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Qualification of casing connections for thermal wells

Qualification des raccordements de boîtiers pour les puits thermométriques

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, Subcommittee SC 5, *Casing, tubing and drill pipe*.

This first edition of ISO/TS 12835 cancels and replaces ISO/PAS 12835:2013, which has been technically revised.

The main changes are as follows:

— all optional tasks moved to Annex D;

— added option to perform thermal cycle test with cooling to intermediate temperatures;

— changed specification for to-failure portions of bend test and limit-strain test, allowing them to be performed with water only.

A list of all parts in the ISO 12835 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

This document, also known to industry users as Thermal Well Casing Connection Evaluation Protocol (TWCCEP), is intended to facilitate assessment and qualification of threaded casing connections for service in intermediate or production casing strings in thermal recovery wells and in other wells experiencing significant temperature excursions such as in geothermal applications.

The extensive effort involved in replicating thermal well field conditions in a laboratory environment limits the extent of physical testing that can reasonably be undertaken in an evaluation program. The evaluation procedure adopted in this document balances technical rigor and practicality to provide a baseline level of confidence in the candidate connection's performance. Connection users should consider the scope of this evaluation and appropriate additions to address operation-specific conditions. Successful field use of a connection meeting the requirements of this protocol does not preclude an operator's need to employ appropriate product quality assurance measures and field operating practices.

Only outcomes of the performed full-scale tests are compared with assessment criteria to determine suitability of the candidate connection for the intended field service. While this document aims to enable a statistically significant full-scale test, it does not demand a rigorous check of a true statistical placement of the tested sample responses relative to field connection performance, and thus inherently assumes that the test specimens are representative of subsequent field connections. For this reason, only connections with the same design parameters as the candidate connection should be considered representative of the connection assessed under this protocol.

This document is the culmination of a thorough review of factors contributing to performance of casing connections in thermal well applications. The evaluation procedure adopted in this document has been developed using input from operators' descriptions of field practices, manufacturers' feedback on connection design and production, available literature, knowledge of past connection qualification programs, and additional analytical and experimental work performed in support of the protocol development.

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Qualification of casing connections for thermal wells

1 Scope

This document provides procedures for assessment of casing connections for those field applications in which the operating temperatures cyclically vary between minimum values appreciably below 180 °C and maximum values that range from 180 °C to 350 °C or above, and in which the primary axial loading on the casing-connection system is strain-based and driven by constrained thermal expansion and leads to a stress state that exceeds the casing-connection system's yield envelope.

NOTE This document can be considered complementary to ISO 13679 (and its core content per API Specification 5C5), which applies to classic elastic-design applications.

This document contains an evaluation procedure for a candidate connection comprising of uniquely defined pin, box and interfacial components. The evaluation procedure includes:

— Material property tests to assess relevant properties of the candidate connection pin and box components;

— Analytical tasks to determine configuration of connection samples for physical tests, which are chosen based on worst-case combinations of the connection geometry and material properties;

— Full-scale testing tasks to measure the candidate connection galling resistance, structural integrity and sealability under loading representative of connection assembly and thermal well service.

This document does not address impacts of external pressure, incomplete lateral pipe support, rotational fatigue, formation-induced shear, or environmentally-induced corrosion or cracking.

Clause 6 describes fundamental assumptions adopted in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

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

ASTM E8, *Standard Test Methods for Tension Testing of Metallic Materials*

ASTM E21, *Standard Test Methods for Elevated-Temperature Tension Tests of Metallic Materials*

ASTM E831-06, *Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis*

ISO 11960, *Petroleum and natural gas industries — Steel pipes for use as casing or tubing for wells*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

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3.1
ambient temperature
ambient temperature in the facility where a physical testing task is executed

3.2
application severity level
connection loading specifications assumed to be representative for a range of operational conditions, which determine the scope of analysis and testing required by the *evaluation procedure* (3.13) for those operational conditions

3.3
assigner
party that commissions an *evaluation program* (3.14), controls its execution, and owns the rights to that evaluation program's data and results

3.4
average string strain
average axial strain along the *controlled elongation interval* (3.11) of a *specimen string* (3.36)

3.5
bend test specimens
subset of *candidate connection specimens* (3.8) subjected to the optional *bending evaluation* (3.6) per the *evaluation procedure* (3.13)

3.6
bending evaluation
analysis and physical testing conducted to determine sensitivity of a *candidate connection* (3.7) to casing curvature

3.7
candidate connection
casing connection product that is being evaluated, and is uniquely defined by its design features and production specifications with respect to size, weight, and component materials including pin, box, and interfacial components

3.8
candidate connection specimens
set of connection specimens that is representative of design and features of the *candidate connection* (3.7), and is provided for an *evaluation program* (3.14) of that candidate connection

3.9
casing pup
short piece of casing pipe cut from a mother joint

3.10
connection
single design-specific assembly of pin and box and interfacial component(s)

3.11
controlled elongation interval
portion of a *specimen string* (3.36), along which the elongation is measured and controlled

3.12
effective string length
portion of the total length of a *specimen string* (3.36) that is assumed to deform appreciably under mechanical forces in the *thermal cycle test* (3.42)

3.13
evaluation procedure
set of analytical and testing tasks performed to assess performance of the *candidate connection specimens* (3.8)

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3.14
evaluation program
evaluation of a *candidate connection* (3.7) by means of the *evaluation procedure* (3.13)

3.15
evaluation report
collectively, all documents prepared by an *evaluator* (3.16), according to applicable reporting requirements, that describe execution history and results of an *evaluation program* (3.14)

3.16
evaluator
party that performs analytical and testing tasks required by an *evaluation procedure* (3.13)

3.17
excluded connection
connection (3.10) that has been evaluated in a full-scale test but whose performance has been excluded from comparison with *threshold performance requirements* (3.44)

3.18
galling
cold welding of contacting material surfaces followed by tearing of metal during subsequent sliding

3.19
high cycle temperature
highest temperature targeted in the *thermal cycle test* (3.42)

3.20
inspection report
collectively, all documents prepared by an *inspector* (3.21) that describe conformance of the executed *evaluation program* (3.14) with applicable specifications

3.21
inspector
party that verifies conformance of the executed *evaluation program* (3.14) with applicable specifications

3.22
integral specimen
single connection consisting of one *casing pup* (3.9) with a box end and one casing pup with a pin end

3.23
interfacial component
design-specific component of a *connection* (3.10) applied to the pin and box either during their manufacturing (e.g. coating) or during the connection assembly (e.g. thread compound)

3.24
limit-strain specimens
subset of *candidate connection specimens* (3.8) subjected to the *limit-strain test* (3.25) per the *evaluation procedure* (3.13)

3.25
limit-strain test
tension test, to structural failure, of the *limit-strain specimens* (3.24)

3.26
low cycle temperature
lowest temperature targeted in the *thermal cycle test* (3.42)

3.27
lower-bound temperature
lowest temperature expected in thermal cycles in field applications

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3.28
make-break specimens
subset of *candidate connection specimens* (3.8) subjected to multiple make-ups and break-outs per the *evaluation procedure* (3.13)

3.29
make-up support pin
pin component of *candidate connection* (3.7) with seal removed, used to support a coupling's open end during make-up and break-out of that coupling's opposite end

3.30
material coupon
cylindrical section of pipe from which *material strip specimens* (3.31) are cut

3.31
material strip specimen
longitudinal steel strip cut from a *material coupon* (3.30) and machined for use in mechanical property characterization tests

3.32
prior evaluation data
set of data acquired in a connection performance assessment carried out by analysis and/or physical tests prior to issuance of this protocol and/or according to a procedure/protocol different than the *evaluation procedure* (3.13)

3.33
program roles
collective reference to the roles of *assigner* (3.3), *supplier* (3.38), *evaluator* (3.16) and *inspector* (3.21)

3.34
repairable galling
galling (3.18) that can be repaired according to a *supplier's* (3.38) field-repair procedure for a *candidate connection* (3.7)

3.35
severe galling
galling (3.18) that cannot be repaired according to a *supplier's* (3.38) field-repair procedure for a *candidate connection* (3.7)

3.36
specimen string
collective reference to a single connection specimen and/or an in-series assembly of two or more connection specimens in a *thermal cycle test* (3.42)

3.37
substantially qualified party
person/company possessing technical skills and experience necessary to perform a task, as designated by the *assigner* (3.3) and the *supplier* (3.38)

3.38
supplier
party that manufactures *candidate connection* (3.7)

3.39
tensile strain threshold
tensile strain value that a connection specimen is expected to survive during a *limit-strain test* (3.25)

3.40
test specimen
connection specimen that is provided for a full-scale test

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3.41
thermal cycle specimens
subset of *candidate connection specimens* (3.8) subjected to the *thermal cycle test* (3.42) per the *evaluation procedure* (3.13)

3.42
thermal cycle test
thermo-mechanical test of connection specimens, in which several thermal cycles are applied between the *low cycle temperature* (3.26) and the *high cycle temperature* (3.19)

3.43
threaded-and-coupled specimen
two connections consisting of a single coupling and two *casing pups* (3.9) with pin ends joined by that coupling

3.44
threshold performance requirements
set of connection performance criteria for a *candidate connection* (3.7) considered as having met applicable minimum performance requirements

3.45
upper-bound temperature
highest temperature expected in thermal cycles in field applications

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4 Abbreviated terms and symbols

4.1 Abbreviated terms

ASL	application severity level
BF	fast box taper
BS	slow box taper
CSS	cyclic steam stimulation
CTE	coefficient of thermal expansion
FEA	finite element analysis
IC	integral connection
max.	maximum
min.	minimum
PF	fast pin taper
PS	slow pin taper
SAGD	steam assisted gravity drainage
TC	threaded-and-coupled connection
TWCCEP	thermal well casing connection evaluation protocol
TF(WGS)	final make-up torque for specimen with WGS configuration
TF(WGT)	final make-up torque for specimen with WGT configuration

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TF(WSC-M) final make-up torque for specimen with WSC configuration and multiple make-ups

TF(WSC-S) final make-up torque for specimen with WSC configuration and single make-up

TF(WST-M) final make-up torque for specimen with WST configuration and multiple make-ups

TF(WST-S) final make-up torque for specimen with WST configuration and single make- up

WGS worst-case tolerance combination for galling in seal

WGT worst-case tolerance combination for galling in threads

WSC worst-case tolerance combination for sealability in compression at high temperature

WST worst-case tolerance combination for sealability in tension at low temperature

4.2 Symbols

D casing outside diameter

L_{CEI} length of controlled elongation interval

L_{eff} effective string length

L_p unsupported pup length (pup length excluding make-up loss, i.e. pin-box overlaps at each end)

L_{TTS} lower-bound temperature strain increment

$p_{SS}(T)$ saturated steam pressure at temperature T

S_{LCF} strain-length compensating factor

S_{RI} temperature range strain increment

t casing wall thickness

T temperature

T_{amb} ambient temperature

T_{hc} high cycle temperature

T_{lb} lower-bound temperature for a given application severity level

T_{lc} low cycle temperature

T_{ub} upper-bound temperature for a given application severity level

α_a average coefficient of thermal expansion

$\Delta\varepsilon_{LL}$ strain increment for application in the limit-strain test

$\Delta\rho$ curvature increment

ε_{TEa} average residual post-cycle strain

ρ_{MAX} maximum test curvature

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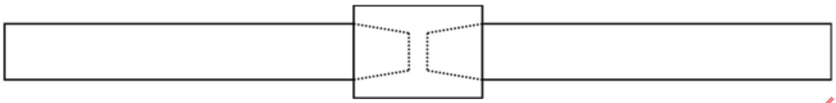
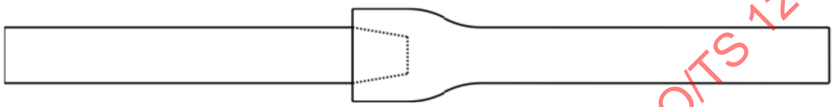
5 Program overview

5.1 Illustrations of selected definitions

Figure 1 illustrates two types of connection specimens that may be submitted for an evaluation program. Figure 1a shows a threaded-and-coupled (TC) specimen and Figure 1b shows an integral connection (IC) specimen. A TC specimen contains two connections (two "sides" of the coupling) creating two possible leak paths. An IC specimen contains one connection, resulting in a single possible leak path.



a) Threaded-and-coupled specimen

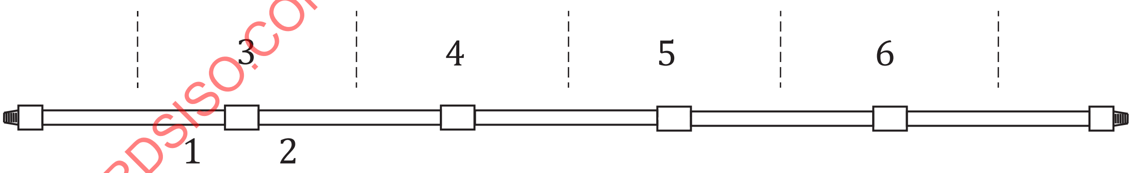


b) Integral connection specimen

Figure 1 — Illustration of connection specimens

When full-scale testing is conducted on strings containing multiple connection specimens assembled in series, some casing pups are shared by two adjacent specimens (which can be either TC or IC). Each such shared casing pup is considered to consist of two halves, with each half belonging to the specimen that includes the corresponding pin end or integral box end.

Figure 2 illustrates an example of a string assembly with four connection specimens. For consistency with requirements for the thermal cycle test, in which a four-specimen string assembly may be used, the example in Figure 2 shows Specimens 3, 4, 5, and 6 (refer to 10.1 for specimen numbers). For TC specimens, the two specimen leak paths can be distinguished by the specimen number and letters "A" and "B" referring to each coupling side.



Key

1 side A leak path 3A
2 side B leak path 3B
3 Specimen 3
4 Specimen 4
5 Specimen 5
6 Specimen 6

Figure 2 — Illustration of connection string assembly

5.2 Program flowchart

Figure 3 illustrates five main components (blocks) of an evaluation program. A detailed description of the program blocks and tasks is provided in Clause 10.

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General principles adopted for the evaluation procedure are described in Clause 6. It is recommended that all users of this document and all parties responsible for a prospective use of an assessed connection in a field application review Clause 6 and become aware of the assumption basis and procedural requirements for the assessment tasks and data reporting.

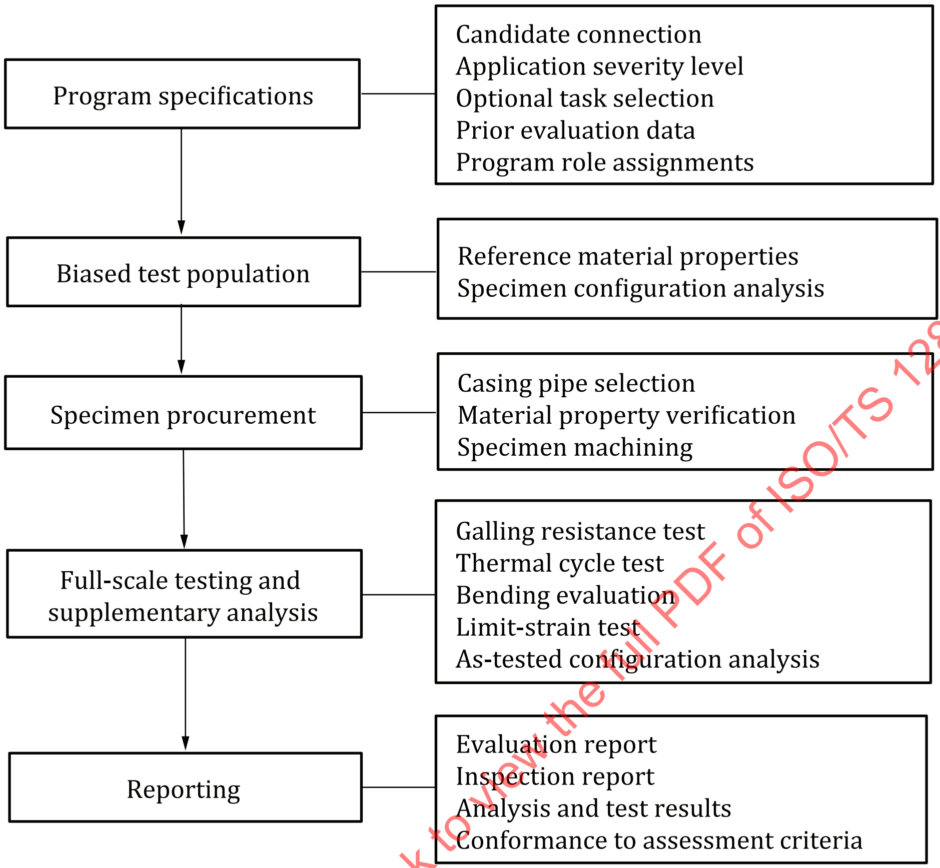

Figure 3 — Evaluation program flowchart

6 Overview and fundamental assumptions

6.1 General

This clause contains an overview of fundamental assumptions adopted for the connection evaluation procedure contained in this document. This overview is provided to facilitate understanding and interpretation of the provisions and procedural requirements specified in this document.

6.2 Main features

6.2.1 Purpose

This document provides procedures for assessing suitability of threaded casing connections for intermediate or production casing strings for thermal recovery wells or other wells experiencing significant temperature excursions. Conducting an assessment of a candidate connection according to the evaluation procedure provides data that can be interpreted by a connection user to complete evaluation of the candidate connection for a specific application.

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6.2.2 Applicability to service conditions

The evaluation procedure described in this document applies to those field applications in which operational temperatures oscillate between a cold level, appreciably below 180 °C, and a hot level, above 180 °C, in which casing deformation is primarily driven by thermo-mechanical strain resulting from the above temperature excursions, and in which the casing body might or might not cyclically yield under the corresponding strain-driven loads.

Specifically, the evaluation procedure applies to two thermal recovery applications: Steam Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS), in which thermal expansion of the casing string is constrained by cementing. This document might also be used for qualifying connections for other extreme-service wells in which tubulars undergo full-body yielding and for which deformation-tolerant design is desired; for example, wells in compacting reservoirs, steam-drive wells, geothermal wells, or some high-pressure high-temperature (HPHT) wells.

6.2.3 Rationale for development

Loading of intermediate casing connections in thermally stimulated wells is very severe and of unique character. Prior to issuance of the TWCCEP, no other connection evaluation procedure had been adopted as an industry standard for those loading conditions. In particular, ISO 13679 and API Specification 5C5 provide procedures for evaluating casing and tubing connections only for elastic-design applications, in which the tubular-body stress state is assumed to remain elastic, and in which maximum operational temperatures do not generally exceed 180 °C. Despite these fundamental differences, several similarities exist between this document and either ISO 13679 or API Specification 5C5. Where practical, such similarities are referred to in this document.

6.2.4 Subject of evaluation

The subject of evaluation is a candidate connection. In general, one or more candidate connections can be assessed in an evaluation program. For simplicity, this document refers to a single candidate connection as a subject of evaluation. If two or more candidate connections are included in a single evaluation program, then all provisions of the evaluation procedure apply to each candidate connection separately.

6.2.5 Application severity levels

The severity of field operating conditions varies. Consequently, multiple application severity levels (ASLs) are distinguished. The ASLs are uniquely defined in terms of maximum operating temperature (see 9.3).

Temperature has been recognized as the primary variable influencing severity of pipe thermo-mechanical loading and the connection response to that loading, including sealability and structural performance. The following arguments support this assumption:

— constrained thermal expansion of cemented casing heated to the maximum operating temperature leads to pipe and/or connection yielding. The magnitude of the axial loads generated during heating (and also subsequent cooling during a well intervention), as well as the degree of post-yield deformation, strongly depend on the applied temperature range;

— in field service, applied internal pressures typically follow the saturated-steam relationship with temperature;

— properties of casing pipe and connection materials vary with temperature – the material yield strength typically decreases with temperature, and creep and stress relaxation effects become more pronounced at elevated temperatures;

— elevated temperatures affect properties of thread compounds (dopes), and thus influence the role of the dope in premium seal activation. Such temperatures can also affect properties of some

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coatings used for dopeless connections. Higher temperatures are typically associated with faster degradation of dopes and coatings;

— the ASL is selected at the onset of each evaluation program. Some aspects of the evaluation procedure, such as severity of loading applied in numerical modelling and physical tests, depend on the selected ASL. The adopted assessment criteria are independent of the selected ASL.

6.3 Assessment philosophy and principles

6.3.1 Fundamental principles

The fundamental assessment philosophy adopted for the evaluation procedure is to:

— distinguish between those connection types that are suitable for thermal well service and those that are not;

— acquire key connection performance data for comparison with adopted minimum performance requirements, and also auxiliary performance data for determination of connection service boundaries;

— be practical to execute by analytical methods and laboratory testing.

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Based on the above philosophy, the following principles for the evaluation basis are assumed:

Principle 1 The evaluation procedure should be conservative with respect to:

a) candidate connection samples: test specimen configurations should be chosen to have the least-favourable characteristics possible within production manufacturing ranges;

b) loading: evaluation procedure should employ the most severe loading that is representative of cited field conditions.

Principle 2 Given that field conditions vary, the evaluation procedure should provide options to tailor the evaluation scope to anticipated operational conditions.

Principle 3 The evaluation procedure should make the best use of available analytical and physical-testing tools.

Principle 4 The evaluation procedure should measure a candidate connection performance with respect to those performance indicators that are considered critical for reliability in field service.

Principle 5 Assessment criteria should be chosen according to reasonable field-performance expectations. Assessment criteria should refer only to results of full-scale tests.

Principle 6 Where practical, auxiliary data should be collected to assess connection performance boundaries and safety margins with respect to cited service conditions.

Principle 7 Where possible and practical, data acquired in prior evaluations can be used, and the evaluation program scope can be reduced accordingly.

Principle 8 Execution of an evaluation program does not require the manufacturer of a candidate connection to reveal confidential connection design information beyond a level that enables third-party inspection.

Principle 9 Results of every evaluation program should be interpreted in the context of the completed evaluation scope and anticipated service conditions.

Principle 10 Perception of conflict of interest in executing an evaluation program should be avoided.

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Each principle listed above is further described in the following clauses. Discussion of some principles is also illustrated by reference to Figure 6 and Table 3, which describe the tasks of the adopted evaluation procedure.

6.3.2 Conservative evaluation procedure

The fundamental premise of the evaluation procedure is that it should verify the adequacy of the candidate connection performance under worst-case combinations of factors that affect its behaviour, including connection geometry, manufacturing tolerances, material properties, assembly, and operational loading. Principle 1 (in 6.3.1) is implemented by the following steps:

a) Determine the worst-case combinations of manufacturing and assembly variables for the candidate connection and treat those combinations as specifications for a biased set (population) of test samples.

b) Evaluate the biased test population under the established representative – but conservative – loading.

c) Compare the measured performance of the biased test population to adopted performance requirements. Assume acceptance if those requirements are met, or failure if those requirements are not met.

d) Assume that any production series of the candidate connection will perform equally well or better in relevant field service than the evaluated biased test population.

Step a) above is referred to as the front-end determination of the biased test population. Steps b) and c) are performed in the evaluation program by full-scale testing and supplementary analyses. Step d) is executed based on the acquired evaluation results.

6.3.3 Mandatory and optional tasks

The evaluation procedure contains mandatory tasks and optional tasks, which allows the evaluation scope to be tailored to specific operational conditions (per Principle 2 in 6.3.1):

— mandatory tasks are considered critical for evaluation of connections for all applications to which this document applies. Completion of all mandatory tasks is required in every evaluation program;

— optional tasks are those tasks that should be chosen so that the evaluation program provides results most relevant for the cited operational conditions. It is recommended to consider all program options, consciously select an optional task scope suitable for each evaluation program, and then execute the selected options according to applicable provisions of this document.

General descriptions of the mandatory and optional tasks are provided in Clause 10, and the tasks are listed in Figure 6 and Table 3 – so that the rationale for each task is presented in a logical order and subsequent option selection decisions are facilitated. Examples of optional tasks are: seal taper analysis, bending evaluation, and seepage measurement in the limit-strain test. Detailed descriptions of the mandatory tasks are provided in the main body of this document; and detailed descriptions of the optional tasks are provided in Annex D.

For some optional tasks, this document provides specific guidance relative to the task scope and/or procedures. For other options, this document provides only general recommendations that the discussed issues should be addressed in the context of the intended application.

In some evaluation programs, a candidate connection can be evaluated at a time when future use of the connection is unknown. When the candidate connection is contemplated for use in a specific application that was unknown at the time of its evaluation, the prospective user of the candidate connection should:

— carefully review the details of the executed evaluation program, including the selected program options;

— determine if the executed scope provides an adequate level of evaluation for the intended application;

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— if need be, consider executing additional evaluation tasks according to other program options that were not selected previously.

6.3.4 Use of analysis and physical testing

Per Principle 3 (see 6.3.1), the evaluation procedure employs both analysis and physical testing. The overall scope of the prescribed analysis and physical-testing includes both mandatory and optional tasks, as described in 6.3.3. Figure 6 summarizes all analytical and testing tasks of the evaluation procedure. Table 3 indicates the categories of data acquired in each task, as described in 6.3.7.

Analysis is an efficient and effective tool to examine connection sensitivity to design and operational variables. In general, an analytical task can involve a combination of engineering derivations based on closed-form solutions and numerical analysis based on the finite element method. Those formulations facilitate parametric studies, in which connection sensitivities can be readily assessed with respect to many – but not all – manufacturing and loading variables.

In this evaluation procedure, analysis is employed to select the biased test population, guide subsequent program execution (see 6.3.2), and acquire auxiliary data on candidate connection performance boundaries (see 6.3.7). Some analytical results may also be used to specify additional testing to verify candidate connection performance under application-specific conditions that are not simulated in the mandatory tests. No analytical results are compared to the threshold performance requirements.

Physical full-scale tests are considered to be an all-inclusive verification of connection performance, because they account for all design variables - i.e. both the variables that are controlled in the connection manufacturing process and the “black-box” variables that are not explicitly controlled, such as pin and box circumferential uniformity (roundness). In preparation of the test specimens, the black-box variables are assumed to be at values representative of production connections. It is recognized that this assumption might not always be conservative because the test samples are prepared according to custom specifications and manufactured outside of standard production runs. For example, the test specimens might have a higher degree of circumferential uniformity (and thus a smaller degree of waviness) than production connections.

Results obtained in the physical testing fall into several categories (see 6.3.7). For example, some results from mandatory tests are key performance indicators. Those are the only results that are compared with the threshold performance requirements (see 6.3.5 and 6.3.6), to determine whether or not the candidate connection performance meets the requirements of this protocol. Other results from mandatory tests and all results from optional tests are considered to be auxiliary performance data.

6.3.5 Performance measures

The following connection performance measures are assessed:

— galling resistance;

— structural integrity;

— sealability.

The above choice of performance measures results from focus on connection response to assembly and thermo-mechanical loading. Assessment of a connection resistance to environmental corrosion and cracking is not included in this document. While environmentally induced corrosion and cracking is a significant loading component active in thermal wells, those loading mechanisms are excluded from consideration in this document until synergies between thermo-mechanical and environmental loading are better understood.

6.3.6 Assessment criteria

Subclause 6.3.10 provides guidelines for interpreting results acquired in an evaluation program in the context of a specific field application. To facilitate this interpretation, reference performance measures are adopted, which are referred to as threshold performance requirements. A candidate connection

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is considered to have met the performance requirements of this protocol if the candidate connection performance meets or exceeds all applicable threshold performance requirements. Only results of full-scale tests are compared with the threshold performance requirements.

The following threshold performance requirements are adopted for the mandatory physical tests:

— no evidence of severe (irreparable) galling in the galling resistance test;

— lack of structural failure in any combined-loading test;

— seepage rates below the adopted threshold rates in sealability tests.

Subclause 6.5.3 provides guidance for seepage threshold rates to be used in sealability tests.

Additional assessment criteria for structural strength and sealability are recommended for the optional physical tests. Use of those assessment criteria is optional at the assigner's discretion. It can also be expected that in some evaluation programs alternative assessment criteria for the optional tasks are adopted by agreement between the assigner, the supplier and the evaluator. This document does not provide any provisions for such agreements but requires that the agreed assessment criteria be documented in the evaluation report.

6.3.7 Task outcomes — data categories

In order to implement Principles 1, 4, and 6 (in 6.3.1), the following categories of data acquired in various tasks are recognized:

— input for further tasks. This data type is acquired in tasks that determine the completion scope of subsequent tasks (e.g. determination of the biased test population);

— key performance measures. These results are compared with the acceptance criteria to determine whether or not the candidate connection meets, or does not meet, the threshold performance requirements;

— auxiliary performance data. These results also assess connection performance but are not graded against any acceptance criteria.

Acquiring data in the first two categories is mandatory in all tasks. Acquiring data in the third category is mandatory in some tasks and optional in some other tasks (see Table 3). Auxiliary data should be collected whenever practical because that data provides valuable information for prospective connection users. This recommendation is particularly relevant for new connection designs, or those connections for which little prior evaluation data (see 6.3.8) are available.

6.3.8 Prior evaluation data

Data acquired in a connection assessment program executed prior to an evaluation program performed according to this document, referred to as prior evaluation data, may be used in lieu of some or all analysis or testing required by the evaluation procedure if it is demonstrated that the scope, procedures, execution history, and documentation that were employed to acquire and record prior evaluation data, all meet or exceed the corresponding requirements of this document (see 8.5).

The purpose of this provision is to enable use of complete or partial results from analysis and/or full-scale tests performed according to other proprietary or standard protocols; for example, historic evaluations performed by some well operators; or assessments performed in-house by connection suppliers; or from material characterization tests done on various OCTG tubulars.

6.3.9 Treatment of confidential design information

It is recognized that connection design information is proprietary by nature, and that connection manufacturers might not want to reveal some of that information, e.g. machining drawings, to any other party. This document is structured so that it can be executed with or without exchange of candidate

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connection drawings among the parties involved in the evaluation tasks (see 7.2). The possible extent of third-party inspection will be influenced by the extent to which the connection design information is revealed.

6.3.10 Interpretation of evaluation results

This document does not provide a single pass-fail "certificate". Instead, it requires that a comprehensive evaluation report be prepared for each evaluation program, and that the report be available to a prospective user of the evaluated connection.

From the connection user's perspective, meeting performance requirements provided by this document can be considered as an indication of conformance to adopted performance standards. Those results should be interpreted with due consideration given to the scope of the completed evaluation program and prospective field-service requirements.

Since it is not practical to anticipate all facets of all field applications, the ultimate judgment on qualifying a connection for use in a given application rests with the connection user. Following completion of an evaluation program, the user should consider the program outcomes and other application-specific factors, in order to decide if results of the completed program indicate that the evaluated candidate connection is suitable for the intended application.

Having optional tasks in the evaluation procedure, per Principle 2 (see 6.3.1), is desirable because it allows the connection assessment to be tailored to specific operational conditions and qualification requirements. As a consequence, comparing data from various programs demands a thorough review because selections of program options and optional tasks might vary. The demand for thoroughness is a positive consequence, because comparison of results among various evaluation programs should always be done consciously and cautiously.

6.3.11 Avoiding perception of conflict of interest

To benefit connection manufacturers and users, this document specifies roles and responsibilities of various parties involved in the evaluation program so that the potential for perception of a conflict of interest is minimized. The parties involved are: the assigner, the supplier, the evaluator and the inspector. It is recommended that at least two independent parties be involved in all major evaluation tasks – see Annex C.

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6.4 Evaluation variables

6.4.1 Connection loading

The evaluation procedure (including both mandatory and optional tasks) accounts for the following external loads:

— make-up torque;

— temperature;

— internal pressure;

— post-yield axial tension and compression generated by constrained thermal expansion;

— curvature-induced bending.

This document does not address impacts of external pressure, fatigue, formation-induced shear (e.g. from geo-mechanical loads), cement voids or environmentally-induced corrosion or cracking.

6.4.2 Impacts of contributing variables

As a consequence of Principle 1 (see 6.3.1), one of the main tasks in the original TWCCEP development process was to assess impacts of design and loading variables contributing to connection performance

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in thermal well service. The first objective of the assessment was to distinguish between variables that exert major and minor impacts, so that the major-impact variables could be considered when selecting the worst-case variable combinations. The second objective was to distinguish “generic” variables, which could be assumed to have the same impacts on most premium connections, from “design-specific” variables, which can result in different performance trends in various connection types. The assessment results were used to develop criteria for selecting the biased connection test population and evaluation load cases.

Engineering analysis, numerical modelling, and reduced-scale testing were employed in the variable-impact assessment. Multiple reference configurations were considered for some variables, because sensitivities with respect to any individual variable can vary for different combinations of the other variables.

A variable was considered to have a major impact when variation of that variable within its production manufacturing tolerances or assembly targets or loading range caused a substantial change to a performance measure. Changes larger than 15 % relative to a value based on nominal conditions were typically considered to be substantial changes.

Following the impact assessment, the design and loading variables were categorized into five groups, as described in the following paragraphs.

Group 1: The first group consisted of the major-impact variables assumed common to most premium connection designs. Sensitivities to those variables were studied at the protocol development stage, and their worst-case combinations were established (“pre-set”) for later use during protocol execution. For example, these investigations included determination of sensitivity of connection sealability to “bake-out” at maximum operating temperature so that sufficient specimen bake-out duration and loading (free versus constrained bake-out) could be specified for the protocol.

Group 2: The second group of variables included those major-impact variables for which different connection types could be expected to display different sensitivity trends. Given the potential for such connection-specific response, a front-end assessment of the sensitivity trends with respect to the variables in that group was included in the evaluation procedure, so that connection-specific choices of the test specimen configuration could be made for each evaluated connection. For example, yield strength of the connection pin material can have a strong impact on the seal contact stress depending on the connection material grade and range of property variations allowed for a given connection. This document requires examination of those impacts for each candidate connection before selecting material specifications for test samples.

Group 3: Variables in the third group were of similar characteristics as in the second group (i.e. having major impact and being design-specific), with a distinction in that inclusion of the third-group variables in the selection of the biased test population was considered impractical because of challenges associated with conducting analysis or controlling those variables in the manufacturing process (e.g. seal tapers). Optional-task evaluations of connection performance with respect to the variables in this group are recommended.

