} = (P_o/P_{co})^{4/3} + (L/L_y)^{4/3} \quad \text{(B.4)}$$

$$(1/\mathrm{SF})^{4/3} = (P_o/P_{co})^{4/3} + (\Gamma/\Gamma_y)^{4/3} \quad \text{(B.5)}$$

where

P_o is the operating external pressure (psi);

P_{co} is the collapse pressure for oval coiled tubing (psi);

L is the operating tensile load (lb);

L_y is the pipe body yield load (lb);

Γ is the operating torque (lb-ft);

Γ_y is the torsional operating strength (lb-ft);

SF is the safety factor ($SF \geq 1$).

The values in Table B.1 for a value of half the yield load ($L = L_y/2$) are computed for a safety factor (SF, see below) of 1, i.e. SF = 1 in Equation (B.4). In practice, such values are easily obtainable with the string hanging under its own weight, and when string sections are being removed from a well.

Using minimum allowable safety factors as determined by the user of the tubing, Equations (B.4) and (B.5) can be solved for allowable external pressure (P_o), allowable tensile load (L), required collapse capacity (P_{co}), required load capacity (L_y), or torque capacity (Γ_y) as needed.

B.6 Utilization and Correction Factors

The allowable external pressure can be found with:

$$P_o = P_{co}K \tag{B.6}$$

The correction factor (K) can be calculated from Equation (B.7) for tensile loading or Equation (B.8) for torque.

$$K = [(1/SF)^{4/3} - (L/L_y)^{4/3}]^{3/4} \tag{B.7}$$

$$K = [(1/SF)^{4/3} - (\Gamma_y/\Gamma_y)^{4/3}]^{3/4} \tag{B.8}$$

The collapse pressure correction factor (K) is listed in Table B.2 as a function of the allowable safety factor (SF) and the load factors (L/L_y or Γ/Γ_y), whichever is applicable.

The utilization factor (U) should be determined by the owner of the string. In order to determine how the collapse pressure rating might be lowered with the age of the string or sections there-of, the user may determine from field experience the utilization (U) of the coiled tubing (from 0 to 100 %) and use the corrections suggested in the coiled tubing utilization of Table B.2. The owner shall estimate or otherwise determine this number.

Table B.2—Coiled Tubing Collapse Pressure Factors for Various Amounts of Utilization

Load Factor	Coiled Tubing Utilization, U							
L/L_y or Γ/Γ_y	$U <$ 20 %	20 % $\leq U <$ 30 %	30 % $\leq U <$ 40 %	40 % $\leq U <$ 50 %	50 % $\leq U <$ 60 %	60 % $\leq U <$ 70 %	70 % $\leq U <$ 80 %	80 % $\leq U <$ 100 %
	Safety Factor (SF)							
	1.25	1.30	1.30	1.50	1.60	1.70	1.80	2.00
	Collapse Pressure Correction Factor (K)							
0.00	0.80	0.77	0.71	0.67	0.63	0.59	0.56	0.50
0.05	0.79	0.75	0.70	0.65	0.61	0.57	0.54	0.48
0.10	0.76	0.73	0.67	0.63	0.58	0.55	0.51	0.46
0.15	0.73	0.70	0.65	0.60	0.55	0.52	0.48	0.42
0.20	0.70	0.67	0.61	0.56	0.52	0.48	0.45	0.38
0.25	0.67	0.64	0.58	0.53	0.48	0.44	0.40	0.34
0.30	0.63	0.60	0.54	0.49	0.44	0.40	0.36	0.29
0.35	0.59	0.56	0.50	0.44	0.39	0.35	0.31	0.24
0.40	0.55	0.51	0.45	0.39	0.34	0.30	0.26	0.18
0.45	0.50	0.46	0.40	0.34	0.29	0.24	0.19	0.11
0.50	0.45	0.41	0.34	0.28	0.23	0.17	0.12	0.00
0.55	0.40	0.36	0.29	0.22	0.16	0.09	0.02	
0.60	0.34	0.30	0.22	0.15	0.07			
0.65	0.28	0.23	0.14	0.05				
0.70	0.21	0.16	0.05					
0.75	0.12	0.06						
0.80								

B.7 Effect of Internal and External Pressure

The external pressure equivalent (PE) of operating external pressure P_o and internal pressure (P_i) can be calculated by Equation (B.9), which is taken from API 5C3, Sixth Edition.

$$\mathrm{PE} = P_o - [1 - 2/(D/t)]P_i \tag{B.9}$$

B.8 Effect of Corrosion and Damage on Collapse Pressure

Corrosion and erosion lower the wall thickness, possibly below the minimum value used to create Table B.1, and may create a region at which there is both wall loss and ovality if localized to one side of the tubing. Dimensional and nondestructive inspection of the tubing provides information on wall loss and ovality. The collapse values given in this section were derived for ovality without wall loss. Extreme care should be taken when assessing the collapse resistance of tubing that has been worn or corroded on one side.

Annex C
(informative)

Reference Tables

C.1 Wall Thickness and Capabilities

Table C.1 provides values that can be used for calculating wall thickness and capabilities of coiled tubing.

Table C.1—Values for Coiled Tubing Calculations on Wall Thickness and Capabilities

Specified: Outside Diameter D (in.)	Specified: Wall Thickness t (in.)	Min Wall t_{min} (in.)	Ratio D/t_{min}	Mass per Unit Length w_{pe} lb/ft	Pipe Metal Cross-sectional area (in.^{2})	Remaining Walls: 95 % Spec Wall Thickness (in.)	Remaining Walls: 90 % Spec Wall Thickness (in.)	Remaining Walls: 87.5 % Spec Wall Thickness (in.)	Calculated: Internal Diameter (in.)	Calculated: Flow Area (flash-free) (in.^{2})	Internal Capacity per 1000 ft (gal)	Internal Capacity per 1000 ft (bbl)	External Displacement per 1000 ft (gal)	External Displacement per 1000 ft (bbl)	Displacement External − Internal per 1000 ft (gal)	Displacement External − Internal per 1000 ft (bbl)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
0.750	0.080	0.075	10.000	0.5730	0.1684	0.076	0.072	0.070	0.590	0.1684	14.202	0.3382	22.950	0.5464	8.748	0.2083
0.750	0.083	0.078	9.615	0.5918	0.1739	0.079	0.075	0.073	0.584	0.1739	13.915	0.3313	22.950	0.5464	9.035	0.2151
0.750	0.087	0.082	9.146	0.6166	0.1812	0.083	0.078	0.076	0.576	0.1812	13.536	0.3223	22.950	0.5464	9.414	0.2241
0.750	0.095	0.090	8.333	0.6652	0.1955	0.090	0.086	0.083	0.560	0.1955	12.795	0.3046	22.950	0.5464	10.155	0.2418
0.750	0.102	0.097	7.732	0.7066	0.2076	0.097	0.092	0.089	0.546	0.2076	12.163	0.2896	22.950	0.5464	10.787	0.2568
0.750	0.109	0.104	7.212	0.7469	0.2195	0.104	0.098	0.095	0.532	0.2195	11.547	0.2749	22.950	0.5464	11.403	0.2715
0.750	0.118	0.110	6.818	0.7972	0.2343	0.112	0.106	0.103	0.514	0.2343	10.779	0.2566	22.950	0.5464	12.171	0.2898
0.750	0.125	0.117	6.410	0.8352	0.2454	0.119	0.113	0.109	0.500	0.2454	10.200	0.2429	22.950	0.5464	12.750	0.3036
1.000	0.075	0.070	14.286	0.7416	0.2179	0.071	0.068	0.066	0.850	0.2179	29.478	0.7019	40.800	0.9714	11.322	0.2696
1.000	0.080	0.075	13.333	0.7868	0.2312	0.076	0.072	0.070	0.840	0.2312	28.788	0.6854	40.800	0.9714	12.012	0.2860
1.000	0.083	0.078	12.821	0.8136	0.2391	0.079	0.075	0.073	0.834	0.2391	28.379	0.6757	40.800	0.9714	12.421	0.2957
1.000	0.087	0.082	12.195	0.8491	0.2495	0.083	0.078	0.076	0.826	0.2495	27.837	0.6628	40.800	0.9714	12.963	0.3086
1.000	0.095	0.090	11.111	0.9191	0.2701	0.090	0.086	0.083	0.810	0.2701	26.769	0.6374	40.800	0.9714	14.031	0.3341
1.000	0.102	0.097	10.309	0.9792	0.2878	0.097	0.092	0.089	0.796	0.2878	25.852	0.6155	40.800	0.9714	14.948	0.3559
1.000	0.109	0.104	9.615	1.0382	0.3051	0.104	0.098	0.095	0.782	0.3051	24.950	0.5941	40.800	0.9714	15.850	0.3774
1.000	0.118	0.110	9.091	1.1126	0.3270	0.112	0.106	0.103	0.764	0.3270	23.815	0.5670	40.800	0.9714	16.985	0.4044
1.000	0.125	0.117	8.547	1.1692	0.3436	0.119	0.113	0.109	0.750	0.3436	22.950	0.5464	40.800	0.9714	17.850	0.4250
1.000	0.134	0.126	7.937	1.2405	0.3646	0.127	0.121	0.117	0.732	0.3646	21.862	0.5205	40.800	0.9714	18.938	0.4509
1.250	0.075	0.070	17.857	0.9421	0.2769	0.071	0.068	0.066	1.100	0.2769	49.368	1.1754	63.750	1.5179	14.382	0.3424
1.250	0.080	0.075	16.667	1.0006	0.2941	0.076	0.072	0.070	1.090	0.2941	48.474	1.1542	63.750	1.5179	15.276	0.3637
1.250	0.087	0.082	15.244	1.0816	0.3179	0.083	0.078	0.076	1.076	0.3179	47.237	1.1247	63.750	1.5179	16.513	0.3932
1.250	0.095	0.090	13.889	1.1730	0.3447	0.090	0.086	0.083	1.060	0.3447	45.843	1.0915	63.750	1.5179	17.907	0.4264
1.250	0.102	0.097	12.887	1.2518	0.3679	0.097	0.092	0.089	1.046	0.3679	44.640	1.0629	63.750	1.5179	19.110	0.4550
1.250	0.109	0.104	12.019	1.3295	0.3907	0.104	0.098	0.095	1.032	0.3907	43.453	1.0346	63.750	1.5179	20.297	0.4833
1.250	0.118	0.110	11.364	1.4279	0.4196	0.112	0.106	0.103	1.014	0.4196	41.950	0.9988	63.750	1.5179	21.800	0.5190
1.250	0.125	0.117	10.684	1.5033	0.4418	0.119	0.113	0.109	1.000	0.4418	40.800	0.9714	63.750	1.5179	22.950	0.5464
1.250	0.134	0.126	9.921	1.5986	0.4698	0.127	0.121	0.117	0.982	0.4698	39.344	0.9368	63.750	1.5179	24.406	0.5811
1.250	0.145	0.137	9.124	1.7128	0.5034	0.138	0.131	0.127	0.960	0.5034	37.601	0.8953	63.750	1.5179	26.149	0.6226
1.250	0.156	0.148	8.446	1.8244	0.5362	0.148	0.140	0.137	0.938	0.5362	35.898	0.8547	63.750	1.5179	27.852	0.6632
1.250	0.175	0.167	7.485	2.0111	0.5910	0.166	0.158	0.153	0.900	0.5910	33.048	0.7869	63.750	1.5179	30.702	0.7310
1.500	0.087	0.082	18.293	1.3141	0.3862	0.083	0.078	0.076	1.326	0.3862	71.738	1.7080	91.800	2.1857	20.062	0.4777
1.500	0.095	0.090	16.667	1.4268	0.4193	0.090	0.086	0.083	1.310	0.4193	70.017	1.6671	91.800	2.1857	21.783	0.5186
1.500	0.102	0.097	15.464	1.5244	0.4480	0.097	0.092	0.089	1.296	0.4480	68.528	1.6316	91.800	2.1857	23.272	0.5541
1.500	0.109	0.104	14.423	1.6208	0.4763	0.104	0.098	0.095	1.282	0.4763	67.056	1.5966	91.800	2.1857	24.744	0.5891
1.500	0.118	0.110	13.636	1.7433	0.5123	0.112	0.106	0.103	1.264	0.5123	65.186	1.5520	91.800	2.1857	26.614	0.6337
1.500	0.125	0.117	12.821	1.8373	0.5400	0.119	0.113	0.109	1.250	0.5400	63.750	1.5179	91.800	2.1857	28.050	0.6679
1.500	0.134	0.126	11.905	1.9567	0.5751	0.127	0.121	0.117	1.232	0.5751	61.927	1.4745	91.800	2.1857	29.873	0.7113
1.500	0.145	0.137	10.949	2.1003	0.6172	0.138	0.131	0.127	1.210	0.6172	59.735	1.4223	91.800	2.1857	32.065	0.7634
1.500	0.156	0.148	10.135	2.2413	0.6587	0.148	0.140	0.137	1.188	0.6587	57.583	1.3710	91.800	2.1857	34.217	0.8147
1.500	0.175	0.167	8.982	2.4787	0.7285	0.166	0.158	0.153	1.150	0.7285	53.958	1.2847	91.800	2.1857	37.842	0.9010
1.500	0.188	0.180	8.333	2.6368	0.7749	0.179	0.169	0.165	1.124	0.7749	51.546	1.2273	91.800	2.1857	40.254	0.9584
1.500	0.204	0.196	7.653	2.8263	0.8306	0.194	0.184	0.179	1.092	0.8306	48.653	1.1584	91.800	2.1857	43.147	1.0273