Group 4: The fourth group was chosen to include variables of similar characteristics as the second and third groups (i.e. having major impact and being design-specific), except that the variables in the fourth group were considered to have those characteristics only in some applications and not in other applications (e.g. severe curvature loading). Similar to the third group, optional-task evaluations of connection performance with respect to the variables in the fourth group are recommended.

Group 5: The fifth group of design and loading variables included those variables that were not considered significant for specifying procedures for the connection performance assessment. For example, some threadform details such as flank angles do affect connection load transfer, but variations of those variables within their manufacturing tolerances do not significantly change connection galling resistance, structural strength or sealability. This document assumes nominal values for the variables in this group.

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6.4.3 Pin-box interferences and tapers

Unless otherwise agreed by the assigner and the supplier, the following shall be adopted:

— Diametric seal interference between the pin and box components of a candidate connection is the interference between the pin outside diameter and the box inside diameter at a reference seal location consistent with design and gauging practice for the candidate connection.

— Diametric thread interference between the pin and box components of a candidate connection is the interference between the pin and box pitch diameters at a reference thread location consistent with design and gauging practice for the candidate connection.

— For seals cut on conical surfaces, a seal taper is the change of seal diameter over a reference axial distance.

— For threads cut on conical surfaces, a thread taper is the change of thread pitch diameter over a reference axial distance.

For some connection designs, load transfer mode in the threads and manufacturing tolerances on thread forms will significantly impact diametral interferences. These impacts should be considered in the selection of minimum and maximum interference configurations for the biased test population (see 12.3.4) and test specimen specifications (see 13.4.6).

6.4.4 Material yield strength

Yield strengths and post-yield stiffnesses of connection component materials affect connection response to loading beyond the elastic limit. In general, two types of post-yield response are expected in a connection subjected to typical thermal well loading:

— localized yielding due to stress-strain concentrations, for example, in thread roots or seal high-contact stress seal band;

— global yielding due to large mechanical strains generated by constrained thermal expansion, for example, in the pipe body and a connection's critical cross-section.

The following assumptions are adopted:

— For most connection designs, the box component is appreciably stiffer than the pin component, and thus yield strength of the box material may be excluded from determination of the biased test population. Consideration of the box yield strength is an optional task;

— Yield strength of the pin material was found to have a major impact on the seal contact stress intensity, and is included as a mandatory task in determination of the biased test population for sealability tests;

— Material yield strength is not explicitly considered in specifying the test specimens for galling resistance tests. Manufacturing of the galling test specimens is guided by material selection based on sealability considerations;

— Impacts of pin and box material yield strength variations (within the candidate connection manufacturing specifications) on localized yielding in thread roots is not explicitly addressed in selecting the biased test population. Those localized-yielding variations are assumed to not have a significant effect on the candidate connection structural strength, which is assessed in the full-scale tests.

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6.5 Evaluation procedure

6.5.1 Safety standards

It is presupposed that all activities required or recommended by the evaluation procedure are conducted to appropriate safety standards, in accordance with safety requirements and policies in place in the facilities conducting those activities.

6.5.2 Seepage assessment — random variations

Connection sealability performance can vary considerably even for connection samples that have been manufactured and assembled according to identical specifications. In particular, variable seepage rates can be expected in physical tests involving elevated temperatures. Such “random” behaviour can result from degradation of thread compound at high temperatures (e.g. dope bake-out), movement of dope solid particles (e.g. as dependent on pin and box surface finish, dope density variations, time), variations of connection geometry not fully controlled in the manufacturing process (e.g. circumferential waviness), and other variables.

Statistical variations in seepage response typically increase with temperature. Some historic evaluations for high-temperature applications (e.g. CSS) addressed this statistical variation by requiring testing of multiple specimens of the same configuration. While there is insufficient data to support a rigorous statistical analysis of how many specimens are required to provide a representative connection population, four specimens have been used as a reasonable compromise between practicality and statistical considerations.

Testing of four specimens is required in the thermal cycle test – see Figure 1 that illustrates specimen definitions for various connection types. Two of those four specimens are manufactured according to the worst-case tolerance combination for sealability at the maximum test temperature and the other two are manufactured according to the worst-case tolerance combination for sealability at the minimum test temperature after one thermal cycle. If those tolerance combinations are found to be the same for the minimum and maximum temperature, then four specimens of the same target configuration are tested.

6.5.3 Seepage rate thresholds

Tolerance for seepage in field application varies, because it depends on the well configuration, properties of the surrounding formation, well location, environmental considerations, and other factors. Based on the current state of industry knowledge, no practical “universal” threshold can be selected to suit all field applications.

For reference purposes, three seepage thresholds are adopted:

— 0,06 ml/min = reportable seepage rate threshold. Any seepage activity observed in any sealability test that is larger than this level shall be reported by the evaluator. This threshold is consistent with ISO 13679 standard and API Specification 5C5;

— 1 ml/min = maximum seepage rate in axisymmetric compression. This threshold is consistent with some historic evaluations performed for CSS applications;

— 10 ml/min = maximum seepage rate in axisymmetric tension and under non-axisymmetric bending. For the axisymmetric tension, this threshold is consistent with some historic evaluations performed for CSS applications.

In combined loading cases involving axial forces and lateral loading, different combinations of external loading will result in varying the stress distribution around the connection circumference. Contact stress intensity in the connection seal can also be expected to vary around the circumference. Nonetheless, a single threshold of 10 ml/min has been adopted for simplicity.

It is understood that the original selection of seepage threshold rates in the historic evaluations referred to above was based on prior investigations that had been conducted on several 177,8 mm (7 in) casing

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connections, with no scaling for other connection sizes. Some connection users can find it justified, for their specific field applications, to adopt seepage thresholds different from the ones listed above. For example, a user can find it justified to scale the above historic seepage thresholds (1 ml/min and 10 ml/min) from the 177,8 mm (7 in) casing size by the ratio of the candidate connection size to the 177,8 mm size. If any threshold modifications are done within a specific evaluation program, they shall be clearly described in the evaluation report. The responsibility for such threshold modifications rests with the assigner and the evaluator.

It is required that:

— seepage rates be measured for individual connections (one side of a connection specimen for threaded-and-coupled connections, or one integral connection);

— the adopted seepage rate thresholds be documented and be applied to each individual connection (not to each specimen unless it is an integral connection, and not to strings with multiple specimens);

— measured seepage rates be reported for each event in which the measured seepage rate exceeds the reportable seepage rate threshold.

The reportable seepage rate threshold applies to each load step that contains a hold in any physical test. Each specified maximum seepage rate threshold applies to an average seepage rate calculated for holds at the same loading targets in all loading cycles (e.g. all high-temperature holds in the thermal cycle test), as described in 14.2.4.4.

In addition to per-connection average seepage rates, average and mean seepage rates for the entire tested population should be calculated for information purposes.

6.5.4 Seal isolation

Sealability checks are conducted on primary connection seals that are isolated from any additional sealing mechanisms that might be active in the connection specimens. As a consequence, seepage detection ports need to be drilled into dope relief grooves, so that seepage across the primary radial seal is observed independently of any seepage blockage that can occur in the threads (see 14.2.4.1).

As another consequence, torque shoulder seals need to be disabled unless those are the primary sealing surfaces. If torque shoulders are the primary sealing surfaces, any other sealing surfaces that might impede gas flow to the seepage detection ports also need to be disabled (see 14.2.3).

It is acknowledged that drilling of the detection ports into the connection dope relief grooves, and in some cases also disabling of the torques shoulder seal, might lead to relieving of the dope entrapment (see 6.5.5) in a manner that is different from the field conditions.

6.5.5 Dope entrapment

Dope entrapment upon make-up can lead to deformation of the pin seal surface that exceeds the design intent, which can be detrimental to the connection sealability. For example, excessive axisymmetric deformation can lead to global reduction in the contact stress intensity. Alternatively, a circumferential buckling mechanism can cause the pin seal to become non-round (increase the pin waviness). Consequently, the seal contact stress distribution will be non-uniform, and seal burnishing might be inadequate.

Dope entrapment is more likely to occur when the amount of the dope applied prior to make-up is increased, and, to a lesser extent, when the make-up speed is increased. In a conservative sealability test, the largest amounts of dope allowed by the connection manufacturer should be applied to the test specimens. The specimen make-ups should be performed at maximum allowable speeds.

6.5.6 Thermal cycle test — bake-out and hold durations

Each thermal cycle includes holds at maximum cycle temperature and at minimum cycle temperature. The duration of those holds should be long enough to capture time-sensitive impacts on the connection

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behaviour, yet as short as possible to minimize the test duration (cost). The major time-dependent factors are: behaviour of the seal components (changes in dope phases, movement of solid particles), and stress relaxation of pin and box materials (impact of multi-axial relaxation on radial contact stress).

It is assumed that a "sufficiently" long bake-out of the test specimens in the sealability test will adequately simulate the time-dependent dope degradation that occurs in field service, and its impact on sealability. The bake-out should be done with external loading, so that the loading conditions are consistent with the field service, where the connections are in axial compression during heating and subsequent hold at elevated temperature.

The evaluation procedure specifies the bake-out duration to be 120 hours in the first thermal cycle (see 14.4.7.2). Regarding dope degradation, it is assumed that once this bake-out is performed, no additional prolonged bake-outs are required at high-temperature holds in subsequent cycles.

For typical OCTG materials, stress relaxation effects follow an exponential-decay with time. The relaxation is more pronounced in the initial portion of any hold than in the later stages of that hold. Stress relaxation strongly depends on temperature – it is higher at elevated temperatures than at room temperature. Stress relaxation also depends on applied stress and strain, with the amount of relaxation typically increasing with the stress-strain magnitude (although that relationship is expected to be material-specific).

Engineering experience indicates that the majority of stress relaxation occurs within 24 to 48 hours, when high-temperature strain is held constant. The adopted bake-out duration is thus adequate for relaxation to be nearly exhausted in the first thermal cycle. Relaxation is small during low-temperature holds, so that subsequent 4 hour high-temperature holds are long enough to counteract low-temperature relaxation.

Any pre-test exposure of the test specimens to elevated temperatures should be carefully considered, to avoid any significant changes of the specimen material properties that would be inconsistent with the operational loading scenario.

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6.5.7 Pressure and temperature loading in thermal cycle test and analysis

The loading procedure for the thermal cycle test (see 14.4.7) is based on the assumption that in thermal operations, internal casing pressure closely follows the saturated-steam relationship with temperature, although the sequence of pressure and temperature changes in field operations might not exactly correspond to the saturated-steam relationship. For example, casing temperature typically lags casing pressure during the heating part of a thermal cycle due to delays caused by finite heat transfer rates. In the cooling part of a cycle, temperature can decrease while well pressure is maintained by ingress of reservoir fluids. The departures of the pressure-temperature loading sequence from the saturated-steam relationship will vary for different field operations, and thus would be challenging to quantify and/or specify for general evaluation purposes. Those loading-sequence differences are considered to have little impact on connection performance during the test holds under full pressure and extreme temperatures. For that reason, and also for practical test-control considerations, those differences are disregarded in the thermal cycle test procedure.

The modelling guidelines in Annex A specify a load path in which pressure changes precede temperature changes in a simulated thermal cycle. In some supplementary numerical evaluations and parametric studies conducted on a generic connection model in support of the original TWCCEP development (prior to publication of ISO PAS 12835:2013), that load path was found to be somewhat more severe than simultaneous application of the pressure and temperature-driven loads. Subsequently, that sequence was chosen for the numerical evaluation tasks associated with selection of the biased test population. The resultant discrepancy between the loading sequence in the analysis and physical test is believed not to be significant for connection evaluation purposes.

6.5.8 Dependence of material strength on temperature

Consistency of material-strength dependency on temperature is assumed. For a given production material, proportional reduction of yield strength at any given elevated temperature is assumed to be the same for samples of that material coming from the lower end and from the higher end of the allowable range of the production yield strength.

It is recognized that material temperature-dependence is typically not controlled in pipe production; consequently, it is recommended that the assigner and the supplier verify the above assumption at the onset of the evaluation program and consider the outcomes of such verification in subsequent modelling and testing tasks (see 6.3.4).

6.6 Scope of reporting

A comprehensive evaluation report shall be issued upon completion of each evaluation program. The evaluation report shall contain a description of the assumed program roles, details of the candidate connection, the data acquired in the analysis and physical testing (as per Clause 15), comparison of the results with threshold performance requirements, and any non-conformances with respect to the evaluation procedure.

The requirement for the evaluation report to contain the data acquired in the analysis and physical testing will enable a thorough assessment of the candidate connection performance, not only at the time when the evaluation program is completed but also at later occasions. Such a future assessment can be conducted by a party that was or was not involved in the original evaluation. It can also be performed for an application that can be similar or different from the application targeted in the original evaluation. Consequently, design engineers working on such future projects will benefit more from knowledge of the connection response to each loading step in the evaluation procedure than from comparison of the selected performance indicators to arbitrary threshold requirements. Therefore, the evaluation report is intended to provide a complete record of the executed evaluation program.

7 Program roles and proprietary design information

7.1 Program execution roles

Given that this document can be followed in different types of connection evaluation programs – some commissioned by users (operators), some by connection manufacturers, and some by groups involving various companies – in order to facilitate definition and interpretation of the evaluation procedure, this document adopts specific program role descriptors, as defined in Clause 3.

Annex C provides recommendations for role assignments, responsibilities and combinations in which single/multiple parties can assume single/multiple program roles.

7.2 Proprietary connection design information

It is recognized that connection design information is proprietary by nature, and that a supplier might not want to reveal some of that information, e.g. machining drawings, to any other party. Consequently, the evaluation procedure is structured so that it can be executed with or without exchange of candidate connection drawings among the parties involved in the evaluation tasks.

The following principles are adopted for handling of proprietary/confidential information for the purpose of performing the evaluation tasks:

— The supplier is not required to provide candidate connection machining drawings to any other party within execution of an evaluation procedure.

— The evaluator is not required to reveal any candidate connection machining drawing details in the evaluation report, except the information that is necessary to uniquely identify the candidate connection (e.g. the interfacial component has to be described with enough detail to allow unique identification of the product that has been tested in an evaluation program).

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- At the onset of each evaluation program, the assigner and the supplier shall agree on the extent of exchange of proprietary information for the purpose of executing the evaluation procedure. If the assigner and the supplier are the same party, then that party alone decides on any such exchange.
- The evaluation report shall describe all role assignments, including selection of parties performing various evaluation tasks and their respective responsibilities, and the agreement between the assigner and the supplier relative to exchange of proprietary design information.

EXAMPLE Evaluation program conducted in-house by a supplier:

When an evaluation program is conducted in-house by a connection manufacturer, the manufacturer can simultaneously assume the roles of the assigner, the supplier, and the evaluator, and hire an independent party to be the inspector. The manufacturer will use the candidate connection drawings internally to build FEA models and perform Task 2.2 Specimen Configuration Analysis (see 12.3.1). The results will be included in the evaluation report, but possibly with no geometry details of the candidate connection. When those details are not revealed to the inspector, then the inspector will be able to review the analysis results but not the consistency of the FEA model with the connection's geometry.

8 Conformance requirements

8.1 Conformant evaluation program

An evaluation program shall be considered conformant with the requirements of this document if and only if either of the following two sets of conditions is satisfied:

- Set 1: The evaluation program was executed in full conformance with all clauses of this document; and such fully conformant execution is documented as such by the evaluation report and the inspection report;
- Set 2: The evaluation program was executed in partial conformance with the clauses of this document; all non-conformances are described by the evaluation report and/or the inspection report, whichever is relevant; and each such non-conformance is accepted as not having substantially alleviated the requirements of this protocol and not having led to a substantial misrepresentation of the candidate connection performance.

Subclause 8.2 defines "non-conformance" and describes the process for accepting a non-conformance as satisfying the above Set 2 conditions.

8.2 Program non-conformances

A non-conformance occurs whenever one or more conditions of a requirement are not satisfied (i.e. non-conformances apply only to requirements). In general, non-conformances can occur with respect to program definitions, analysis or test procedures, or reporting.

The practicality of carrying out an evaluation program can sometimes suggest that non-conformances be accepted during the program execution (e.g. when a test specimen gets damaged and needs to be replaced by another specimen, and the available replacement specimen has a different loading history than the damaged specimen) or after the program execution (e.g. when data review indicates that a specimen temperature was outside the allowed range in a certain location). Acceptance of a non-conformance will be facilitated when the intended use of the evaluation program results is known at the time of the program execution, for example when a candidate connection is being evaluated for use in an existing operation with defined specific requirements. In other cases, acceptance of a non-conformance can be more difficult, for example when a candidate connection is evaluated for future applications with operational conditions unknown at the time of the evaluation program execution; or when a connection manufacturer evaluates a new connection for several prospective users/applications that might differ in non-conformance tolerance.

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The following principles shall be observed in the process of accepting a non-conformance as not having substantially alleviated the requirements of this protocol and not having led to a substantial misrepresentation of a candidate connection performance:

— at least two different parties performing the program roles assess the rationale and potential implications of the non-conformance, and agree on accepting the non-conformance;

— one of the parties mentioned above is the assigner. The other party is the first party that is different from the assigner in the following order: supplier, evaluator or inspector;

— all non-conformances are documented and the relevant documentation explaining the rationale for accepting each non-conformance is retained by the assigner as part of the evaluation report.

8.3 Performance acceptance

In any single evaluation program, a candidate connection shall be considered to have met the performance requirements of this protocol for the selected ASL if all of the following conditions are satisfied:

— the evaluation program conforms with the requirements of this protocol (according to criteria specified in 8.1);

— the candidate connection performance, measured by the evaluation procedure, has met all applicable threshold performance requirements (only results of full-scale testing shall be considered in meeting the threshold performance requirements);

— execution and results of the evaluation program have been fully documented in an evaluation report and, as applicable, in an inspection report; and copies of the evaluation report and the inspection report have been delivered to the assigner.

8.4 Conformance of results from previous evaluations

Subject to agreement between the assigner and the supplier, an evaluation program carried out in accordance with prior versions of the TWCCEP or ISO/PAS 12835:2013 (previous program) may be considered representative of an evaluation carried out in accordance with this document, provided that the subsequent protocol revisions have not caused a substantial change in the evaluation procedure or the threshold performance requirements. The determination whether any such change is substantial (or not) should be decided by agreement between the assigner, the evaluator and the supplier. If a substantial change has been determined, then the previous program might be considered insufficient for some applications, and incremental evaluation might be required. The scope of any such incremental evaluation should be decided by agreement between the assigner and the supplier.

In all cases, the evaluation report and the inspection report shall indicate the TWCCEP version or the edition of this document to which the previous program and any incremental evaluations have been conducted.

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8.5 Use of data from previous evaluations

Prior evaluation data may sometimes be used in lieu of some or all analysis or testing required by the evaluation program. Any party involved in the evaluation program execution may propose use of prior evaluation data, but any such use should be agreed by the assigner and the supplier.

In general, use of prior evaluation data is allowed when either: 1) that data is fully conformant with requirements of this document; or 2) that data is not fully conformant with requirements of this document, but some additional conditions are satisfied. The following paragraphs provide provisions for either of the above two scenarios.

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The following process shall be followed for use of any prior evaluation data in an evaluation program. Prior evaluation data may be used in an evaluation program if:

a) a person/company who is a substantially qualified party to perform connection evaluation (analysis and/or testing, whatever the case might be) and interpret results thereof:

   1) conducts a thorough technical review of the prior evaluation data;

   2) verifies that the scope, procedures, execution history, and documentation that were employed to acquire prior evaluation data have all met or exceeded the respective requirements of this document for the candidate connection;

   3) issues a written confirmation that such verification was conducted and includes the conclusions reached;

b) if the person/company in a) acts on behalf of the supplier of the connection for which use of prior evaluation data is proposed, then at least one other person/company that is a substantially qualified party to interpret prior evaluation data and is independent from that connection supplier provides written concurrence with the conclusions of the verification referred to in a).

If a review of prior evaluation data is conducted as referred to in a) and b) and the prior evaluation data is found to not meet all requirements of this document (for example, because significant discrepancies are identified between the prior evaluation and the evaluation procedure of this document), then:

c) if the review of prior evaluation data is done by a person/company independent from the supplier of the connection for which use of prior evaluation data are proposed, as discussed in a) above, that person/company shall recommend additional analysis and/or testing to supplement the prior evaluation data such that the combined extent of the prior evaluation data and the additional analysis and/or testing will satisfy all requirements of this document; or

d) if the review of the prior evaluation data is done by the supplier of the connection for which use of prior evaluation data are proposed, and that review is verified by an independent party, as discussed in a) and b) above, then the supplier and that independent party shall agree on additional analysis and/or testing to supplement the prior evaluation data such that the combined extent of the prior evaluation data and the additional analysis and/or testing will satisfy all requirements of this document.

Upon that additional analysis and/or testing being carried out as discussed in c) or d) and confirmed in writing as having been carried out, the prior evaluation data and the additional analysis and/or testing shall be deemed to jointly satisfy the requirements of this document.

Any prior evaluation data used in an evaluation program shall be included in the evaluation report for the corresponding evaluation program.

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8.6 Conformance to lower ASLs

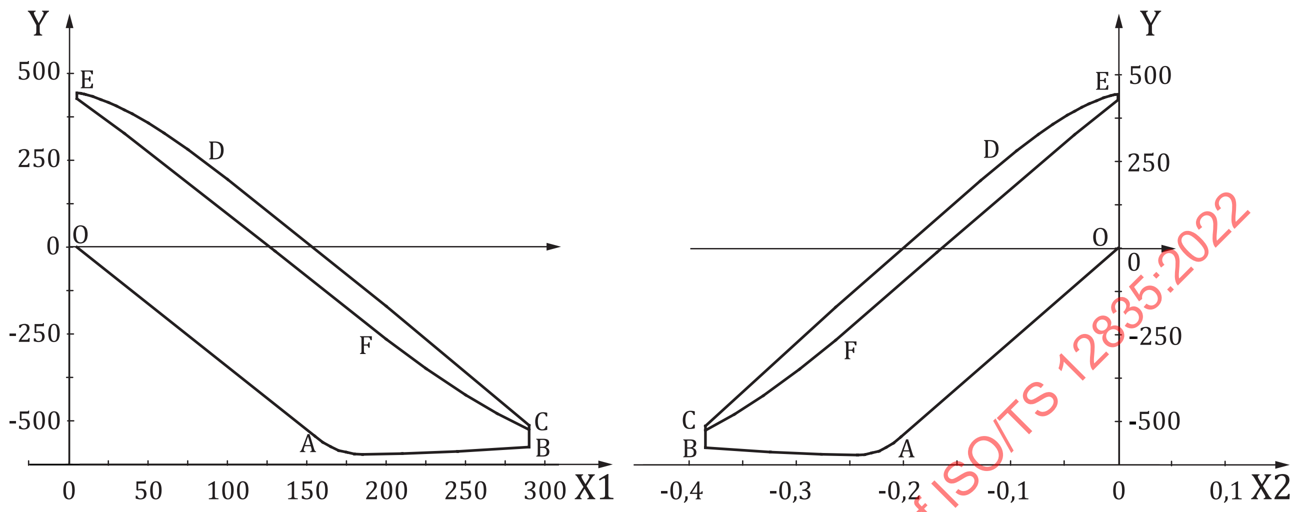
Conformance of the assessment results of the candidate connection to the performance requirements for the selected ASL shall be interpreted as conformance to all other ASLs defined by lower temperatures than the ASL to which the candidate connection has been evaluated.

9 Application severity levels

9.1 Thermal well load path

It is recognized that casing connections in thermally-stimulated wells, such as SAGD or CSS wells, experience a common loading scenario in which axial loads on the casing pipe-connection system and internal casing pressures are largely driven by cyclic temperature changes.

Temperature-driven axial force contributes the majority of the loading on the pipe-connection system. As an example, Figure 4 illustrates a typical axial load cycle experienced by an L80 casing cycled between a minimum (lower-bound) temperature of 5 °C and a maximum (upper-bound) temperature of 290 °C (specifications for the distinguished temperature ranges are provided in 9.3). Figure 4a shows the relationship between the pipe body stress and well temperature and Figure 4b shows the same relationship in terms of mechanical strain generated by axially constrained thermal expansion.



a) Stress-temperature plot

b) Stress-strain plot

Key

X1 temperature, °C

X2 mechanical strain, %

Y stress, MPa

Figure 4 — Example of thermal well load path (1,5 thermal cycles)

The load cycle ("thermal cycle") commences with constrained heating, in which compressive axial stress initially builds according to the elastic stress-strain relationship (load path OA). The casing string yields when the compressive yield strength is reached (at approximately 180 °C in this case). The casing response to further temperature increase is influenced by the temperature-dependence of the yield strength, which typically reverses the slope of the stress-temperature curve, although this trend can be somewhat offset by strain hardening (load path AB). During steaming at maximum temperature, stress relaxation occurs, which reduces the compressive axial stress in the pipe-connection system (path BC). When cooling, the string experiences constrained thermal contraction, which generates axial tension (path CD). The reverse loading curve demonstrates a reduction of the elastic range and a corresponding rounded shape of the cyclic stress-strain curve. In the example illustrated in Figure 4, the casing yields again under tension (at approximately 100 °C). The maximum tensile stress is reached upon return to the lower-bound temperature (path DE). Heating in the second cycle follows a cyclic stress-temperature (or stress-strain) curve (path EF). Subsequent loading in the second cycle and later cycles qualitatively follows the cyclic heating-cooling loop (path EFCDE), although each cycle can result in a slight change (typically increase) of the tensile stress at the cycle-end. The width of the hysteresis loop EFCDE provides a measure of average pipe-body plastic strain accumulated in each cycle. Specific progression of the load-deformation loops depends on cyclic properties of the casing material. For example, modest increases in the end-of-cycle tension typically occur with further cycling.

Internal casing pressure typically constitutes a less severe loading component than axial tension and compression, but it can have a significant impact on the casing deformation when the casing yields due to the axial forces. In the event that a connection leaks, the magnitude of the internal pressure can also be expected to impact the leak rate.

Internal pressure loading applied in the evaluation procedure is based on the assumption that in thermal operations the internal pressure closely follows the saturated-steam relationship with temperature,

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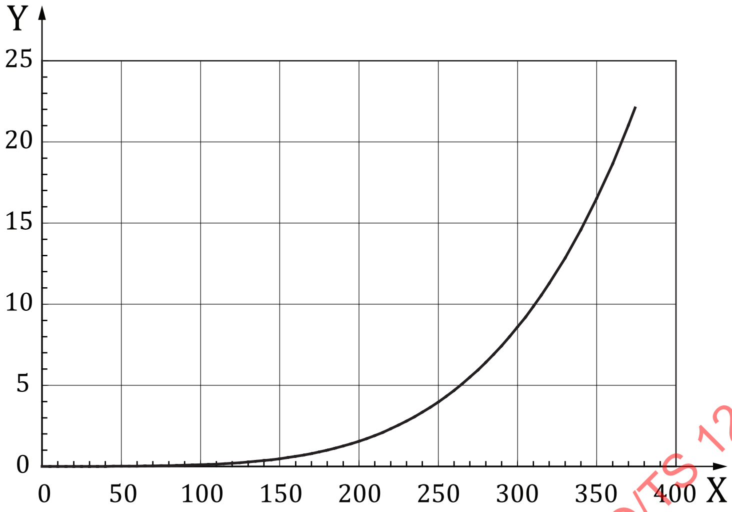
although it is recognized that cooling can also occur with retained reservoir pressures. The adopted pressure-temperature relationship for saturated steam is illustrated in Figure 5.



Key

X temperature, °C

Y absolute pressure, MPa

Figure 5 — Relationship between pressure and temperature for saturated steam

The cyclic loading sequence described in the above paragraphs is assumed as the basic load path for the analytical and testing evaluation tasks, with some modifications resulting from practical considerations (also see 6.5.7). The following three characteristic stages of the thermal cycle were chosen as reference loading conditions:

a) connection make-up;

b) maximum-temperature hold;

c) return to low temperature at the end of the thermal cycle.

9.2 Temperature as controlling parameter

The following list summarizes the reasons for which temperature is recognized as the major parameter influencing thermal well loading and connection sealability and structural response:

— Constrained thermal expansion of cemented casing, when heated to the maximum operating temperature, generates high compressive loads that can lead to pipe body and/or connection yielding. The magnitude of the cyclic axial loads generated during temperature excursions, and the degree of thermally-driven deformation, strongly depend on the applied temperature range;

— In field service, applied internal pressures typically follow the pressure-temperature relationship for saturated steam;

— Properties of casing pipe and connection materials vary with temperature. The material yield strength typically decreases as temperature rises, and creep and relaxation effects become more pronounced at elevated temperatures;

— Elevated temperatures affect properties of connection interfacial components (e.g. thread compounds, coatings), and thus influence their role in premium seal effectiveness. Higher temperatures are typically associated with faster property changes in coatings and thread compounds, although resistance to such degradation can vary substantially between different coatings and compounds.

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The above list excludes geomechanical activity and corrosive effects, which are not addressed by this document.

9.3 Specifications for application severity levels

Thermal well operations are diverse. While the thermal well loading sequence is assumed to be common (and consistent with the loading path described in 9.1), operational temperature ranges vary. Assuming a single reference temperature for connection evaluation purposes would lead to the evaluation conditions being too severe compared to some field applications, and perhaps not severe enough for other applications. To permit consistent use of the evaluation procedure for various severities of thermal well operations, this document defines multiple ASLs that relate to increasingly arduous service conditions, and consequently specify increasingly arduous evaluation conditions.

This document categorizes the ASLs based on the upper-bound temperature, as shown in Table 1. For example, ASL-290 denotes a severity level choice appropriate for operations in which the maximum operating temperature will not exceed 290 °C. Applications in which maximum temperature does not exceed 180 °C are not addressed by this document.

This document assumes 5 °C as the default lower-bound temperature for all ASLs. This choice is considered conservative for operations in moderate or colder climates, because the casing string is not expected to be at a lower temperature during cementing, and is not expected to cool down to a lower temperature during the operational cycles.

It is recognized that the casing string might not cool down to 5 °C in some climates and/or in some thermal cycles. Assuming the default lower-bound temperature of 5 °C for those field applications leads to the test loading being somewhat more severe than the field loading. This results in an extra conservatism of the assessment, which provides an additional safety margin for future use of the candidate connection, and enables a “qualified” connection to be used in various climates without a need to repeat any testing. Clause D.1 provides guidance for optional evaluations with non-default temperature ranges.

All axisymmetric loads applied in the evaluation procedure are derived from the ASL specifications. Axial loads are strain driven, resulting from constrained thermal expansion and contraction within the range defined by the lower-bound and upper-bound temperatures. Consequently, the magnitudes of axial forces are material-specific. They depend on the coefficient of thermal expansion of the casing pipe (and to a lesser degree of the coupling material), and the material stress-strain-temperature characteristics.

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Table 1 — Application severity levels

Application severity level (ASL)	Maximum operating temperature	Lower-bound temperature	Upper-bound temperature
°C			
Not applicable	180	-	180
240	181 to 240	5	240
290	241 to 290	5	290
325	291 to 325	5	325
350	326 to 350	5	350

The internal pressures derived from the relationship between saturated-steam pressure and temperature are listed in Table 2. The saturated-steam pressure p_{SS} at a given temperature T is subsequently referenced as $p_{SS}(T)$. Some field applications can involve operational pressures other than the pressures resulting from the saturated steam curve. When the operational pressures are lower than the saturated steam pressure, then the resulting extra conservatism can be treated as a margin that will enable a “qualified” connection to be used in a variety of applications in which internal pressure can vary from time to time. This document does not address loading scenarios in which the operational pressures exceed the saturated steam pressure. Customized evaluations are recommended for those operations.

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Table 2 — Resultant derivative loads

Upper-bound temperature	Axial loads	Maximum internal pressure
°C	(Strain-driven)	MPa
180	Resultant from constrained thermal expansion between lower- and upper-bound temperatures	1,0
240		3,3
290		7,4
325		12,1
350		16,5

9.4 Selection of application severity level

The assigner shall select the ASL for each evaluation program at the program onset.

An ASL with an upper-bound temperature higher than the maximum temperature expected in the relevant field service should be chosen for the evaluation program.

Prior to program commencement, the assigner should consult with the supplier to confirm that the selected ASL conforms to the supplier's intended service environment for the candidate connection.

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10 Program blocks and tasks

10.1 Evaluation procedure overview

The basic structure of the evaluation procedure is outlined in Figure 6. The procedure consists of the following blocks (groups of related tasks): program specifications; biased test population; specimen procurement; full-scale testing and supplementary analysis; and reporting.

The program specifications block (see Clause 11) describes the assumed program roles, the candidate connection, and the selected program options, such as the ASL. If relevant prior data is available and intended for use in the program being commissioned, it needs to be referenced in this block as well. The program specifications are selected in Task 1.1 to Task 1.4.

Selection of program specifications for the candidate connection can impact subsequent use of the program results. For example, since the connection interfacial components (i.e. coating and thread compound) play a fundamental role in connection sealability in thermal applications, the evaluation program results are considered valid only for the interfacial components that are used in the test specimens, unless it is demonstrated that use of a different interfacial component does not result in a substantial change of the candidate connection performance.

Determination of the biased test population (see Clause 12) is conducted to derive specifications for the full-scale connection testing specimens. This front-end assessment consists of two tasks: Task 2.1 Initial Material Property Characterization, and Task 2.2 Specimen Configuration Analysis. Task 2.1 is conducted to obtain reference properties of the candidate connection component material(s). These reference properties are acquired by coupon-scale laboratory tests of a random sample of the connection production material(s), at temperatures spanning the selected ASL. The acquired reference properties are used to formulate a constitutive material model for subsequent numerical simulations. Task 2.2 Specimen Configuration Analysis is a parametric finite-element sensitivity study. It is conducted to select worst-case combinations of geometric and material-property variables allowed by the manufacturing tolerances, and to select target make-up torques for sealability tests. Subclause 12.3 describes the scope of this analysis, and Annex A provides associated modelling guidelines.

To facilitate program execution, the material characterization and sensitivity analysis can be performed well in advance of the other evaluation tasks. Pre-existing material data and FEA results can also be used if their conformance to requirements of this document is demonstrated.

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The results of the front-end analysis affect decisions relative to the procurement of specimen material(s), as described in Clause 13. If material properties are shown to have a significant impact on the candidate connection structural response, the range of material properties allowed for the test samples is biased to those properties that lead to worst-case combinations of the material variables. If no significant impact of the material variables is found, the test samples can be procured from any material with properties in the range allowed by the candidate connection production specifications.

After the test specimen's mother pipes are procured in Task 3.1, their mechanical properties are verified in Task 3.2, by a limited number of coupon-scale tests. Since the purpose of those tests is to confirm consistency of the test sample material with the specifications defined by the front-end configuration analysis, they can be referred to as quality-assurance checks. The test specimens are then machined and gauged according to the selected geometrical specifications in Task 3.3. Manufacturing variables not predetermined in this document are assumed to be within normal production values. It is recommended that duplicate specimens (replacement spares) be manufactured for each full-scale test specimen configuration.

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Block		Task			Description	Clause
1	Program elements	1.1	Program Roles		Assignment of program roles	11.2
		1.2	Candidate Connection		Unique identification of pin,box,interfacial component	11.3
		1.3	Program Options		Selection of ASL and optional tasks	11.4
		1.4	Prior Evaluation Data		Use of analysis/test data from prior evaluations	11.5
2	Determination of Biased Test Population	2.1	Initial Material Property Characterization		Material property test of a random production sample Reference properties for input into FEA model	12.2
		2.2	Specimen Configuration Analysis		Parametric analysis to determine critical design-specific configurations for test specimens	12.3, D.2, D.3, D.4
			2.2.1	Nominal Reference	Nominal geometry, material properties, assembly torque	
			2.2.2	Specimen Geometry	Worst diametric interferences and thread tapers	
			2.2.3	Seal Tapers [a]	Variations due to tolerances for seal tapers	
			2.2.4	Material Properties	Worst yield strength range for pin and box materials	
			2.2.5	Make-up Torques	Target make-up torques for sealability tests	
			2.2.6	Test vs Production [a]	Best test specimen vs worst production specimen	
3	Test Specimen Procurement	3.1	Specimen Pipe Procurement		Pipe joints and coupling stock as per specifications for biased test population	13.2
		3.2	Material Property Verification		Verification of material properties of procured pipes	13.3
		3.3	Specimen Machining and Gauging		Per specifications for biased test population 1 2 3 4 5 6 Spares	13.4, 13.6
4	Full-Scale Tests and Supplementary Analyses	4.1	Galling Resistance Test		Multiple make-ups and break-outs 1 2 3 5	14.3
		4.2	Thermal Cycle Test		Axisymmetric configuration and loading 10 thermal cycles from room to maximum ASL temperature 3 4 5 6 Specimens re-labeled based on results of thermal cycle test: RX RY	14.4
		4.3	Bending Evaluation		Sensitivity to non-axisymmetric bending	14.5, D.5
			4.3.1	Bending Analysis [a]	Bending limit for structural integrity and sealability	
			4.3.2	Bend Test [a]	2 RY	
		4.4	Limit-Strain Test		Strength and sealability at increasing tensile strains	
			4.4.1	Loc.Strain Seepage [a]	1 RX	D.6
			4.4.2	Tension Limit	1 RX	14.6
		4.5	As-Tested Configuration Analysis [a]		Analysis of as-tested configuration in support of acquired experimental results	14.7, D.7
5	Reporting	5.1	Evaluation Report		Data and results from analysis and testing Comparison with threshold performance requirements	15
		5.2	Inspection Report		Conformance with evaluation program requirements	

[a] denotes optional task.

Figure 6 — Blocks and tasks of evaluation procedure

Six specimens are subjected to full-scale testing. Clause 13 describes specimen configurations and the corresponding numbering convention. As much as practical, the configuration of each specimen is designed to represent the worst-case combination of tolerances with respect to performance measures assessed in those tests to which the specimen is subjected. The testing sequence for each specimen is illustrated in Figure 6 (specimen numbers are marked in blue boxes).

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The fourth block contains specifications for full-scale tests and supplementary analyses (see Clause 14). Some tasks in this block are mandatory and some are optional. The mandatory tasks in this block are: Task 4.1 Galling Resistance Test, Task 4.2 Thermal Cycle Test, and Task 4.4.2 Tension Limit. The optional tasks are: Task 4.3 Bending Evaluation (both subtasks), Task 4.4.1 Localized Strain Seepage, and Task 4.5 As-Tested Configuration Analysis.

Table 3 summarizes the mandatory and optional tasks and associated data categories. The task outcomes are categorized according to the data types described in 6.3.7: input for subsequent tasks, key performance measures, and auxiliary performance data.

Table 3 — Mandatory and optional tasks and resultant data categories

Task		Completion	Resultant data category	Clause
2.1	Initial Material Property Characterization	Mandatory	Input for subsequent tasks	12.2
2.2	Specimen Configuration Analysis:		Input for subsequent tasks and auxiliary performance data	12.3
	2.2.1 Nominal Reference	Mandatory		12.3.3
	2.2.2 Specimen Geometry	Mandatory		12.3.4
	2.2.3 Seal Tapers	Optional		D.2
	2.2.4 Material Properties:			12.3.6
	2.2.4.1 Pin Yield Strength	Mandatory		12.3.6.2
	2.2.4.2 Box Yield Strength	Optional		D.3
	2.2.5 Make-Up Torques	Mandatory		12.3.7
	2.2.6 Test Versus Production	Optional		D.4
3.2	Material Property Verification	Mandatory	Input for subsequent tasks	13.3
4.1	Galling Resistance Test	Mandatory	Key performance measure	14.3
4.2	Thermal Cycle Test	Mandatory	Key performance measure	14.4
4.3	Bending Evaluation:		Auxiliary performance data	D.5
	4.3.1 Bending Analysis	Optional		
	4.3.2 Bend Test	Optional		
4.4	Limit-Strain Test:			14.6
	4.4.1 Localized Strain Seepage	Optional	Auxiliary performance data	D.6
	4.4.2 Tension Limit	Mandatory	Key performance measure and auxiliary performance data [a]	14.6.6
4.5	As-Tested Configuration Analysis	Optional	Auxiliary performance data	D.7

[a] Data is auxiliary beyond average thermal strain.

The scope of the full-scale tests has been structured to reflect the loading encountered by casing and connection systems during assembly and field service. The galling resistance test is conducted to verify that the candidate connection can withstand multiple make-ups and break-outs without severe galling of thread surfaces or appreciable deterioration of seal surfaces. The thermal cycle test assesses the candidate connection sealability and structural integrity under combined, thermally-induced cyclic loading. This test includes specimen bake-out and multiple thermal cycles with temperature and pressure changes consistent with the selected ASL. Four specimens are cycled, either in one or more strings or individually. Upon completion of the thermal cycle test, the specimens are re-ordered according to their performance in that test. One cycled specimen and one non-cycled specimen are designated for the optional bend test, in which the connection sealability and structural integrity are assessed under curvature loading. One cycled specimen and one non-cycled specimen are subjected to the limit-strain test, in which limits of connection structural integrity and (optionally) sealability are assessed under increasing, tensile axial strain. Detailed test procedures and threshold performance requirements for each test are included in Clause 14 (mandatory tests) and Annex D (optional tasks).

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Galling resistance, structural strength, and sealability measured in the full-scale tests are the only evaluation results that are compared to threshold performance requirements; i.e. only these full-scale test results contribute to the pass-fail assessment of the tested candidate connection.

Supplementary analyses are recommended to evaluate connection performance indicators that can be critical for some operations but not for others. Task 4.3.1 Bending Analysis is recommended for applications in which severe bending and/or shear is anticipated during installation or during well operation due to geo-mechanical loading. Task 4.5 As-Tested Configuration Analysis is recommended to be conducted in support of interpreting the acquired experimental results; for example, when some tested connections are considered for classification as excluded connections.

Results of supplementary analysis are not compared to threshold performance requirements but may be used to specify additional testing to assess connection performance under application-specific conditions that are not simulated in the mandatory tests.

Program reporting is conducted in Task 5.1 Evaluation Report. The evaluation report contains all analytical and test data collected in the evaluation program. Data acquired in full-scale tests is compared with the threshold performance requirements. The inspection report is prepared in Task 5.2 and may be attached to the evaluation report. The inspection report verifies conformance of the conducted evaluation program with the procedures required by this document. Clause 15 describes the reporting requirements in detail.

10.2 Critical path tasks

Several tasks in the evaluation procedure are distinguished as critical path tasks, whose output has substantial impact on subsequent task execution and on resultant assessment of the candidate connection. A list of the critical path tasks is given in Table 4.

It is recommended that execution and results of the critical path tasks be independently reviewed, to ensure that correct output from those tasks is incorporated in other related tasks and in comparisons with the threshold performance requirements. The extent of such an independent review should be considered in view of guidelines provided in Annex C and selected by agreement between the assigner and the supplier.

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Table 4 — Critical path tasks

Task		Clause
1.4	Prior Evaluation Data	11.5
2.1	Initial Material Property Characterization	12.2
2.2	Specimen Configuration Analysis:	12.3
	2.2.1 Nominal Reference	12.3.3
	2.2.2 Specimen Geometry	12.3.4
	2.2.3 Seal Tapers [a]	D.2
	2.2.4 Material Properties [a]	12.3.6 and D.3
	2.2.5 Make-Up Torques	12.3.7
	2.2.6 Test versus Production [a]	D.4
3.2	Material Property Verification	13.3
3.3	Specimen Machining and Gauging	13.4, 13.6
4.1	Galling Resistance Test	14.3
4.2	Thermal Cycle Test	14.4
4.3	Bending Evaluation:	D.5
	4.3.1 Bending Analysis [a]	
	4.3.2 Bend Test [a]	
4.4	Limit-Strain Test:	14.6
	4.4.1 Localized Strain Seepage [a]	D.6
	4.4.2 Tension Limit	14.6.6
4.5	As-tested Configuration Analysis [a]	D.7

[a] Applies only to the performed optional tasks.

11 Program specifications

11.1 Task overview

This clause describes the first block of the evaluation procedure, which deals with program specifications (see Figure 6). The tasks in this block are conducted to specify information that will allow unique identification of parties involved in the evaluation program, the candidate connection, and the options selected for the evaluation procedure.

This block contains four tasks: Task 1.1 Program Roles (see 11.2), Task 1.2 Candidate Connection (see 11.3), Task 1.3 Program Options (see 11.4), and Task 1.4 Prior Evaluation Data (see 11.5). All tasks in this block are mandatory.

Additional information shall be included in program specifications when necessary to achieve unique identification of the candidate connection and the selected program options.

All information obtained in the program input shall be documented in the evaluation report.

11.2 Identification of program roles

Task 1.1 Program Roles is performed to identify all parties known to be involved in the evaluation program at its onset, and their assigned tasks. If other parties become involved in the evaluation program during its execution, then the information about those parties shall be added to program specifications accordingly. If multiple parties are assigned to a role, the program specifications shall indicate the assigned sets of responsibilities within the shared role.

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Table 5 illustrates the required extent and recommended format of program specifications on role assignments. Specific assignments in Table 5 are listed as examples and are not to be interpreted as provisions of this document.

Table 5 — Example of program specifications for role assignments

Program role	Company	Responsibility/task	Source/sub-task
Assigner	Operator A	Selection of ASL	This example assumes a program jointly commissioned/ funded by Operator A and Manufacturer B
	Manufacturer B	Selection of candidate connection	
		All other assigner tasks are shared	
Supplier	Manufacturer B	Provision of mother pipe and test samples	
Evaluator	Manufacturer B	Material property characterization	Prior evaluation data
		Specimen configuration analysis	Existing previous results
	Engineering Firm C	Specimen configuration analysis	Additional analysis
	Engineering Firm D	Full-scale testing	
Inspector	Engineering Firm D	Specimen machining and gauging	Third-party thread/seal gauging
	Engineering Firm C	Full-scale testing	Galling resistance test
	Engineering Firm E	Full-scale testing	Thermal cycle test
	Engineering Firm F	All other inspection tasks	

11.3 Identification of candidate connection

In Task 1.2, specifications for the candidate connection shall uniquely identify the connection product that is the subject of assessment in the evaluation program, and the candidate connection assembly procedure recommended by the supplier. Table 6 illustrates the required scope of, and recommended format for, the candidate connection specifications.

The first group of specifications in Table 6 relates to the candidate connection production specifications, and include the connection name, size, weight, pin and box materials, and interfacial components.

If the candidate connection pin and/or box materials are manufactured to a design-specific set of specifications that are different from standard grade specifications (e.g. a narrowed-down range of yield strength), then those design-specific production manufacturing specifications shall be identified in Task 1.2 and subsequently used in determination of the biased test population (Task 2.1 and 2.2, see 12.2 and 12.3) and for procurement of specimens for full-scale testing (Task 3.1, see 13.2).

Table 6 — Extent and format of candidate connection specifications

1. Identification of candidate connection
Product name
Size
Weight
Pin material designation [a]
Box material designation [a]
Interfacial components
2. Connection schematic [b]

[a] Reference to standard or product-specific grade specifications.

[b] Drawing detail to the extent needed to perform evaluation tasks.

[c] Identification of the manufacturing process.

[d] Torque-turn graphs up to maximum achieved torque.

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Table 6 *(continued)*

Diagram: attach separate page(s) with schematic cross-sectional diagram	
3. Production specifications [c]	
Process control/quality management plan	Drawing or document revision and date
Pin drawing(s)	
Box drawing(s)	
Pin surface treatment/type specification	
Box surface treatment/type specification	
Swage/stress relief procedure	
Gauge calibration procedure	
Gauging and geometry inspection/QA procedure	
Material property inspection/QA procedure	
Interfacial component inspection/QA procedure	
4. Assembly specification	
Mill make-up procedure	Document revision and date
Field running procedure	
Connection repair procedure	
Sample make-up curves [d]	Reference to make-up procedure

[a] Reference to standard or product-specific grade specifications.

[b] Drawing detail to the extent needed to perform evaluation tasks.

[c] Identification of the manufacturing process.

[d] Torque-turn graphs up to maximum achieved torque.

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The second group of specifications relates to the candidate connection schematic drawings. The schematic drawings shall contain sufficient amount of detail to enable execution of the evaluation tasks required by the evaluation procedure.

The third group of input specifications relates to the candidate connection manufacturing procedure. These specifications are required to uniquely identify the manufacturing process of the evaluated product, for later reference. This document does not require provision of confidential design or manufacturing information.

The fourth group of candidate connection input specifications relates to connection assembly. The mill make-up and field running procedures and connection repair procedures are provided for use in Task 4.1 Galling Resistance Test (see 14.3). Samples of make-up torque-turn curves are provided to verify accuracy of the candidate connection model in Task 2.2 Specimen Configuration Analysis (see 12.3).

11.4 Program options

In Task 1.3, the assigner shall consider and select from the following program-execution options:

a) Application severity level;

b) Task 2.2.3 Seal Tapers – indicate if that analysis will be carried out in the evaluation program or not;

c) Task 2.2.4.2 Box Yield Strength – indicate if that analysis will be carried out in the evaluation program or not, and if yield strength of the box material will be considered in determination of the biased test population;

d) Task 2.2.6 Test versus Production – indicate if that analysis will be carried out in the evaluation program or not;

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e) Task 4.3 Bending Evaluation – indicate the selected scope of the bending evaluation: none, bending analysis only, bend test only, or both options;

f) Task 4.4.1 Localized Strain Seepage – indicate if that test will be carried out in the evaluation program or not;

g) Task 4.5 As-Tested Configuration Analysis – indicate if that analysis will be carried out in the evaluation program or not.

The assigner shall communicate the selected options to the supplier, the evaluator and the inspector. The evaluator shall document all selected options in the evaluation report.

11.5 Data from prior evaluations

In Task 1.4, input of any prior evaluation data intended for use in the evaluation program shall be conducted as follows:

a) source and contents of any existing data that is intended to be utilized in the current evaluation program as prior evaluation data shall be identified;

b) conformance of that existing data to requirements for prior evaluation data shall be verified as stipulated in 8.5.

12 Determination of biased test population

12.1 Task overview

This clause describes the second block of the evaluation procedure: determination of biased test population (see Figure 6). The main purpose of this block is to select those combinations of design variables and make-up torques that represent worst-case scenarios with respect to the assumed performance measures for the candidate connection. The selected combinations are subsequently used to derive specifications for the connection specimens to be manufactured for full-scale testing and for the target make-up torques to be applied upon specimen assembly for sealability tests. The secondary purpose of this block is to provide reference results for determination of load steps that will be applied in physical testing.

This program block consists of two tasks: Task 2.1 Initial Material Property Characterization (see 12.2), and Task 2.2 Specimen Configuration Analysis (see 12.3). Details of those two tasks are described in the following clauses. Implications of the front-end analysis results on decisions relative to procurement of the test specimens are also described.

To facilitate program execution, the material characterization task and the specimen configuration analysis can be performed in advance of the other evaluation tasks.

Material property specifications (for example, yield strength range) used for Task 2.1 and Task 2.2 shall be consistent with candidate connection specifications provided in Task 1.2 (11.3).

Prior evaluation data on material property characterization, specimen configuration and make-up torque analysis may be utilized in lieu of some or all subtasks of Task 2.1 and Task 2.2, if applicability of that prior evaluation data to the candidate connection and its conformance to the requirements of this document is demonstrated according to the provisions in 8.5. In such cases, prior evaluation data can be used, for example, to select specimen specifications and/or make-up torques for full-scale testing without conducting all material characterization and analysis cases required in Task 2.1 and Task 2.2.

Results of analyses conducted to determine specifications for the biased test population are not intended to be compared with the threshold performance requirements of this document.

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12.2 Initial material property characterization

12.2.1 Task description, definitions, methods

12.2.1.1 Task purpose

Task 2.1 Initial Material Property Characterization is conducted to obtain material properties of the candidate connection pipe (pin) and coupling stock (box) needed as input for FEA modelling in Task 2.2 Specimen Configuration Analysis. These properties include tensile stress-strain response and thermal expansion coefficient at temperatures spanning the selected ASL.

The following eight material property data sets are defined to facilitate completion of the connection analyses in Task 2.2:

— As-characterized pin

— As-characterized box

— Maximum-yield pin

— Minimum-yield pin

— Median-yield pin

— Maximum-yield box

— Minimum-yield box

— Median-yield box

Subclauses 12.2.1.2 and A.2.3 describe features and intended use of the above material property data sets.

12.2.1.2 As-characterized, minimum yield, median yield, maximum yield properties

The ranges of the pin and box yield strengths possible to encounter in the candidate connection production samples are assumed to correspond, respectively, to the ranges allowed by the supplier's specifications for the pin and box materials. It is assumed that the post-yield stress-strain response and the thermal expansion coefficient of each material do not vary substantially within the specified yield strength range.

Consequently, the following sets of stress-strain properties are defined for either the pin or the box material:

— "as-characterized" – stress-strain response obtained from testing of representative material samples or adopted from prior evaluation data (see 12.2.1.3). In general, this property set will correspond to the yield strength somewhere between the minimum and the maximum strength allowed by the production specifications;

— "minimum-yield" – stress-strain response of a sample with the minimum yield strength allowed by the production specifications. This response is obtained by interpretation of the "as-characterized" response, as described in 12.2.4;

— "maximum-yield" – stress-strain response of a sample with the maximum yield strength allowed by the production specifications. This response is also obtained by interpretation of the "as-characterized" response, as described in 12.2.4.

— "median-yield" – stress-strain response corresponding to the median of the yield strength range, as defined for specific modelling cases in Task 2.2 – see 12.3.6.2 and D.3.

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The thermal expansion coefficient is assumed unchanged for the as-characterized, minimum-yield, maximum-yield, and median-yield sets of stress-strain response (see 12.2.2.3).

12.2.1.3 Methods to obtain as-characterized properties

The as-characterized properties may be obtained using one of the following methods:

— coupon-scale laboratory testing of samples representative of the candidate connection pin and box production materials. These tests will generate “as-characterized pin” and “as-characterized box” properties;

— testing of one representative material, either pin or box, if those two materials are considered to have substantially the same properties. This testing will generate one “as-characterized pin-box” set of properties;

— using data from prior material property tests, if it is considered representative for the candidate connection materials (prior evaluation data, also see 6.3.8). Use of prior evaluation data can generate either “as-characterized pin” and/or “as-characterized box” and/or “as-characterized pin-box” set of properties.

The method for obtaining as-characterized material properties should be selected with due consideration given to later mandatory verification of material properties of the test specimens in Task 3.1 – see 12.2.1.4 and 13.3.3. It is also recommended that this method be selected by agreement between the evaluator, the supplier, and the assigner. The selected method shall be documented in the evaluation report.

Any material property tests executed within Task 2.1 shall be performed in conformance with applicable provisions of 12.2.2 and 12.2.3. If both pin and box materials are tested, then the testing scope should be the same for the pin and box samples.

The as-characterized material properties are used to define material property data sets for subsequent use in Task 2.2 Specimen Configuration Analysis (see 12.3).

12.2.1.4 Variability and later verification of material properties

Mechanical properties of pipe materials used for full-scale evaluation tests will in general be similar, but not exactly the same, as the properties of the pipes and couplings used in the field. Variability exists in material properties at both ambient and elevated temperatures. Analyses of connection models have shown that yield and post-yield material properties affect contact forces in premium connection seals, and thus variability in those properties can be expected to influence connection sealability in qualification tests and field use. Consequently, that variability is considered in the procedure adopted for selecting the candidate connection specimens.

Upon procurement of materials for the full-scale test specimens, conformance of their properties with requirements for the biased test population is verified by physical testing in Task 3.2 Material Property Verification (see 13.2 and 13.3). It is recommended to review the scope and provisions of Task 3.2 Material Property Verification at the onset of Task 2.1 Initial Material Property Characterization, to facilitate conformance with provisions in both tasks.

12.2.2 Testing conditions and scope

12.2.2.1 Application of provisions

Provisions of 12.2.2.2, 12.2.2.3 and 12.2.2.4 apply to testing conducted as part of the evaluation program on the candidate connection to obtain the as-characterized material properties.

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12.2.2.2 Stress-strain response

The stress-strain response of typical OCTG materials is known to depend on the temperature and rate at which the material is strained. Evaluation of the temperature-dependence of the stress-strain material response is mandatory, unless existing material testing results are utilized as prior evaluation data. Since the purpose of this initial evaluation is to support subsequent specimen configuration analysis, and given the complexity and difficulty associated with evaluating material strain rate-dependence, that aspect of the material evaluation is recommended but not required.

The following testing scope shall be conducted to assess stress-strain response of the pin and/or box components. At least one uniaxial tensile test shall be conducted at each of the following temperatures, up to the temperature corresponding to the selected ASL:

— 15 °C to 35 °C (ambient temperature)

— 180 °C (transition temperature)

— 240 °C (ASL-240)

— 290 °C (ASL-290)

— 325 °C (ASL-325)

— 350 °C (ASL-350)

Circumferential variability in properties should be checked by conducting at least one additional test on a sample taken approximately 120° away (circumferentially) from the first sample. It is recommended that the circumferential variability test(s) be performed at 180 °C. If a variation of more than 10 % is observed in the measured yield strain specified in ISO 11960 (API Specification 5CT), similar tests should be conducted at each of the other test temperatures. For each temperature at which multiple tests are conducted, the resulting stress-strain curve that exhibits the lowest yield strength should be used as the as-characterized material description. If variability in test results is suspected to be an artefact of the testing system, further testing should be performed to determine the repeatability of the results.

Table 7 summarizes the scope for Task 2.1 Initial Material Property Characterization, including the mandatory and recommended tensile tests for each ASL.

Table 7 — Scope of material characterization tensile tests

<table>
<tr><th>Application Severity Level</th><th>Mandatory tensile tests</th><th>Recommended circumferential consistency test(s)</th><th>Total number of tests = mandatory plus recommended</th></tr>
<tr><td>240 °C</td><td>3 (ambient, 180 °C, 240 °C)</td><td rowspan="4">At least 1 test
(recommended at 180 °C)</td><td>4</td></tr>
<tr><td>290 °C</td><td>4 (ambient, 180 °C, 240 °C 290 °C)</td><td>5</td></tr>
<tr><td>325 °C</td><td>5 (ambient, 180 °C, 240 °C 290 °C, 325 °C)</td><td>6</td></tr>
<tr><td>350 °C</td><td>6 (ambient, 180 °C, 240 °C 290 °C, 325 °C, 350 °C)</td><td>7</td></tr>
</table>

Material properties derived from pin material tests are identified as the as-characterized pin material data set and material properties derived from box material tests are labelled the as-characterized box material data set.

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12.2.2.3 Thermal expansion coefficient

In Task 2.1 Initial Material Property Characterization, the average coefficient of thermal expansion (α_a) of a material may be determined according to one of the following methods:

a) assume an average α_a of 14 με/°C, if it is considered representative of the pipe material over the temperature range corresponding to the selected ASL;

b) quantify the thermal expansion coefficient over the temperature range corresponding to the selected ASL by laboratory tests as described for Task 3.2 Material Property Verification (see 13.3), and calculate an average value corresponding to that temperature range;

c) use existing data and/or test results from a material sample if they are considered representative for the temperature range corresponding to the selected ASL;

d) calculate α_a according to a temperature-dependent formula that is considered representative over the temperature range corresponding to the selected ASL.

The method for determination of α_a in Task 2.1 should be selected by agreement between the assigner, the supplier and the evaluator. The adopted method and the assumed and/or measured α_a value(s) shall be documented in the evaluation report.

As an example, based on data from material property investigations completed prior to initial issuance of TWCCEP, the following temperature-dependent formula was derived for several carbon steel casing materials to determine an average thermal expansion coefficient between 5°C and an elevated temperature *T*, in Celsius:

$$\alpha_a = (10{,}94 + 0{,}008\ 13 \cdot T) \cdot 10^{-6}$$

Measurement of actual α_a of pipes used for manufacturing specimens for physical tests is addressed in 13.3.4.

12.2.2.4 Material strip specimens

The material strip specimens for stress-strain characterization shall be longitudinal strip specimens cut from full-circumference "coupon" sections of the source pipe. Where practical, the material strip specimens should utilize a full-thickness rectangular cross-section or equivalent cylindrical or semi-cylindrical cross-section, and specimen geometry should be selected to satisfy the control and measurement requirements defined in 12.2.3. In the as-characterized evaluation, specimen properties will be interpreted as an indication of average mechanical response.

Relative circumferential locations of all material strip specimens shall be recorded as they are removed from the mother tubes. Where possible, all material strip specimens should be removed from the same cross-section. If this is not possible, extra strip specimens shall be extracted from an adjacent cross-section not more than 0,3 m (12 in) away, and from the same circumferential position. Material strip specimens manufactured from ERW tube should be extracted at least 90° from the weld centreline. For small-diameter tubes for which the above-recommended specimen spacing is not possible, the circumferential distance between the specimen locations and the weld centreline should be maximized.

12.2.3 Procedure for tensile tests

Tensile tests shall be conducted using testing procedures that meet applicable provisions in ASTM A370, ASTM E8 and ASTM E21 for ambient and elevated-temperature material mechanical property tests. It is recommended that specimen loading in the tests be conducted in a strain-control mode at a strain rate no greater than 0,5 %/minute.

Strain in the reduced section of each material strip specimen shall be measured with a strain measurement device (e.g. strain gauge, extensometer or optical system) to a strain of at least 10 %.

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Example of strain-strain data to be acquired in the tensile tests are shown in Figure 7. These results need to be further processed and interpreted in order to obtain material property input for FEA modelling purposes. The figure details and result interpretation procedure are described in 12.2.4.

12.2.4 Interpretation and processing of tensile test results

12.2.4.1 Scope of result interpretation

Once the as-characterized properties are obtained with one of the methods described in 12.2.1.3, they are interpreted for subsequent use in Task 2.2. The following constitutive material descriptions are the product of this interpretation (as defined in 12.2.1.2):

— as-characterized;

— minimum-yield;

— maximum-yield.

An example of the as-characterized set of properties is shown in Figure 7. For reference purposes, “API yield strain” in Figure 7 (and also in Figure 9 and Figure 10) denotes the strain at which the yield strength is measured according to ISO 11960 or API Specification 5CT.

The minimum-yield set is meant to approximate results that would be obtained if tests were conducted on samples with the minimum ambient-temperature yield strength. Similarly, the maximum-yield properties represent an estimate of the properties that would be measured from samples with the maximum ambient-temperature strength in the material’s yield strength range. This range is typically defined by standard grade designations (such as the ones listed in ISO 11960 and API Specification 5CT), but if a manufacturer certifies that the ambient-temperature yield strength range of its production material is different than the standard range, then the maximum and minimum of the manufacturer-specified yield range shall be used instead. If the connection configuration meets performance requirements of this document through use of a non-standard yield strength range, close attention should subsequently be paid to the strength of field-installed tubulars to ensure the material strength remains within the range considered in this evaluation.

Ideally, the minimum-yield and maximum-yield constitutive descriptions should indicate the stress response of the material as a continuous function of strain and temperature. Such models are complex, particularly where cyclic behaviour occurs. As a minimum, the derived constitutive descriptions shall contain adequate detail to provide the monotonic stress-strain response of the material at each tensile-test temperature.

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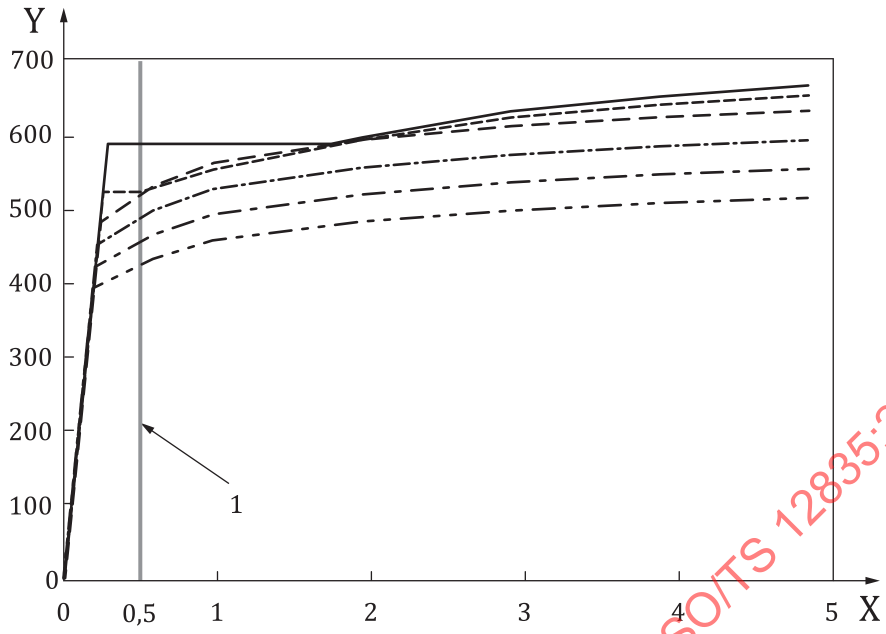

Key

X engineering strain, %

Y engineering stress, MPa

1 API yield strain

——— ambient

- - - - transition: 180 °C

— — — ASL 240 °C

—·—·— ASL 290 °C

— — — ASL 325 °C

—·—·— ASL 350 °C

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Figure 7 — Examples of as-characterized monotonic stress- strain curves

12.2.4.2 As-characterized material model

Yield strengths derived from the material tests shall be tabulated and used to create a thermal degradation function that non-dimensionally describes strength variations with temperature. Measured yield strength is defined per ISO 11960 (API Specification 5CT).

For this purpose, the normalized yield strength is introduced and defined as in Formula (1):

$$\varphi_{\text{norm}}^{T} = \frac{\sigma_{y}^{T}}{\sigma_{y}^{\text{ambient}}} \tag{1}$$

where

$\sigma_{y}^{\text{ambient}}$ is the measured yield strength at ambient temperature;

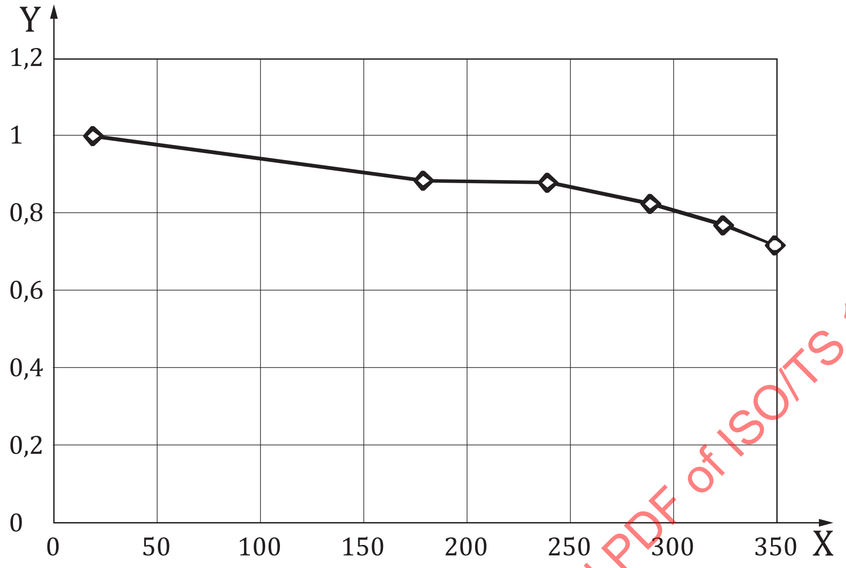
σ_{y}^{T} is the measured yield strength at a given elevated temperature;

$\varphi_{\text{norm}}^{T}$ is the normalized yield strength at the given elevated temperature.

The thermal degradation function consists of discrete points, where each point corresponds to the normalized yield strength calculated at a different testing temperature (see Figure 8 as an example).

The thermal degradation function for each material shall be assumed consistent for all analysis cases in Task 2.2 Specimen Configuration Analysis.

While it is recognized that material thermal degradation functions are not typically controlled in pipe production, it is recommended that those factors be monitored whenever practical, so that material databases could be enhanced for use in tubular designs for high-temperature applications.



Key

X temperature, °C

Y $\varphi_{\text{norm}}^{T}$ normalized yield strength

Figure 8 — Example of thermal degradation function

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12.2.4.3 Minimum and maximum yield models at ambient temperature

Ambient-temperature properties shall be based on the post-yield stress progression derived from the as-characterized property set, and the specified yield strength at the corresponding minimum or maximum yield for the candidate connection pipe/box material. These are identified as the minimum-yield and maximum-yield material property data sets.