Specified: Outside Diameter D (in.)	Specified: Wall Thickness t (in.)	Min Wall t_{min} (in.)	Ratio D/t_{min}	Mass per Unit Length w_{pe} lb/ft	Pipe Metal Cross-sectional area (in.²)	Remaining Walls: 95 % Spec Wall Thickness (in.)	Remaining Walls: 90 % Spec Wall Thickness (in.)	Remaining Walls: 87.5 % Spec Wall Thickness (in.)	Calculated: Internal Diameter (in.)	Calculated: Flow Area (flash-free) (in.²)	Calculated: Internal Capacity per 1000 ft (gal)	Calculated: Internal Capacity per 1000 ft (bbl)	Calculated: External Displacement per 1000 ft (gal)	Calculated: External Displacement per 1000 ft (bbl)	Calculated: Displacement External − Internal per 1000 ft (gal)	Calculated: Displacement External − Internal per 1000 ft (bbl)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1.750	0.095	0.090	19.444	1.6807	0.4939	0.090	0.086	0.083	1.560	0.4939	99.291	2.3641	124.950	2.9750	25.659	0.6109
1.750	0.102	0.097	18.041	1.7969	0.5281	0.097	0.092	0.089	1.546	0.5281	97.517	2.3218	124.950	2.9750	27.433	0.6532
1.750	0.109	0.104	16.827	1.9121	0.5619	0.104	0.098	0.095	1.532	0.5619	95.759	2.2800	124.950	2.9750	29.191	0.6950
1.750	0.118	0.110	15.909	2.0586	0.6050	0.112	0.106	0.103	1.514	0.6050	93.522	2.2267	124.950	2.9750	31.428	0.7483
1.750	0.125	0.117	14.957	2.1714	0.6381	0.119	0.113	0.109	1.500	0.6381	91.800	2.1857	124.950	2.9750	33.150	0.7893
1.750	0.134	0.126	13.889	2.3149	0.6803	0.127	0.121	0.117	1.482	0.6803	89.610	2.1336	124.950	2.9750	35.340	0.8414
1.750	0.145	0.137	12.774	2.4878	0.7311	0.138	0.131	0.127	1.460	0.7311	86.969	2.0707	124.950	2.9750	37.981	0.9043
1.750	0.156	0.148	11.824	2.6582	0.7812	0.148	0.140	0.137	1.438	0.7812	84.368	2.0088	124.950	2.9750	40.582	0.9662
1.750	0.175	0.167	10.479	2.9464	0.8659	0.166	0.158	0.153	1.400	0.8659	79.968	1.9040	124.950	2.9750	44.982	1.0710
1.750	0.188	0.180	9.722	3.1392	0.9225	0.179	0.169	0.165	1.374	0.9225	77.025	1.8339	124.950	2.9750	47.925	1.1411
1.750	0.204	0.196	8.929	3.3715	0.9908	0.194	0.184	0.179	1.342	0.9908	73.479	1.7495	124.950	2.9750	51.471	1.2255
1.750	0.224	0.216	8.102	3.6541	1.0739	0.213	0.202	0.196	1.302	1.0739	69.164	1.6468	124.950	2.9750	55.786	1.3282
1.750	0.250	0.242	7.231	4.0088	1.1781	0.238	0.225	0.219	1.250	1.1781	63.750	1.5179	124.950	2.9750	61.200	1.4571
2.000	0.109	0.104	19.231	2.2034	0.6475	0.104	0.098	0.095	1.782	0.6475	129.561	3.0848	163.200	3.8857	33.639	0.8009
2.000	0.118	0.110	18.182	2.3740	0.6977	0.112	0.106	0.103	1.764	0.6977	126.957	3.0228	163.200	3.8857	36.243	0.8629
2.000	0.125	0.117	17.094	2.5055	0.7363	0.119	0.113	0.109	1.750	0.7363	124.950	2.9750	163.200	3.8857	38.250	0.9107
2.000	0.134	0.126	15.873	2.6730	0.7855	0.127	0.121	0.117	1.732	0.7855	122.393	2.9141	163.200	3.8857	40.807	0.9716
2.000	0.145	0.137	14.599	2.8753	0.8450	0.138	0.131	0.127	1.710	0.8450	119.303	2.8406	163.200	3.8857	43.897	1.0452
2.000	0.156	0.148	13.514	3.0751	0.9037	0.148	0.140	0.137	1.688	0.9037	116.253	2.7679	163.200	3.8857	46.947	1.1178
2.000	0.175	0.167	11.976	3.4141	1.0033	0.166	0.158	0.153	1.650	1.0033	111.078	2.6447	163.200	3.8857	52.122	1.2410
2.000	0.188	0.180	11.111	3.6416	1.0702	0.179	0.169	0.165	1.624	1.0702	107.605	2.5620	163.200	3.8857	55.595	1.3237
2.000	0.204	0.192	10.417	3.9166	1.1510	0.194	0.184	0.179	1.592	1.1510	103.406	2.4621	163.200	3.8857	59.794	1.4237
2.000	0.224	0.212	9.434	4.2527	1.2498	0.213	0.202	0.196	1.552	1.2498	98.275	2.3399	163.200	3.8857	64.925	1.5458
2.000	0.250	0.238	8.403	4.6769	1.3745	0.238	0.225	0.219	1.500	1.3745	91.800	2.1857	163.200	3.8857	71.400	1.7000
2.000	0.276	0.264	7.576	5.0866	1.4948	0.262	0.248	0.242	1.448	1.4948	85.546	2.0368	163.200	3.8857	77.654	1.8489
2.000	0.281	0.269	7.435	5.1637	1.5175	0.267	0.253	0.246	1.438	1.5175	84.368	2.0088	163.200	3.8857	78.832	1.8770
2.375	0.109	0.104	22.837	2.6404	0.7760	0.104	0.098	0.095	2.157	0.7760	189.828	4.5197	230.138	5.4795	40.309	0.9597
2.375	0.118	0.110	21.591	2.8470	0.8367	0.112	0.106	0.103	2.139	0.8367	186.673	4.4446	230.138	5.4795	43.464	1.0349
2.375	0.125	0.117	20.299	3.0066	0.8836	0.119	0.113	0.109	2.125	0.8836	184.238	4.3866	230.138	5.4795	45.900	1.0929
2.375	0.134	0.126	18.849	3.2101	0.9434	0.127	0.121	0.117	2.107	0.9434	181.130	4.3126	230.138	5.4795	49.008	1.1669
2.375	0.145	0.137	17.336	3.4566	1.0158	0.138	0.131	0.127	2.085	1.0158	177.367	4.2230	230.138	5.4795	52.771	1.2564
2.375	0.156	0.148	16.047	3.7005	1.0875	0.148	0.140	0.137	2.063	1.0875	173.644	4.1344	230.138	5.4795	56.494	1.3451
2.375	0.175	0.167	14.222	4.1157	1.2095	0.166	0.158	0.153	2.025	1.2095	167.306	3.9835	230.138	5.4795	62.832	1.4960
2.375	0.188	0.180	13.194	4.3953	1.2917	0.179	0.169	0.165	1.999	1.2917	163.037	3.8818	230.138	5.4795	67.101	1.5976
2.375	0.204	0.192	12.370	4.7344	1.3914	0.194	0.184	0.179	1.967	1.3914	157.859	3.7585	230.138	5.4795	72.279	1.7209
2.375	0.224	0.212	11.203	5.1507	1.5137	0.213	0.202	0.196	1.927	1.5137	151.504	3.6072	230.138	5.4795	78.634	1.8722
2.375	0.250	0.238	9.979	5.6791	1.6690	0.238	0.225	0.219	1.875	1.6690	143.438	3.4152	230.138	5.4795	86.700	2.0643
2.375	0.276	0.264	8.996	6.1930	1.8200	0.262	0.248	0.242	1.823	1.8200	135.592	3.2284	230.138	5.4795	94.546	2.2511
2.375	0.281	0.269	8.829	6.2901	1.8486	0.267	0.253	0.246	1.813	1.8486	134.108	3.1931	230.138	5.4795	96.029	2.2864
2.375	0.300	0.288	8.247	6.6545	1.9556	0.285	0.270	0.263	1.775	1.9556	128.546	3.0606	230.138	5.4795	101.592	2.4189
2.625	0.145	0.137	19.161	3.8441	1.1297	0.138	0.131	0.127	2.335	1.1297	222.451	5.2964	281.138	6.6938	58.687	1.3973
2.625	0.156	0.148	17.736	4.1174	1.2100	0.148	0.140	0.137	2.313	1.2100	218.279	5.1971	281.138	6.6938	62.859	1.4966
2.625	0.175	0.167	15.719	4.5833	1.3470	0.166	0.158	0.153	2.275	1.3470	211.166	5.0278	281.138	6.6938	69.972	1.6660
2.625	0.188	0.180	14.583	4.8977	1.4393	0.179	0.169	0.165	2.249	1.4393	206.366	4.9135	281.138	6.6938	74.771	1.7803
2.625	0.204	0.192	13.672	5.2796	1.5516	0.194	0.184	0.179	2.217	1.5516	200.536	4.7747	281.138	6.6938	80.602	1.9191
2.625	0.224	0.212	12.382	5.7493	1.6896	0.213	0.202	0.196	2.177	1.6896	193.365	4.6039	281.138	6.6938	87.773	2.0898
2.625	0.250	0.238	11.029	6.3472	1.8653	0.238	0.225	0.219	2.125	1.8653	184.238	4.3866	281.138	6.6938	96.900	2.3071
2.625	0.276	0.264	9.943	6.9306	2.0368	0.262	0.248	0.242	2.073	2.0368	175.331	4.1745	281.138	6.6938	105.806	2.5192
2.625	0.281	0.269	9.758	7.0411	2.0693	0.267	0.253	0.246	2.063	2.0693	173.644	4.1344	281.138	6.6938	107.494	2.5594
2.625	0.300	0.288	9.115	7.4563	2.1913	0.285	0.270	0.263	2.025	2.1913	167.306	3.9835	281.138	6.6938	113.832	2.7103