The ambient-temperature stress-strain curves for the minimum-yield and maximum-yield descriptions shall be created using the following guidelines:

a) Determine the elastic modulus from the as-characterized ambient-temperature test data. The minimum and maximum yield strength curves shall have the same elastic modulus as the as-characterized curve at ambient temperature.

b) From the as-characterized material curve, determine the stress and strain at which the response departs from the linear elastic response. This point on the stress-strain curve is commonly known as the proportional limit. Note that the proportional limit can be different from the yield strength.

c) Reduce the provided set of data points beyond the proportional limit to an efficient size, while ensuring that the curve remains representative of the material behaviour in areas of the curve where the slope is changing considerably.

d) Translate each of the readings on the stress-strain curve beyond the proportional limit on the as-characterized curve along the slope of the elastic modulus so that the stress at the API yield strain is equal to the minimum yield strength (as defined in 12.2.4.1). The set of translated points will be used to represent the post-proportional-limit stress-strain response of the minimum-yield curve.

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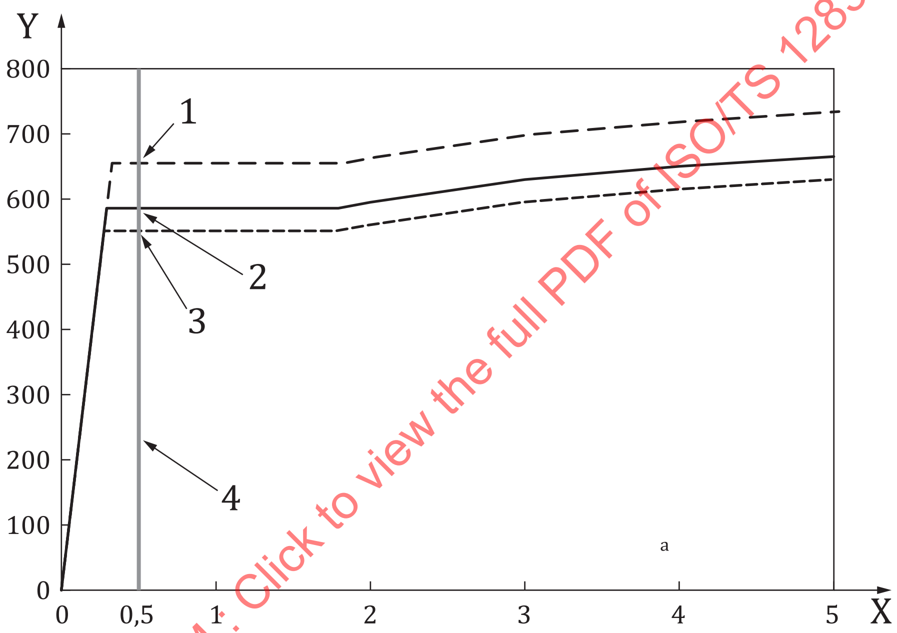
e) The points preceding the proportional limit of the minimum-yield curve shall constitute the elastic region of the curve, and thus should follow the elastic modulus of the as-characterized curve as calculated in Step a) of this procedure.

f) Translate each of the readings, on the stress-strain curve beyond the proportional limit on the as-characterized curve, along the slope of the elastic modulus so that the stress at the API yield strain is equal to the maximum yield strength (as defined in 12.2.4.1). The set of translated points will be used to represent the post-proportional-limit stress-strain response of the maximum-yield curve.

g) The points preceding the proportional limit of the maximum-yield curve shall constitute the elastic region of the curve, and thus should follow the elastic modulus of the as-characterized curve as calculated in Step a) of this procedure.

Figure 9 shows an example of the as-characterized, minimum-yield, and maximum-yield curves at ambient temperature.



Key

X engineering strain, %
Y engineering stress, MPa
1 max. yield - 655 MPa
2 as-characterized - 586 MPa
3 min. yield - 552 MPa
4 API yield strain
a Ambient temperature of 20 °C.
________ as-characterized
-------- minimum yield
_ _ _ _ _ maximum yield

Figure 9 — Example of ambient-temperature stress-strain curves

12.2.4.4 Minimum and maximum yield models at elevated temperatures

Elevated-temperature properties shall be based on the thermal degradation function and post-yield stress progression derived from the as-characterized property set, and the specified yield strength at the corresponding minimum or maximum yield limit for the candidate connection pipe material.

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For each elevated temperature, stress-strain curves for the minimum-yield and maximum-yield descriptions shall be created using the following guidelines:

a) Determine the elastic modulus from the as-characterized elevated-temperature test data. The minimum-yield and maximum-yield curves shall have the same elastic modulus as the as-characterized curve at the specified elevated temperature.

b) From the as-characterized elevated-temperature material curve, determine the stress and strain at which the response departs from the linear elastic response (proportional limit).

c) Reduce the provided set of data points beyond the proportional limit to an efficient size, while ensuring that the curve remains representative of the material behaviour in areas of the curve where the slope is changing considerably.

d) Evaluate the thermal degradation function at the specified temperature and apply it to the minimum yield strength of the material at ambient temperature to obtain the stress at the API yield strain for the minimum-yield elevated-temperature curve. This stress will be referred to as the minimum yield strength of the elevated-temperature curve.

e) Translate the points beyond the proportional limit on the as-characterized elevated-temperature curve along the slope of the elastic modulus so that the stress at the API yield strain is equal to the minimum yield strength of the elevated-temperature curve. The set of translated points will be representative of the post-proportional-limit stress-strain response of the minimum-yield curve at the specified elevated temperature.

f) The points preceding the proportional limit of the minimum-yield curve at the specified elevated temperature shall constitute the elastic region of the curve, and thus should follow the elastic modulus of the as-characterized elevated-temperature curve as calculated in Step a) of this procedure.

g) Evaluate the thermal degradation function at the specified temperature and apply it to the maximum yield strength of the material at ambient temperature to obtain the stress at the API yield strain for the maximum-yield elevated-temperature curve. This stress will be referred to as the maximum yield strength of the elevated-temperature curve.

h) Translate the points beyond the proportional limit on the as-characterized elevated- temperature curve along the slope of the elastic modulus so that the stress at the API yield strain is equal to the maximum yield strength of the elevated temperature curve. The set of translated points will be representative of the post-proportional- limit stress-strain response of the maximum-yield curve at the specified elevated temperature.

i) The points preceding the proportional limit of the maximum-yield curve at the specified elevated temperature shall constitute the elastic region of the curve, and thus should follow the elastic modulus of the as-characterized elevated temperature curve as calculated in Step a) of this procedure.

Figure 10 shows an example of the as-characterized, minimum-yield, and maximum-yield curves at a selected elevated temperature of 240 °C.

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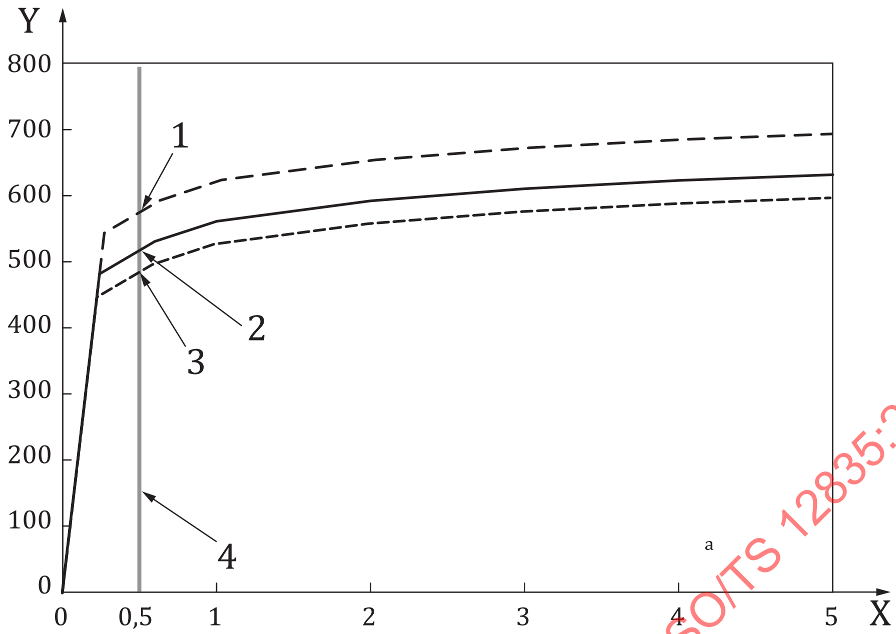

Key

X engineering strain, %
Y engineering stress, MPa
1 max. yield - 576 MPa
2 as-characterized - 516 MPa
3 min. yield - 486 MPa
4 API yield strain
a Temperature: 240 °C.
_________ as-characterized
\-\-\-\-\-\-\-\- minimum yield
_ _ _ _ _ maximum yield

Figure 10 — Example of ASL-240 material properties

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12.3 Specimen configuration analysis

12.3.1 Task description

Task 2.2 Specimen Configuration Analysis is a parametric finite-element sensitivity study (FEA), which is conducted to:

— select worst-case combinations of geometric and material-property variables allowed by manufacturing tolerances of the candidate connection;

— select target torques from a specified range for make-up of the candidate connection specimens designated for sealability tests;

— determine equivalent low-stiffness and high-stiffness lengths for the candidate connection (formulae to determine the low-stiffness and high-stiffness lengths are provided in Annex B).

The worst-case combinations of manufacturing variables are assumed as follows:

— For galling resistance, the combinations that result in the highest peak contact stress between the connection pin and box components, either in the threads or in the seal.

— For sealability, the combination that results in the lowest contact stress intensity between the connection pin and box components in the connection primary seal.

The peak contact stress in the threads is defined as the highest normal stress that acts on any contact surface of the modelled pin or box threads (either complete or truncated threads). The peak contact stress in the seal is defined as the highest normal stress that acts on the contact surface of the connection primary seal.

The seal contact stress intensity is defined as the integral of the contact stress over the axial length of the seal region. In an axisymmetric case, this corresponds to the total contact force per unit length of the seal circumference (i.e. line load). This measure allows a comparison that is independent from the contact band width and the seal diameter. Higher contact stress intensity is associated with better sealing potential.

Task 2.2 Specimen Configuration Analysis consists of six subtasks:

— Task 2.2.1 Nominal Reference – all-nominal case to obtain a baseline reference response of the candidate connection (see 12.3.3);

— Task 2.2.2 Specimen Geometry – identification of worst-case geometry configurations with respect to galling resistance and sealability (see 12.3.4);

— Task 2.2.3 Seal Tapers – optional analysis to examine impacts of seal tapers (Clause D.2);

— Task 2.2.4 Material Properties – quantification of impacts of material property variations: pin yield strength analysis (see 12.3.6) and box yield strength analysis (Clause D.3);

— Task 2.2.5 Make-up Torques – selection of worst-case make-up torques for sealability tests (see 12.3.7);

— Task 2.2.6 Test versus Production – optional analysis to assess potential variations in sealability between "best" test specimens and "worst" production specimens (Clause D.4).

Execution of Tasks 2.2.1, 2.2.2 and 2.2.5 is mandatory. In Task 2.2.4, evaluation of pin yield strength is mandatory, and evaluation of box yield strength is optional. Tasks 2.2.3 and 2.2.6 are optional.

In some evaluation programs, interim results can allow reduction of the analysis scope; for example, when the same geometry configuration corresponds to worst-case scenarios under multiple loading conditions (see 12.3.4); or when multiple make-ups do not produce incremental plastic deformation (see 12.3.7).

Results of the above analyses fall into two categories: input for subsequent tasks and auxiliary performance data.

The following clauses describe the required and recommended analysis scopes and procedures for result interpretation.

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12.3.2 Modelling and reporting requirements

The analyses to be performed in Task 2.2 require use of an axisymmetric finite-element model of the candidate connection. All analysis cases in Task 2.2 shall be performed in accordance with applicable provisions of the modelling guidelines provided in Annex A. In particular, the pin and box material properties shall be modelled in accordance with A.2.3, and the loading sequence (simulation steps) shall be executed in accordance with A.2.7.

It is recognized that the complexity of the FEA model development, combined with the diversity of available modelling tools and choices, introduces a sensitivity of the FEA results with respect to the modelling assumptions. In the event that execution of an evaluation program requires additional modelling assumptions outside of the scope addressed in Annex A, those additional assumptions shall be agreed on by the assigner, the supplier and the evaluator and documented in the evaluation report.

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Modelling results shall be reported according to general reporting requirements stipulated in 15.2 and A.2.10, and specific per-task requirements indicated in the following subclauses.

12.3.3 Nominal reference case

The nominal-reference analysis (Task 2.2.1) shall be conducted to establish a baseline structural response of the candidate connection. Two primary objectives of this analysis are as follows:

— Determination of design-specific equivalent low-stiffness length and equivalent high-stiffness length in a threaded pin-box interval of a made-up connection (A.2.9). These lengths shall be used as input for the formulae determining strain compensations to be applied in the thermal cycle test (14.4.5 and derivations in B.1);

— Calculation of seal contact stress intensity for the candidate connection nominal configuration, for later study of its sensitivity to configuration variations.

Connection geometry for the nominal reference case shall be per the supplier's target dimensions for manufacturing the candidate connection. In particular, nominal values for the following dimensions shall be used:

— thread diameter;

— thread taper;

— seal diameter;

— seal taper.

Pipe diameter and wall thickness of the mother pipes shall correspond to nominal values specified by ISO 11960.

Only one analysis case is required in Task 2.2.1. The load path for that analysis case shall consist of one connection make-up and one thermal cycle between the ASL's lower-bound temperature and upper-bound temperature. The load path is described in A.2.7.

Nominal reference case analysis requirements are listed in Table 8.

Table 8 — Nominal reference case – analysis requirements

Connection model attribute	Requirement
Connection geometry	Nominal thread and seal geometry
Pin material data set	As-characterized pin or as-characterized pin- box[a]
Box material data set	As-characterized box or as-characterized pin-box[a]
Load path	Make-up followed by one thermal cycle
Make-up torque	Manufacturer specified optimum torque
Thermal cycle	Based on ASL per Table 1 and Table 2

[a] Refer to 12.2.1 for as-characterized property descriptions.

Results of primary interest that shall be retained for comparison with sensitivity analysis and documented in the evaluation report are:

— equivalent low-stiffness and high-stiffness lengths in the threaded pin-box interval (see formulae in B.3);

— thread contact stress distribution (including peak contact stress);

— seal contact stress distribution (including peak contact stress);

— seal contact stress intensity.

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The equivalent high-stiffness length shall be calculated by applying an incremental unload by applied force or prescribed displacement at the lower-bound temperature condition as described in A.2.9. Thread and seal peak contact stress shall be calculated and reported at full make-up. Seal contact stress intensity shall be calculated and reported at full make-up, at maximum temperature during the thermal cycle, and at the end of the thermal cycle, according to loading sequence and conditions described in A.2.7.

12.3.4 Worst-case geometry configurations

This clause describes the analysis (Task 2.2.2) that shall be conducted to identify worst-case geometry configurations of the candidate connection with respect to galling resistance and sealability (as defined in 12.3.1) for subsequent use in specifications for the full-scale test specimens.

Table 9 summarizes the worst-case tolerance combinations and corresponding codes used to specify the specimen geometry configurations.

Table 9 — Worst-case geometry configurations and codes

Combination of tolerances	Code
Worst-case for galling in seal	WGS
Worst-case for galling in threads	WGT
Worst-case for sealability in tension at low temperature	WST
Worst-case for sealability in compression at high temperature	WSC

The worst-case geometry configurations are defined in terms of pin-box diametric interference in seal, pin-box diametric interference in threads, and pin-and-box thread tapers (refer to 6.4.3 for interference and taper definitions). Inclusion of seal tapers in the worst-case geometry configurations is optional (see 12.3.5).

Table 10 summarizes the interference and thread taper tolerance combinations and corresponding codes used to specify the geometry configurations for the test specimens. Each specified pin-box diametric interference is either minimum or maximum, and each thread taper is either slow or fast.

The minimum and maximum interference values refer, respectively, to the minimum and maximum diametric interferences that result from candidate connection manufacturing tolerances for pin and box diameters assuming nominal tapers (also see Figure 12).

Slow/fast tapers refer to extreme taper combinations allowed by candidate connection manufacturing tolerances for the pin and box components, where “slow” corresponds to the minimum taper angle and fast corresponds to the maximum taper angle (also see Figure 13).

Table 10 — Interference and taper tolerance combinations and codes

Pin-box diametric interference	
Description	**Code**
Minimum interference	Min.
Maximum interference	Max.
Thread tapers	
Description	**Code**
Slow pin/fast box	PS/BF
Fast pin/slow box	PF/BS

The analysis requirements for the worst-case geometry configurations are given in Table 11.

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Table 11 — Worst-case geometry configurations – analysis requirements

Connection model attribute	Requirement
Connection geometry	Geometry tolerance combinations as per Table 12
Pin material data set	As-characterized pin or as-characterized pin-box[a]
Box material data set	As-characterized box or as-characterized pin-box[a]
Load path	Make-up followed by one thermal cycle for Cases 1 to 4 and make-up only for Cases 5 to 8 per Table 12
Make-up torque	Manufacturer-specified optimum torque
Thermal cycle	Based on ASL per Table 1 and Table 2

[a] Refer to 12.2.1 for as-characterized property descriptions.

Table 12 illustrates the procedure to determine which interference and taper tolerance combinations from the set identified in Table 10 will result in the worst-case scenarios with respect to galling resistance and sealability, as identified in Table 9.

In Step 1 of the procedure illustrated in Table 12, eight analysis cases shall be run for different combinations of seal and thread interferences and thread tapers. If both pin and box materials have been characterized, then pin and box material constitutive relations shall use the as-characterized pin and box material property data sets, respectively (per 12.2). If only one material (either the pin or the box) has been characterized, then both pin and box shall use that as-characterized pin-box material property data set in the constitutive relation. The load path for analysis cases 1 to 4 consists of connection make-up to optimum torque and one thermal cycle corresponding to the selected ASL (see load sequence specified in Annex A). Load path for analysis cases 5 to 8 consists of only one connection make up to optimum torque.

In Step 2, the results of the analyses conducted in Step 1 are used to examine contact stress conditions in the connection primary seal and thread areas. Galling susceptibility in the threads and seal shall be assessed based on peak contact stress in, respectively, the threads and seal area; unless otherwise agreed by the assigner, the supplier and the evaluator. Assessment of sealability potential shall be based on the seal contact stress intensity upon make-up, under maximum compression at the maximum operating temperature (upper-bound temperature), and under maximum tension at the end of the thermal cycle (lower-bound temperature), as described in A.2.7.

In Step 3, the contact stress conditions determined in Step 2 are compared to determine relative severity rankings, and to identify which analysis cases resulted in the highest and lowest severity with respect to galling susceptibility and sealability. For cases where the calculated contact stress measures (peak or intensity) vary less than 5 % of the targeted highest or lowest measure (whichever applies) for various interference and taper combinations, engineering judgement should be used to select the interference and taper combinations for the test specimens, by agreement between the assigner, the supplier and the evaluator.

In Step 4, the interference and taper combinations corresponding to the analysis cases selected in Step 3 are assigned to geometry configurations WGS, WGT, WST, and WSC, which are subsequently prescribed for the test specimens (as listed in Table 9). The prescribed interference shall be either "minimum interference" or "maximum interference". The prescribed taper combination shall be either "PS/BF" or "PF/BS".

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Table 12 — Determination of worst-case geometry configurations

	Case	Tolerance combinations: Interference – Seal	Tolerance combinations: Interference – Threads	Tolerance combinations: Taper – Threads	Load path	Contact stress condition: Peak (MPa) – Seal – Make-up	Contact stress condition: Intensity (N/mm) – Seal – Upper-bound temp.	Contact stress condition: Intensity (N/mm) – Seal – Lower-bound temp.	Contact stress condition: Peak (MPa) – Threads – Make-up
	Step 1 - Analysis					**Step 2 - Result summary** [a]			
As-characterized material properties	1	Min.	Min.	PS/BF	Make-up + 1 cycle				
	2			PF/BS					
	3		Max.	PS/BF					
	4			PF/BS					
	5	Max.	Min.	PS/BF	Make-up				
	6			PF/BS					
	7		Max.	PS/BF					
	8			PF/BS					
	Step 4 - Configuration [c]					**Step 3 - Severity ranking** [b]			
	WGS					Highest			
	WGT								Highest
	WST							Lowest	
	WSC						Lowest		

[a] Green fields are filled based on contact stress conditions at respective locations.

[b] Severity ranking based on results summarized in Step 2.

[c] Seal and thread interferences (min. or max.) and thread tapers (slow or fast) selected as per severity ranking obtained in Step 3.

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For some connection designs, the severity ranking of seal contact stress intensity might be consistent throughout the thermal cycle, i.e. the tolerance combination that results in the lowest contact stress intensity at the upper-bound temperature can be the same as the tolerance combination that results in the lowest contact stress intensity at the lower-bound temperature. If that is the case, then the above single tolerance combination shall be selected for both WST and WSC configurations, and the analysis prescribed in the following clauses shall be executed only for that single tolerance combination. If the intensity ranking is different at the low and high temperatures, then the WST and WSC configurations shall have different tolerance combinations.

12.3.5 Seal taper analysis

Execution of seal taper analysis (Task 2.2.3) is optional at the assigner's discretion. The decision to conduct or not to conduct the seal taper analysis shall be documented in the evaluation report.

Rationale and recommended procedures for the seal taper analysis are provided in Clause D.2.

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12.3.6 Impacts of material property variations

12.3.6.1 Task scope

This clause describes an analysis (Task 2.2.4) to quantify potential impacts of material property variations on the candidate connection sealability, and to select the range of material properties allowable for the full-scale test specimens. In general, if the analysis results show that material property variations can have a significant impact on seal contact stress, then the range of material properties allowed for the test samples is biased to those properties that lead to worst-case combinations of the material variables. If no significant impact of the material variables is identified, the samples can be procured from any production-series pipe that has properties within the range allowed by production specifications for the candidate connection.

Task 2.2.4 contains two subtasks for determining impacts of the following material properties:

— yield strength of the pin material – mandatory Task 2.2.4.1, see 12.3.6.2;

— yield strength of the box material – optional Task 2.2.4.2, see Clause 3.

Guidance for selecting material properties for further analyses is provided in 12.3.6.2. If Task 2.2.4.2 is performed, follow the guidance in Clause D.3 for selecting the box material properties for box material yield strength analyses and subsequent analyses.

Table 13 summarizes the yield strength variations and corresponding codes used to specify the material properties in the constitutive models. The minimum and maximum yield strength values denote, respectively, the minimum and maximum yield strength allowed by production specifications for the candidate connection pin or box material.

Table 13 — Yield strength variations and codes

Yield strength	
Description	**Code**
Minimum strength	Min.
Maximum strength	Max.

12.3.6.2 Pin yield strength analysis

Analysis of impacts of pin yield strength variation (Task 2.2.4.1) is mandatory. This analysis shall be conducted in accordance with analysis requirements summarized in Table 14 and according to the analysis procedure given in Table 15.

Table 14 — Pin yield strength analysis requirements

Connection model attribute	Requirement
Connection geometry	Worst-case geometries WST and WSC
Pin material data set	Minimum-yield and maximum-yield pin
Box material data set	As-characterized box or as-characterized pin-box [a]
Load path	Make-up followed by one thermal cycle
Make-up torque	Manufacturer-specified optimum torque
Thermal cycle	Temperature limits and pressure based on ASL per Table 1 and Table 2
[a] Refer to 12.2.1 for as-characterized property descriptions.	

Table 15 illustrates the procedure to determine whether variation of the pin yield strength within the candidate connection production range can be expected to have a significant impact on the seal contact stress.

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In Step 1, four analysis cases shall be run for different combinations of connection geometry configuration and pin yield strength; except if WST and WSC configurations are the same, then only two analysis cases shall be run.

In Step 2, the results of the analyses conducted in Step 1 are used to assess contact stress conditions in the connection primary seal. Seal contact stress intensity shall be used to assess the connection sealability potential upon make-up and at various stages of the thermal cycle. For each analysis case, the stress intensity shall be calculated at the upper-bound temperature and the lower-bound temperature, as described in A.2.7.

In Step 3, average intensity and intensity variance are calculated separately for each connection geometry configuration (i.e. separately for WST and WSC) at the upper-bound temperature and the lower-bound temperature at cycle end, according to the formulae indicated in Table 15. The largest of the four variances calculated is taken as the maximum intensity variance that can be expected due to pin yield strength variation.

In Step 4, the maximum intensity variance calculated in Step 3 is compared against a set of criteria in order to determine the significance of the pin yield strength variation and to decide whether the selection of tubulars for the pipe body components of the test specimens needs to be restricted:

— If the maximum intensity variance is less than or equal to 15 %, then selection of the pin material is not restricted. The pin components can be made from any pipe that has yield strength within the production specifications.

— If the maximum intensity variance is between 15 % and 30 %, then selection of the pin material shall be restricted to half of the range allowed for the yield strength by production specifications. The two contact stress intensities that gave the maximum intensity variance in Step 3 shall be used to specify the restricted production range. If the lower contact stress intensity corresponds to the minimum yield strength assumed in the constitutive model, then the test sample material shall have a yield strength within the lower half of the ambient-temperature production range. Conversely, if the lower contact stress intensity corresponds to the maximum yield strength assumed in the constitutive model, then the test sample material shall have a yield strength within the upper half of the ambient-temperature production range.

— If the maximum intensity variance is equal to or larger than 30 %, then selection of the pin material shall be restricted to one-third of the range allowed for the yield strength by production specifications. The two contact stress intensities that gave the maximum intensity variance in Step 3 shall be used to specify the restricted production range. If the lower contact stress intensity corresponds to the minimum yield strength assumed in the constitutive model, then the test sample material shall have a yield strength within the lowest one-third of the ambient-temperature production range. Conversely, if the lower contact stress intensity corresponds to the maximum yield strength assumed in the constitutive model, then the test sample material shall have a yield strength within the highest one-third of the ambient-temperature production range.

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Table 15 — Determination of allowable yield strength range for pin components

Case	Tolerances		Load path	Seal contact stress intensity (N/mm)			
	Geometry	Pin yield strength		ASL upper-bound temperature		ASL lower-bound temperature	
Step 1 - Analysis				**Step 2 - Result summary [a]**			
1	WST	Min.	Make-up + 1 cycle				
2		Max.					
3	WSC	Min.					
4		Max.					
				Step 3 - Severity ranking [b]			
	Average = (Higher + Lower)/2			Average	Average	Average	Average
	Variance = (Higher - Lower)/Average (%)			Variance	Variance	Variance	Variance
				Maximum intensity variance			

Step 4 - Selection of material property range		
Maximum intensity variance	Allowable pin yield strength range	
%	% of production range	Selection
Variance ≤ 15	100	Unrestricted
15 < Variance < 30	50	Restricted to subrange with lowest intensity
30 ≤ Variance	33	

[a] Green fields are filled based on contact stress intensity at respective locations.

[b] Severity ranking based on results summarized in Step 2.

The following pin yield strength shall be assumed for subsequent analyses in Task 2.2.4.2 (see D.3) and Task 2.2.5 (12.3.7):

— If selection of the pin material for the test samples is unrestricted based on the results of the analysis conducted in this Task 2.2.4.1, the constitutive model for the pin material shall be based on the as-characterized properties of the production pipe sample determined per 12.2;

— If selection of the pin material for the test samples is restricted based on the results of the analysis conducted in this Task 2.2.4.1, the constitutive model for the pin material shall be assumed as follows:

  — the median-yield strength, corresponding to the median value of the restricted range;

  — the post-yield characteristic assumed as per 12.2.

The median-yield pin material property data set is generated following the same procedure as for producing the minimum- and maximum-yield material property data sets described in 12.2.4.3 and 12.2.4.4.

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12.3.6.3 Box yield strength analysis

Determination of potential impacts of box yield strength variation (Task 2.2.4.2) is optional at the assigner's discretion, and only needs to be considered for threaded-and-coupled connections where the box (coupling) material is normally manufactured separately from the pin (pipe) material. The decision to conduct or not to conduct the box yield strength analysis shall be documented in the evaluation report. Rationale and procedures for the box yield strength analysis are provided in Clause D.3.

If Task 2.2.4.2 is not conducted, the constitutive model for the box material shall be the as-characterized box material property data set if the box material was specifically evaluated; or the box material model shall be the as-characterized pin-box material property data set if only one (either pin or box) material was evaluated (per 12.2).

12.3.7 Make-up torque for sealability tests

This clause describes the analysis that shall be conducted to select target torques for final make-up of the candidate connection specimens designated for sealability tests (Task 2.2.5). The objective of this analysis is to select those torques from the range allowed by the supplier that will result in the lowest contact stress intensity in the seal area – so that the sealability tests are based on conservative scenarios with respect to connection make-up. While in some cases the lowest torque might seem to be a reasonable and conservative target, counterintuitive results were obtained in some connection evaluation programs for thermal well applications – which prompted introduction of this analysis in the original TWCCEP scope and in this document.

Table 16 summarizes the make-up torque variations and corresponding codes used to specify the torque selections. The minimum and maximum torque values denote, respectively, the minimum and maximum torque allowed by the supplier's make-up procedure for the candidate connection.

Table 16 — Torque variations and codes

Make-up torque target	
Description	**Code**
Minimum torque	Min.
Maximum torque	Max.

Table 17 and Table 18, respectively, illustrate the analysis requirements and the procedure to determine the final make-up torque that shall be used for assembly of specimens for sealability tests. The scope of the analysis assumes that specimens with all geometry configurations listed in Table 9 can be subjected to sealability tests, even though sealability tests of some of those configurations are optional. The rationale for such choice is to gain understanding of connection performance at a relatively low incremental cost of the associated analyses.

Table 17 — Analysis requirements for evaluation of make-up torque for sealability tests

Connection model attribute	Requirement
Connection geometry	Worst-case geometries WST, WSC, WGS and WGT
Pin material data set	Median-yield pin
Box material data set	Median-yield box [a] or as-characterized box or pin-box [b]
Load path	One or two make-ups followed by one thermal cycle
Make-up torque	Manufacturer specified minimum and maximum torques as specified in Table 18
Thermal cycle	Based on ASL per Table 1 and Table 2

[a] Median-yield box material data set is used if box yield strength analysis is completed.

[b] If box yield strength analysis is not completed, then in the order of priority: either use as-characterized box material data set or pin-box material data set.

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In Step 1 of the procedure illustrated in Table 18, several analysis cases shall be run for different combinations of connection geometry configurations. The default number of cases is 12, but that number may be reduced by agreement between the assigner, the supplier and the evaluator, if it is demonstrated that no incremental plasticity occurs in the connection seal upon break-out and/or second make-up to the same torque, in which case the reduction of the analysis scope might apply to cases 2, 4, 6, and 10. If geometry configurations WSC and WST are the same, the number of cases shall be reduced correspondingly.

The constitutive model for the pin and box materials shall use median yield strengths of the required test-specimen pin and box yield strength ranges calculated in Task 2.2.4.1 (see 12.3.6.2) and optional Task 2.2.4.2 (see Clause D.3). The median-yield constitutive model is calculated following the procedure described in 12.2.4.3 and 12.2.4.4 by substituting the median yield strength for one of the minimum or maximum yield strength. If optional Task 2.2.4.2 is not completed, the constitutive model for the box material shall use the as-characterized box material property data set (per 12.2) if coupling stock was characterized and the as-characterized pin-box material property data set if it was not.

The load path for analysis cases 7, 8, 11 and 12 consists of a single make-up to a case-specific torque and one thermal cycle corresponding to the selected ASL. The load path for all other analysis cases consists of two consecutive make-ups to case-specific torques separated by a zero-load (zero-interference) step simulating a break-out, and one thermal cycle corresponding to the selected ASL.

In Step 2, the results of the analyses conducted in Step 1 are used to illustrate contact stress conditions in the connection primary seal. Selection of conditions for input of the seal contact stress intensity in Table 18 shall be based on the contact stress intensity at the maximum internal pressure; and at the upper-bound temperature for WSC geometry, and at the lower-bound temperature at cycle end for WST geometry.

In Step 3, the contact stress intensities determined in Step 2 are compared to determine the case that resulted in the lowest intensity within each pair of analysis cases conducted on the same geometry configuration and make-up sequence.

In Step 4, the final make-up torques associated with the cases determined in Step 3 are selected as targets TF(XXX) for the final make-ups of the specimens for the sealability tests, where TF(XXX) targets will be either “minimum torque” or “maximum torque” allowed by the supplier’s make-up procedure. For the WST and WSC geometry configurations, the target torques are either TF(XXX-S) or TF(XXX-M), which respectively correspond to the target torques for either single make-up specimens or multiple make-up specimens.

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Table 18 — Determination of torque for make-up of sealability test specimens

Step 1 - Analysis					Step 2 - Result summary [a]	Step 3 - Severity ranking	Step 4 - Final torque selection [b]
Case	Geometry config.	Load path	Torque target		Seal contact stress intensity (N/mm)	Lowest intensity in each pair	Min. or Max.
			1st make-up	2nd make-up			
1	WGS	2 make-ups + 1 cycle	Max.	Min.		Lowest from cases 1 and 2	TF(WGS)
2			Max.	Max.			
3	WGT	2 make-ups + 1 cycle	Max.	Min.		Lowest from cases 3 and 4	TF(WGT)
4			Max.	Max.			
5	WST	2 make-ups + 1 cycle	Max.	Min.		Lowest from cases 5 and 6	TF(WST-M)
6			Max.	Max.			
7		1 make-up + 1 cycle	Min.			Lowest from cases 7 and 8	TF(WST-S)
8			Max.				
9	WSC	2 make-ups + 1 cycle	Max.	Min.		Lowest from cases 9 and 10	TF(WSC-M)
10			Max.	Max.			
11		1 make-up + 1 cycle	Min.			Lowest from cases 11 and 12	TF(WSC-S)
12			Max.				

[a] Green fields are filled based on the contact stress intensity at the maximum internal pressure, and at the upper-bound temperature for WSC geometry, and at the lower-bound temperature at cycle end for WST geometry.

[b] "-M" denotes multiple make-ups; "-S" denotes single make-up.

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12.3.8 Test versus production specimens

Execution of the test-versus-production analysis (Task 2.2.6) is optional at the assigner's discretion. The decision to conduct or not to conduct this analysis shall be documented in the evaluation report.

Rationale and recommended procedures for the test-versus-production analysis are provided in Clause D.4.

13 Specimen procurement

13.1 Task overview

This clause describes the third block of the evaluation procedure (see Figure 6), which deals with procurement and preparation of connection samples (specimens) for full-scale testing. The tasks in this program block cover procurement of specimen component pipes and verification of their material properties, specifications for specimen machining, specimen quality control and geometry verification (gauging), procurement of connection interfacial component(s), specimen handling and storage, and treatment of damaged specimens.

This program block contains three tasks: Task 3.1 Specimen Pipe Procurement (in 13.2), Task 3.2 Material Property Verification (in 13.3), and Task 3.3 Specimen Machining and Gauging (in 13.4). Details of those three tasks are described in the following clauses. All tasks in this block are mandatory.

Six candidate connection specimens shall be machined for full-scale testing. These specimens are numbered Specimen 1 to Specimen 6. Specimen numbering convention is associated with the specimen configuration and tolerances, which are explained in Table 19 and 13.4.4.

For threaded-and-coupled connections, one additional pin end with seal removed shall be provided to support open ends of couplings during make-up and break-out. This pin is referred to as the make-up support pin.

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It is recommended that one or more replacement specimens (spares) be machined for each test specimen configuration at the time when the test specimens are manufactured, and in accordance with the same procurement and machining guidelines as for the primary test specimens. It is acknowledged that the process of substituting spares for damaged or unusable specimens can become complex when a part being replaced, such as a coupling, affects more than one connection; or when a part being replaced, such as a pin-by-pin intermediate pup, affects more than one specimen (see 13.8.2).

Specifications for the test specimens, replacement spares, and make-up support pin are provided in the following clauses.

13.2 Specimen pipe procurement

Task 3.1 Specimen Pipe Procurement is executed to obtain mother tubes for manufacturing of connection samples for full-scale testing (test specimens).

Pin components for the test specimens shall be machined from pipes with yield strengths that conform to the requirements included in 12.3.6.2 and Table 15.

For threaded-and-coupled connections, if the optional Task 2.2.4.2 Box Yield Strength has been executed, box components for the test specimens shall be machined from coupling stock with yield strengths that conform to the requirements included in Clause D.3 and Table D.1. When the optional Task 2.2.4.2 Box Yield Strength has not been executed, box components shall be machined from pipes with properties within the range allowed by the candidate connection production specifications, and the coupling stock should be selected to have properties as close as practical to average production values.

Applicable mill certificates in accordance with ISO 11960 shall be provided for all pipe and coupling stock procured for candidate connection specimens. Copies of those certificates shall be included in the evaluation report.

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13.3 Material property verification

13.3.1 Task description

Task 3.2 Material Property Verification is a mandatory task. Completion of this task may be achieved by utilization of prior evaluation data or be tests performed prior to machining of the candidate connection specimens. The scope of this task includes verification tests of tensile properties and thermal expansion coefficient of the mother pipe and coupling stock intended for manufacturing the candidate connection specimens.

The tensile verification tests (see 13.3.2 and 13.3.3) are performed to confirm that the material properties of the tubes procured in Task 3.1 (see 13.2) conform to specifications for the biased test population determined in Task 2.2.4 (see 12.3.6).

The verification test of the thermal expansion coefficient (see 13.3.4) is performed to determine the average expansion coefficient (α_a), which is needed in the thermal cycle test for calculation of mechanical strain compensations (see 14.4.5) and can also be used for calibration of the elongation-strain measuring system (see 14.4.6).

13.3.2 Specimens for tensile verification tests

The material-property verification tests shall be performed on axially-oriented material strip specimens cut from material coupons – i.e. from full-circumference short lengths of pipe – extracted from mother pipe and coupling stock used for manufacturing the candidate connection specimens. The specimen manufacture could be undertaken prior to conducting the material property verification tests, but the use of connection test specimens with material mechanical properties shown not to conform to the requirements specified in 12.3.6 constitutes a program non-conformance (see 8.2).

One material coupon (full-circumference tubular sample) shall be obtained from each length of mother tubes used to manufacture the full-scale test specimen pups and couplings. The coupon may

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be extracted from any axial location within the mother joint, but if substantial axial variability in mechanical properties is anticipated, extraction of more coupons is recommended. The axial position of the coupon relative to the connection test specimens shall be recorded. Coupon length should be adequate to enable machining of strip specimens and samples for any other material evaluations that might be warranted. If ERW pipe is used, the weld location should be identified and clearly marked, and the circumferential location of any strip specimens identified with respect to the weld centreline. Retention of the remaining material from the coupon is recommended, in the event that any further characterization of mechanical properties, microstructure, or chemistry of the test material is later required.

At least three longitudinal material strip specimens shall be manufactured from each coupon taken from a mother pipe used in the manufacture of any primary or spare pup or coupling, for use in the tests described in 13.3.3. Machining of additional strip specimens is recommended for backup purposes.

The material strip specimens should utilize a full-thickness rectangular cross-section or equivalent cylindrical or semi-cylindrical cross-section. All strip specimens should be of a similar geometry.

The material strip specimens should be extracted from within a single quadrant of the pipe circumference, and preferably from immediately adjacent circumferential positions. Material specimens manufactured from ERW pipe should be extracted at least 90° from the weld centreline. For small-diameter pipes for which the above-recommended specimen spacing is not possible, the circumferential distance between the specimen locations and the weld centreline should be maximized.

Relative circumferential locations of the extracted material strip specimens shall be recorded as the specimens are removed from the pipe coupon.

13.3.3 Scope of tensile verification tests

The following tensile verification tests shall be conducted on the material strip specimens cut from each material coupon:

— A minimum of three tensile tests for each coupon from each mother pipe used to manufacture specimens for full-scale tests at elevated temperatures:

  — one test at ambient conditions;

  — one test at 180 °C;

  — one test at the upper-bound temperature of the selected ASL.

— A minimum of one tensile test at ambient conditions for each coupon from each mother pipe used to manufacture specimens for full-scale tests at ambient temperatures.

The above tests shall be conducted using testing procedures that meet applicable provisions in ASTM specifications A370, E8 and E21. Utilization of the same procedure as previously used to complete Task 2.1 Initial Material Property Characterization is suggested to facilitate comparison of results.

The yield strength (per ISO 11960) and the stress-strain curves shall be recorded in the evaluation report for each tensile verification test performed.

The yield strength measured in each ambient-temperature verification test shall be compared to the allowable range determined in Task 2.2 Specimen Configuration Analysis. The material yield strength shall be within the range determined in Task 2.2 in order for a connection made from that material to be used in the full-scale test.

The yield strengths measured in the elevated-temperature verification tests shall be compared to the elevated-temperature test results acquired in Task 2.1, and that comparison shall be recorded in the evaluation report. It is recommended that the normalized yield strength be calculated for each material sample and each elevated temperature (using the formula introduced in 12.2.4.2), and that differences between the observed thermal degradation functions and those previously used for the specimen configuration analysis (Task 2.2) be recorded.

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Inclusion of the obtained stress-strain data in the evaluation report is mandatory in order to:

— preserve a detailed record of the relevant mechanical properties together with the connection sealability and structural integrity testing results;

— enable subsequent users of the evaluation results to gain or maintain confidence in the applicability of the test results;

— facilitate future product line evaluation activities.

13.3.4 Coefficient of thermal expansion verification test

Verification of coefficient of thermal expansion (CTE) of the pin material is mandatory. Verification of CTE of the box material is recommended if its value adopted for Task 2.1 (see 12.2.2.3) was based on an assumption or when CTEs for pin and box samples tested in Task 2.1 (see 12.2.2.3) were substantially different (i.e. differed by more than 15 % of their average value).

For each material (i.e. pin and/or box), samples for the verification CTE testing shall be extracted from one of the mother pipes used to make the candidate connection specimens unless agreed otherwise by the assigner and the evaluator and the supplier.

In each verification test, CTE data shall be obtained, and the average thermal expansion coefficient α_a shall be determined over the range of test temperatures corresponding to the selected ASL, with the allowances described below.

The method for determination of the α_a may be either as recommended below or as otherwise agreed by the assigner and the supplier.

CTE testing should be conducted according to the requirements of ASTM E831-06, and should quantify the expansion response in the axial direction of the pipe. In general, the CTE can be expected to increase with temperature. CTE tests should provide continuous experimental data indicating the measured change in sample geometry (and the associated thermal strain, $\Delta\varepsilon_{therm}$) as a function of temperature through at least one complete thermal cycle (including ramp-up and ramp-down). That data should be used to calculate the average coefficient of thermal expansion α_a between the lower-bound temperature and upper-bound temperature for the selected ASL:

$$\alpha_a = \frac{\Delta\varepsilon_{therm}}{\Delta T} \tag{2}$$

The expansion coefficient should be expressed in units of °C^{-1}.

Continuous thermal expansion testing results (elongation/strain versus temperature) should be retained, because they can aid confirmation of the accuracy of the strain measurement system used for the thermal cycle test, as discussed in 14.4.

For practical reasons, a laboratory test of the thermal expansion coefficient may be conducted in the temperature range from the low cycle temperature to the high cycle temperature (see 14.4.4) selected for the thermal cycle test. The obtained test data may be utilized as follows:

— average thermal expansion coefficient for the range from the lower-bound temperature to the low cycle temperature (i.e. from T_{lb} to T_{lc}) may be assumed to be equal to the average coefficient obtained in the CTE test between T_{lc} and 40 °C;

— average thermal expansion coefficient for the range from lower-bound temperature to the upper-bound temperature (i.e. from T_{lb} to T_{ub}) may be assumed to be equal to the average coefficient obtained in the CTE test between T_{lc} and T_{hc}.

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13.4 Test specimen machining and gauging

13.4.1 General requirements

In Task 3.3 Test Specimen Machining and Gauging, the candidate connection specimens for full-scale physical testing are manufactured according to specifications determined for the biased test population (see 12.3).

For threaded-and-coupled connections, all couplings shall be machined at both ends, including those intended for the galling resistance test.

Only mechanical cutting is allowed. Torch cutting or abrasive cutting shall not be used.

13.4.2 Specimen naming convention

The six candidate connection specimens that are required for full-scale testing shall be numbered as Specimen 1, 2, 3, 4, 5 and 6 (refer to Table 19 for correlations between specimen numbers and the required geometrical configurations).

The replacement specimens for any of the above specimens shall be numbered by the original specimen number followed by a period and the replacement number – for example, Specimen 1.1 denotes the first replacement specimen for Specimen 1, and Specimen 1.2 denotes the second replacement specimen for Specimen 1, etc.

The pin and box components of each specimen shall be identified by the corresponding specimen number (either original or replacement); and for threaded-and-coupled connections, each pin and box component shall also be identified by a letter uniquely corresponding to each connection within a given specimen, according to the following convention.

For integral connections (IC):

— each box component shall be identified by its specimen number;

— each end of each pin component shall be identified by its specimen number.

For threaded-and-coupled (TC) connections:

— each box component shall be identified by its specimen number and a letter A or B, with each letter corresponding to one side of the coupling;

— each end of each pin component shall be identified by its specimen number and a letter A or B, with each letter corresponding to the matching box component.

For both IC and TC connections:

— pin/box components shared by multiple specimens (e.g. for string assemblies) shall be identified by the number-letter combinations for each end, separated by "-";

— unthreaded ends shall be identified as blank.

Naming examples for integral connections:

— Pin 2-blank – designates pin component for Specimen 2.

— Pin 3-Box 4 – designates pin-box component for a string assembly, with the pin end belonging to Specimen 3 and the box end belonging to Specimen 4.

Naming examples for TC connections:

— Pin 2A-blank – designates pin component for Specimen 2 side A.

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— Pin 3B-4A – designates pin component for a string assembly, with one end belonging to Specimen 3 side B, and the other end belonging to Specimen 4 side A.

— Box 5A – designates side A of Specimen 5.

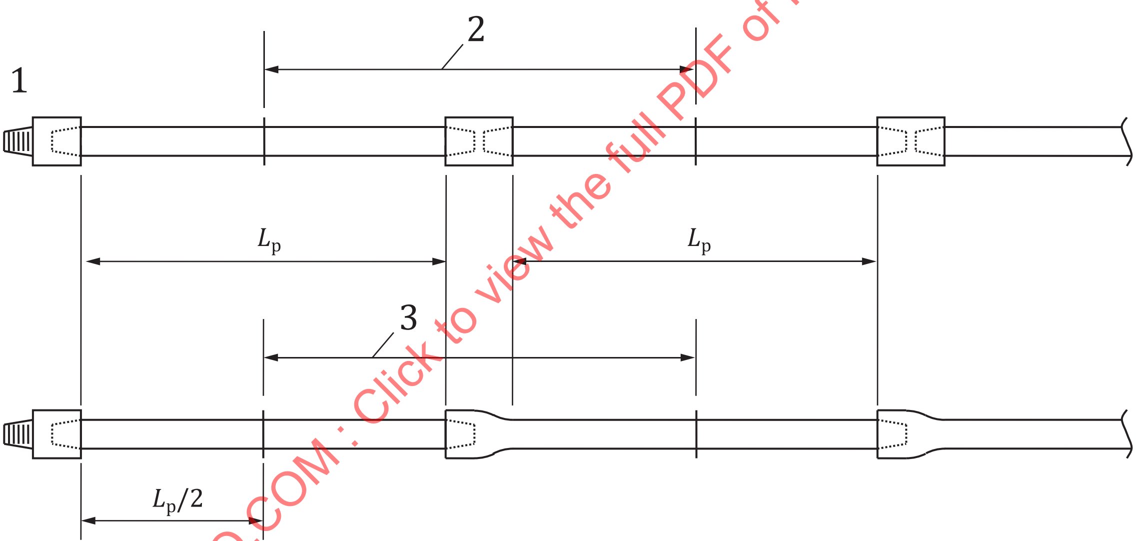
13.4.3 Specimen length and length-reference requirements

A minimum length for each specimen pin component (casing pup) to be used in the combined-load full-scale tests is specified for two reasons:

— to ensure that each pup contains an interval free of end effects introduced by supports at both ends of that pup (end effects might be generated either by an end fixture or an adjacent connection in a string assembly);

— to provide for the length-dependent strain localization effects that can be expected to take place in the field during thermo-mechanical cycling to be reasonably simulated in the test configuration.

The pup length requirements are specified in terms of the minimum unsupported pup length. The unsupported pup length L_p is defined as the pup length that remains outside of the end fixture and/or coupling(s) after the pup is made up at both ends. The definition of the unsupported pup length is illustrated in Figure 11. The same concept applies to both TC and IC connections (see 5.1).



Key

1 end fixture
2 TC specimen
3 IC specimen

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Figure 11 — Definition of unsupported pup length

The following requirements shall apply to each casing pup that belongs to each connection specimen:

— unsupported pup length L_p shall not be less than the maximum of the following:

— $2x\left[D+6\sqrt{Dt}\right]$ (twice as long as the minimum length per ISO 13679);

— 600 mm (24 in).

— additional length for gripping and/or end fixtures shall be provided.

The following requirement shall apply to the make-up support pin:

— unsupported length should be no less than 300 mm (12 in).

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13.4.4 Geometrical configurations

Table 19 describes correlations between the specimen numbers and the required geometrical configurations for six candidate connection specimens that are subjected to full-scale testing. Geometry configuration codes WGS, WGT, WST, and WSC denote worst-case combinations of design variables selected for the biased test population, as described in 12.3.4 and 12.3.6. If configuration WST is the same as configuration WSC then specifications for Specimen 3 and Specimen 4 are the same as for Specimen 5 and Specimen 6.

The make-up support pin shall have fast thread taper.

Machining tolerances for interferences and tapers corresponding to various geometry configurations are provided in 13.4.6.

Table 19 — Geometrical configurations for test specimens and replacement specimens

Test specimen	Replacement specimens	Geometry code	Worst-case condition target
1	1.1, 1.2...	WGS	Galling in seal
2	2.1, 2.2...	WGT	Galling in threads
3	3.1, 3.2...	WST	Sealability in tension at low temperature
4	4.1, 4.2...	WST	
5	5.1, 5.2...	WSC	Sealability in compression at high temperature
6	6.1, 6.2...	WSC	

13.4.5 Mother pipe for specimens

The following principles shall be observed for specimen source pipe:

— All pipe segments for Specimen 3, Specimen 4, Specimen 5, and Specimen 6 shall be from the same heat and lot of steel, as shall all spares for these segments;

— Whenever possible, pipe segments for Specimens 3, 4, 5, and 6 should be made from a single mother joint;

— If Specimens 3, 4, 5 and 6 are indeed manufactured from a single mother joint as recommended above, then the material properties of that mother joint shall conform to specifications for the biased test population as determined in 12.3.6;

— If Specimens 3, 4, 5 and 6 are not all manufactured from a single mother joint, then the material properties of every mother joint used for those specimens shall conform to specifications for the biased test population as determined in 12.3.6, and the mother joints should be selected to have their material properties as similar as possible;

— Replacement pipe segments for Specimens 3, 4, 5 and 6 should be made from another single mother joint, and that mother joint should be selected to have material properties as similar as possible to the joint(s) from which the original specimens were made.

Uniformity of applied stresses is desirable for all pipe segments subjected to thermal cycle testing. When the segments are connected in series, their products of yield strengths and average wall thicknesses should be equal, to the extent practical. Pipe wall thicknesses of Specimens 3, 4, 5 and 6, and of spare pipe segments that might replace those originally intended for thermal cycle testing, shall be measured and traceably recorded. Thickness measurements shall be made at 90° circumferential intervals, at axial locations adjacent to each relevant pin thread and, for integral connections, adjacent to the external upset. Accuracy of the measurement method shall be ±0,025 mm (±0.001 in) or better. The products of yield strength and average thickness shall be considered, in addition to connection dimensions, whenever pipe segments assembled for a thermal cycle test are not manufactured from a single mother joint.

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13.4.6 Specimen machining tolerances

Candidate connection specimens shall be manufactured to achieve interference-taper combinations as defined in 6.4.3, specified in 12.3.4, and referenced in Table 19. Upon completion of Task 2.2 Specimen Configuration Analysis, the targets for the diametric interferences in the seal and thread areas are specified as either minimum or maximum, and the targets for the pin and box thread tapers are specified as either slow or fast. This clause provides machining specifications and tolerance ranges for the actual interferences and tapers of the test specimens, within which the test specimens shall be considered conformant with the above requirements for the minimum/maximum interference and fast/slow taper.

Dimensions not specified by this document requirements shall be within tolerances on manufacturing drawings.

Candidate connection specimens shall be machined so that all the following conditions are satisfied for each pin-box assembly:

a) for each interference location (thread or seal), at least one of the diameters of individual members (pin or box) shall be within the sub-range of its design tolerances as specified by Table 20. The other diameter may be outside of its design tolerance as long as the interference at that location conforms to the condition b) below;

b) for each interference location (thread or seal), the interference based on the as-machined diameters in the assembled condition consistent with nominal make-up position, shall be within the range specified in Table 21;

c) each thread taper shall be within the range specified in Table 22;

d) each seal taper shall be within its production tolerance range.

Additionally, if bored pin tips will have diameters smaller than the pipe's internal diameter, the boring of all pin tips that might be used in a thermal cycle test shall be extended so the casing segments will nowhere have internal diameters smaller than the specified tip-bore diameters.

Table 20 — Allowable diameter range within design tolerance

Target interference	Allowable component diameter range	
	Pin [a]	**Box [a]**
Maximum	Upper half of pin tolerance band	Lower half of box tolerance band
Minimum	Lower half of pin tolerance band	Upper half of box tolerance band

[a] At least one component, i.e. either pin or box, is within the allowable diameter range for each target interference case. The same principle applies to seal and thread interferences.

Table 21 defines and Figure 12 illustrates the interference ranges allowed for candidate connection specimens in terms of minimum interference and maximum interference that result from the candidate connection production specifications for component diameters (nominal dimensions and tolerances). The following symbols are used in Table 21 and in Figure 12:

I_{max} maximum design interference in reference thread location or reference seal location, resulting from pin and box diameter specifications;

I_{min} minimum design interference in reference thread location or reference seal location, resulting from pin and box diameter specifications;

I_{range} range of design interference in reference thread location or reference seal location, equal to I_{max} minus I_{min}

I_{rt4} interference range threshold of 0,04 mm (0.001 6 in)

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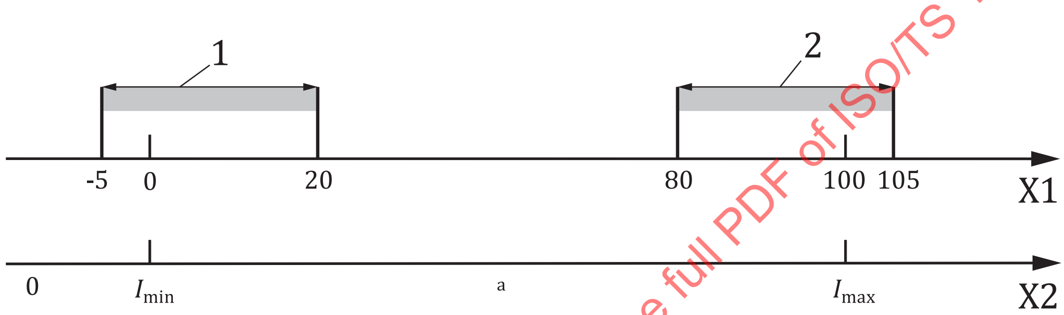
I_{rt1} interference range threshold of 0,01 mm (0.000 4 in)

By agreement between the assigner and the supplier, other tolerances may be considered when defining tolerance and interference ranges (for example, tolerances on thread height or torque shoulder depth). Any such additional considerations shall be documented in the evaluation report.

Table 21 — Interference ranges for test specimens

Target interference	Allowable specimen interference range [a]	
	From	**To**
Maximum	$I_{max} - \max\left[I_{rt4}, 20\% \cdot I_{range}\right]$	$I_{max} + \max\left[I_{rt1}, 5\% \cdot I_{range}\right]$
Minimum	$I_{min} - \max\left[I_{rt1}, 5\% \cdot I_{range}\right]$	$I_{min} + \max\left[I_{rt4}, 20\% \cdot I_{range}\right]$

[a] The same principle applies to seal and thread interferences.



Key

X1 interference range, %

X2 interference, mm (or in)

1 minimum interference range

2 maximum interference range

a design interference values

Figure 12 — Illustration of allowable interference ranges for specimen components

Table 22 defines the thread taper ranges allowed for candidate connection specimens in terms of minimum and maximum thread tapers that result from the candidate connection production specifications.

Table 22 — Thread taper ranges for test specimens

Taper designation	Allowable thread taper ranges [a]	
	From	**To**
Slow	No lower limit	Slow taper limit during production plus 0,025 mm/25,4 mm (0.001 in/1 in)
Fast	Fast taper limit during production minus 0,025 mm/25,4 mm (0.001 in/1 in)	No upper limit

[a] Taper tolerances apply to every incremental measurement of taper along a thread.

Figure 13 illustrates the adopted taper naming convention and the allowable taper ranges for test specimen components described in Table 22.

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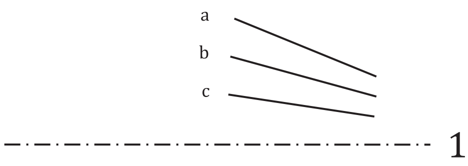
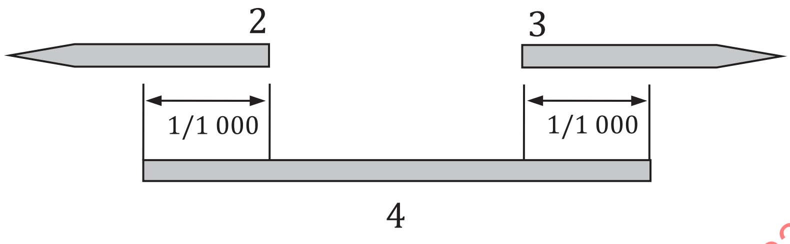


a) Taper naming convention



b) Allowable taper ranges

Key

1 component centreline
2 allowable slow taper range for testing
3 allowable fast taper range for testing
4 allowable taper range for production
a fast taper
b nominal taper
c slow taper

Figure 13 — Illustration of allowable thread taper ranges for test specimens

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13.5 Markings

All couplings, pipe segments and material samples shall be clearly marked with metal stamps.

Markings shall identify each pin and box component of each pipe and coupling according to the specimen naming convention described in 13.4.2.

Couplings shall be marked at each end. Redundant markings are encouraged. Preferred stamping locations are the unthreaded faces of the pipe segments, the faces of the couplings and the faces of material samples.

13.6 Specimen geometry verification

13.6.1 Gauging inspection scope

Geometry of all test specimens shall be verified by gauging. Gauging shall be completed by the supplier according to the supplier's procedure. All gauging sheets and setting standards used to control the specimens' dimensions and measurements shall be traceable to the drawings of the candidate connection being evaluated.

Gauging results should be confirmed by the inspector. The scope of the inspector's specimen geometry verification should be agreed by the assigner and the supplier.

As provided by 7.2, this document does not require that any confidential connection design information (e.g. connection drawings) be revealed by the supplier in the course of the gauging inspection.

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The inspector should obtain current calibration records for any gauging equipment (e.g. setting standards or bias zero settings) used by the supplier, and include those calibration records in the inspection report.

13.6.2 Inspection extent – example cases

In general, connection gauging and quality inspection procedures vary depending on the connection manufacturer, connection design, availability of gauges, and quality-management program in place. The following paragraphs in this clause illustrate two example cases of possible inspection scope, depending on the extent to which the inspector has access to the supplier's design information. The extent of that access shall be agreed between the assigner and the supplier.

a) Case 1 - no design information on the candidate connection is provided to the inspector.

   The inspector is to verify conformance of specimen dimensions to the supplier's specimen gauging sheets, either through absolute dimensioning or by gauging referenced to traceable standards.

b) Case 2 - design information on the candidate connection is provided to the inspector.

   The inspector is to verify conformance of the supplier's specimen gauging sheets with the candidate connection design drawings and production procedures, or alternatively with production line gauging sheets and production procedures, to confirm that the specimen gauging sheets satisfy dimensional requirements of this document. After that verification, the inspector is to verify conformance of specimen dimensions to the specimen gauging sheets, either by absolute dimensioning or by gauging referenced to traceable standards.

The assigner shall specify the extent of the inspector's verification of specimen dimensions (e.g. the assigner might limit verification gauging to specimen dimensions restricted by 13.4.3 and 13.4.6).

13.6.3 Geometry inspection guidelines

Some additional specimen geometry-verification guidelines include:

— It is recommended that gauging equipment should have a resolution of at least 10 % of the tolerance bands of specimen diameters and tapers. If such high-resolution instrumentation is not available, then the gauging equipment should have a resolution of at least 20 % of the tolerance bands of specimen diameters and tapers.

— If possible, gauging frames that hold dial indicators should be stiffer than the frames used at the production line.

— If setting standards are not available, and gauge blocks are used to zero dial indicators, compensating corrections that depend on surface tapers and diameters of the contact tips should be calculated.

— Temperatures of gauging frames, dial indicators, setting standards and specimens being gauged should be consistent both at the time of dial indicator zeroing and at the time of specimen gauging. Only 1 °C difference in temperature between a gauging frame and a carbon steel specimen will cause 0,002 5 mm (0.000 1 in) measurement error in 230 mm (9 in) diameter, an error equal to 10 % of a representative tolerance band for a specimen's diameter. This might require allowing time for a specimen's temperature to stabilize following machining.

A dimensional inspection report should allow a reader to understand how accurately the specified dimensions and diametric interferences conform to requirements, but without publishing the actual dimensions. Achieving both of these reporting objectives might require some adaptability. Thread tapers can be documented as the amount that measured tapers differ from minimum or from maximum production values. Conformance of pin or box diameters to Table 20 can be reported simply as yes or no. Diametric interferences can be reported as percentage values, with reference to production ranges as 0 % to 100 %, if the supplier chose that alternative for determining specimen interferences from production interferences. Otherwise, diametric interferences can be reported as the amount that they differ from minimum or maximum production values, similarly to the reporting of thread tapers.

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Dimensional interferences cannot be directly measured, and need to be calculated from specimens' diameter measurements. Recording those diameter measurements (in a parallel manner to interferences) will enhance traceability of the calculated interferences and facilitate the choosing of a spare specimen to substitute for an inadvertently damaged specimen. Nevertheless, a matrix showing diametric interferences of all possible pin and box combinations can be prepared, allowing a supplier to request that individual diameters not be included in either interim or permanent inspection records.

13.7 Procurement and quality control of connection interfacial components

Connection interfacial components are treated as inherent elements of a connection's design and specific elements of the candidate connection specimens submitted for an evaluation program. This is because interfacial components affect not only the connection assembly and galling resistance but also sealability. The impact of the interfacial components on sealability can be particularly significant during and after exposure to high temperatures.

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In general, interfacial components can be divided into two classes:

Class 1: interfacial components that are applied to the casing pipes and couplings (pin and box components) as part of the pin and box manufacturing process, e.g. phosphate coatings;

Class 2: interfacial components that are applied upon connection assembly, e.g. thread compounds.

All interfacial components utilized in the candidate connection specimens shall conform to the supplier's design specifications.

The supplier shall perform quality control of the Class 1 interfacial component(s), which have been applied to the pin and box components of the candidate connection specimens during their manufacturing, and provide a corresponding written confirmation to the assigner and the evaluator. That quality-control confirmation shall be included in the evaluation report.

The assigner and the supplier shall agree on the procurement of the Class 2 interfacial component(s) that will be applied during assembly of the candidate connection specimens. By default, those interfacial components will be provided by the supplier or by a party designated by the supplier. The supplier shall ensure that the procured interfacial components are supplied with relevant product certificates that will enable unique identification of the supplied product. Those certificates shall be supplied to the assigner and the evaluator, and shall be included in the evaluation report.

The assigner, the supplier and the evaluator shall agree on the extent of the quality control that shall be performed on the supplied interfacial components.

13.8 Specimen handling and storage

13.8.1 Handling recommendations

All specimens shall be handled with due care and attention to avoid any accidental damage to or undesirable effect on the specimens. If they are needed, the supplier should provide instructions for special handling or storage of specimens.

Care of test specimens starts at the machine shop, even before machining begins. Specimens shall not be dropped, whether or not they have been machined, or residual stresses might cause unpredictable behaviour. The cost of rejections after specimens and spares leave the machine shop is potentially very large, so precautions should be commensurate.

Prudent practice will involve selection of pipe segments for thermal cycle testing according to products of yield strengths and average wall thicknesses, as discussed in 13.4.5.

Impact damage to machined surfaces is to be avoided. Usually impact damage to threads can be repaired, if it is noticed before it causes galling during testing activities, but most suppliers prohibit seal surface repairs. The potential for handling damage in the machine shop can only be minimized with good work practices. The potential for handling damage after specimens leave the machine shop can be reduced by packaging on pallets or in bundles, with special attention to protection of pipe segment ends.

More subtle sources of damage should be avoided, too. Care should be exercised to avoid contact of grinder wheels with seal surfaces when manually removing sharp edges of vanishing threads nearest those seals. Grit should be removed from machined surfaces and from thread protectors before those thread protectors are installed. Corrosion protection products (e.g. Kendex or equivalent) should be applied to machined surfaces quite soon after machining is finished, especially in hot and humid climates.

Experience in specimen handling and storage is valuable. Any doubt about the adequacy of precautions should be resolved conservatively.

13.8.2 Treatment of damaged specimens

The procedure to be followed if a test specimen is inadvertently damaged, after leaving the machine shop, will depend on timing and circumstances. If damage is detected before testing of a pin or box component begins, selection of a replacement from the spares should be relatively straight-forward, based on satisfaction of diametric interferences per 13.4.6 and on matching of pipe segment strengths per 13.4.5, if applicable. The correct response is less clear if inadvertent damage occurs after beginning a history-dependent sequence, such as sequential make-ups and break-outs of Specimens 1, 2, 3 and 5. The replacement strategy might become additionally complicated when a damaged part affects multiple specimens; for example, when the damage occurs to a pin-by-pin pup intended to become an intermediate pup in a specimen string for the thermal cycle test. If the number of spares does not allow restarting the history-dependent sequence with a fresh pin and a fresh box, a decision about acceptable resolution needs to be reached.

When test specimens get damaged, the assigner and the supplier shall jointly choose from the available action alternatives and decide on procedure to continue testing.

Combined scope of testing performed on the original and/or replaced test specimens before the damage and after the damage shall not be less than required by specifications of this document for undamaged specimens.

All occurrences of specimen damage and corresponding actions taken shall be documented in the evaluation report.

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14 Full-scale physical tests and supplementary analyses

14.1 Task overview

This clause describes the fourth block of the evaluation procedure, which consists of full-scale tests and supplementary analyses (see Figure 6). The tasks in this block are conducted to assess performance of the candidate connection under loading conditions consistent with the selected ASL, with respect to galling resistance, structural strength, and sealability.

This block contains five tasks: Task 4.1 Galling Resistance Test, Task 4.2 Thermal Cycle Test, Task 4.3 Bending Evaluation, Task 4.4 Limit-Strain Test, and Task 4.5 As-Tested Configuration Analysis. Task 4.3 contains two subtasks: Task 4.3.1 Bending Analysis and Task 4.3.2 Bend Test. Task 4.4 also consists of two subtasks: Task 4.4.1 Localized Strain Seepage and Task 4.4.2 Tension Limit.

The full-scale testing tasks in this block are: Task 4.1 Galling Resistance Test, Task 4.2 Thermal Cycle Test, Task 4.3.2 Bend Test, and Task 4.4 Limit-Strain Test. The supplementary analyses tasks are: Task 4.3.1 Bending Analysis and Task 4.5 As-Tested Configuration Analysis.

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Mandatory tasks in this block are: Task 4.1 Galling Resistance Test, Task 4.2 Thermal Cycle Test, and Task 4.4.2 Tension Limit.

Optional tasks in this block are: Task 4.3 Bending Evaluation, including Task 4.3.1 Bending Analysis and Task 4.3.2 Bend Test; Task 4.4.1 Localized Strain Seepage; and Task 4.5 As-Tested Configuration Analysis.