Specified: Outside Diameter D (in.)	Specified: Wall Thickness t (in.)	Min Wall t_{min} (in.)	Ratio D/t_{min}	Mass per Unit Length w_{pe} lb/ft	Pipe Metal Cross-sectional area (in.^{2})	Remaining Walls: 95 % Spec Wall Thickness (in.)	Remaining Walls: 90 % Spec Wall Thickness (in.)	Remaining Walls: 87.5 % Spec Wall Thickness (in.)	Calculated: Internal Diameter (in.)	Calculated: Flow Area (flash-free) (in.^{2})	Calculated: Internal Capacity per 1000 ft (gal)	Calculated: Internal Capacity per 1000 ft (bbl)	Calculated: External Displacement per 1000 ft (gal)	Calculated: External Displacement per 1000 ft (bbl)	Calculated: Displacement External − Internal per 1000 ft (gal)	Calculated: Displacement External − Internal per 1000 ft (bbl)
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**	**(17)**
2.875	0.125	0.117	24.573	3.6747	1.0799	0.119	0.113	0.109	2.625	1.0799	281.138	6.6938	337.238	8.0295	56.100	1.3357
2.875	0.134	0.126	22.817	3.9264	1.1539	0.127	0.121	0.117	2.607	1.1539	277.295	6.6023	337.238	8.0295	59.942	1.4272
2.875	0.145	0.137	20.985	4.2316	1.2436	0.138	0.131	0.127	2.585	1.2436	272.635	6.4913	337.238	8.0295	64.603	1.5382
2.875	0.156	0.148	19.426	4.5343	1.3326	0.148	0.140	0.137	2.563	1.3326	268.014	6.3813	337.238	8.0295	69.224	1.6482
2.875	0.175	0.167	17.216	5.0510	1.4844	0.166	0.158	0.153	2.525	1.4844	260.126	6.1935	337.238	8.0295	77.112	1.8360
2.875	0.188	0.180	15.972	5.4001	1.5870	0.179	0.169	0.165	2.499	1.5870	254.796	6.0666	337.238	8.0295	82.441	1.9629
2.875	0.204	0.192	14.974	5.8248	1.7118	0.194	0.184	0.179	2.467	1.7118	248.312	5.9122	337.238	8.0295	88.925	2.1173
2.875	0.224	0.212	13.561	6.3480	1.8656	0.213	0.202	0.196	2.427	1.8656	240.325	5.7220	337.238	8.0295	96.912	2.3074
2.875	0.250	0.238	12.080	7.0153	2.0617	0.238	0.225	0.219	2.375	2.0617	230.138	5.4795	337.238	8.0295	107.100	2.5500
2.875	0.276	0.264	10.890	7.6682	2.2535	0.262	0.248	0.242	2.323	2.2535	220.170	5.2421	337.238	8.0295	117.067	2.7873
2.875	0.281	0.269	10.688	7.7921	2.2900	0.267	0.253	0.246	2.313	2.2900	218.279	5.1971	337.238	8.0295	118.959	2.8324
2.875	0.300	0.288	9.983	8.2580	2.4269	0.285	0.270	0.263	2.275	2.4269	211.166	5.0278	337.238	8.0295	126.072	3.0017
3.250	0.145	0.137	23.723	4.8129	1.4144	0.138	0.131	0.127	2.960	1.4144	357.473	8.5113	430.950	10.2607	73.477	1.7494
3.250	0.156	0.148	21.959	5.1597	1.5163	0.148	0.140	0.137	2.938	1.5163	352.179	8.3852	430.950	10.2607	78.771	1.8755
3.250	0.175	0.167	19.461	5.7526	1.6906	0.166	0.158	0.153	2.900	1.6906	343.128	8.1697	430.950	10.2607	87.822	2.0910
3.250	0.188	0.180	18.056	6.1538	1.8085	0.179	0.169	0.165	2.874	1.8085	337.003	8.0239	430.950	10.2607	93.947	2.2368
3.250	0.204	0.192	16.927	6.6426	1.9521	0.194	0.184	0.179	2.842	1.9521	329.540	7.8462	430.950	10.2607	101.410	2.4145
3.250	0.224	0.212	15.330	7.2459	2.1295	0.213	0.202	0.196	2.802	2.1295	320.329	7.6269	430.950	10.2607	110.621	2.6338
3.250	0.250	0.238	13.655	8.0175	2.3562	0.238	0.225	0.219	2.750	2.3562	308.550	7.3464	430.950	10.2607	122.400	2.9143
3.250	0.276	0.264	12.311	8.7746	2.5787	0.262	0.248	0.242	2.698	2.5787	296.992	7.0712	430.950	10.2607	133.958	3.1895
3.250	0.281	0.269	12.082	8.9185	2.6210	0.267	0.253	0.246	2.688	2.6210	294.794	7.0189	430.950	10.2607	136.156	3.2418
3.250	0.300	0.288	11.285	9.4607	2.7803	0.285	0.270	0.263	2.650	2.7803	286.518	6.8219	430.950	10.2607	144.432	3.4389
3.500	0.156	0.148	23.649	5.5766	1.6389	0.148	0.140	0.137	3.188	1.6389	414.664	9.8730	499.800	11.9000	85.136	2.0270
3.500	0.175	0.167	20.958	6.2202	1.8280	0.166	0.158	0.153	3.150	1.8280	404.838	9.6390	499.800	11.9000	94.962	2.2610
3.500	0.188	0.180	19.444	6.6562	1.9561	0.179	0.169	0.165	3.124	1.9561	398.183	9.4805	499.800	11.9000	101.617	2.4195
3.500	0.204	0.192	18.229	7.1878	2.1124	0.194	0.184	0.179	3.092	2.1124	390.067	9.2873	499.800	11.9000	109.733	2.6127
3.500	0.224	0.212	16.509	7.8446	2.3054	0.213	0.202	0.196	3.052	2.3054	380.040	9.0486	499.800	11.9000	119.760	2.8514
3.500	0.250	0.238	14.706	8.6856	2.5526	0.238	0.225	0.219	3.000	2.5526	367.200	8.7429	499.800	11.9000	132.600	3.1571
3.500	0.281	0.269	13.011	9.6695	2.8417	0.267	0.253	0.246	2.938	2.8417	352.179	8.3852	499.800	11.9000	147.621	3.5148
3.500	0.300	0.288	12.153	10.2624	3.0159	0.285	0.270	0.263	2.900	3.0159	343.128	8.1697	499.800	11.9000	156.672	3.7303

C.2 Gauge Parameters

Table C.2 can be used for gauge parameters on coiled tubing.

Table C.2—Coiled Tubing Gauge Parameters

Specified		Gauge Ball Diameter	Calculated Inside Diameter	ID Area Coverage	Round Tubing			Ovalled Tubing					
Outside Diameter	Wall Thickness				Standoff (Flash Free)	Max Permitted Flash Height	Standoff Flash Present	2 % Ovality Max OD	2 % Ovality Min OD	Min Opening at Min OD Inc. Flash	5 % Ovality Max OD	5 % Ovality Min OD	Min Opening at Min OD Inc. Flash
D	t	d_{ball}	d		$S_{R,O}$		S_R	D_{max}	D_{min}		D_{max}	D_{min}	
(in.)	(in.)	(in.)	(in.)	(%)		(in.)	(in.)	(in.)	(in.)	(in.)	(in.)	(in.)	(in.)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0.750	0.080	0.375	0.590	40.4	NA	0.080	0.510	0.758	0.743	0.503	0.769	0.731	0.491
0.750	0.083	0.375	0.584	41.2	NA	0.083	0.501	0.758	0.743	0.494	0.769	0.731	0.482
0.750	0.087	0.375	0.576	42.4	NA	0.087	0.489	0.758	0.743	0.482	0.769	0.731	0.470
0.750	0.095	0.375	0.560	44.8	NA	0.090	0.470	0.758	0.743	0.463	0.769	0.731	0.451
0.750	0.102	0.375	0.546	47.2	NA	0.090	0.456	0.758	0.743	0.449	0.769	0.731	0.437
0.750	0.109	0.375	0.532	49.7	NA	0.090	0.442	0.758	0.743	0.435	0.769	0.731	0.423
0.750	0.118	0.375	0.514	53.2	NA	0.090	0.424	0.758	0.743	0.417	0.769	0.731	0.405
0.750	0.125	0.375	0.500	56.3	NA	0.090	0.410	0.758	0.743	0.403	0.769	0.731	0.391
1.000	0.083	0.625	0.834	56.2	NA	0.083	0.751	1.010	0.990	0.741	1.025	0.975	0.726
1.000	0.087	0.625	0.826	57.3	NA	0.087	0.739	1.010	0.990	0.729	1.025	0.975	0.714
1.000	0.095	0.625	0.810	59.5	NA	0.090	0.720	1.010	0.990	0.710	1.025	0.975	0.695
1.000	0.102	0.625	0.796	61.7	NA	0.090	0.706	1.010	0.990	0.696	1.025	0.975	0.681
1.000	0.109	0.625	0.782	63.9	NA	0.090	0.692	1.010	0.990	0.682	1.025	0.975	0.667
1.000	0.118	0.625	0.764	66.9	NA	0.090	0.674	1.010	0.990	0.664	1.025	0.975	0.649
1.000	0.125	0.625	0.750	69.4	NA	0.090	0.660	1.010	0.990	0.650	1.025	0.975	0.635
1.250	0.087	0.750	1.076	48.6	NA	0.087	0.989	1.263	1.238	0.977	1.281	1.219	0.958
1.250	0.095	0.750	1.060	50.1	NA	0.090	0.970	1.263	1.238	0.958	1.281	1.219	0.939
1.250	0.102	0.750	1.046	51.4	NA	0.090	0.956	1.263	1.238	0.944	1.281	1.219	0.925
1.250	0.109	0.750	1.032	52.8	NA	0.090	0.942	1.263	1.238	0.930	1.281	1.219	0.911
1.250	0.118	0.750	1.014	54.7	NA	0.090	0.924	1.263	1.238	0.912	1.281	1.219	0.893
1.250	0.125	0.750	1.000	56.3	NA	0.090	0.910	1.263	1.238	0.898	1.281	1.219	0.879
1.250	0.134	0.750	0.982	58.3	NA	0.090	0.892	1.263	1.238	0.880	1.281	1.219	0.861
1.250	0.145	0.750	0.960	61.0	NA	0.090	0.870	1.263	1.238	0.858	1.281	1.219	0.839
1.250	0.156	0.750	0.938	63.9	NA	0.090	0.848	1.263	1.238	0.836	1.281	1.219	0.817
1.250	0.175	0.750	0.900	69.4	NA	0.090	0.810	1.263	1.238	0.798	1.281	1.219	0.779
1.500	0.095	1.000	1.310	58.3	0.290	0.090	1.220	1.515	1.485	1.205	1.538	1.463	1.183
1.500	0.102	1.000	1.296	59.5	0.276	0.090	1.206	1.515	1.485	1.191	1.538	1.463	1.169
1.500	0.109	1.000	1.282	60.8	0.262	0.090	1.192	1.515	1.485	1.177	1.538	1.463	1.155
1.500	0.118	1.000	1.264	62.6	0.244	0.090	1.174	1.515	1.485	1.159	1.538	1.463	1.137
1.500	0.125	1.000	1.250	64.0	0.230	0.090	1.160	1.515	1.485	1.145	1.538	1.463	1.123
1.500	0.134	1.000	1.232	65.9	0.212	0.090	1.142	1.515	1.485	1.127	1.538	1.463	1.105
1.500	0.145	1.000	1.210	68.3	0.190	0.090	1.120	1.515	1.485	1.105	1.538	1.463	1.083
1.500	0.156	1.000	1.188	70.9	0.168	0.090	1.098	1.515	1.485	1.083	1.538	1.463	1.061
1.500	0.175	1.000	1.150	75.6	0.130	0.090	1.060	1.515	1.485	1.045	1.538	1.463	1.023
1.500	0.188	0.750	1.124	44.5	0.354	0.090	1.034	1.515	1.485	1.019	1.538	1.463	0.997
1.500	0.204	0.750	1.092	47.2	0.322	0.090	1.002	1.515	1.485	0.987	1.538	1.463	0.965
1.750	0.102	1.313	1.546	72.1	0.213	0.090	1.456	1.768	1.733	1.439	1.794	1.706	1.412
1.750	0.109	1.313	1.532	73.5	0.199	0.090	1.442	1.768	1.733	1.425	1.794	1.706	1.398
1.750	0.118	1.313	1.514	75.2	0.181	0.090	1.424	1.768	1.733	1.407	1.794	1.706	1.380
1.750	0.125	1.313	1.500	76.6	0.167	0.090	1.410	1.768	1.733	1.393	1.794	1.706	1.366
1.750	0.134	1.313	1.482	78.5	0.149	0.090	1.392	1.768	1.733	1.375	1.794	1.706	1.348
1.750	0.145	1.313	1.460	80.9	0.127	0.090	1.370	1.768	1.733	1.353	1.794	1.706	1.326
1.750	0.156	1.000	1.438	48.4	0.418	0.090	1.348	1.768	1.733	1.331	1.794	1.706	1.304
1.750	0.175	1.000	1.400	51.0	0.380	0.090	1.310	1.768	1.733	1.293	1.794	1.706	1.266
1.750	0.188	1.000	1.374	53.0	0.354	0.090	1.284	1.768	1.733	1.267	1.794	1.706	1.240
1.750	0.204	1.000	1.342	55.5	0.322	0.090	1.252	1.768	1.733	1.235	1.794	1.706	1.208
2.000	0.109	1.500	1.782	70.9	0.262	0.090	1.692	2.020	1.980	1.672	2.050	1.950	1.642