Six full-scale candidate connection specimens are required for the full-scale test program. The specimens shall be manufactured as per the requirements described in Clause 13.

Results of the mandatory full-scale tests are the only results of the evaluation program that require comparison with threshold performance requirements. Results of the supplementary analyses are not compared to the threshold performance requirements, but may be considered in the assessment of the candidate connection performance under application-specific conditions that are not simulated in the mandatory tests. These results may also be used to guide decisions relative to additional testing that might be desired for some applications.

Test data and results from other connection assessment programs may be utilized in lieu of some or all subtasks of Task 4.1, 4.2, 4.3, 4.4 and 4.5, if applicability of that prior evaluation data to the candidate connection and its conformance to requirements of this document is demonstrated according to the provisions in 8.5.

The following clauses describe requirements for the full-scale tests and supplementary analyses, including test and analysis scope, set-up and execution, result interpretation, and reporting.

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14.2 Full-scale tests - general requirements

14.2.1 Ambient temperature at test site

Full-scale tests according to this document can be conducted in various laboratories around the world in which average ambient temperatures could be different. Local temperatures can also vary with seasons of the year and even on a daily basis.

This document provides means to correct for impacts of different ambient conditions on some test procedures, e.g. the ranges of cyclic temperature variations in the thermal cycle test (see 14.4.4 and 14.4.5). In addition to those procedural adjustments, the range allowed for the ambient temperature variations is restricted to limit their impacts on various aspects of the connection evaluation - for example, temperature-dependence of instrumentation, assembly procedures, or connection interfacial component properties.

Ambient temperature T_{amb} in the facility where a full-scale test is executed in accordance with this document shall be between 5 °C and 40 °C during the execution of that test:

$$5\ °C \leq T_{amb} \leq 40\ °C$$

14.2.2 Calibration of instrumentation

Calibration of all gauges and instrumentation shall be current. The accuracy and calibration frequency of instrumentation to be used during testing shall satisfy the requirements of ISO 13679.

The test laboratory standards for calibration and all the calibrations shall be documented. Copies of calibration reports for the devices measuring forces, pressures, torques, and displacements shall be included in the evaluation report.

Relative calibration of measuring devices, i.e. with a candidate measuring device being calibrated against a reference measuring device is permitted only when the reference device has been calibrated to traceable standards. Any such relative calibration shall be documented.

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Calibration of instrumentation may be further verified by additional calibration activities. The extent of such activities shall be determined by agreement between the assigner, the evaluator and the inspector.

14.2.3 Disabling of secondary seals

Connection sealability assessments shall be based only on primary sealing surfaces. Any other potential sealing surfaces that might impede gas flow to seepage detection ports shall have sealability demonstrably disabled.

In connections whose primary seals are flank seals and have torque shoulders in the flow path from the connections' interiors to seepage detection ports, disabling of torque shoulder sealability shall be ensured.

Disabling of secondary seals can be achieved by machining two grooves across the sealing face(s) of a connection component (as provided by ISO 13679) or by any other method that will ensure that the pressure of the test medium acting on the primary connection seal is the same as the specimen internal pressure.

Disabling of secondary seals shall be performed prior to the final assembly of the affected specimens. In specimens subjected to multiple make-breaks before a sealability test, disabling of the axial seals may be performed either before or after the make-ups associated with the galling resistance test.

14.2.4 Seepage measurement and rate definitions

14.2.4.1 Seepage collection – configuration

In any sealability test, seepage past a primary connection seal shall be routed to a monitoring device via ports drilled radially through the coupling wall at the low-pressure side of the seal. Representative locations for such ports are illustrated in Figure 14. Two ports shall be circumferentially located 180° apart at each axial location. Ports should be approximately 2,4 mm (3/32 in) in diameter and may be enlarged at their outer ends for attachment of seepage monitoring tubing if required, but enlargement should be minimized. The ports shall be drilled after final make-up of each connection whose seepage will be monitored, or closed during all make-ups to prevent loss of thread compound from the connections.

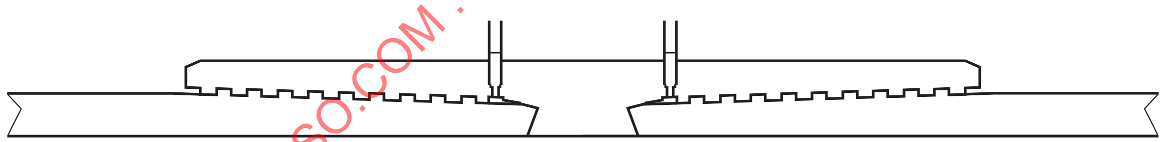

Figure 14 — Seepage detection ports

After the ports have been drilled, communication between each connection's two drilled ports should be cleared by injection of air or inert gas into one of those ports. Pressure of injected air or gas should not exceed the lowest value of 1 000 kPag (140 psig) and 25 % of the connection's rating for internal pressure.

Seepage from both ports at each axial location shall be jointly routed to a monitoring device that measures seepage volume or seepage rate. Tubing shall be small to minimize internal volume; metal tubing with 3,2 mm (1/8 in) outside diameter and working pressure greater than 25 % of the connection's pressure rating is recommended. The monitoring device shall be capable of measuring gas volumes as small as 1 ml or seepage rates as small as 0,06 ml/min. If the seepage rate exceeds the monitoring device capacity, seepage rate shall be recorded as the arithmetic average of manual samplings. Those samplings shall be taken no more than one hour apart, and no less frequently than at the beginning and end of any time interval in which testing conditions are held constant while internal pressure is applied to the connection specimen being tested.

A simple example of an acceptable method of seepage measurement is displacement of water in a graduated cylinder during a measured time interval. That example configuration is illustrated in

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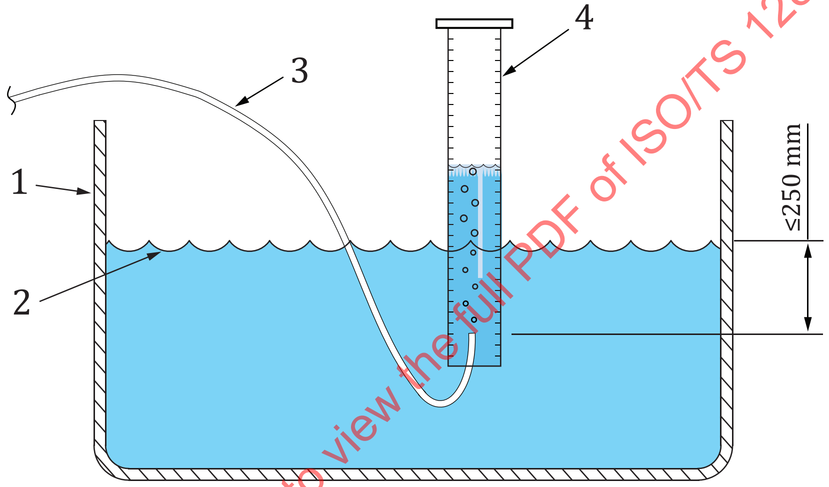
Figure 15. Its main principle of operation is that an inverted graduated cylinder is inserted in a reservoir with water. Near-vacuum is drawn inside the cylinder, which draws a certain water column inside the cylinder. In a test, gas seeped from a connection is conducted via a detection tube. The detection tube end is inserted into the immersed portion of the graduated cylinder. As more and more of the seeped gas bubbles through into the near-vacuum space, gas pressure builds up in that space and pushes the water level down. The amount of water displacement is calibrated to the volume of the seeped gas.

If that method is used, then all volume measurements shall be with respect to ambient laboratory temperature and atmospheric pressure. It is assumed that at the beginning of each detection period the detection tube is entirely filled with gas, so that a bubble is "just-forming" at its end inserted in the graduated cylinder. In that state, the back pressure in the tube depends on the depth of the tube's open end beneath the water's free surface in the reservoir. To minimize back-pressure in the gas collection system, differences in elevation between the detection tube end and the water level in the reservoir at the time of volume measurement shall not exceed 250 mm, (10 inches) which corresponds to ±2,4 % maximum measurement error relative to typical atmospheric pressure.



Key

1 reservoir

2 free water surface

3 detection tube

4 graduated cylinder

Figure 15 — Basic seepage volume measurement

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It is assumed that the gas trapped in the inverted cylinder will have its temperature, and hence its volume, influenced by the temperature of the water bath. To minimize temperature-related effects on the gas in the collection system, the water temperature shall not differ from the ambient laboratory temperature by more than 5 °C, which corresponds to ±1,7 % maximum measurement error relative to an ambient temperature of 293°K (assuming ideal gas behaviour).

Other methods of measuring seepage volumes or rates shall have errors no larger than ±5 %.

14.2.4.2 Seepage data acquisition frequency

Seepage data shall be measured and recorded at regular intervals during all load steps (holds) requiring seepage monitoring. The time intervals between measurement recordings shall not exceed:

— 5 minutes for each hold at ambient temperature and/or at the low-cycle temperature;

— 15 minutes for each hold at an elevated temperature.

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If needed, the measurement recording intervals should be adjusted to enable determination of seepage rate trends during the holds (increasing, decreasing, or stable).

In the event of a significant leak, monitoring and recording rate may need to be increased and correlated with adjustments of volume/levels of fluids being displaced in the leak collection system.

14.2.4.3 Seepage monitoring lines – maintenance

Seepage monitoring tubing (lines) shall be checked for blockage before and after each seepage-monitoring interval, unless:

— seepage is evident, or

— two or more consecutive monitoring intervals occur at the same target temperature and are not separated in time by more than 8 h, in which case the lines shall be checked before the first and after the last of those intervals.

Checking shall be done by monitoring transmission of air or gas from the outlet end of one tube to the outlet end of the other tube for each connection. Pressure of the injected air or gas shall not exceed 20 kPag (3 psig) during these checks. All checking events shall be documented. Any blocked tubing shall be cleared or replaced and the time of blockage detection recorded.

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14.2.4.4 Gas seepage rates during holds and average per-connection rates

Gas seepage volume during any hold interval shall be the volume of gas, at standard temperature and pressure, released during the duration of the hold interval.

Per-hold seepage rate for a given hold interval shall be equal to the ratio of the gas seepage volume (as defined above) in that hold interval divided by the duration of that hold interval.

Per-connection average seepage rate for a given loading condition is the sum of that connection's per-hold seepage rates in all hold intervals divided by the number of hold intervals at that loading condition.

EXAMPLE Average rate under compression in the thermal cycle test:

Per-connection average seepage rate at high cycle temperature is the sum of that connection's per-hold seepage rates in all intervals at high cycle temperature (i.e. in all cycles) divided by the number of cycles performed in the thermal cycle test.

14.2.5 Load application rates

Mechanical loads shall be applied to test specimens at loading rates consistent with loading rate guidelines in ISO 13679.

Rates of temperature-induced straining loads shall be controlled by applicable rates of temperature changes, as indicated in 14.4.6.7 and 14.4.6.8.

14.2.6 Excluded connections

Performance of some connections that have been tested in any full-scale test in accordance with this document can sometimes be excluded from comparison with the threshold performance requirements. Any such connection is referred to as an excluded connection. Observed and/or measured performance of excluded connections shall be reported in the evaluation report, but such performance shall not be considered in determining whether or not the threshold performance requirements have been met.

Any party assigned to a program role in an evaluation program (assigner, supplier, evaluator or inspector) can present rationale for granting the excluded connection status to one or more connections that have been tested in any full-scale test.

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A connection shall be granted the status of an excluded connection if, and only if, all the following conditions are satisfied:

a) A circumstance occurs during test execution that substantially affects that connection performance in a way that is inconsistent with test specifications;

b) The evaluator or the inspector provides a written description of the above circumstance and all pertaining evidence (e.g. photos) to the assigner, and the assigner provides that material to the supplier;

c) The assigner and the supplier review the provided evidence and agree on granting excluded connection status to the affected connection;

d) At least two independent parties performing the protocol roles are involved in reaching the agreement on excluded connection status referred to in c) above. For example, if the assigner is the same party as the supplier, the evaluator or the inspector needs to review the evidence and concur with the assigner; and if a single party combines the roles of assigner, supplier and evaluator, the inspector needs to act as the second independent party;

e) The evidence relative to the circumstance described in a) and b), and the agreement reached in c) and d) are included in the evaluation report.

Examples of conditions that can justify connection exclusion include, but are not limited to:

— localized loading inconsistent with the intended test procedure. For example, local buckling occurred during thermal cycling due to inadequate lateral support of the specimen or string in that area;

— inadequate execution of the test procedure. For example, seepage detection lines were found to have been plugged or disconnected for a portion of the test;

— connection post-mortem examination indicated damage that occurred during specimen assembly and/or testing that is considered to not have resulted from the intended test loads.

If the number of excluded connections in any full-scale test (galling resistance test or thermal cycle test or bend test or limit-strain test) does not exceed one connection (single leak path), then no repeat testing is required. Otherwise, replacement specimens for the specimens that contain excluded connections shall be re-tested, and the number and testing sequence of those replacement specimens shall be consistent with the number and testing sequence of the excluded connections to the degree that is possible, and any differences in history and/or testing sequence between the replacement specimens and excluded connection specimens shall be documented.

14.3 Galling resistance test

14.3.1 Task description

The galling resistance test is a full-scale test conducted on four specimens of the candidate connection. This test constitutes Task 4.1 of the evaluation procedure (see Figure 6). This task does not contain any subtasks.

Execution of Task 4.1 is mandatory.

Results of this test are key performance measures that are compared with the threshold performance requirements.

Subclauses 14.3.2 to 14.3.8 describe the rationale, specimens, scope, set-up, procedure, performance requirements, and reporting for the galling resistance test.

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14.3.2 Rationale and objectives

Two categories of galling damage to connection seal and thread surfaces are recognized: repairable galling or severe galling, which refer to damage that, respectively, can or cannot be repaired according to the supplier's field-repair procedure for the candidate connection.

Because casing connections can experience multiple make-ups and break-outs during casing string assembly in field service, the objective of the galling resistance test is to verify the candidate connection ability to withstand multiple make-ups and break-outs without severe galling.

Optionally, monitoring of connection deformation during make-ups and break-outs can provide additional insight into the connection's response to multiple make-ups.

14.3.3 Make-break specimens

Four candidate connection specimens shall be submitted for the galling resistance test: Specimen 1, Specimen 2, Specimen 3 and Specimen 5. Collectively, these specimens are referred to as make-break specimens.

The galling resistance test may be conducted prior to or together with the assembly of specimens for subsequent full-scale tests. If the specimen assembly for further testing is conducted at the same time as the galling resistance test, then Specimen 4 and Specimen 6 shall also be provided together with the make-break specimens.

Thread compound (dope) shall be obtained in accordance with the supplier's specifications for the candidate connection. A Material Safety Data Sheet (MSDS) for the obtained thread compound shall be provided and included in the evaluator report.

14.3.4 Scope of galling resistance test

The scope of Task 4.1 Galling Resistance Test includes multiple make-up and break-out cycles performed on make-break specimens and final assembly of connection specimens required for subsequent full-scale testing. Table 23 illustrates the scope of the make-break activities and target torques for the make-ups in the galling test and final specimen assembly.

Table 23 — Make-break sequence and final specimen make-up

<table>
<tr><th rowspan="2">Geometry config.</th><th rowspan="2">Specimen</th><th colspan="3">Make-break activity</th><th colspan="2">Assembly for subsequent testing</th></tr>
<tr><th>Specimen make-up number</th><th>Target make-up torque</th><th>Break-out</th><th>Full-scale test after final make-up</th><th>String assembly recommended</th></tr>
<tr><td rowspan="4">WGS</td><td rowspan="4">1</td><td>1</td><td rowspan="3">Maximum</td><td rowspan="3">Yes</td><td rowspan="3"></td><td rowspan="4">No</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4 = final</td><td>TF (WGS)</td><td>No</td><td>Limit strain test</td></tr>
<tr><td rowspan="4">WGT</td><td rowspan="4">2</td><td>1</td><td rowspan="3">Maximum</td><td rowspan="3">Yes</td><td rowspan="3"></td><td rowspan="4">No</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4 = final</td><td>TF (WGT)</td><td>No</td><td>Bend test</td></tr>
<tr><td rowspan="4">WST</td><td rowspan="3">3</td><td>1</td><td rowspan="2">Maximum</td><td rowspan="2">Yes</td><td rowspan="2"></td><td rowspan="2">No</td></tr>
<tr><td>2</td></tr>
<tr><td>3 = final</td><td>TF (WST-M)</td><td>No</td><td>Thermal cycle test</td><td>Yes</td></tr>
<tr><td>4</td><td>1 = final</td><td>TF (WST-S)</td><td>No</td><td>Thermal cycle test</td><td>Yes</td></tr>
</table>

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Table 23 *(continued)*

Geometry config.	Specimen	Make-break activity			Assembly for subsequent testing	
		Specimen make-up number	Target make-up torque	Break-out	Full-scale test after final make-up	String assembly recommended
WSC	5	1	Maximum	Yes		No
		2				
		3 = final	TF (WSC-M)	No	Thermal cycle test	Yes
	6	1 = final	TF (WSC-S)	No	Thermal cycle test	Yes

The codes for the final make-up torques TF(XXX) in Table 23 are consistent with specifications provided in Table 16 and Table 18. Upon completion of the analysis described in 12.3.7, the targets TF(XXX) for the final make-up torques become either minimum torque or maximum torque, in accordance with specifications and tolerances for the minimum and maximum target torques provided in 14.3.6.3.

Specimen 1 shall undergo three make-ups to the maximum torque, followed by a final make-up to a final torque TF(WGS), which will be either the minimum or the maximum torque.

Specimen 2 shall undergo three make-ups to the maximum torque, followed by a final make-up to a final torque TF(WGT), which will be either the minimum or the maximum torque.

Specimen 3 shall undergo two make-ups to the maximum torque, followed by a final make-up to a final torque TF(WST-M), which will be either the minimum torque or the maximum torque.

Specimen 4 shall be made up once to a final torque TF(WST-S), which will be either the minimum or the maximum torque.

Specimen 5 shall undergo two make-ups to the maximum torque, followed by a final make-up to a final torque TF(WSC-M), which will be either the minimum torque or the maximum torque.

Specimen 6 shall be made up once to a final torque TF(WSC-S), which will be either the minimum or the maximum torque.

Seal and thread surfaces of each specimen shall be examined upon each break-out. Any evidence of repairable galling and/or severe galling shall be recorded.

14.3.5 Set-up and instrumentation

14.3.5.1 Make-up process

Experimental set-up for the galling resistance test shall be adequate to carry out the make-break activities in accordance with the supplier's make-up and break-out procedure for the candidate connection.

Make-up and break-out conditions should be representative of the field conditions to the degree possible in the laboratory facilities where the testing is performed. Vertical make-up orientation is preferred to alleviate potential for pin-box misalignment, but horizontal make-up can be used provided that the assigner, the supplier and the evaluator agree on such orientation and additional test-specific requirements, if any are required (e.g. regarding the string make-up for the thermal cycle test). This document does not address challenges relative to slant make-up.

For coupled connections, floating of the coupling shall not be performed (i.e. each side shall be made up separately). Floating is not permitted to ensure that controlled make-up torque is applied to each connection separately and incremental make-ups of any test connections are avoided.

For each make-up and break-out of a coupling that contains an open end, the make-up support pin or a specimen pin shall be used to support that open end.

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When gripping couplings (or boxes), clamping forces should be controlled to prevent adverse distortion of the internally threaded member.

14.3.5.2 Torque-turns measurement

Applied torque and specimen turns shall be simultaneously monitored and recorded during each make-up and break-out on torque-versus-turn plots.

Resolution of the turn data recording system shall be at least 1/1 000th of a turn.

Turns may be measured with a wheel in contact with the rotating specimen, such as a turn potentiometer.

Torque may be measured with a load cell on a line attached to the moment arm of the tong. Adjustments might be required if the line is not perpendicular to the moment arm.

14.3.5.3 Use of strain gauges

It is recommended that deformation of each make-break specimen be monitored during each make-up and break-out.

Specimen instrumentation layout and strain measurement procedure should be according to ISO 13679.

14.3.6 Test procedure

14.3.6.1 General requirements

Unless otherwise required by this document, make-ups and break-outs of specimens shall be conducted according to the procedure provided by the supplier. The procedure provided by the supplier for the evaluation program shall be consistent with the procedure used for field assembly of the candidate connection.

The galling resistance test shall be performed at ambient temperature.

14.3.6.2 Thread compound application

When required, thread compound (dope) shall be applied according to specifications provided by the supplier plus additional requirements outlined below. In the event that the dope application requirements listed in this clause contradict the supplier's specifications, the supplier's specifications shall override the requirements listed below and any such occurrence shall be documented.

Connection seals and threads shall be clean and dry prior to dope application.

The same thread compound type shall be used for all test specimens.

All dope application shall be performed with a fine-bristled brush or a paint brush. The brushes shall be new or in a condition that does not show any damage or extensive use.

If the supplier's specifications indicate that dope amounts in the field application must be controlled by weight, then:

— amount of dope to be applied for each make-up in the test shall be controlled by weight;

— for make-ups performed to maximum target torque, the dope amount shall be no more than the minimum amount plus 10 % of the amount range specified by the supplier;

— for make-ups performed to minimum target torque, the dope amount shall be no less than the maximum amount minus 10 % of the amount range specified by the supplier;

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If the supplier's specifications indicate that dope amounts in the field application must be controlled by visual standards only, then:

— amount of dope to be applied for each make-up in the test shall be controlled by visual standards;

— for make-ups performed to maximum target torque, the dope amount shall be as close as practically possible to the minimum amount allowed by the supplier;

— for make-ups performed to minimum target torque, the dope amount shall be as close as practically possible to the maximum amount allowed by the supplier.

14.3.6.3 Make-up torque specifications

The torque achieved at the first make-up of each make-break specimen, which is performed to maximum target torque, shall not be less than the maximum torque allowed by the supplier minus the greater of the following:

— 10 % of the maximum torque allowed by the supplier;

— 20 % of the difference between the maximum torque and minimum torque allowed by the supplier.

The torque achieved at each make-up performed to maximum target torque, other than the first make-up of each make-break specimen, shall not be less than the maximum torque allowed by the supplier minus the greater of the following:

— 5 % of the maximum torque allowed by the supplier;

— 10 % of the difference between the maximum torque and minimum torque allowed by the supplier.

The torque achieved at each make-up performed to minimum target torque shall not be greater than the minimum torque allowed by the supplier plus the greater of the following:

— 5 % of the maximum torque allowed by the supplier;

— 10 % of the difference between the maximum torque and minimum torque allowed by the supplier.

If the above torque specifications are not achieved in a make-up of a connection in a make-break specimen, then the connection shall be broken out and made up again.

If the above torque specifications are not achieved in a make-up of a connection in Specimen 4 or Specimen 6, then either that connection shall be broken out and made up again or a replacement specimen shall be used, and the choice between those two options shall be made so that the total number of make-ups experienced by the pin and box components of the affected Specimen 4 or the affected Specimen 6 or their replacement specimens is minimized.

14.3.6.4 Repairs

Observed repairable galling shall be repaired. The repairs shall be performed according to the field repair procedure and recommendations provided by the supplier.

14.3.7 Performance assessment

The following threshold performance requirements for the galling resistance test are provided for reference purposes in accordance with adopted principles for the assessment criteria and result interpretation specified in 6.3.6 and 6.3.10.

A candidate connection shall be considered to have met threshold performance requirements in the galling resistance test if all of the following conditions have been satisfied for all connections included in the make-break specimens except any excluded connections:

a) Each connection has achieved the required number of make-break cycles;

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b) Make-up torques have been within limits specified for this test;

c) No severe galling on seal or threads has been observed;

d) Any observed repairable galling on seal or threads has been repaired according to the supplier's repair procedure.

14.3.8 Reporting

As a minimum, reporting of Task 4.1 Galling Resistance Test shall contain the following items:

— Identification of candidate connection specimens submitted for this test;

— Description of any excluded connections, as required in 14.2.6;

— Material safety data sheet for applied thread compound;

— Photographs of make-up equipment and at least one connection being made up;

— Photographs of at least one connection before and after doping (but before make-up);

— Consecutive number, date and time for each make-up and break-out;

— Targeted and achieved torques in each make-up;

— Break-out torques for each break-out;

— Torque-turn curves for all make-ups and break-outs;

— Observations of connection seal and thread surfaces upon each break-out;

— Photographs of at least one undamaged connection cleaned after break-out;

— Photographs of the connections that were representative of the worst post-break-out conditions (with or without galling) of pin and box seal and thread surfaces;

— Description and photographs of all occurrences of galling and performed repairs.

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14.4 Thermal cycle test

14.4.1 Task description

The thermal cycle test is a full-scale test conducted on four specimens of the candidate connection. This test constitutes Task 4.2 of the evaluation procedure (see Figure 6). This task does not contain any subtasks.

Execution of Task 4.2 is mandatory.

Results of this test are key performance measures that are compared with the threshold performance requirements.

Subclauses 14.4.2 to 14.4.10 describe the rationale, specimens, scope, set-up, procedure, performance requirements, and reporting for the thermal cycle test.

14.4.2 Rationale and objectives

The thermal cycle test is considered to be the most severe test in the test matrix included in the evaluation procedure. This test is conducted to evaluate a candidate connection structural integrity and sealability under cyclic thermo-mechanical loading representing a thermal well application, as described in 9.1. Conceptually, the test is configured to simulate a section of casing that is constrained at the ends and subjected to temperature excursions with associated internal pressure loading. The end supports control and limit the casing's axial expansion and contraction during the test.

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Inside the supported section, constrained heating induces axial compression due to conversion of thermal-expansion strain into compressive mechanical strain. Constrained cooling induces tension due to conversion of the thermal-contraction strain into tensile mechanical strain. The axial force acting along the supported section results from the overall deformation of the casing, and is constant in that section. The strain distribution in the casing depends on the temperature profile along the supported section. It is desirable that the temperature distribution be as uniform as possible along a strain-monitoring length that spans all included specimens.

A straight casing configuration is used for this test. This selection is based on results from studies conducted during the original TWCCEP development, which indicate that the impacts of the thermally-induced axial loads on seal contact stress are in general substantially larger than the impacts of the non-axisymmetric loads considered within typical thermal well operational scenarios that do not include significant geo-mechanical loads.

14.4.3 Thermal cycle specimens

Four candidate connection specimens shall be subjected to the thermal cycle test:

— Specimen 3, which is a make-break specimen made up three times;

— Specimen 4, made up only once;

— Specimen 5, which is a make-break specimen made up three times;

— Specimen 6, made up only once.

Collectively, these specimens are referred to as thermal cycle specimens.

Thermal cycle specimens may be tested individually or in string assemblies containing two or four specimens, as described in 14.4.6. The specimens assembled for a thermal cycle test are collectively referred to as a specimen string. Unless noted otherwise, provisions for a specimen string apply to all specimen configurations allowed for this test (i.e. an individual specimen, a two-specimen string, or a four-specimen string).

All thermal cycle specimens shall have their secondary seals disabled per 14.2.3 and their seepage detection ports drilled as per 14.2.4. Any spares substituted for those specimens shall have their secondary seals similarly disabled and seepage detection ports similarly drilled.

14.4.4 Scope of thermal cycle test

Each specimen string shall be subjected to 10 thermal cycles in which global strain is controlled and maintained at close-to-zero values over a portion of the specimen string including all connections in that string, and in which the string temperature is controlled and varied between a low target temperature prescribed as low cycle temperature and a high target temperature prescribed as high cycle temperature. In each cycle, the specimen string is held in compression at the high cycle temperature for a prolonged time (high-temperature hold) and subsequently in tension at the low cycle temperature (low-temperature hold).

The evaluator shall select a single temperature between 5 °C and 40 °C for the low cycle temperature, which shall remain fixed for the entire thermal cycle test. In order to facilitate test control, the selected low cycle temperature should be as close as reasonably possible to the average ambient temperature in the test laboratory during the thermal cycle test.

The high cycle temperature shall be not lower than, and as close as reasonably possible to, the upper-bound temperature of the ASL selected for the evaluation program.

Any pre-test exposure of the test specimens to elevated temperatures should be carefully considered, to minimize chances for any significant changes of the specimen material properties that would be inconsistent with the operational loading scenario.

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The loading sequence for the thermal cycle test is illustrated in Figure 16 and later specified in Table 24. The top chart in Figure 16 shows the relationship between the average string strain and the average string temperature. The bottom chart in Figure 16 shows the relationship between the thermally-induced mechanical strain and the average string temperature. The temperature axes of the top chart and the bottom chart are aligned.

The basic path corresponding to a thermal cycle between the low cycle temperature T_{lc} and the high cycle temperature T_{hc} at a constant zero strain is path QRQ.

In order to compensate for approximations that result from laboratory simulations of the intended field loading, two mechanical strain compensations are applied in addition to the above basic load path: lower-bound temperature strain increment (L_{TTS}) and temperature range strain increment (S_{RI}). Inclusion of those two mechanical-strain compensations modifies the cyclic load sequence to path PQRSWQP (Figure 16). Point S represents a high-temperature hold. Point P represents a low-temperature hold. Path QWX represents unloading to zero load upon completion of the last cycle. The L_{TTS} and S_{RI} compensations are derived in 14.4.5.

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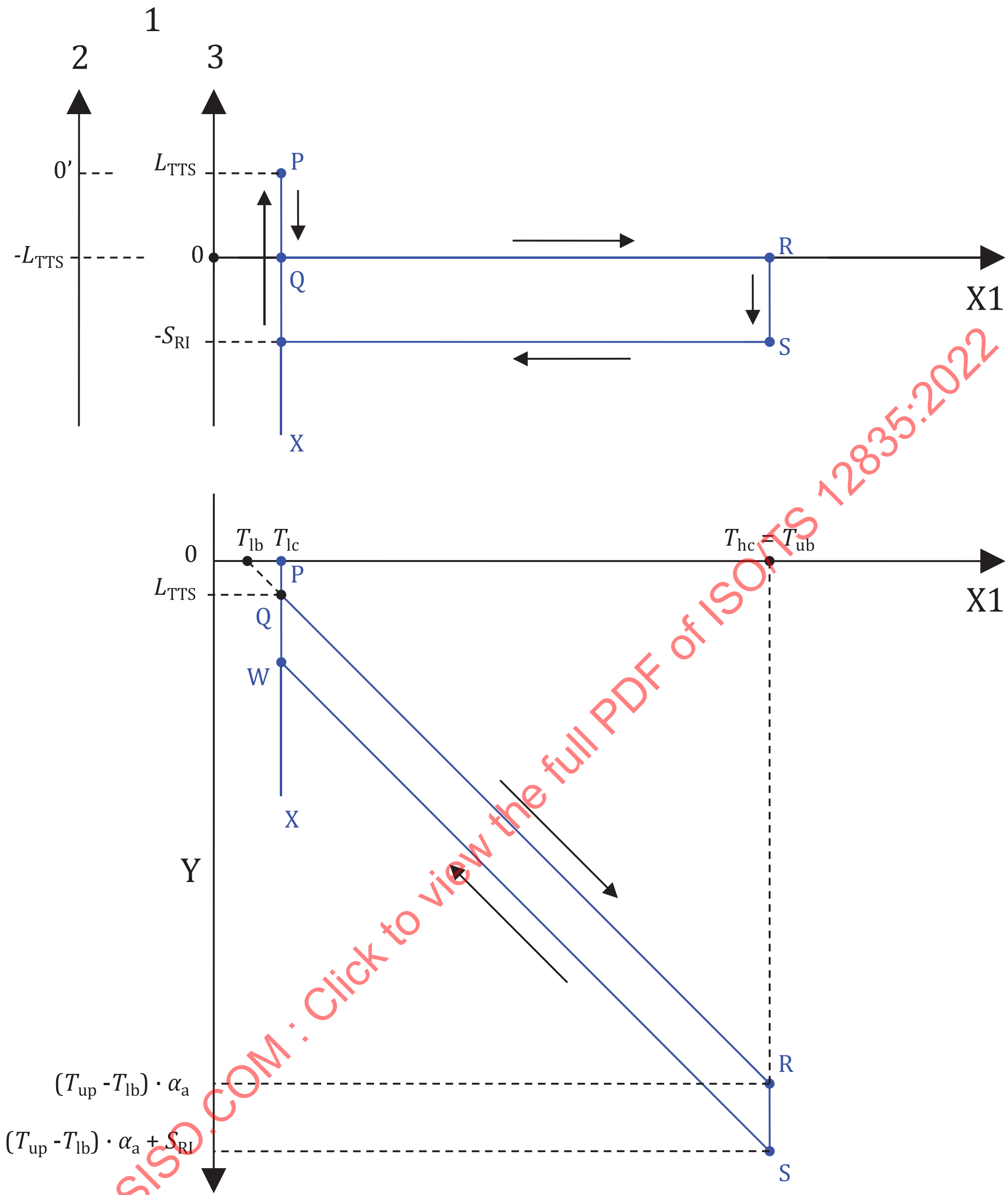

Key

X1 temperature, °C

Y compressive mechanical strain

1 average string strain

2 before initial offset

3 after initial offset

Figure 16 — Thermal cycle test sequence

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14.4.5 Mechanical strain compensations

14.4.5.1 General formulae

The following mechanical strains are applied to account for differences between the casing string configuration in a well and the specimen string in a thermal cycle test:

— Difference between the low cycle temperature T_{lc} used in the test and the lower-bound temperature T_{lb} assumed for the field conditions and defined by the selected ASL is compensated by applying an additional mechanical strain referred to as lower-bound temperature strain increment L_{TTS};

— Potential non-uniformities in the heat distribution along the specimen string, strain localization effects, and inaccuracies of temperature compensation of the elongation-measuring devices, are collectively addressed by applying an additional mechanical strain referred to as temperature-range strain increment S_{RI};

— Constrained thermal expansion within a given temperature excursion causes a bigger mechanical strain in the test string than in the well string, due to the difference in length between casing joints (well) and pups (specimen string). Unless pipe body strain is directly controlled in the test, this effect is compensated by reducing the S_{RI} increment by a strain offset referred to as strain-length compensating factor S_{LCF}. The L_{TTS} compensation is not affected by the strain-length effect, because the specimen string is not subjected to constrained thermal expansion between T_{lb} and T_{lc}.

Based on the above, the following general formulae are used for L_{TTS} and S_{RI}:

$$L_{TTS} = L_{TTS0} \quad (3)$$

$$S_{RI} = S_{RI0} - S_{LCFS} \quad (4)$$

where L_{TTS0} and S_{RI0} are strain increments based on the applicable temperature range, S_{LCFS} is the corresponding strain-length compensating factor, and L_{TTS} and S_{RI} are the strain compensations applicable in the thermal cycle test procedure (see Table 24). Formulae for S_{LCF}, L_{TTS} and S_{RI} are given in 14.4.5.2, 14.4.5.3 and 14.4.5.4. Derivation of S_{LCF} and examples of calculations for L_{TTS} and S_{RI} are provided in Annex B. All strain compensation factors apply to pipe body strains.

The evaluator shall report the input parameters and the resultant calculations for the L_{TTS} and S_{RI} strain compensations in the evaluation report.

In all strain compensation formulae, the average value of the thermal expansion coefficient (α_a) shall be assumed as the relevant mean of the local CTE values at the two temperatures bounding the applicable temperature range, as determined in Task 3.2 Material Property Verification (see 13.3). Downward extrapolation of measured CTE values might be required to determine the local CTE value at 5 °C.

Application of L_{TTS} and S_{RI} strain compensations might require alterations to the testing sequence prescribed by Figure 16 and Table 24. For some geometry-length combinations, S_{LCFS} might be larger than S_{RI0}. If S_{RI} becomes negative, it shall be applied before the relevant boundary of cyclic temperatures is reached. Such application sequence is required to avoid introducing excessive high-temperature strain, which might be caused by holding the length of the controlled elongation interval (see 14.4.6.2) constant until time to apply an adjustment strain; and to avoid unloading of the specimen string while arriving at the prescribed target strain. If an alteration of the test sequence is required, any such alteration shall be agreed between the assigner, the supplier and the evaluator.

Either positive or negative L_{TTS} and/or S_{RI} compensations of absolute magnitude less than 50 microstrains can be ignored, subject to agreement among the assigner, the supplier and the evaluator.

14.4.5.2 Strain-length compensating factor

If a controlled elongation interval in a thermal cycle test contained only casing pipe of uniform strength, and so did the field's wells, the strain during testing could be matched to the field strain just by holding

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length of the controlled elongation interval constant during all heating and cooling load steps in the test. The same approach would be equally valid if the proportions of stiff intervals (central regions of connections) to casing pipe lengths were the same in a test as in the field. That simplicity is lost when the proportions of stiff intervals to casing pipe lengths are not the same in both instances, and corrections need to be made to preserve strain similarity in the differing lengths of pipe.

The corrections to achieve strain similarity are achieved by introducing a strain-length compensating factor S_{LCF} given in Formula (5):

$$S_{LCF} = \Delta T \cdot \alpha_a \left(\frac{L_{therm}^{test}}{L_{mech}^{test}} - \frac{L_{therm}^{field}}{L_{mech}^{field}} \right) \quad (5)$$

where

ΔT is the applicable temperature range;

α_a is the average value of the thermal expansion coefficient in the temperature range ΔT;

and where the following length parameters depend on the specimen string configuration selected for the thermal cycle test (see 14.4.6.1) and the field configuration simulated by that specimen string configuration:

— L_{therm}^{test} is the length of the controlled elongation interval;

— L_{mech}^{test} is the length assumed to be deforming appreciably under mechanical forces in the test configuration, which is somewhat shorter than L_{therm}^{test}

— L_{therm}^{field} is the thermal-expansion length in the field configuration that is simulated in the test configuration (i.e. having the same number of connections), based on an assumed pipe joint length of 12,5 m (41 ft);

— L_{mech}^{field} is the length assumed to be deforming appreciably under mechanical forces in the field configuration, which is somewhat shorter than L_{therm}^{field}.

The evaluator shall determine, or be responsible for determining, an effective stiff length of the candidate connection. L_{mech}^{test} shall be adopted as L_{therm}^{test} minus a number of effective stiff lengths equal to the number of connections within the controlled elongation interval. L_{therm}^{field} shall be adopted as the typical pipe joint length of 12,5 m (41 ft) times the number of connection specimens within the controlled elongation interval (one or two or four). L_{mech}^{field} shall be adopted as L_{therm}^{field} minus the same number of the effective stiff lengths as contained within the controlled elongation interval.

Annex B provides a list of assumptions and resultant derivations of the formulae for calculating the length parameters listed above and the S_{LCF}. If any of the assumptions adopted for those calculations are considered invalid in a particular evaluation program, then the assigner, the supplier and the evaluator shall agree on measures needed to account for those discrepancies in the evaluation procedure.

14.4.5.3 Lower-bound temperature strain compensation

The lower-bound temperature strain increment (L_{TTS}) accounts for the difference between the test low cycle temperature T_{lc} and the lower-bound temperature T_{lb} defined by the ASL.

It is considered impractical to specify the ASL lower-bound temperature (5 °C) to be a uniquely prescribed low cycle temperature, because most laboratories would have to employ powerful cooling systems to bring the string temperature down to that temperature in every cycle. Instead, a higher low cycle temperature may be selected; and if it is, then an additional mechanical strain is applied to account for the difference between the selected low cycle temperature and the ASL lower-bound temperature. This additional strain is first applied in compression at the low cycle temperature to

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simulate compression that the specimen string would have undergone had the test begun at the ASL lower-bound temperature. Upon return to the low cycle temperature at the end of each thermal cycle, the same amount of strain is applied in tension.

The additional strain L_{TTS0} resultant from constrained thermal expansion between T_{lc} and T_{lb} in a field configuration is equal to Formula (6):

$$L_{TTS0} = (T_{lc} - T_{lb}) \cdot \alpha_a \cdot \left(\frac{L_{therm}^{field}}{L_{mech}^{field}} \right) \quad (6)$$

The value for α_a in Formula (6) shall be adopted according to the average thermal expansion coefficient in the temperature range from T_{lb} to T_{lc}, as determined in 13.3.4.

The corresponding strain in a test configuration is equal to the same strain as in the field configuration, because the test string does not experience any constrained thermal expansion in the temperature range from T_{lb} to T_{lc}.

Based on Formula (3) and Formula (6), the following L_{TTS} strain compensation shall be applied in the test procedure:

$$L_{TTS} = (T_{lc} - T_{lb}) \cdot \alpha_a \cdot \left(\frac{L_{therm}^{field}}{L_{mech}^{field}} \right) \quad (7)$$

Caution: L_{TTS} determined by Formula (7) applies to average string strain as determined in 14.4.6.4.

After the strain compensation L_{TTS} is first applied as a compressive strain at the beginning of the test, the strain-measuring system is offset to indicate zero strain with the L_{TTS} applied. This offset sequence results in a vertical shift of the average-strain axis in Figure 16: from origin 0' (before the initial offset) to origin 0 (after the initial offset).

14.4.5.4 Temperature range strain compensation

The temperature range strain increment S_{RI} is introduced to account for potential non-uniformities in the heat distribution along the specimen string, strain localization effects, and inaccuracies of temperature compensation of the elongation-measuring devices. All those potential impacts are considered to depend on the applied temperature range.

This document specifies a collective strain compensation that amounts to 10 % of the mechanical strain associated with the thermal strain corresponding to the temperature range between the lower-bound temperature and the upper-bound temperature for the selected ASL:

$$S_{RI0} = 0,1 \cdot (T_{ub} - T_{lb}) \cdot \alpha_a \cdot \left(\frac{L_{therm}^{field}}{L_{mech}^{field}} \right) \quad (8)$$

The value for α_a in Formula (8) shall be adopted according to the average thermal expansion coefficient in the temperature range from T_{lb} to T_{ub}, as determined in 13.3.4.

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The corresponding strain-length compensating factor is equal to:

$$S_{\mathrm{LCFS}} = (T_{\mathrm{ub}} - T_{\mathrm{lb}}) \cdot \alpha_{\mathrm{a}} \cdot \left(\frac{L_{\mathrm{therm}}^{\mathrm{test}}}{L_{\mathrm{mech}}^{\mathrm{test}}} - \frac{L_{\mathrm{therm}}^{\mathrm{field}}}{L_{\mathrm{mech}}^{\mathrm{field}}} \right) \tag{9}$$

Based on Formula (4), Formula (8) and Formula (9), the following S_{RI} strain compensation shall be applied in the test procedure:

$$S_{\mathrm{RI}} = (T_{\mathrm{ub}} - T_{\mathrm{lb}}) \cdot \alpha_{\mathrm{a}} \cdot \left(0{,}1 \cdot \frac{L_{\mathrm{therm}}^{\mathrm{field}}}{L_{\mathrm{mech}}^{\mathrm{field}}} - \left(\frac{L_{\mathrm{therm}}^{\mathrm{test}}}{L_{\mathrm{mech}}^{\mathrm{test}}} - \frac{L_{\mathrm{therm}}^{\mathrm{field}}}{L_{\mathrm{mech}}^{\mathrm{field}}} \right) \right) \tag{10}$$

Caution: S_{RI} determined by Formula (10) applies to average string strain as determined in 14.4.6.4.

See applicable provisions in 14.4.5.1 if the above expression yields a negative value.

14.4.6 Set-up and instrumentation

14.4.6.1 Test configuration

Allowable test configurations are:

— one single string of four specimens,

— two strings of two specimens,

— four individual specimens.

When thermal cycle specimens are tested in two strings of two specimens, one string shall contain Specimen 3 and Specimen 4 and the other string shall contain Specimen 5 and Specimen 6 (this configuration requirement for two strings is to ensure specimen selection procedures in 14.4.9 work in all cases).

The allowable test configurations are illustrated in Figure 17. For each configuration, Figure 17 shows a corresponding length of the controlled elongation interval (as described in 14.4.6.2).

The length requirements for the controlled elongation interval are shown only for one end of the 4-specimen string assembly. The same requirements apply to both ends of any specimen string and to all test configurations.

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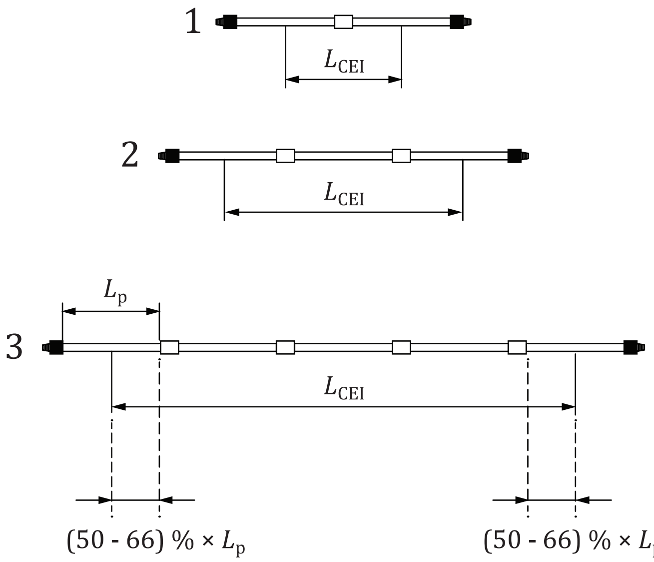

Key

1 1-specimen string

2 2-specimen string

3 4-specimen string

Figure 17 — Allowable configurations for thermal cycle test

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14.4.6.2 Controlled elongation interval

In order to control global (and average) strain of a specimen string, axial deformation of the specimen string (i.e. its elongation or shortening) shall be measured and controlled over an interval that is referred to as the controlled elongation interval. The controlled elongation interval shall:

— include all test specimen connections assembled in the specimen string (can be one, two, or four couplings or integral connections); and all intermediate pups between adjacent connection specimens assembled in-series;

— include at least half but no more than two-thirds of each casing pup between an end fixture and the nearest connection specimen;

— be wholly included in the insulated portion of the specimen string (and thus be at “uniform” temperature during the various stages of the test).

Instrumentation used to control axial deformation in the controlled elongation interval shall be configured so that no significant loss of accuracy results from temperature effects due to cyclic heating and cooling of the specimen string. Variations less than ±5 % of the controlled elongation interval’s free thermal expansion between T_{lb} and T_{ub} determined from the measured average thermal expansion coefficient α_a shall be considered acceptable. Larger variations may be accepted for practical reasons by agreement between the evaluator and the assigner, noting that global strain is primarily controlled to be zero in the thermal cycle test.

Control of a specimen string’s elongation within the controlled elongation interval should be based on measurements acquired by linear potentiometers sufficiently far from the insulated surface of the specimen string to minimize heat effects on the instruments. Two potentiometers on circumferentially opposing sides of the specimen string should be used to provide an indication of any string curvature developing in the plane of the instruments, and to provide elongation measurements insensitive to any curvature effects by averaging the two potentiometers’ outputs.

When possible and practical, strains in individual casing pups should be acquired, so that strain distribution along the specimen string could be assessed, and local strains could be compared with the

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average string strain within the controlled elongation interval. Additionally, connection loads imposed during the thermal cycle test will be much less susceptible to any error in determination of the difference between L_{therm}^{test} and L_{mech}^{test}, if testing control emphasizes strains in individual casing segments over strain in the controlled elongation interval, when differences might arise.

14.4.6.3 Effective string length

For the purpose of controlling strain in a specimen string, an effective string L_{eff} shall be adopted equal to length L_{mech}^{test} that is assumed to be deforming appreciably under mechanical forces in the thermal cycle test, which is introduced in 14.4.5 and calculated according to formulae in Annex B:

$$L_{eff} = L_{mech}^{test} \tag{11}$$

The above formulation of the effective string length is considered suitable for application of the mechanical strain compensations in a thermal cycle test. Use of the effective string length for other purposes shall be agreed between the assigner, the supplier and the evaluator.

For each specimen string, the relationship between the elongation in the controlled elongation interval and the strain imposed by mechanical tension and compression shall be verified prior to test commencement. This can be done by applying modest axial loads to the specimen string (within 30 % to 50 % of pipe body yield) and comparing the load-elongation-strain measurements to results obtained from closed-form load-deformation and stress-strain formulae; or by an alternative method as agreed by the assigner, the supplier, and the evaluator.

Strain gauges and/or local-strain measuring devices should also be placed on individual casing pups to relate global elongation measurements to local strains.

The assumed effective string length and the verification measurements shall be reviewed by the evaluator and the inspector to verify accuracy of the strain control system and correctness of the effective string length calculation. Some discrepancies might result from that review, in that the obtained load-elongation measurements might indicate that the string length deforming appreciably under the applied mechanical loads is somewhat different from the effective string length assumed according to Formula (11). This can be due to, for example, variations between the actual pipe wall thickness and the thickness assumed in Annex B calculations, or other string-configuration variations. Those discrepancies should be resolved by agreement between the evaluator and the inspector.

The evaluator shall report the determined effective string length and the acquired verification measurements in the evaluation report.

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14.4.6.4 Average string strain

Average string strain shall be used to control loading of a specimen string in the thermal cycle test.

Average string strain shall be calculated by either of the following alternatives:

— If elongation of the controlled elongation interval is measured but pipe strains in individual casing pups are not measured, calculate the average string strain by dividing the elongation of the specimen string within the controlled elongation interval by the effective string length.

— If elongation of the controlled elongation interval is measured and pipe strains in individual casing pups are directly measured without including stiff lengths in the strain measurements, determine the average axial strain based on the combination of the acquired elongation and strain measurements as agreed by the assigner, the supplier, and the evaluator.

As mentioned in 14.4.5.1, expressions provided for L_{TTS} and S_{RI} apply to pipe body strains. If the latter method of obtaining average string strain (from the two methods listed above) is employed, the expressions for L_{TTS} and S_{RI} might have to be adjusted depending on the method of controlling the average string strain, as agreed by the assigner, the supplier, and the evaluator.

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14.4.6.5 Axial force

The following terminology related to axial forces is adopted:

— Axial force – a force acting in the direction of the symmetry axis of the pipe or connection

— External axial force – an axial force applied to the test specimen by external test fixtures (e.g. load frame actuator)

— Capped-end axial force – an axial force resulting from capped-end effect of internal pressure

— Specimen axial force – an axial force experienced by the test specimen due to combined effects of external axial force and capped-end axial force.

External axial force applied to each specimen string shall be measured and recorded throughout each thermal cycle test.

When a single specimen string is tested in a hydraulically-driven testing system, the external axial force can be measured using differential pressure acting on the hydraulic actuator, provided no appreciable axial force is reacted by the end fixtures installed between the actuator and the specimen string. A redundant force measurement by a load cell installed in-series with the specimen string is recommended, since the actuator might not be free of frictional drag if the piston becomes misaligned in its cylinder.

For multiple strings tested in parallel, external axial force acting on each specimen string shall be measured independently.

Load cells used for axial force measurement shall be configured so that no appreciable loss of accuracy results from temperature effects due to cyclic heating and cooling of the specimen strings. Temperature-compensated instrumentation should be used, or the load cells should be cooled to minimize temperature-related loss of accuracy, or both of these techniques might be utilized. Load cell errors less than ±3 % of the true force shall be considered acceptable. Differences larger than ±3 %, between axial force measured by a load cell and axial force measured by actuator pressure, should be investigated and resolved.

14.4.6.6 String insulation

Each specimen string shall be covered with thermal insulation to minimize heat loss at elevated temperature and to distribute the heat as uniformly as possible along the string.

The insulation shall cover the entire controlled elongation interval, plus an additional length of at least one pup diameter beyond each end of the controlled elongation interval.

14.4.6.7 Heating

Heating of the specimen string may be accomplished by any means capable of producing sufficiently high temperatures throughout the length of the controlled elongation interval, such as heat pads or induction heating. The heating apparatus shall not induce substantial temperature differences between components of the specimen string, in particular between adjacent specimens or between adjacent pins and boxes.

Rate of temperature change at any thermocouple location along the specimen string during heating shall not exceed 5 °C (9 °F) per minute.

14.4.6.8 Cooling

Cooling of the specimen string from the high cycle temperature to the low cycle temperature by ambient air might take a long time, which is likely to be undesirable in most evaluation programs. The following cooling options are permitted:

— natural cooling by ambient air;

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— accelerated cooling by forced convection cooling with ambient air;

— accelerated cooling by circulating water or other cooling fluid inside or outside the string, as long as it does not interfere with the leakage detection system.

The cooling fluid should be restricted from contacting hot connection surfaces. For example, this can be accomplished by circulating the fluid inside a mandrel that is inserted inside the specimen string (also see comments about the internal mandrel in 14.4.6.10). The cooling apparatus shall not induce substantial temperature differences between components of the specimen string, in particular between connected pins and boxes.

The assigner, supplier and evaluator shall agree on either natural or accelerated cooling at the onset of the evaluation program.

Rate of temperature change at any thermocouple location along the specimen string during cooling should not exceed 5 °C (9 °F) per minute.

14.4.6.9 Temperature measurements

Temperature of the specimen string shall be measured by thermocouples. Multiple thermocouples shall be used to permit assessment of temperature distribution along the specimen string and facilitate controlled input of heat during temperature excursions.

As a minimum, thermocouples shall be placed in the following axial locations of the specimen string inside the controlled elongation interval:

— on casing pup bodies within 10 cm (4 in) from each connection, with the distance measured from each box face or, for integral connections, from the external upset;

— for threaded-and-coupled connections, at the axial centre of each coupling; for integral connections, near the axial centre of the increased-diameter interval of the box component;

— in the centre of each pup belonging to two specimens within the specimen string;

— on casing pup bodies at ends of the controlled elongation interval.

Additional thermocouples may be placed outside the controlled elongation interval, or anywhere else, to provide enhanced data on temperature distribution along the specimen string.

At least one thermocouple shall be placed in each axial location. Redundant thermocouples may be placed around any circumference to ensure continuing measurements in case of thermocouple failure.

Circumferential location of a thermocouple may be arbitrary when a specimen string is tested in a vertical orientation. For horizontal testing orientation, thermocouples should be located as close as practical to the horizontal symmetry plane of the specimen string.

All thermocouples except those that have failed shall be considered active thermocouples.

Failed thermocouples within the controlled elongation interval shall be replaced as soon as it is practical to do so. Failed thermocouples outside the controlled elongation interval should also be replaced. Use of pre-installed, redundant thermocouples is equivalent to thermocouple replacement.

14.4.6.10 Internal mandrel

A pressure-tight internal mandrel or filler bar may be inserted inside each specimen string.

Rationale for the use of the mandrel or filler bar is to:

— reduce the volume of gas used to pressurize the string, and consequently reduce the energy stored in the compressed gas;

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— provide additional bending stiffness to reduce potential for local buckling of the specimen string under compression;

— optionally, when a hollow mandrel is used, provide a conduit for circulating cooling fluid. The circulation of fluid through the mandrel allows accelerated cooling of the specimen string in each thermal cycle.

The internal mandrel should be dimensioned to reduce the internal specimen string volume significantly but shall not result in any diametral interference with the connection specimens. The internal mandrel should provide sufficient lateral support to resist the specimen string's column buckling tendencies and keep the specimen string as straight as practical.

To maximize specimen string straightness, the mandrel should be sleeved or shimmed at each tested connection, if necessary, to leave its effective outside diameter no larger than the specimen string's drift diameter and no smaller than the drift diameter minus 2 mm (0.080 in). The mandrel should be sleeved or shimmed at both ends, if necessary, such that diametric clearance is between 2 mm and 4 mm at those locations. If used, sleeves or shims shall be firmly attached to the mandrel and long enough to account for relative movement.

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Some additional mandrel design guidelines are:

— The mandrel should be resistant to collapse at pressures and temperatures corresponding to the high cycle temperature.

— The mandrel should be as long as possible while allowing for end clearance and accounting for thermal expansion differences between the specimen string and the mandrel.

— Temperature degradation of the mandrel's strength should be accounted for in the design.

— Design conservatism of the mandrel should be generous as mandrel failure would be detrimental to the evaluation. Possible conservatism could include:

  — assuming the specimen string is moment-free at end fixtures, intermediate supports and other contact points between the specimen string and the mandrel;

  — estimating the specimen string's maximum axial load conservatively and assuming maximum possible lateral displacement of the specimen string;

  — including the mandrel's calculated bending stress in collapse calculations and using large design factors.

— Mandrel lateral deflection should be minimized, with calculated lateral deflection no larger than 1/200th of the span between lateral restraints being a realistic design goal if the mandrel is considered a simple beam between each pair of lateral restraints. One or more laterally stiff external supports should be considered if this deflection design goal cannot be achieved without such external supports. External supports should not contact the specimen string within one pipe diameter of any connection specimen.

14.4.6.11 Internal pressure

Internal gas pressure shall be applied with a dry, inert gas such as nitrogen. As an option, a 5 % helium tracer gas may be added.

Internal pressure in each specimen string shall be measured continuously during the test and recorded by the data acquisition system. System pressure monitoring accuracy shall be consistent with applicable guidance provided by ISO 13679, unless otherwise agreed by the assigner and the evaluator.

14.4.6.12 Data acquisition

A computerized data acquisition system shall be used.

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As a minimum, the data acquisition system shall enable acquiring and recording the following data continuously during each test, except for test maintenance periods:

— Temperatures at all thermocouple locations;

— Elongation of the specimen string within the controlled elongation interval (this should be equal to zero or L_{TTS} for most load steps);

— Average string strain (calculated from the elongation measurement above);

— Axial stroke of the test frame actuator;

— External axial force imposed on the specimen string;

— Internal pressure;

— Seepage from each connection;

— Date and time.

The following minimum data acquisition frequency is recommended for the thermal cycle test:

— 0,5 Hz during heating and cooling;

— 0,25 Hz during constant-temperature holds;

— 0,05 Hz during each unrestrained portion of the bakeout.

14.4.6.13 Test frame and instrumentation checks

Integrity of the test assembly and accuracy of instrumentation measurements shall be checked, and where possible also verified, prior to test commencement.

As a minimum, the scope of the assembly checks shall include:

— Specimen string elongation measurements and/or other measurements to be used for strain control;

— Specimen string pressure integrity (e.g. by applying axial compression-tension and internal pressure up to 10 % of equivalent yield stress);

— Pressure integrity of the internal mandrel;

— Connectivity and clearance of seepage measurement lines;

— Functioning of data acquisition system.

14.4.7 Test procedure

14.4.7.1 Specimen configuration

The thermal cycle specimens shall be tested either individually or in a string assembly. In any configuration, all thermal cycle specimens shall be subjected to the same load steps, as described below.

14.4.7.2 Load steps

Table 24 contains the load steps for the thermal cycle test. Path indicators (points P, Q, R, S, W, and X) indicated in Table 24 are consistent with Figure 16. Symbols used in Table 24 are explained in 4.2.

Average pipe strain upon test initiation in load step 0.1 is indicated as 0", because the zero-strain position is reset ("re-zeroed") twice in later load steps. The first such reset takes place in load step 0.5, after a series of elastic loading and unloading. That re-zeroed strain is denoted as 0'. The second strain

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reset takes place in load step 0.8, after the L_{TTS} strain compensation is applied. The zero-strain position after that load step is denoted as 0. The 0'-strain and 0-strain positions are illustrated in Figure 16.

In load step 0.3 and load step 0.4, internal pressure and external axial forces are applied by mechanical compression and tension to target specimen axial force magnitudes -$F_{33\,\%}$ and +$F_{33\,\%}$, which respectively denote the compressive and tensile specimen axial forces producing equivalent stress equal to 33 % of the pipe-body nominal yield strength at room temperature.

In all other load steps of the thermal cycle test that involve non-zero specimen axial loads, the magnitudes of those axial loads shall result from the controlled temperature excursions, strain compensations, and internal pressure.

Internal pressure shall be applied as indicated in Table 24. For the majority of the load steps, the target pressures correspond to the saturated-steam pressure-temperature relationship (see 9.2 and 9.3), although in some load steps an arbitrary pressure value has been selected for practical reasons. In the load steps that involve changes of both pressure and temperature, those changes should be applied so that the saturated-steam pressure-temperature relationship is followed as closely as practical. It is acknowledged that the sequence of the pressure and temperature application in the thermal cycle test is somewhat different from the corresponding sequence used in Task 2.2 Specimen Configuration Analysis (see 12.3), for reasons explained in 6.5.7.

Average string strain in Table 24 refers to the average axial strain of the specimen string, as defined in 14.4.6.4. In order to achieve pipe body strain in the specimen string that is equivalent to the pipe body strain in the simulated field configuration, the target strains in the test procedure are compensated for strain-length effects and other influencing factors by applying L_{TTS} and S_{RI} compensation factors, as determined in 14.4.5.

In load step 1.3, the prescribed default hold time is 120 hours. This hold constitutes the specimen bake-out, which is needed to allow temperature- and time-dependent property changes to occur in the test specimens (e.g. changes in dope consistency and steel relaxation), so that their condition is representative of connections subjected to long-term field loading (see 6.5.6). Given that those property changes in general depend on external loading, the evaluation procedure requires conducting the 120-hour specimen bake-out under compression, as resultant from the prescribed loading sequence.

If conducting the default hold under compression is not possible in load step 1.3 for practical or other reasons, then by agreement between the assigner, the supplier, and the evaluator, a pre-test bake-out may be conducted on each specimen in an unconstrained condition prior to the thermal cycle test. In that case, the duration of the hold in load step 1.3 shall be the longer of 24 hours and the difference between 120 hours and the pre-test bake-out. If the thermal cycle test is conducted on individual specimens, this provision shall apply to each specimen separately. If the test is conducted on a multi-specimen string, then the hold in load step 1.3 shall correspond to the longest duration required for the specimens included in that string. All cases when the bake-out in load step 1.3 differs from the default of 120 hours under compression are considered deviations from the procedure prescribed by this document and shall be reported as such in the evaluation report.

In load step R1, average string strain measured after completion of the last thermal cycle and during unloading of the specimen string from zero average string strain (point Q in Figure 16) to zero load (point X in Figure 16) is assumed as a residual post-cycle strain. The absolute magnitude of that strain is denoted as ε_{TE}. Typically, the residual post-cycle strain can be expected to be compressive, in which case "-ε_{TE}" will be a negative value.

If the thermal cycle test is conducted on a single 4-specimen string, then the ε_{TE} value obtained for that string shall be adopted as the average post-cycle strain ε_{TEa}, for use in the limit-strain test. If the thermal cycle test is conducted on multiple strings, then ε_{TEa} shall be calculated as the average of the ε_{TE} values obtained for all specimen strings. For example, if upon unloading from point Q to point X, average string strain changes from 0 to −500 microstrains, then the value referenced as - ε_{TE} in Table 24 will be −500 microstrains. If this strain magnitude is also assumed for the average post-cycle strain, then the ε_{TEa} value used in the limit-strain test (see Table 25 and Table 26) will be +500 microstrains.

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Table 24 — Load steps for thermal cycle test

Load step	Cycle	Description	Path	Temp °C	Specimen axial force	Average string strain με	Internal pressure MPa	Duration (minutes or as noted)	Comments
0.1	0	Test initiation	P	T_{lc}	0	0”	0		Zero strain upon test initiation
0.2		Maximum pressure hold			Resultant	Resultant	$p_{SS}(T_{hc})$	15	For comparison with limit-strain test
0.3		Elastic compression			$-F_{33\,\%}$			15	
0.4		Elastic tension			$+F_{33\,\%}$			15	Approximate comparison with ISO 13679
		Depressurize and release load			↓ 0		↓ 0		
0.5		Re-zero total strain	P		0	0'	0		Assume current strain as zero strain after elastic loading
0.6		Compress by L_{TTS}	P-Q		Resultant	$-L_{TTS}$			Strain-compensation L_{TTS} is applied in compression
0.7		Maximum pressure hold	Q				$p_{SS}(T_{hc})$	15	Compare with Specimen 1 in limit-strain test load step 0.7
		De-pressurize					↓0		
0.8		Re-zero total strain				0	0		Assume current strain as zero strain after L_{TTS} compensation
0.9		Lock strain reference							For subsequent load steps, the L_{TTS}-compensated strain is assumed as zero

[a] Default hold time is 120 hours. This default may be changed only in accordance with applicable procedural and reporting provisions in 14.4.7.2.

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Table 24 *(continued)*

Load step	Cycle	Description	Path	Temp °C	Specimen axial force	Average string strain με	Internal pressure MPa	Duration (minutes or as noted)	Comments
1.1	1	Heat and pressurize	Q-R	↑	Resultant	0	↑ $p_{SS}(T)$		Constrained heating. Compression and pressure increasing with temperature
1.1.1		Interim temperature T_{i1}=180 °C		180			$p_{SS}(180)$	15	Maximum temperature to which ISO 13679 applies
1.1.2.... 1.1.N		Interim temperatures from T_{i2} to T_{iN}		T_{ik}			$p_{SS}(T_{ik})$	15	T_{ik} = 240, 290 325, 350 °C for as long as T_{ik}<T_{hc}
			R	T_{hc}			$p_{SS}(T_{hc})$		Arrive and stabilize at T_{hc}
1.2		Compress to -S_{RI} strain	R-S			0 ↓ -S_{RI}			Strain compensation S_{RI} is applied in compression
1.3		High temperature hold	S			-S_{RI}		120 hours [a]	Default hold duration is 5 days. See footnote [a] below and applicable guidance in 14.4.7.2
1.4		Cool and de-pressurize	S-W	↓ T_{lc}			$p_{SS}(T)$ ↓ 1		Let pressure drop with temperature. Maintain 1 MPa minimum pressure after cooling
			W				1		Arrive and stabilize at T_{lc}
1.5		Tension to zero control strain	W-Q	T_{lc}		-S_{RI} ↑ 0			Strain compensation S_{RI} is applied in tension
1.6		Re-pressurize	Q			0	↑ $p_{SS}(T_{hc})$		
1.7		Tension to lower-bound temperature strain	Q-P			0 ↑ L_{TTS}	$p_{SS}(T_{hc})$		Strain compensation L_{TTS} is applied in tension
1.8		Low temperature hold	P			L_{TTS}		120	Hold at T_{lc} is 2 h
1.9		De-pressurize. Return to zero control strain	P-Q			L_{TTS} ↓ 0	↓ 1		De-pressurize to 1 MPa. Re-compress by L_{TTS}

[a] Default hold time is 120 hours. This default may be changed only in accordance with applicable procedural and reporting provisions in 14.4.7.2.

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Table 24 *(continued)*

Load step	Cycle	Description	Path	Temp °C	Specimen axial force	Average string strain με	Internal pressure MPa	Duration (minutes or as noted)	Comments
2.1	2	Heat and pressurize	Q-R	↑ T_{hc}	Resultant	0	↑ $p_{SS}(T)$		Constrained heating. Pressure increasing with temperature
2.2		Compress to -S_{RI} strain	R-S	T_{hc}		0 ↓ -S_{RI}	$p_{SS}(T_{hc})$		Strain compensation S_{RI} is applied in compression
2.3		High temperature hold	S			-S_{RI}		240	Hold at T_{hc} is 4 h
2.4		Cool and de-pressurize	S-W	↓ T_{lc}			$p_{SS}(T)$ ↓ 1		Let pressure drop with temperature. Maintain 1 MPa minimum pressure after cooling
2.5		Tension to zero control strain	W-Q	T_{lc}		-S_{RI} ↑0	1		Strain compensation S_{RI} is applied in tension
2.6		Re-pressurize	Q			0	↑ $p_{SS}(T_{hc})$		
2.7		Tension to lower-bound temperature strain	Q-P			0 ↑ L_{TTS}	$p_{SS}(T_{hc})$		Strain compensation L_{TTS} is applied in tension
2.8		Low temperature hold	P			L_{TTS}		120	Hold at T_{lc} is 2 h
2.9		De-pressurize and return to zero control strain	P-Q			L_{TTS} ↓ 0	↓ 1		De-pressurize to 1 MPa. Re-compress by L_{TTS}
Cycles 3 to 10 identical to cycle 2									
F.1	Post- cycling	Unload to zero load and zero pressure	Q-X	T_{lc}	↓ 0	-ε_{TE}	↓0	15	Record residual compressive strain -ε_{TE} at zero load and zero pressure
F.2		Re-pressurize	X		Resultant	Resultant	↑ $p_{SS}(T_{hc})$		
F.3		Post-test zero load hold					$p_{SS}(T_{hc})$		Compare with limit-strain test load step 0.2
F.4		De-pressurize			↓ 0		↓0		
F.5		Test end			0	-ε_{TE}	0		

[a] Default hold time is 120 hours. This default may be changed only in accordance with applicable procedural and reporting provisions in 14.4.7.2.