Specified		Gauge	Calculated		Round Tubing			Ovalled Tubing					
								2 % Ovality			5 % Ovality		
Outside Diameter D (in.)	Wall Thickness t (in.)	Ball Diameter d_{ball} (in.)	Inside Diameter d (in.)	ID Area Coverage (%)	Standoff (Flash Free) $S_{R,O}$	Max Permitted Flash Height (in.)	Standoff Flash Present S_R (in.)	Max OD D_{max} (in.)	Min OD D_{min} (in.)	Min Opening at Min OD Inc. Flash (in.)	Max OD D_{max} (in.)	Min OD D_{min} (in.)	Min Opening at Min OD Inc. Flash (in.)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2.000	0.118	1.500	1.764	72.3	0.244	0.090	1.674	2.020	1.980	1.654	2.050	1.950	1.624
2.000	0.125	1.500	1.750	73.5	0.230	0.090	1.660	2.020	1.980	1.640	2.050	1.950	1.610
2.000	0.134	1.500	1.732	75.0	0.212	0.090	1.642	2.020	1.980	1.622	2.050	1.950	1.592
2.000	0.145	1.500	1.710	76.9	0.190	0.090	1.620	2.020	1.980	1.600	2.050	1.950	1.570
2.000	0.156	1.500	1.688	79.0	0.168	0.090	1.598	2.020	1.980	1.578	2.050	1.950	1.548
2.000	0.175	1.500	1.650	82.6	0.130	0.090	1.560	2.020	1.980	1.540	2.050	1.950	1.510
2.000	0.188	1.313	1.624	65.4	0.291	0.090	1.534	2.020	1.980	1.514	2.050	1.950	1.484
2.000	0.204	1.313	1.592	68.0	0.259	0.090	1.502	2.020	1.980	1.482	2.050	1.950	1.452
2.000	0.224	1.313	1.552	71.6	0.219	0.090	1.462	2.020	1.980	1.442	2.050	1.950	1.412
2.375	0.109	1.750	2.157	65.8	0.387	0.090	2.067	2.399	2.351	2.043	2.434	2.316	2.008
2.375	0.118	1.750	2.139	66.9	0.369	0.090	2.049	2.399	2.351	2.025	2.434	2.316	1.990
2.375	0.125	1.750	2.125	67.8	0.355	0.090	2.035	2.399	2.351	2.011	2.434	2.316	1.976
2.375	0.134	1.750	2.107	69.0	0.337	0.090	2.017	2.399	2.351	1.993	2.434	2.316	1.958
2.375	0.145	1.750	2.085	70.4	0.315	0.090	1.995	2.399	2.351	1.971	2.434	2.316	1.936
2.375	0.156	1.750	2.063	72.0	0.293	0.090	1.973	2.399	2.351	1.949	2.434	2.316	1.914
2.375	0.175	1.750	2.025	74.7	0.255	0.090	1.935	2.399	2.351	1.911	2.434	2.316	1.876
2.375	0.188	1.750	1.999	76.6	0.229	0.090	1.909	2.399	2.351	1.885	2.434	2.316	1.850
2.375	0.204	1.750	1.967	79.2	0.197	0.090	1.877	2.399	2.351	1.853	2.434	2.316	1.818
2.375	0.224	1.500	1.927	60.6	0.407	0.090	1.837	2.399	2.351	1.813	2.434	2.316	1.778
2.375	0.237	1.500	1.901	62.3	0.381	0.090	1.811	2.399	2.351	1.787	2.434	2.316	1.752
2.375	0.250	1.500	1.875	64.0	0.355	0.090	1.785	2.399	2.351	1.761	2.434	2.316	1.726
2.625	0.175	1.750	2.275	59.2	0.505	0.090	2.185	2.651	2.599	2.159	2.691	2.559	2.119
2.625	0.188	1.750	2.249	60.5	0.479	0.090	2.159	2.651	2.599	2.133	2.691	2.559	2.093
2.625	0.204	1.750	2.217	62.3	0.447	0.090	2.127	2.651	2.599	2.101	2.691	2.559	2.061
2.625	0.224	1.750	2.177	64.6	0.407	0.090	2.087	2.651	2.599	2.061	2.691	2.559	2.021
2.625	0.237	1.750	2.151	66.2	0.381	0.090	2.061	2.651	2.599	2.035	2.691	2.559	1.995
2.625	0.250	1.750	2.125	67.8	0.355	0.090	2.035	2.651	2.599	2.009	2.691	2.559	1.969
2.875	0.125	2.250	2.625	73.5	0.355	0.090	2.535	2.904	2.846	2.506	2.947	2.803	2.463
2.875	0.134	2.250	2.607	74.5	0.337	0.090	2.517	2.904	2.846	2.488	2.947	2.803	2.445
2.875	0.145	2.250	2.585	75.8	0.315	0.090	2.495	2.904	2.846	2.466	2.947	2.803	2.423
2.875	0.156	2.250	2.563	77.1	0.293	0.090	2.473	2.904	2.846	2.444	2.947	2.803	2.401
2.875	0.175	2.250	2.525	79.4	0.255	0.090	2.435	2.904	2.846	2.406	2.947	2.803	2.363
2.875	0.188	2.250	2.499	81.1	0.229	0.090	2.409	2.904	2.846	2.380	2.947	2.803	2.337
2.875	0.204	2.250	2.467	83.2	0.197	0.090	2.377	2.904	2.846	2.348	2.947	2.803	2.305
2.875	0.224	2.000	2.427	67.9	0.407	0.090	2.337	2.904	2.846	2.308	2.947	2.803	2.265
2.875	0.237	2.000	2.401	69.4	0.381	0.090	2.311	2.904	2.846	2.282	2.947	2.803	2.239
3.500	0.145	2.875	3.210	80.2	0.315	0.125	3.085	3.535	3.465	3.050	3.588	3.413	2.998
3.500	0.156	2.875	3.188	81.3	0.293	0.125	3.063	3.535	3.465	3.028	3.588	3.413	2.976
3.500	0.175	2.875	3.150	83.3	0.255	0.125	3.025	3.535	3.465	2.990	3.588	3.413	2.938
3.500	0.188	2.875	3.124	84.7	0.229	0.125	2.999	3.535	3.465	2.964	3.588	3.413	2.912
3.500	0.204	2.875	3.092	86.5	0.197	0.125	2.967	3.535	3.465	2.932	3.588	3.413	2.880
3.500	0.224	2.625	3.052	74.0	0.407	0.125	2.927	3.535	3.465	2.892	3.588	3.413	2.840
3.500	0.237	2.625	3.026	75.3	0.381	0.125	2.901	3.535	3.465	2.866	3.588	3.413	2.814
3.500	0.250	2.625	3.000	76.6	0.355	0.125	2.875	3.535	3.465	2.840	3.588	3.413	2.788
3.500	0.281	2.625	2.938	79.8	0.293	0.125	2.813	3.535	3.465	2.778	3.588	3.413	2.726
3.500	0.300	2.625	2.900	81.9	0.255	0.125	2.775	3.535	3.465	2.740	3.588	3.413	2.688
4.000	0.188	3.125	3.624	74.4	0.479	0.125	3.499	4.040	3.960	3.459	4.100	3.900	3.399
4.000	0.204	3.125	3.592	75.7	0.447	0.125	3.467	4.040	3.960	3.427	4.100	3.900	3.367
4.000	0.224	3.125	3.552	77.4	0.407	0.125	3.427	4.040	3.960	3.387	4.100	3.900	3.327
4.000	0.237	3.125	3.526	78.5	0.381	0.125	3.401	4.040	3.960	3.361	4.100	3.900	3.301
4.000	0.250	3.125	3.500	79.7	0.355	0.125	3.375	4.040	3.960	3.335	4.100	3.900	3.275
4.000	0.281	3.125	3.438	82.6	0.293	0.125	3.313	4.040	3.960	3.273	4.100	3.900	3.213
4.000	0.300	3.125	3.400	84.5	0.255	0.125	3.275	4.040	3.960	3.235	4.100	3.900	3.175
4.000	0.312	3.125	3.376	85.7	0.231	0.125	3.251	4.040	3.960	3.211	4.100	3.900	3.151
4.500	0.204	3.500	4.092	73.2	0.572	0.125	3.967	4.545	4.455	3.922	4.613	4.388	3.855

Specified		Gauge	Calculated		Round Tubing			Ovalled Tubing					
								2 % Ovality			5 % Ovality		
Outside Diameter D (in.)	Wall Thickness t (in.)	Ball Diameter d_{ball} (in.)	Inside Diameter d (in.)	ID Area Coverage (%)	Standoff (Flash Free) $S_{R,O}$	Max Permitted Flash Height (in.)	Standoff Flash Present S_R (in.)	Max OD D_{max} (in.)	Min OD D_{min} (in.)	Min Opening at Min OD Inc. Flash (in.)	Max OD D_{max} (in.)	Min OD D_{min} (in.)	Min Opening at Min OD Inc. Flash (in.)
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**
4.500	0.224	3.500	4.052	74.6	0.532	0.125	3.927	4.545	4.455	3.882	4.613	4.388	3.815
4.500	0.237	3.500	4.026	75.6	0.506	0.125	3.901	4.545	4.455	3.856	4.613	4.388	3.789
4.500	0.250	3.500	4.000	76.6	0.480	0.125	3.875	4.545	4.455	3.830	4.613	4.388	3.763
4.500	0.281	3.500	3.938	79.0	0.418	0.125	3.813	4.545	4.455	3.768	4.613	4.388	3.701
4.500	0.300	3.500	3.900	80.5	0.380	0.125	3.775	4.545	4.455	3.730	4.613	4.388	3.663
4.500	0.312	3.500	3.876	81.5	0.356	0.125	3.751	4.545	4.455	3.706	4.613	4.388	3.639

NOTE 1 Gauge ball stand off for flash-free coiled tubulars included permitted allowance for high flash, i.e. 0.020 in.

NOTE 2 2 % ovality values computed from D_{max} = 1.01D, D_{min} = 0.99D, using Ovality = (D_{max} – D_{min})/D.

NOTE 3 5 % ovality values computed from D_{max} = 1.025D, D_{min} = 0.975D, using Ovality = (D_{max} – D_{min})/D.

NOTE 4 Minimum opening at minimum ID (including flash) is the distance cross the annular opening with the maximum flash occurring at the minimum diameter.

C.3 Yield Radius, Reel, and Guide Arch Dimensions

Table C.3 can be used for dimensions on coiled tubing yield radius, reel, and guide arch.

Table C.3—Dimensions for Yield Radius, Reel, and Guide Arch

Specified OD (in.)	Yield Radius of Curvature R_Y (in.)					Shipping Reel Core R_S (in.)	Typical Reel Core Radii R_{REEL} (in.)	Typical Tubing Guide Arch Radii R_{TGA} (in.)
	70 KSI	80 KSI	90 KSI	100 KSI	110 KSI			
0.750	161	141	125	113	102	24	24	48
1.000	214	188	167	150	136	24	20–30	48–54
1.250	268	234	208	188	170	30	25–36	48–72
1.500	321	281	250	225	205	36	30–40	48-72
1.750	375	328	292	263	239	36	35–48	72–96
2.000	429	375	333	300	273	40	40–48	72–96
2.375	509	445	396	356	324	48	48–54	96–120
2.625	563	492	438	394	358	54	54–58	96–120
2.875	616	539	479	431	392	54	54–58	96–120
3.250	696	609	542	488	443	60	65–70	96–120
3.500	750	656	583	525	477	65	65–70	96–120

Annex D
(informative)

In-service Imperfections Found in Coiled Tubing

D.1 Corrosion

D.1.1 Acid Attack at a Butt Weld

Left in acid, butt welds may corrode faster than the tubing (Figure D.1).

Figure D.1—Acid Corrosion at a Butt Weld

D.1.2 Storage Corrosion

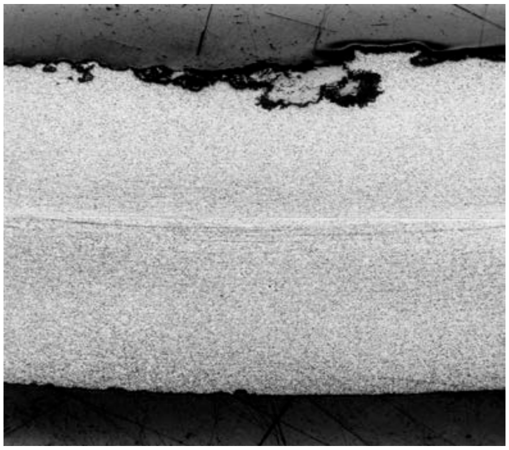
Photographs of the inside surface of tubing (Figures D.2 and D.3) that was located at the lowest point in the tubing while on the reel. Fluid (acidic solutions, seawater) congregate under gravity at the lowest point while the tubing is not in use, and can embrittle the metal. Stresses in the tubing wall may cause fatigue cracking to occur.

(a)

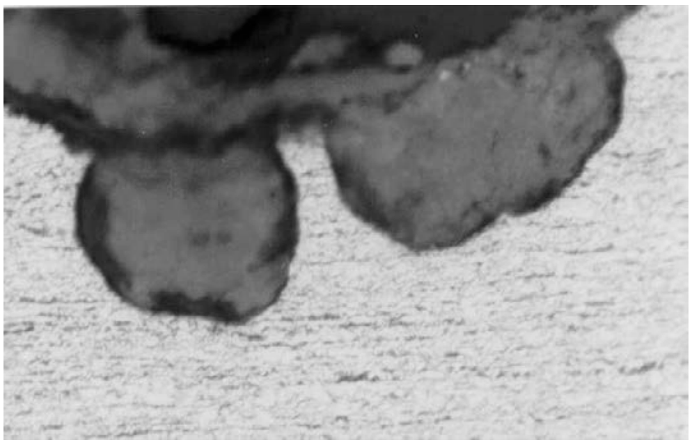
Figure D.2—Pitting that Occurred from Acid During Storage (Transversely Oriented Fatigue Cracks in Base of Pitting Inside Tubing at Location of Storage Corrosion)

(b)

Figure D.2—Pitting that Occurred from Acid During Storage (Transversely Oriented Fatigue Cracks in Base of Pitting Inside Tubing at Location of Storage Corrosion) (Continued)



(a)



(b)

Figure D.3—Mild and Deeper Corrosion Occurring at the Lowest Point on the ID of Stored Tubing

D.1.3 Corrosion Pit with Cracks

Figure D.4 shows fatigue cracks in the base of a pit in the inside surface of tubing.

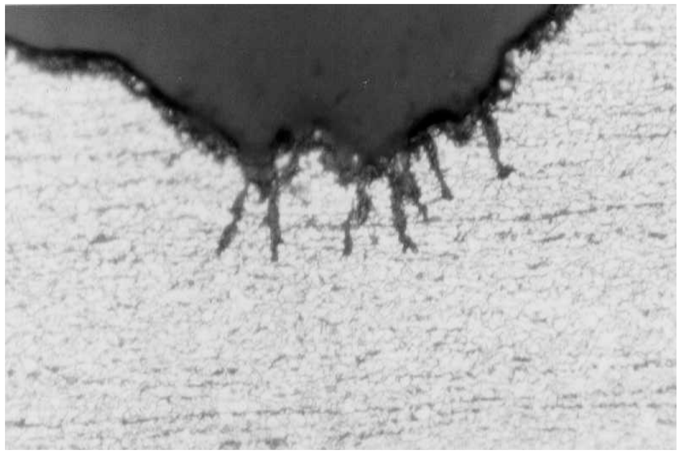


Figure D.4—Corrosion Pit on ID with Fatigue Cracks

D.1.4 CO_2 Pitting in Hang-off Tubing

Figure D.5 shows carbon dioxide pitting inside tubing that was used in a hang-off situation.

Figure D.5—Carbon Dioxide Pitting in Hang-off Tubing

D.1.5 Microbial Corrosion

Unless severely inhibited, microbial attack (Figure D.6) may occur as pitting inside tubing (and other rig parts) in fracking operations. Certain aerobic and anaerobic bacteria form colonies at pit sites, often in regions such as welds.

Figure D.6—Microbial Corrosion Pitting Inside Tubing

D.2 Hydrogen-induced Damage Found in Coiled Tubing Operations

D.2.1 Sulphide Stress Cracking

Figure D.7 illustrates SSC, which occurs when susceptible high-strength materials are exposed to a sour environment when loaded in tension, below the yield strength. The temperature shall be in a critical temperature range. The cracking is trans-granular, perpendicular to the stress.

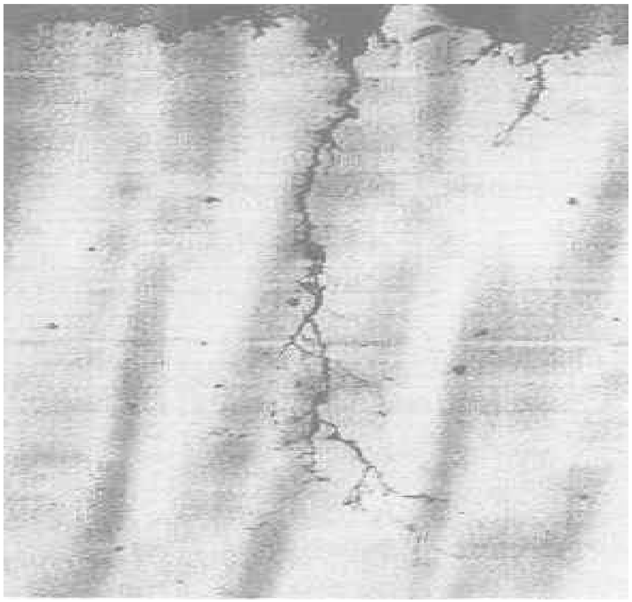


Figure D.7—Example of Sulphide Stress Cracking

D.2.2 Hydrogen-induced Cracking

HIC occurs in lower strength material that is exposed to a sour environment. No loading to low loading is needed. Multiple cracks, which originate at inclusions and areas of high stress may occur and follow grain boundaries. Figure D.8 shows an example of HIC.

Figure D.8—Hydrogen-induced Cracking

D.2.3 Stress-oriented Hydrogen-induced Cracking

SOHIC, as shown in Figure D.9, occurs in lower strength material that is exposed to a sour environment. The material shall undergo sustained loading that is above 90 % of the yield strength of the product. Multiple cracks transverse to the applied load appear, originating at inclusions and high internal stress sites.

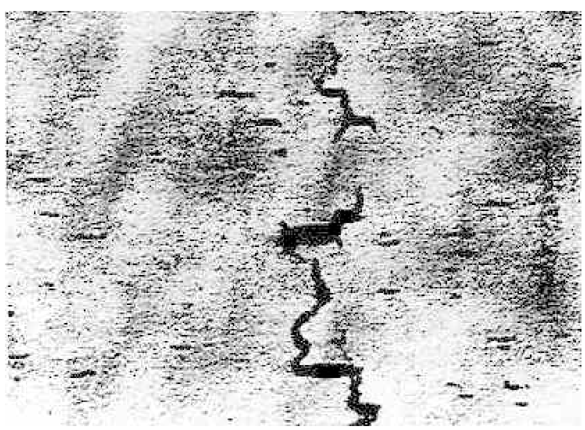


Figure D.9—Stress-oriented Hydrogen-induced Cracking

D.3 Fatigue

D.3.1 General

Fatigue in structures originates as submicroscopic damage to the microstructure and progresses to macroscopic cracks that are generally oriented perpendicular to the stress. In the case of coiled tubulars, these cracks originate either at a discontinuity or on the inside surface. In Figure D.10, the crack has progressed through the tubing wall as a result of LCF in ductile and has become a fatigue pinhole. It exhibits a characteristic "Y" at its terminal ends. Such cracks are generally of short length ~6 mm (0.25 in.) if the crack occurred at low to moderate pressures, ≤35 MPa (~5000 psi). They are generally not considered a catastrophic failure since fluid leakage is relatively low and tubing will not separate or part in two.

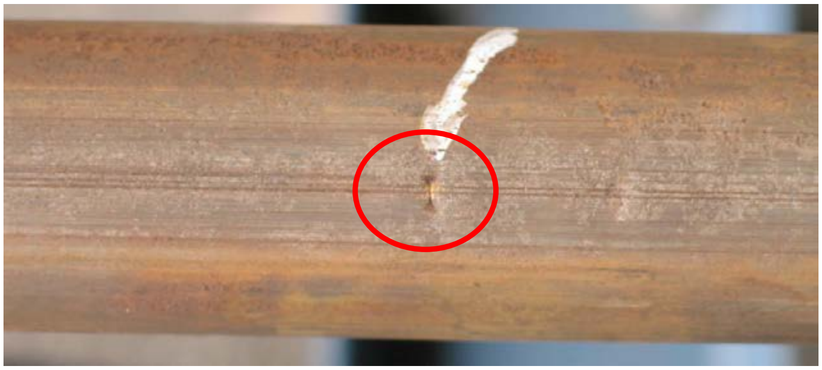


Figure D.10—Fatigue Pinhole

In Figure D.11, the fatigue crack is the result of a LCF fracture in ductile tubing at high pressures, >35 MPa (~5000 psi), or embrittled tubing at lower pressures. Fatigue life is lowered substantially when CT is cycled at higher pressures. This is considered a catastrophic failure since fluid leakage is high and tubing may separate either under sufficient tension.

Figure D.11—Fatigue Crack Originating with High Pressure Inside the Tubing

D.3.2 Fatigue Fracture, Bias Weld

Figure D.12 depicts the separation or parting of a CT string due to LCF of a factory “bias” weld. Whenever localized necking (wall thickness thinning) along the helical line of deposited weld metal occurs, it is usually an indication that fatigue failure of the bias weld is imminent. Note that the “hot spot” for fatigue crack initiation occurred at the intersection of the bias weld and the longitudinal seam weld. Note also that the fatigue crack in this ductile tubing propagated nearly half the CT circumference before failure of the remaining ligament caused complete fracture upon spooling.

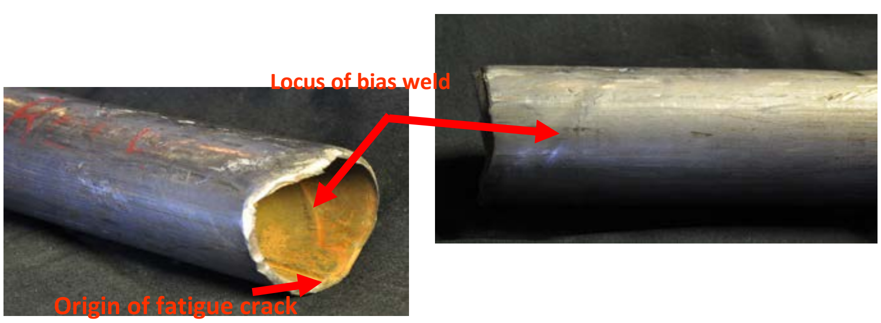


Figure D.12—Fatigue Break at a Factory Skelp-end Weld

D.4 Tensile Failures

D.4.1 Tensile Fracture, Ductile

Figure D.13 shows separation or parting of the tubing due to ductile axial overload that exceeded the ultimate tensile strength of the CT string. It is accompanied by a local reduction in the CT diameter and wall thickness referred to as "necking." The fracture surface exhibits sections of shear fracture on a plane inclined at 45° and sharp edges known as a "shear lip."

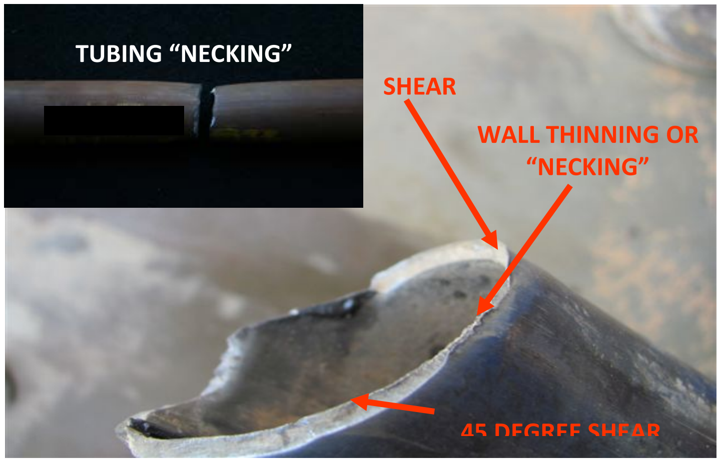


Figure D.13—Ductile Tensile Fracture (Showing "Necking" and a 45° Shear Lip)

D.4.2 Tensile Fracture, Brittle

Figure D.14 depicts the separation or parting of the tubing due to axial overload that exceeded the ultimate tensile strength of the CT string. The brittle fracture is not accompanied by a local reduction in the CT diameter and wall thickness. The fracture surface may exhibit sections of 45° shear, but a large portion of the fracture surface is square or perpendicular to the tubing axis. Embrittlement is typically caused by exposure to sour conditions, acids, or other environmental degradation of the tubing ductility. Note the presence of SSC from exposure to wet hydrogen sulphide, H_2S (i.e. "sour") conditions.

(a)

(b)

Figure D.14—Tensile Failures with Brittle Fractures

D.4.3 Tensile Fracture, Flexure

A local separation of a segment of the tubing cross section due to tensile overload under flexure (i.e. plastic bending; Figure D.15) over the guide arch or spool. Overload occurs due to a local wear spot causing sufficient wall thinning to initiate a tear of sufficient size to cause it to propagate approximately half the circumference to the CT. Lower tubing in photo shows the remaining ligament on the opposite side of the fractured section.

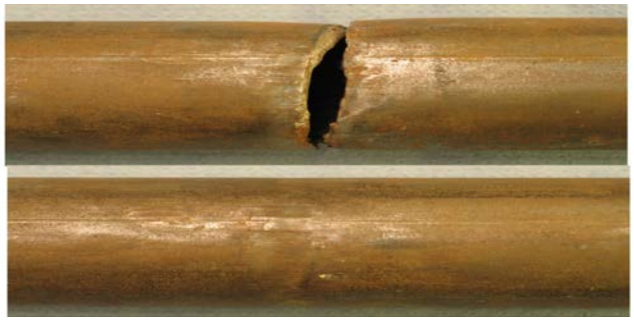


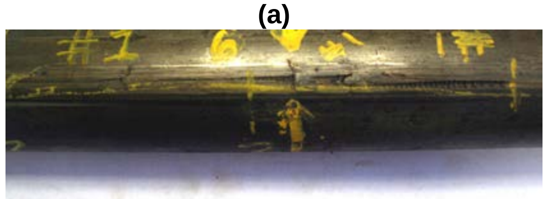
Figure D.15—Separation Caused by Tensile Overload Under Flexure

D.5 Mechanical Damage

D.5.1 Plough or Plow Marks

This is damage commonly imparted on CT strings in which surface material is scraped off from the OD and piled up at the “terminal point” where the string separates from the contacting member. These “plough marks” may be isolated or occur in shorter lengths at multiple locations as illustrated in Figure D.16. Isolated shallow plough marks are canditates for possible grind repair.

(a)



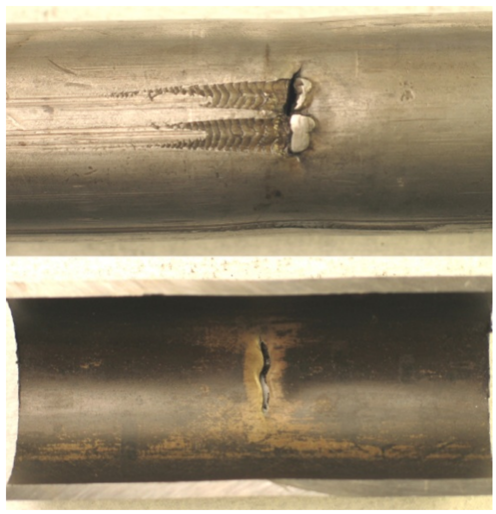
(b)

(c)

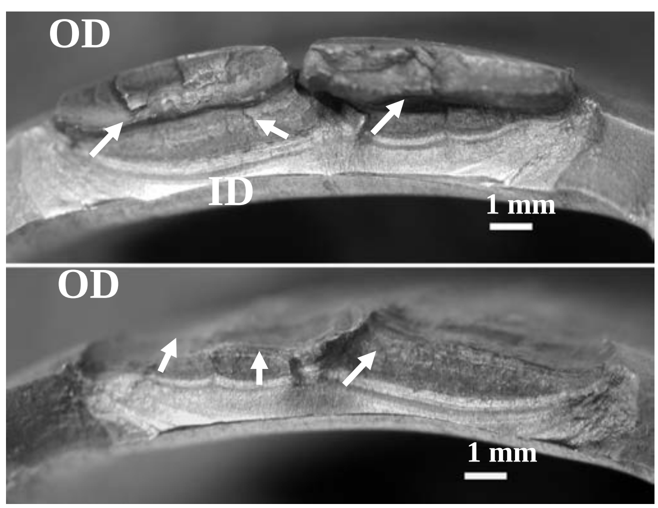
Figure D.16—Relatively Shallow Plough Marks on the Outer Surface of Coiled Tubing

The terminal points of plough marks form “transverse edge cracks” to varying depth. “Edge cracks” at the base or root of these terminal points, as indicated by the arrows in the photograph below, may also be present at these terminal points and act as “fatigue starter cracks.”

“Plough marks” are usually accompanied by “chatter marks” that when viewed in cross section appear as “saw-tooth” profiles as shown in Figures D.17 and D.18. Tests have demonstrated that even shallow saw tooth marks can substantially reduce the fatigue life if not ground smooth. The depth of penetration at the termination of the plough mark, the transverse orientation, and the presence of edge cracks are critical factors that make plough marks particularly susceptible to fatigue cracking. Plough marks are examples of severe damage detail that may require only one or two trips into the hole before a “pinhole” is formed as shown at the ID of the CT in Figure D.17.

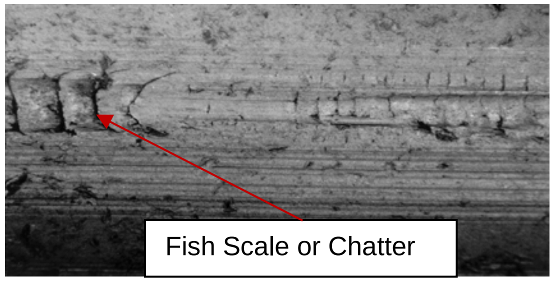


(a)

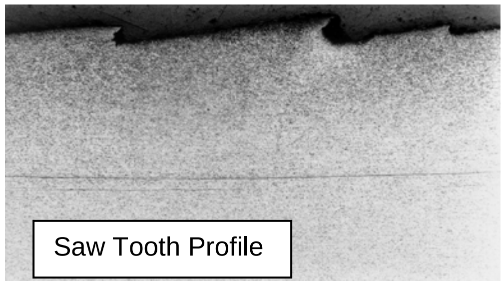


(b)

Figure D.17—Deep Plough Marks Resulting in Fatigue Cracks



(a)



(b)

Figure D.18—Transversely Oriented "Chatter" ("Fish-scale") Marks That Generally Accompany "Plough" Marks

D.5.2 Gouges

Local damage caused by forceful removal of metal with little or no associated denting from local area on the surface of the pipe that may work harden to make it more susceptible to cracking.

Gouges may be longitudinal and continuous as shown in Figure D.19 or transverse and of finite length as shown in Figure D.20. Those with a transverse orientation are considerably more severe with respect to loss of fatigue strength compared to those for the longitudinal orientation of the gouge with similar cross-sectional dimensions. It should be noted, however, that longitudinal gouges may exhibit "chatter marks" (such as those that are usually accompanied in "plough marks"). Such "chatter marks" (also known as "fish scale marks") exhibit a sawtooth type profile with teeth only a few thousands of an inch deep but an associated roughness sufficient to reduce the LCF life in the order of 25 %.

Isolated shallow gouges are candidates for possible grind repair.

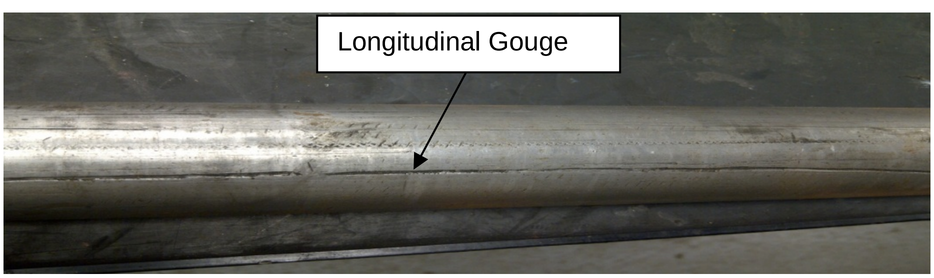
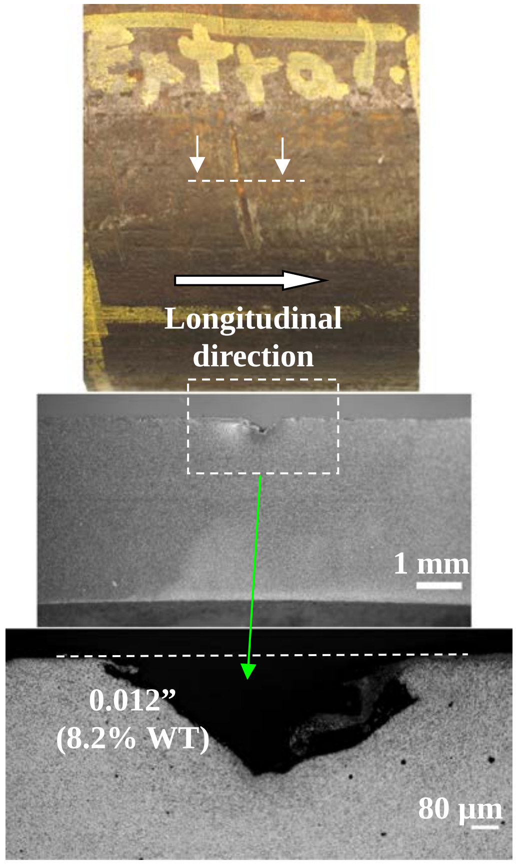


Figure D.19—Longitudinal Gouge



(a)

(b)

Figure D.20—Gouges with Transverse Orientation

Figure D.21 shows longitudinal gouges with chatter marks.

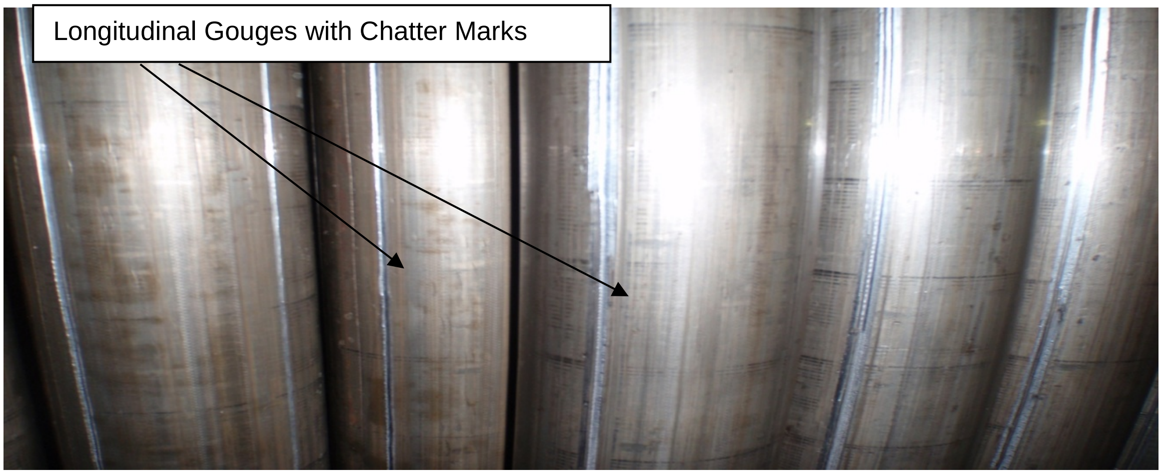
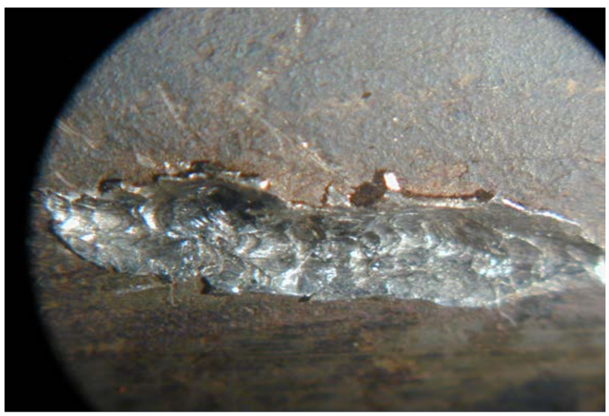


Figure D.21—Elongated Gouges with Chatter Marks

Figure D.22 shows relatively large gouges with a transverse component.



(a)

(b)

Figure D.22—Gouges with Large Transverse Component

D.5.3 Scratches

Figure D.23 depicts scratches that are lines caused by the abrasion of one surface against another without removal of metal such as that occurring in gouging and ploughing damage. "Scratch marks," whether longitudinal or transverse to the tubing axis, constitute minor surface damage, with negligible effect on LCF unless the scratch marks are accompanied by wear of the tubing wall. (See D.3.)

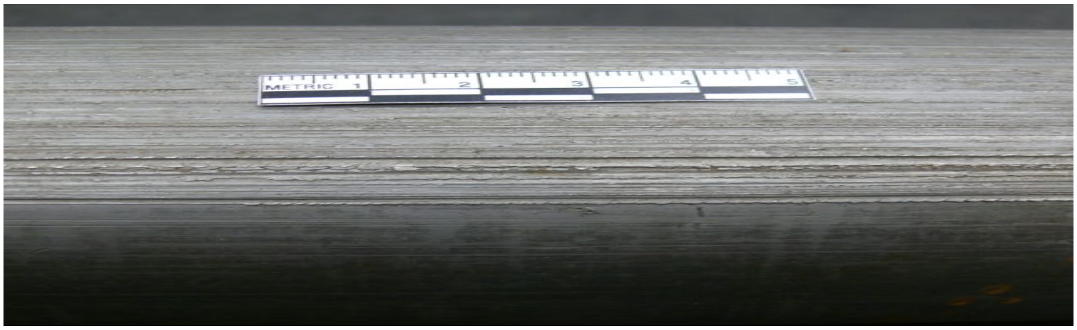


Figure D.23—Longitudinal Scratches

D.5.4 Scoring

Figure D.24 depicts scoring that is marring or scratching marks on sliding metallic surfaces in the form of long, distinct scratches in the direction of motion. "Scoring marks" are a form of "scratch marks" resulting from debris, such as drill cuttings sliding along a CT string or from the CT string sliding along a tubing or casing as for example in a horizontal well bore section. Similar to "scratch marks", "scoring marks" have negligible effect on LCF unless the scoring damage is due to wear of the tubing wall. (See D.3.)

Figure D.24—Scoring Marks on the Tube Outside Diameter

D.6 Wall Thinning

D.6.1 General

Wall thinning in CT strings is caused by wear or erosion (Figures D.25 and D.26), and can result in loss of fatigue strength, and may cause a "burst" failure if the internal pressure is sufficiently high. Wall thinning also occurs in CT strings from cyclic plastic bending and from "ballooning" (i.e. growth in the tubing diameter).

(a)

(b)

Figure D.25—Wall Thinning on the Outside Diameter (left) and Internal Erosion from Sand (right)

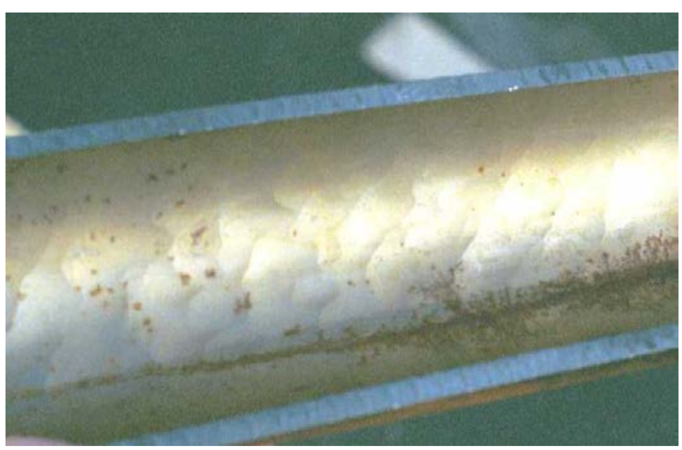


Figure D.26—Erosion of the Inside Surface from Sand That Can Result in Serious Wall Loss

D.6.2 Wear

Wear is the attrition or rubbing away of the surface of a material as a result of mechanical action. Wear can be classified as “adhesive wear” or “galling” and as “abrasive wear” or “cutting.” Three-body abrasive wear involves separate particles between sliding surfaces such as drill cuttings that caused the wall thinning due to scoring and scratching shown in Figure D.27. Galling occur when two smooth bodies are slid over each other and fragments are pulled off one surface and adhere to the other. Typical CT surface features resulting from “galling” due to sliding contact with steel casing are shown in Figure D.27.

Figure D.27—Wear with Galling

D.6.3 Erosion

Destruction or removal of material by abrasive action of moving fluids (or gases) usually accelerated by the presence of solid particles or matter in suspension. Also referred to as “particle erosion” defined as solid particles interacting with solid surfaces in liquid or gas environments. When the interacting particles are liquid, the term “drop erosion” is used to make a distinction with solid particles.

A form of erosion encountered with coiled tubing involves a sand laden fluid jet or “slurry” impinging on the tubing (Figure D.28) or on sand jetting perforating tools due to reflected fluid streams, hence the term “impingement erosion” as illustrated in the photo below.

Figure D.28—Impingement Erosion

D.7 Burst

A burst (Figure D.29) causes the tubing to come open or fly apart suddenly or violently, especially from excessive internal pressure, usually resulting in a longitudinal split. A “burst failure” is considered to be catastrophic. A catastrophic failure is a sudden and generally unexpected failure of the tubing causing loss of pressure integrity. An example of a catastrophic failure is the uncontrolled release of sour gases into the atmosphere from a burst opening in the CT string.

Burst failures in CT strings have several possible root causes including wall thinning from wear, erosion or general corrosion, internal pressures exceeding the burst strength of the CT at the point of the burst, or “cold weld” defects in the longitudinal weld seam (Figure D.30).

Figure D.29—Burst at Thin Wall Area in Tubing

(a)

(b)

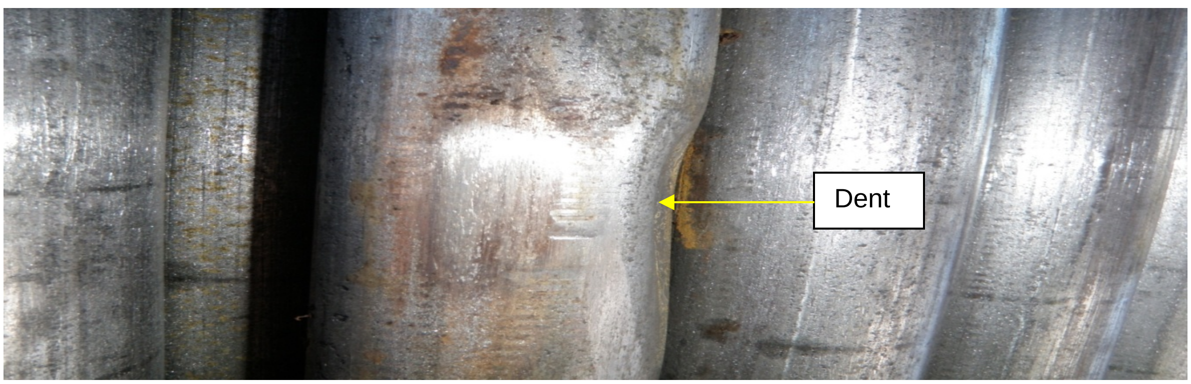
Figure D.30—Burst Failures at Seam Weld (Possibly from a "Cold Weld")

D.8 Dents

D.8.1 Metal Displacement

Dents are depressions or hollows made by a blow, pressure, or concentrated load static or dynamic load. Since "dents" involve the displacement of metal rather the removal of metal, they are also classified as "impressed defects". Dents in coiled tubing can appear in many different shapes and forms as illustrated in Figure D.31.

(a)

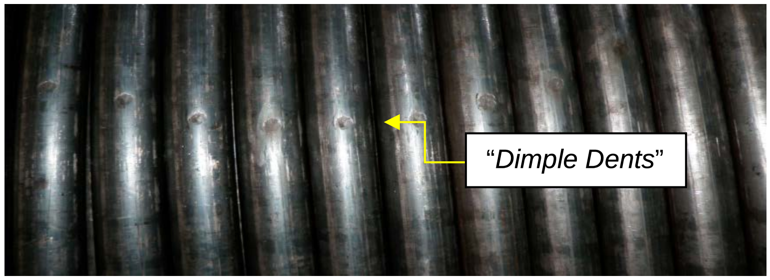


(b)

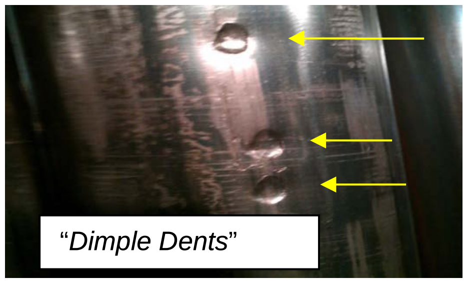
Figure D.31—Examples of Dents

A particular type of dent that may be encountered during CT operations has a shape that is either circular, cylindrial, hemispherical, or ellipsoidal. A common impression made in CT to affect mechanical connections in CT is the dimpling tool. This tool imparts a hemispherical impression at several locations in the tubing so dents having similar shapes are referred to as "dimple dents" (Figures D.32 and 33). The following photographs present several examples.

Tests on CT dents and other impressed defects have shown that the reduction in fatigue life can be appreciably less for defects involving only metal displacement (i.e. "impressed defects") compared with those involving the removal of surface material such as occurs with gouges.



(a)



(b)

Figure D.32—Examples of Dimple Dents

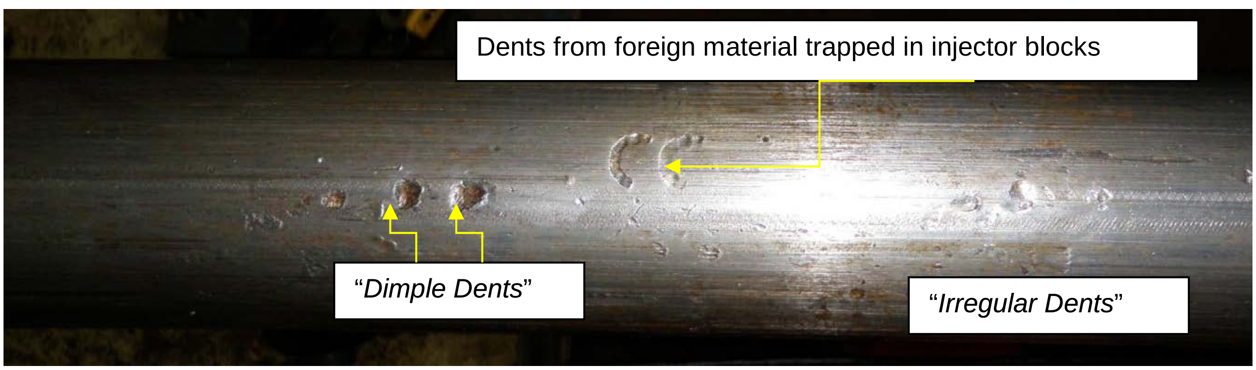


Figure D.33—Example of Multiple Types of Dents

D.8.2 Fatigue Cracks Associated with Dents

Impressed defects imparted under realistic operating conditions can produce severe plastic deformation and/or work hardening of the surface resulting in micro-cracks or surface fissures at the base of the discontinuity, as illustrated in Figure D.34. Such secondary damage can be expected to exacerbate the loss of fatigue strength and initiate fatigue pinholes at the impressed defect as shown by laboratory tests in the lower photographs.

(a)

(b)

Figure D.34—Laboratory-manufactured Dent with Fatigue Cracks

Figure D.34 shows fatigue cracking initiating in the artificial hemispherical impressed discontinuities. Careful attention to detail shall therefore be given when classifying dents as either cut or impressed.

D.8.3 Elongated Dents

Elondated dents are partial flattening of the tubing over relatively short distances of several diameters in length as illustrated Figure D.35. Such dents form essentially short sections of highly ovalized tubing that may exhibit an ovalty that may be considerably greater than the maximum acceptable based upon the local collapse pressure.

Figure D.35—Elongated Dent

The effect of “elongated dents” on LCF has not been systematically quantified since highly ovalized tubing has little servicability value. However, areas of excessive ovality are susceptible to form local “kinks” under plastic bending deformation. Kinked tubing can be expected to fail by large tears after only a few bend and straightening cycles.

D.9 Kink

A kink is a narrow transverse, inward indentation of the pipe diameter with a low radius of curvature. Kinks may also show bulging around their perimeter.

D.10 Buckle

A buckle is a partial axial collapse of the coiled tubing that is due to excessive bending or axial compressive loading. Given sufficient radial clearance with a casing or liner, a CT string can fold back over itself and permanently deform due to plastic bending (Figure D.36). Extended reach is often limited by helical buckling of the CT string causing it to lock up to resist further entry into the wellbore. The tubing string in this case is only deformed elastically so that it will restore its original shape when withdrawn from the well.

(a)

(b)

Figure D.36—Buckled Tubing

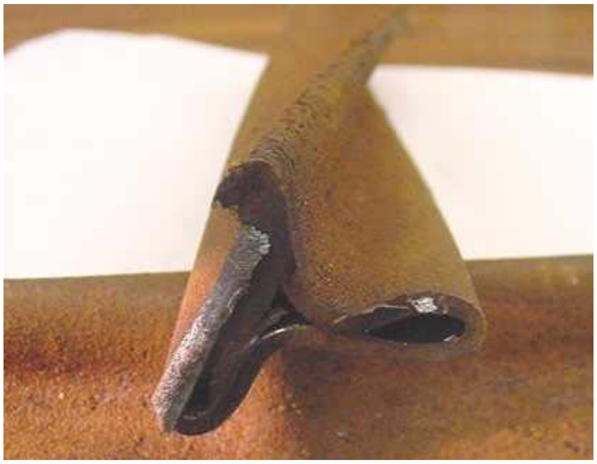
Figure D.36 (right) illustrates buckling that occurred due to misalignment of the tubing entering into the injector.

D.11 Collapse

Collapse (Figure D.37) of coiled tubing is the complete flattening of the tubing due to an excessive net external pressure. For tubing with low diameter (*D*) to wall thickness (*t*) ratios, the "collapse strength" increases with increasing yield strength (i.e. CT grade). With larger *D/t* ratios, collapse failure is governed more by instability of the CT cross section, which is independent of the yield strength. Whenever possible, CT diameter and wall thickness combinations should be selected such that the *D/t* ratio is ≤18.

The collapse strength is strongly affected by CT ovality and axial tension and to some extent by bending of the CT string as occurs for example in the build section of a horizontal well bore. Higher bottomhole temperatures (BHTs) can also reduce CT collapse strength by virtue of a reduction in yield strength at elevated temperatures. The pressure to initiate a collapse is higher than the pressure to propagate the collapse failure. A propagating collapse failure will be arrested once the pressure differential between the higher external and lower internal pressure becomes less than the collapse strength and/or the axial tension is reduced causing an effective increase in collapse strength.

(a)

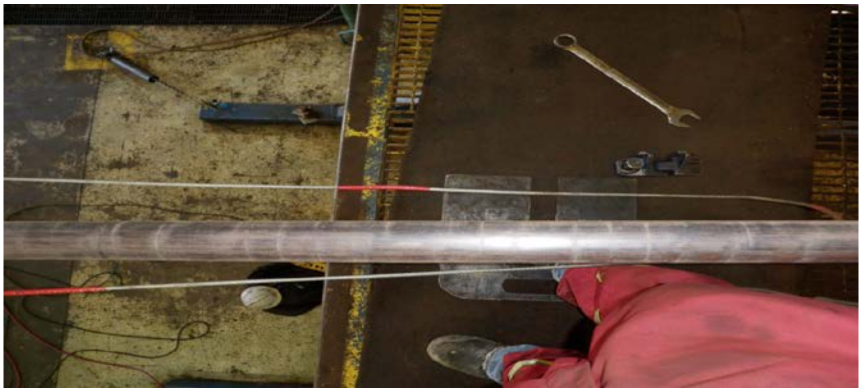


(b)

Figure D.37—Collapse in Two and Three Directions (One Node Is the Seam Weld) due to Tension and High External Pressure

D.12 CT Injector Gripper Marks

Gripper marks (Figure D.38) are circumferentially impressed grooves due to contact between the injector chain block "inserts" and the coiled tubing. "Gripper marks" are visible with the naked eye.



(a)

(b)

Figures D.38—Gripper Marks

Fatigue cracks can initiate when gripper block marks are cycled. Figure D.39 shows a fatigue crack in a gripper block mark that has washed.

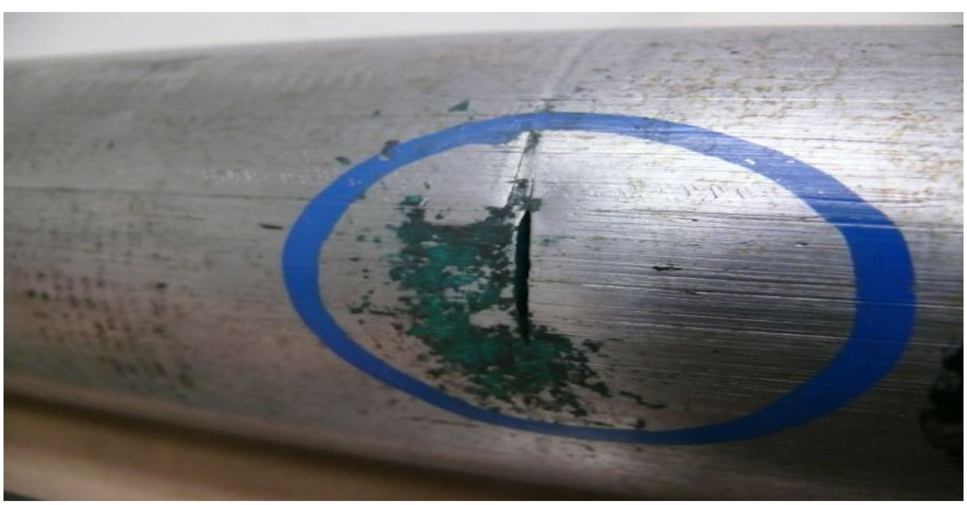


Figure D.39—Gripper Block Mark with Fatigue Crack

D.13 Injector Ring Compression Marks

Figure D.40 shows shallow compression marks that were caused by injector rings. Regions of high hardness form under these marks and can be precursors to fatigue cracks and can adversely affect the tubing's performance in sour service.

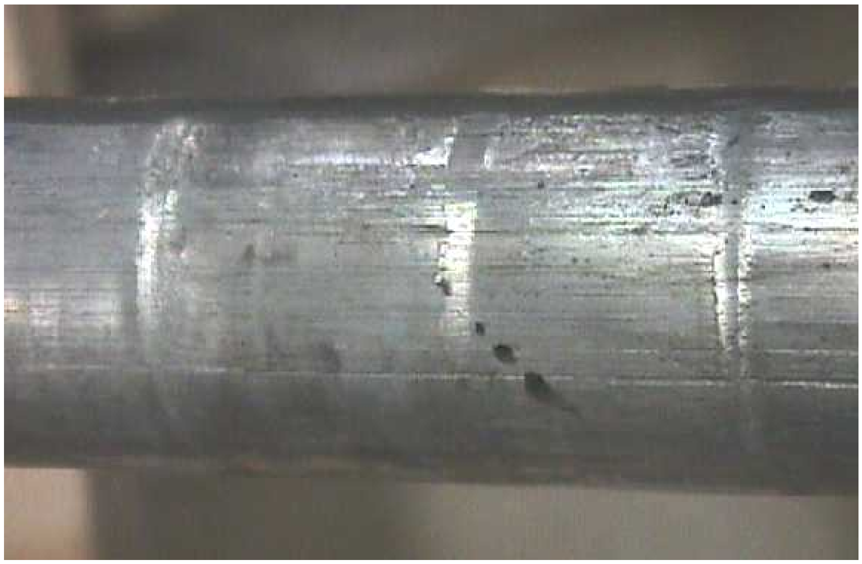


Figure D.40—Injector Ring Damage

Annex E
(informative)

Example Forms

The following figures in this annex are merely examples for illustration purposes only. [Each company should develop its own approach.] It is not considered to be exclusive or exhaustive in nature. API makes no warranties, express or implied, for reliance on or any omissions from the information contained in this document.

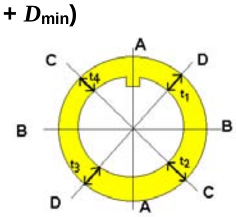
Tubing Description

Size____ Wall______ Grade_______ String No._____ On__________
Material___________ Diameter _____ Weight_______ Length________

Skelp-end Welds = * Tube-to-tube welds = // A-A - EW Location (if possible)

ft	Diameter, in.					Ovality	Wall Thickness (mils)					CSA	Comments
	A-A	B-B	C-C	D-D	D_{av}	%						(in.²)	
	D_1	D_2	D_3	D_{min}			t_1	t_2	t_3	t_{min}	t_{av}		

Additional Comments: Ovality (as a percentage) computed from $\Theta = 200(D_{max} - D_{min})/(D_{max} + D_{min})$



Inspector___________________ **Date__________________**

Figure E.1—Example Form for Visual and Dimensional Inspection Report

Customer: ____________________________ Job No.:_______________ Date: __________________Page: _of______

TUBING DESCRIPTION

Size: ___________________ Wall: __________________ Original Grade: _________ String No.: ____________________

On: Reel ☐ Spool ☐ Material: Wood ☐ Metal ☐ ID No.: _______________

Diameter: ______________ Calibration Test No.: ____________________ Total Footage: ________________________

Inspection Level: 5 % ☐ 10 % ☐ Inspected by: _________________________

Indicate: skelp-end weld by * Tube-to-tube weld by // A-A = Seam Weld (where possible)

ft	**Outside Diameter (in.)**				**Oval**	**Wall Thickness (in.)**				**Flaw Location**				**Comments**
	A-A	**B-B**	**C-C**	**D-D**	**%**	t_1	t_2	t_3	t_{min}	**Q1**	**Q2**	**Q3**	**Q4**	

NOTE Quadrants Q1–Q4 are on the tubing and should be marked on the inspection head; Quadrant 1 is 315-0-45 deg; One diameter column to contain D_{max} and one diameter column to contain D_{min}.

Figure E.2—Example Form for Electromagnetic NDT Report (Part 1)

	ACCEPTABLE	
	YES	NO
1. Areas of string inspected?	ft	
2. Date & time of inspection		
3. Ovality *(New)* $100[D_{max} - D_{min}]/D$ is within 0 to 5 %?		
4. Ovality *(Used)* $200[D_{max} - D_{min}]/[D_{max} + D_{min}]$ is within 0 to 5 %		
5. Is OD within −4 % and +6 % of specified OD?		
6. Metal loss is less than 5 %? Description: Internal pits/external pits/gouges/erosion/rig damage/other		
7. Metal loss is less than 10 %? Description: Internal pits/external pits/gouges/erosion/rig damage/other		
8. Metal loss is less than 15 %? Description: Internal pits/external pits/gouges/erosion/rig damage/other		
9. Less than 15 % decrease in specified wall thickness?		
10. Detected through-wall defects, e.g. pinhole, longitudinal split, transverse fatigue crack		
11. Area on reel/string damaged/corrosion found? (i.e. at the 6 o'clock position)		
12. Locations of heavily worked areas?		
13. Other		
14. Comments:		
Coiled Tubular Inspection Co warrants that the inspection has been performed to written procedures by trained and certified personnel. The stated results represent good faith measurements made within the limitations of the equipment employed, which is maintained under a quality system. Notwithstanding this, the company does not warrant the future performance of the tubing.		
Signed: ___________________________ Date: ______________________		

Figure E.3—Example Form for Electromagnetic NDT Inspection Report (Part 2)

Preservation of Coiled Tubing—Maintenance Checklist		
String Number: Reel Number:		Size:
Each Day in Operation	**OK**	**Remarks**
1) Spray tubing		
2) When pulling out of hole for the last time on the rig, spray with Eniss Fluid G		
3) Displace reel with fresh water and nitrogen		
Upon Arrival at Base		
4) Spray with Ensis Fluid G (if required)		
5) Flush string with fresh water and measure pH value and note		
6) If pH value is below 7, mix soda ash in tank, flush the string again, then measure the pH value and note		
7) Pump a pill of ethylene glycol of volume approximately 50 liters		
8) Pump a foam pig and flush with nitrogen until the tube is free of fluid		
9) Blank off both tubing ends and build up a pressure of nitrogen between 200 psi to 400 psi (Label both the connections and the reel with “N2 Under Pressure” in English and any other appropriate language)		
Date:______________________ Performed by:__________________ SUPERVISOR:___________________ Sign:_____________________		

Figure E.4—Example Form for Preservation of Coiled Tubing Checklist

Preservation of Coiled Tubing Equipment Offshore—if to be left offshore—Maintenance Checklist				
Platform:	Operator:		Contract #:	
String #:	**Reel #:**	**Size:**	**OK**	**Remarks**
1) When pulling out of hole for the last time on the rig, spray with Eniss Fluid G				
2) Spray with Ensis Fluid G (if required)				
3) Inspect/regrease all grease nipples				
4) Flush string with fresh water and measure pH value and note				
5) If pH value is below 7, mix soda ash in tank, flush the string again, then measure the pH value and note				
6) Pump a foam pig and flush with nitrogen until the tube is free of fluid				
7) Blank off both tubing ends and build up a pressure of nitrogen between 200 psi and 400 psi (Label both the connections and the reel with “N2 Under Pressure” in English and any other appropriate language)				
Blowout Preventer Number:				
8) Disassemble and clean				
9) All parts to be greased				
Shear Seal Number:				
10) Disassemble and clean				
11) All parts to be greased				
Power Packer Number:				
12) Disassemble and clean				
13) Top-off hydraulic oil				
Injector Head Number:				
14) Oil chains				
15) Inspect/Regrease all grease nipples				
Stripper Number:				
16) Disassemble and clean				
Riser/WH Cross-over Number:				
17) Inspect and regrease				
Downhole Tool Number:				
18) Disassemble and clean				
19) Coat all parts in oil				
Risers with Cross-overs				
20) Clean all flanges				
21) Grease all threads and mount protector caps				
Date:_____________________ Performed by:_________________ SUPERVISOR:__________________ Sign:____________________				

Figure E.5—Example Form for Preservation of Coiled Tubing Equipment Offshore

PRE-TEST

Sample Number: ____________________

Defect ID Number: ____________________

Vendor: ____________________

Material Grade (ksi): ____________________

Nominal Diameter (in.): ____________________

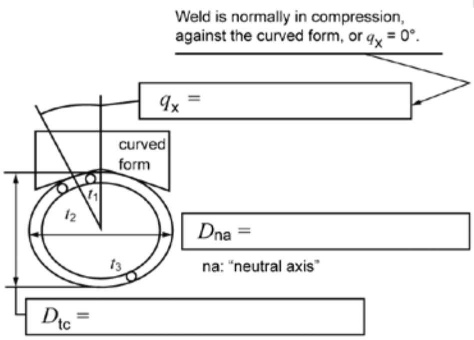
Nominal Wall (in.): ____________________

P_{act} (psi) = ____________________

R (in.) = ____________________

Operator Name: ____________________

Date: ____________________



tc: "tension-compression axis"

t_1 = ____________

t_2 = ____________ } t_{avg} = ____________

t_3 = ____________

Comments:

POST-TEST

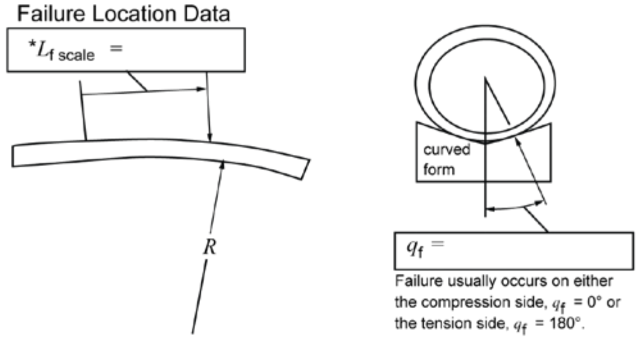
Number of Cycles to Failure

N_f = ____________

Operator Name: ____________________

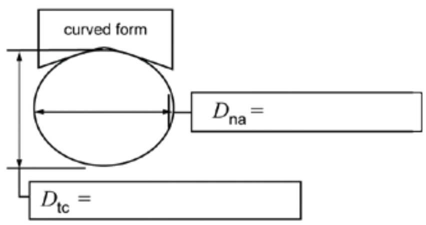
Date: ____________________

Failure Location Data



*Length taken from scale on fatigue machine's straight form

Final Tube Dimensions (Measure at location of MAXIMUM diametral growth. If different from failure site, note below.)



Data Acquisition Filename = ____________________

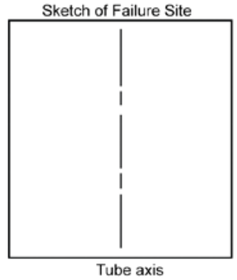
$P_{peak\ from\ data}$ (psi) = ____________________

$P_{average\ from\ data}$ (psi) = ____________________

Pressure can vary slightly over the duration of a test. The average pressure during the test is determined from measurements recorded with the data acquisition system.

Failure Site Description

Sketch of Failure Site



Failure Location: ____ on defect ____ other

Width of Crack (at OD) = ____________

Crack Initiation: ____ inside ____ outside

Exterior dimpling of the tube's surface in the region of the failure area indicates that crack initiation began on the interior of the specimen.

Defect Image Filename (pre-test) = ____________________

Defect Image Filename (post-test) = ____________________

Figure E.6—Example Form for Fatigue Testing Data Collection Sheet

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