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14.4.7.3 Criteria for achieving target temperatures

Prior to beginning any hold interval, temperatures measured by all thermocouples inside each controlled elongation interval shall be within the following limits:

— at pipe body locations: within ±10 °C from the specified target temperature;

— at coupling locations and within increased-diameter sections of integral-connection boxes: from −20 °C to +10 °C from the specified target temperature.

Best effort shall be exercised to keep all temperatures inside each controlled elongation interval within the above limits throughout the duration of each hold.

14.4.7.4 Permanent deformation of test pipes

While this document prescribes consistent specifications for geometrical and material properties of all thermal cycle specimens, some variations of those properties can still occur, and lead to strength contrasts between individual specimen components. During thermal cycles, loading of the specimen string is controlled on global strain, and strength contrasts between individual pups can lead to strain localization and non-uniform distribution of plastic strain.

It is recommended that the permanent deformation (plastic strain) remaining after the thermal cycle test should be assessed for each casing pup of each thermal cycle specimen. This assessment is recommended to indicate if any significant strain localization occurred in the specimen components. Such information can be useful as auxiliary performance data and/or in excluded connection considerations.

Recommended procedure for assessment of permanent specimen deformation:

— upon assembly of specimens for the thermal cycle test, measure distances between the two box components attached to each casing pup (coupling face or end cap face might be chosen as a convenient reference), to obtain initial undeformed lengths;

— measure the same distances after the thermal cycle test, to obtain post-test deformed lengths;

— for each pup, divide the difference between its initial undeformed length and its post-test deformed length by its initial undeformed length. This ratio can be considered representative of the permanent deformation (elongation or shortening) of that pup.

Each measured permanent pup deformation shall be reported in the evaluation report.

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14.4.8 Performance assessment

The following threshold performance requirements for the thermal cycle test are provided for reference purposes in accordance with the adopted assessment criteria and result interpretation specified in 6.3.6 and 6.3.10, and in accordance with assumptions for seepage thresholds described in 6.5.3.

A candidate connection shall be considered to have met threshold performance requirements in the thermal cycle test if all of the following conditions have been satisfied for all connections included in the thermal cycle specimens, except any excluded connections:

a) No structural failure has occurred;

b) Per-connection average seepage rate for holds at high cycle temperature does not exceed 1 ml/minute, except as allowed by 6.5.3;

c) Per-connection average seepage rate for holds at low cycle temperature does not exceed 10 ml/minute, except as allowed by 6.5.3.

Per-connection average seepage rate for each connection in each loading condition shall be calculated in accordance with 14.2.4.4.

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All the above seepage rate thresholds apply to each individual connection – i.e. not to a connection specimen unless it is an integral connection specimen, and not to test strings with multiple specimens.

Any seepage that exceeds 0,06 ml/min over any 15 min interval (1 ml in 15 min) shall be identified in the evaluation report. This threshold rate is consistent with ISO 13679; this document does not consider it to be a pass-fail criterion but specifies it as a reportable threshold.

Average per-specimen seepage rates (i.e. for two connections in a threaded-and-coupled specimen) at the high cycle temperature and the low cycle temperature should be calculated and documented for information purposes.

14.4.9 Selection of cycled specimens for bend test and limit-strain test

Following completion of the thermal cycle test, the thermal cycle specimens shall be ranked according to their structural behaviour and sealability performance in the thermal cycle test, to enable selection of thermally-cycled specimens for the bending evaluation and the limit-strain test.

The following selection procedure shall be applied:

a) remove all specimens that contain excluded connections from further selection;

b) from the remaining set of thermal cycle specimens, select the specimen with the connection that seeped at the highest average rate at room temperature in all cycles, and designate that specimen as Specimen RX for use in Task 4.4 Limit-Strain Test;

c) from the specimens that remain available after the selection of Specimen RX, select the specimen with the connection that seeped at the highest average rate at room temperature in all cycles, and designate that specimen as Specimen RY for use in Task 4.3.2 Bend Test.

14.4.10 Reporting

As a minimum, reporting of Task 4.2 Thermal Cycle Test shall contain the following items:

— Identification of candidate connection specimens submitted for this test;

— Description of any excluded connections, as required in 14.2.6;

— Calculated values for strain compensations L_{TTS} and S_{RI};

— Overall description of the test set-up, including a schematic showing the test configuration, controlled strain interval, temperature control points, heating/cooling elements, and seepage detection points;

— Photographs of the test set-up and specimen string(s) installed in the test frame;

— Locations of installed thermocouples;

— Determined effective string length;

— Performed test frame and instrumentation checks;

— For each load step executed per Table 24, at the beginning, midpoint, and end of that load step: date and time, cycle and load step number, measured temperatures, measured deformation within controlled elongation interval, average string strain, external axial force, and applied internal pressure;

— For each load step with a hold at stable conditions: hold duration, and average seepage rate in excess of 0,06 ml/min from each connection.

14.5 Bending evaluation

Execution of Task 4.3 Bending Evaluation is optional at the assigner's discretion. The decision to conduct or not to conduct those tasks shall be documented in the evaluation report.

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Rationale and recommended procedures for the bending evaluation are provided in Clause D.5.

14.6 Limit-strain test

14.6.1 Task description

The limit-strain test is a full-scale test conducted on two specimens of the candidate connection. This test constitutes Task 4.4 of the evaluation procedure (see Figure 6). Task 4.4 contains two subtasks: Task 4.4.1 Localized Strain Seepage and Task 4.4.2 Tension Limit. Those two subtasks are structured so that both of them can be performed in a single test sequence on each specimen, involving the same experimental set-up and a continuous test execution procedure. The subtask numbering sequence corresponds to the order in which the two tasks would be executed in a physical test.

Execution of Task 4.4.1 Localized Strain Seepage is optional at the assigner's discretion. The decision to complete or not to complete Task 4.4.1 shall be documented in the evaluation report.

Execution of Task 4.4.2 Tension Limit is mandatory.

Results acquired in Task 4.4. Limit-Strain Test will include key performance measures obtained in Task 4.4.2, and can include auxiliary performance data obtained in Task 4.4.1. Regardless of the executed scope, all acquired results shall be documented in the evaluation report.

To facilitate understanding of the overall scope and provisions for Task 4.4, objectives and set-up requirements for both Task 4.4.1 and Task 4.4.2 are described together in 14.6.2 and 14.6.5.

Subclauses 14.6.3, 14.6.4, 14.6.6, 14.6.7 and 14.6.8, describe requirements for the test specimens, test scope, set-up, procedure, and performance assessment for Task 4.4.2 Tension Limit.

The provisions for the optional Task 4.4.1 Localized Strain Seepage are given in D.6.3. The procedure described in D.6.3 is for executing both Task 4.4.1 and Task 4.4.2 in a single test set-up and loading sequence.

It is recognized that compressed gas stores a large amount of elastic energy. No to-failure testing should be performed with gas pressure (even at low pressures) because of concerns regarding personnel safety and potential for equipment damage associated with sudden release of the substantial energy of compressed gas. If a to-failure test with gas pressure is nonetheless desired, it can be conducted as an extra-scope test, with its rationale, practicality and feasibility determined by agreement between the assigner, the supplier, and the evaluator; and with careful consideration given to applicable hazards and safety requirements.

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14.6.2 Rationale and objectives

Loading of casing strings in thermal wells is dominated by constrained thermal expansion, which typically leads to casing yielding and appreciable post-yield deformation of the entire casing string. Furthermore, mechanical strain induced by the constrained thermal expansion can be non-uniform along the casing length, and some (weaker) sections of the string can experience localized strain that is greater than the average strain. Consequently, the candidate connection performance shall be assessed under increasing straining, in order to acquire information regarding how much plastic strain can be tolerated.

In field applications, strain localization can occur due to axial variations in string geometry (cross-sectional area) and material properties (yield strength, post-yield stiffness). The magnitude of strain localization is also influenced by cement support. For example:

— If the entire string is perfectly constrained from any axial movement, then no strain localization will occur.

— If every coupling is constrained from axial movement but the pipe body is free to move axially, then strain localization can occur within a single joint.

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— If some couplings are constrained from axial movement but other couplings and the pipe body are free to move axially, then strain localization can occur along multiple joints.

Frictional interaction is generally expected to exist between the pipe body and cement so the “effective free length” for strain localization can be a non-integer multiple of the joint length. Due to variability in manufactured casing geometry and material properties and uncertainty in downhole conditions, strain localization can be expected to take place in field operations but the magnitude of the strain localization is uncertain.

Knowledge of the structural limit of the candidate connection is of critical importance in the process of the connection evaluation, and therefore Task 4.4.2 Tension Limit is mandatory (this approach is analogous to ISO 13679 and API Specification 5C5).

In addition, the assigner should carefully consider intended applications of the candidate connection when deciding whether to commission the optional portion of the limit-strain test, i.e. Task 4.4.1 Localized Strain Seepage. Performing that task is recommended whenever one or more of the following circumstances occur:

— Substantial strain localization is expected during thermal cycles in field service;

— Significant strength contrasts are possible in the well-completion casing string;

— Likelihood of discontinuous cement support cannot be excluded;

— The candidate connection is being qualified for a variety of applications.

Based on the above considerations, the following objectives are specified for the two tasks of the limit-strain test:

— Task 4.4.1 Localized Strain Seepage (optional): assess the candidate connection sealability in conditions of strain localization, under strains greater than the average mechanical strain induced by constrained thermal expansion.

— Task 4.4.2 Tension Limit (mandatory): assess the candidate connection structural integrity and tension limit under increasing axial-tensile strain.

14.6.3 Limit-strain specimens

Two connection specimens shall be subjected to the mandatory Task 4.4.2 Tension Limit:

— Specimen 1, a make-break specimen that has not been thermally cycled;

— Specimen RX, a thermally cycled specimen (see 14.4.9 for selection procedure for Specimen RX).

Collectively, the above two specimens are referred to as limit-strain specimens.

14.6.4 Mandatory test description

14.6.4.1 Scope of mandatory test

The mandatory part of the limit-strain test (Task 4.4.2) consists of pulling a connection specimen to failure by gradually increasing the axial tensile strain at ambient temperature. The pull-to-failure loading is performed on each limit-strain specimen with no substantial internal pressure and no sealability checks. Small internal pressure with water can be applied to help detect failure.

If the mandatory Task 4,4,2 is executed together with the optional Task 4.4.1 in the same test setup, then the combined test procedure provided in D.6.3 and D.6.4 should be followed to prevent specimen failure under gas pressure.

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The loading sequence for the mandatory part of the limit-strain test is specified in Table 25 for Specimen 1 and in Table 26 for Specimen RX (see 14.6.6.2). The loading consists of progressively increasing tensile strains. The total strain range from zero to failure is divided into three strain intervals:

a) Strain interval 1 (“comparative assessment range”) – tensile strain increases from zero to the average strain applied in the thermal cycle test. Structural response of each limit-strain specimen is compared to the performance of the specimens subjected to the thermal cycle test.

b) Strain interval 2 (“localized strains”) – tensile strain continues to increase to a localized strain value (defined in 14.6.4.2), which is higher than the average thermal strain experienced in the thermal cycle test. Structural integrity is assessed.

c) Strain interval 3 (“structural limit range”) – tensile strain continues to increase until structural failure occurs or a decrease of external axial force with increasing strain is observed.

Constant-strain holds in each strain interval shall be performed as given in 14.6.6.2 (Table 25 and Table 26).

14.6.4.2 Localized strain value

Localized strain value is selected to approximately correspond to the magnitude of pipe strain that can be experienced downhole by the casing pipe-connection assembly when strain localization occurs.

For the purpose of the limit-strain test, the localized strain value shall be the greater of:

— three times the free axial expansion strain that would be induced by temperature excursions between the lower-bound temperature (5 °C) and the upper-bound temperature of the selected ASL;

— 1,5 % pipe strain.

14.6.4.3 Tensile strain threshold

A connection subjected to increasing tensile strain can fail by material fracture or by thread jump-out. Whatever the mode of failure, the connection’s design should maintain its structural integrity under strains that are somewhat higher than the strains expected in field service, to allow for a reasonable safety factor. A tensile strain threshold is adopted as the minimum tensile pipe strain below which the connection needs to maintain structural integrity.

The tensile strain threshold shall be the greater of:

— five times the free axial expansion strain that would be induced by temperature excursions between the lower-bound temperature (5 °C) and the upper-bound temperature of the selected ASL;

— 3 % pipe strain.

14.6.4.4 Strain increments

Specimen loading in the limit-strain test is controlled by application of discrete strain increments.

In Strain interval 1, each target strain can be achieved in a single strain increment consistent with the required loading.

In Strain interval 2 and Strain interval 3, each target strain shall be achieved by applying strain increments $\Delta\varepsilon_{LL}$ that shall be targeted to be equal to or less than 0,1 %.

If any applied strain increment differs from the target strain increment, then the next strain increment shall be adjusted to compensate for the difference.

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14.6.5 Set-up and instrumentation

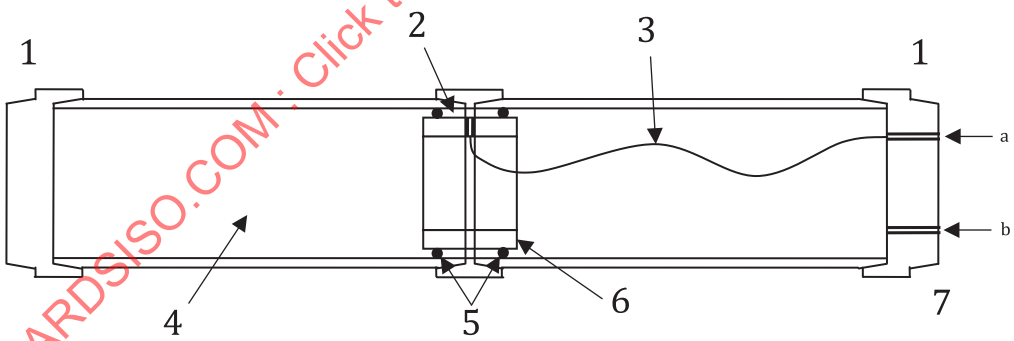
14.6.5.1 Test configuration

The limit-strain test can be performed in any test configuration that gradually applies tensile axial strain to the test specimen.

If optional Task 4.4.1 is performed, the test configuration for Strain intervals 1 and 2 (see 14.6.4.1) shall allow application of internal pressure with gas and seepage monitoring (see 14.2.4). The volume of gas used to apply the internal pressure should be minimized, to reduce the energy stored in the compressed gas – this can be achieved by use of an internal mandrel or filler bars. Appropriate safety measures shall also be in place in the event of an unexpected connection failure and release of gas pressure. For Strain interval 3, the use of water pressure (or no internal pressure) will reduce the amount of stored energy in the test medium, while still allowing determination of the connection strain limit (Task 4.4.2).

If an internal mandrel or filler bars are present, they shall not impede diametric contraction of the test specimen, and shall not interfere with the axial load applied to the test specimen. Before the test, the evaluator and the supplier should consider the mandrel-fitting considerations outlined in 14.4.6.10, and jointly determine the minimum diametric clearance needed to prevent the mandrel-specimen interference on properties and configuration of those parts. After the test, the evaluator and the inspector should visually inspect the test specimen and confirm that no undesirable interference has taken place.

Figure 18 schematically illustrates an example of a test set-up that accommodates the needs of both Tasks 4.4.1 and 4.4.2. Only the test specimen and its internal and end fixtures are shown. An internal mandrel with a pair of elastomeric seals is used to create a small annular space spanning the axial location of the coupling. This annular space is filled with the gas test medium and connected to an external gas pressure source through a length of small tubing. The remaining volume within the specimen is filled with liquid (water). The gas and liquid pressures should be applied simultaneously to balance the loads acting on the elastomeric seals. The end fixtures include appropriate bleed ports to ensure all gas is vented from the remaining volume when it is filled with liquid.



Key

1 end fixture

2 small annular space filled with gas

3 tubing for gas supply

4 remaining interior volume of specimen filled with liquid

5 elastomeric seals

6 internal mandrel

7 equal gas and liquid pressure applied simultaneously

a gas

b liquid

Figure 18 — Illustrative example set-up for limit-strain test

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The end fixtures should be designed so that they are stronger than the test specimen, in order to allow straining of the test specimen beyond its ultimate strength without a risk of failure in the end fixtures.

14.6.5.2 Internal pressure

If gas is selected to apply pressure in the annular space inside the coupling (or integral connection), then it shall be applied with an inert gas such as nitrogen. Internal liquid pressure in the remaining interior volume, if present, should be applied with water.

For the test configuration illustrated in Figure 18, external test fixtures should be configured to ensure that equal gas and liquid pressure will be applied simultaneously to the specimen interior so that there is no net differential pressure across the elastomeric seals.

Any gas remaining in the test specimen after completion of sealability checks in Strain interval 1 and Strain interval 2 should be fully vented, and checked to have been vented, to ensure complete relief of gas pressure prior to commencements of structural failure steps in Strain interval 3.

14.6.5.3 Average pipe strain

In Task 4.4, the average pipe strain in a limit-strain specimen is described as the mean of the pipe-body axial tensile strains in each casing pup belonging to that specimen.

The test set-up shall be configured so that the average pipe strain can be determined at each load step required by the task execution procedure.

Redundant strain measurements should be adopted for determination of the average pipe strain. Possible methods to provide redundant measurements are:

— use of LVDTs or linear potentiometers measuring elongation over a defined interval including the specimen connection(s) and converting this measurement to a "global" average strain, in a similar way as the average string strain is determined in a thermal cycle test (see 14.4.6.4);

— use of strain gauges on each casing pup;

— calibration of stroke of the test frame's actuator to average strain in the casing pups.

The following cautions should be considered:

— specimen fracture shock can be destructive to displacement-measuring instruments;

— strain gauges typically have a strain measurement range up to between 3 % and 4 %, and additional strain measurement techniques need to be employed for strains beyond that range.

If redundant measurements of the average pipe strain obtained with various methods described above are inconsistent and their reconciliation is impossible or impractical, it is recommended that the "global" average strain be treated as the measured strain.

14.6.5.4 Data acquisition

A computerized data acquisition system shall be used.

As a minimum, the following data shall be acquired and recorded continuously during the test, except for test maintenance periods:

— Specimen elongation, if used to determine average pipe strain;

— Average pipe strain, as derived from the above elongation measurement, and/or directly measured by strain gauges, or other method;

— Axial stroke of the test frame's actuator;

— External axial force;

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— Internal pressure, when applied;

— Seepage from each connection, when measured;

— Date and time.

Additionally, pipe diameters midway between each connection and the end fixtures shall be measured and recorded before and after each limit-strain test.

The minimum data acquisition frequency of 0,5 Hz is recommended for the limit-strain test.

14.6.5.5 Test frame and instrumentation checks

Integrity of the test assembly and accuracy of instrumentation measurements shall be checked, and where possible also verified, prior to test commencement.

As a minimum, the scope of the assembly checks shall include:

— instrumentation and measurements to be used for strain control;

— functioning of data acquisition system.

If the optional Task 4.4.1 Localized Strain Seepage is performed, the scope of checks shall also include:

— specimen pressure integrity;

— connectivity and clearance of seepage measurement lines.

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14.6.6 Mandatory test procedure

14.6.6.1 Specimen configuration and general requirements

Each limit-strain specimen shall be tested individually.

Specimen 1 and Specimen RX shall be tested in specific load step sequences, as described in Table 25 and Table 26. The differences in the load sequences for those two specimens result from the fact that Specimen RX has been cycled and permanently deformed in the thermal cycle test, and is submitted for the limit-strain test with some residual axial strain. Specimen 1 has only been subjected to the galling resistance test, with no appreciable axial plastic strain imposed.

Each limit-strain test shall be conducted at ambient temperature.

Applied strain rate shall not exceed 0,1 %/minute.

Either no internal pressure or low internal pressure with water can be applied (see 14.6.5.1 and 14.6.5.2).

14.6.6.2 Load steps

Table 25 contains the load steps for the mandatory part of the limit-strain test of Specimen 1. Some initial load steps in the loading sequence of this specimen are consistent with the load steps previously applied to Specimen RX in the thermal cycle test, so that structural responses of Specimen 1 and Specimen RX can be compared at equivalent loading conditions.

Table 26 contains the load steps for the mandatory part of the limit-strain test of Specimen RX. Some initial load steps in the loading sequence of this specimen are consistent with the final load steps previously applied to that specimen in the thermal cycle test, so that structural responses of that specimen in the two tests can be compared at equivalent loading conditions, and also compared to the responses of Specimen 1.

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Path indicators (points P, Q, W, and X) indicated in Table 25 and Table 26 are consistent with Figure 16. Symbols used in Table 25 and Table 26 are explained in 4.2.

Average post-cycle strain $\varepsilon_{\mathrm{TEa}}$ shall be adopted according to 14.4.7.2.

In load step 0.3 and load step 0.4 in Table 25, external axial forces $-F_{33\ \%}$ and $+F_{33\ \%}$ denote, respectively, the compressive and tensile axial force that together with the capped-end pressure loading (if present) produces equivalent stress equal to 33 % of the pipe-body nominal yield strength at room temperature.

Zero-strain positions 0", 0'and 0 indicated in Table 25 are consistent with zero-strain positions described in 14.4.7.2.

All load steps in Strain interval 3 can be executed either with internal water pressure or without internal pressure.

The test may be terminated when the measured axial force decreases with strain for two consecutive strain increments (i.e. a maximum of axial load is observed), although those two consecutive axial force decreases might not be observed before a test specimen parts.

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Table 25 — Load steps for mandatory part of limit-strain test of Specimen 1

Load step	Description [a]	Path	Specimen axial force	Average pipe strain	Internal pressure [a]		Duration	Comments
			kN	με	MPa	Medium	Min.	
Strain interval 1 - Comparative assessment range								
0.1	Test initiation		0	0"	0	Water or none		Zero strain upon test initiation
0.3	Elastic compression		$-F_{33\%}$	Resultant	Between 0 and 1 [b]		1	
0.4	Elastic tension		$+F_{33\%}$				1	
	Depressurize and release load		↓ 0		0			
0.5	Re-zero total strain	P	0	0'	0			Assume current strain as zero strain after elastic loading
0.6	Compress by L_{TTS}	P-Q	Resultant	$-L_{TTS}$				Strain-compensation L_{TTS} is applied in compression
	Re-zero total strain	Q		0	0			Assume current strain as zero strain after L_{TTS} compensation
	Lock strain reference							For subsequent load steps, the L_{TTS} compensated strain is assumed as zero
0.8	Tension to residual post-cycle strain plus L_{TTS}			$0 \uparrow (\varepsilon_{TEa} + L_{TTS})$	0			
0.9	Pressurize			$\varepsilon_{TEa} + L_{TTS}$	Between 0 and 1 [b]		1	Execute only if water pressure present
Strain interval 2 - Localized strains								
i.1	Increase strain to $(\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot i)$		Resultant	$\uparrow (\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot i)$	Between 0 and 1 [b]	Water or none		i=1,2,3,...until limit condition is reached Each strain increment = $\Delta\varepsilon_{LL}$
Steps i.1 are repeated until Localized Strain Value is reached								
Strain interval 3 - Structural limit range								

[a] Pressure medium and magnitudes shown for execution of Task 4.4.2 only.

[b] Load steps may be executed with or without internal pressure.

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Table 25 *(continued)*

Load step	Description [a]	Path	Specimen axial force	Average pipe strain	Internal pressure [a]		Duration	Comments
			kN	με	MPa	Medium	Min.	
j.1	Depressurize, and change pressure medium, if desired		Resultant	$\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot i$	Between 0 and 1 [b]	Water or none		$j=i+1$, where i corresponds to last iteration in Strain interval 2
j.2	Increase strain to $(\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot j)$			$\uparrow (\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot j)$				$j=i+1, i+2, i+3, \ldots$ until limit condition is reached Each strain increment = $\Delta\varepsilon_{LL}$
j.3	Hold			$\varepsilon_{TEa} + L_{TTS} + \Delta\varepsilon_{LL} \cdot j$			1	Axial force check
Steps j.2 to j.3 are repeated until structural failure occurs or a decrease of axial force with increasing strain is observed for two consecutive load steps								

[a] Pressure medium and magnitudes shown for execution of Task 4.4.2 only.

[b] Load steps may be executed with or without internal pressure.

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Table 26 — Load steps for mandatory part of limit-strain test of Specimen RX

Load step	Description [a]	Path	Specimen axial force	Average pipe strain	Internal pressure [a]		Duration	Comments
			kN	με	MPa	Medium	Min.	
Strain interval 1 - Comparative assessment range								
0.1	Test initiation	X	0	$-\varepsilon_{TEa}$	0	Water or none		Reset strain to be equal to residual strain after thermal cycle test
0.4	Tension to thermal-cycle zero strain	X-Q	Resultant	↑ 0	0	Water or none		Zero strain approximately the same as at the end of the thermal cycle test
0.8	Tension to L_{TTS}	Q-P	Resultant	0 ↑ L_{TTS}	0	Water or none		
0.9	Pressurize	Q-P	Resultant	L_{TTS}	Between 0 and 1 [b]	Water or none	1	Execute only if water pressure present
Strain interval 2 - Localized strains								
i.1	Increase strain to $L_{TTS} + \Delta\varepsilon_{LL} \cdot i$		Resultant	↑ ($L_{TTS} + \Delta\varepsilon_{LL} \cdot i$)	Between 0 and 1 [b]	Water or none		i=1,2,3,... until limit condition is reached Each strain increment = $\Delta\varepsilon_{LL}$
Steps i.1 are repeated until Localized Strain Value is reached								
Strain interval 3 - Structural limit range								
j.1	Depressurize, and change pressure medium, if desired		Resultant	$L_{TTS} + \Delta\varepsilon_{LL} \cdot i$	Between 0 and 1 [b]	Water or none		j=i+1, where i corresponds to last iteration in Strain interval 2
j.2	Increase strain to $L_{TTS} + \Delta\varepsilon_{LL} \cdot j$		Resultant	↑ ($L_{TTS} + \Delta\varepsilon_{LL} \cdot j$)	Between 0 and 1 [b]	Water or none		j=i+1,i+2,i+3,... until limit condition is reached Each strain increment = $\Delta\varepsilon_{LL}$
j.3	Hold		Resultant	$L_{TTS} + \Delta\varepsilon_{LL} \cdot j$	Between 0 and 1 [b]	Water or none	1	Axial force check
Steps j.2 to j.3 are repeated until structural failure occurs or a decrease of axial force with increasing strain is observed for two consecutive load steps								

[a] Pressure medium and magnitudes shown for execution of Task 4.4.2 only.

[b] Load steps may be executed with or without internal pressure.

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14.6.7 Performance assessment

The following threshold performance requirements are provided for reference purposes in accordance with principles for assessment criteria and result interpretation specified in 6.3.6 and 6.3.10.

For Task 4.4.2 Tension Limit, the candidate connection shall be considered to have met threshold performance requirements if all of the following conditions have been satisfied for all connections included in the limit-strain specimens, except any excluded connections:

a) No structural failure occurs before the average pipe strain in each limit-strain specimen exceeds the tensile strain threshold;

b) No decrease in axial force with increase in average pipe strain (indicating a maximum in the axial force) is observed for two consecutive strain increments before the average pipe strain exceeds the tensile strain threshold.

14.6.8 Reporting

As a minimum, reporting of Task 4.4 Limit-Strain Test shall contain the following items:

— Identification of candidate connection specimens submitted for this test;

— Description of any excluded connections, as required in 14.2.6;

— Calculated localized strain value and tensile strain threshold;

— Average post-cycle strain $\varepsilon_{\mathrm{TEa}}$ used in testing;

— Overall description of the test set-up, including a schematic showing the test configuration, and seepage detection points (if applicable);

— Photographs of the test set-up and at least one limit-strain specimen installed in the test frame;

— Performed test frame and instrumentation checks;

— Ambient temperature during testing of each specimen;

— For each load step executed per Table 25 and Table 26: date and time, load step number, average specimen strain, axial force, and internal pressure (if applied);

— For each load step with a hold at stable conditions: hold duration, and, if measured, average seepage rate in excess of 0,06 ml/min from each connection;

— Mode of failure and test termination conditions;

— Description and photographs of specimen condition upon test termination.

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14.7 As-tested configuration analysis

Execution of Task 4.5 As-Tested Configuration Analysis (Task 4.5) is optional at the assigner's discretion. The decision to conduct or not to conduct the seal taper analysis shall be documented in the evaluation report.

Rationale and recommended procedures for Task 4.5 are provided in Clause D.7.

15 Evaluation and inspection reports

15.1 Reporting deliverables

The main and mandatory deliverable of each evaluation program is the evaluation report. The evaluation report shall include a description of the organizations and/or individuals who fulfilled

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program roles, details of the candidate connection, all data acquired in the analysis and physical testing, and comparison of the results with threshold performance requirements. Each non-conformance with respect to the evaluation procedure shall be documented as well. The evaluation report shall be prepared by the evaluator.

The inspection report is a supplementary mandatory deliverable of each evaluation program. The inspector shall prepare the inspection report according to the scope of the performed inspection, as recommended in C.2.4 and any additional inspection work performed in the evaluation program. The inspection report shall be prepared separately from the evaluation report, provided to the assigner, and then attached to the evaluation report.

The evaluator and the inspector shall prepare their reports in electronic format.

The evaluator shall maintain copies of the evaluation report and acquired evaluation data according to the evaluator's corporate procedures for document retention.

The inspector shall maintain copies of the inspection report and acquired inspection data according to the inspector's procedures for document retention.

All photographs included in the evaluation report and the inspection report shall include identification of significant items shown in the photographs.

Subclause 15.2 describes the minimum required scope of the evaluation report.

Subclause 15.3 describes the recommended reporting format and contains sample reporting templates.

15.2 Reporting scope and contents

As a minimum, the evaluation report shall contain the following items:

a) General information on the executed evaluation program and the assessed candidate connection:

   1) ISO 12835 version (release) used in the conducted evaluation program;

   2) Program role assignments, Table 5 provides a sample format;

   3) Candidate connection identification, per Table 6;

   4) Options selected for the evaluation program and the evaluation procedure:

      i) Application severity level (ASL);

      ii) Task 2.2.3 Seal Tapers;

      iii) Task 2.2.4.2 Box Yield Strength;

      iv) Task 2.2.6 Test versus Production;

      v) Task 4.3 Bending Evaluation;

      vi) Task 4.4.1 Localized Strain Seepage;

      vii) Task 4.5 As-Tested Configuration Analysis.

b) Prior evaluation data, including source and the process followed for data acceptance per 8.5.

c) Conformance of the evaluation program and the candidate connection with requirements of this document:

   1) Statement of full or partial conformance of the evaluation program (per 8.1);

   2) Description of program non-conformances, if applicable (per 8.2);

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3) Assessment of the candidate connection performance relative to threshold performance requirements (per 8.3).

d) Results of Task 2.1 Initial Material Property Characterization:

1) Identification and mill certificate for each tested material;

2) Test references (such as ASTM standards);

3) Test data for each material specimen, including test parameters and acquired measurements;

4) Assumed/measured average thermal expansion coefficient;

5) Calculated thermal degradation functions for as-characterized properties;

6) As-characterized maximum-yield and minimum-yield stress-strain curves for each test temperature.

e) Results of Task 2.2 Specimen Configuration Analysis:

1) Executed scope of Task 2.2.1 Nominal Reference, Task 2.2.2 Specimen Geometry, Task 2.2.3 Seal Tapers, Task 2.2.4 Material Properties, Task 2.2.5 Make-up Torques, and Task 2.2.6 Test versus Production;

2) Description of finite element models used in the performed analysis, documenting agreement with the modelling basis provided in Annex A and use of any additional modelling assumptions;

3) Results obtained for all analysis cases;

4) Determined worst-case geometrical configurations (per Table 12);

5) Conclusions from the optional seal taper analysis, if performed;

6) Determined allowable range for yield-strength of pin components (per Table 15);

7) Determined allowable range for yield-strength of box components (per Table D.1), if Task 2.2.4.2 was performed;

8) Determined make-up torques for final make-up of specimens for sealability tests (per Table 18);

9) Comparison of “best” test specimen to “worst” production specimen (per Table D.3), if determined.

f) Results of Task 3.1 Specimen Pipe Procurement:

1) Mill certificates for all pipe and coupling stock procured for candidate connection specimens.

g) Results of Task 3.2 Material Property Verification:

1) Identification and mother-pipe location for each tested material sample;

2) Test procedure references (such as ASTM standards);

3) Test data for each material specimen, including test parameters and acquired measurements;

4) Verification of conformance of specimen pipe properties with requirements of this document (as specified in 12.3.6);

5) Determined average thermal expansion coefficient.

h) Results of Task 3.3 Specimen Machining and Gauging:

1) Calculated minimum pup length;

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2) Summary of test specimen geometry targets (specimen numbers and tolerance combinations per Table 19);

3) Products of yield strength times wall thickness for mother pipe(s) for Specimens 3, 4, 5 and 6;

4) Verification of conformance with required component diameter ranges (per Table 20), interference ranges (per Table 21), and thread taper ranges (per Table 22);

5) Outcomes of the performed specimen geometry verification:

   i) Acquired measurements;

   ii) Calibration records for all gauging equipment.

6) Treatment of damaged specimens, if any damage occurred in transportation, handling or storage (per 13.8.2).

i) General full-scale test conditions:

1) Ambient temperature;

2) Calibration records of gauges, load frames, and all other instrumentation used during testing, including laboratory standards to which the instruments were calibrated (if applicable);

3) Verification of disabling of axial seals (per 14.2.3);

4) Method of seepage collection and measurement (per 14.2.4);

5) Number of excluded connections, and the circumstances and process followed to grant the excluded connection status (per 14.2.6).

j) Results of Task 4.1 Galling Resistance Test (the following list of reporting items is repeated from 14.3.8):

1) Identification of candidate connection specimens submitted for this test;

2) Description of any excluded connections, as required in 14.2.6;

3) Material safety data sheet for applied thread compound;

4) Photographs of make-up equipment and at least one connection being made up;

5) Photographs of at least one connection before and after doping (but before make-up);

6) Consecutive number, date and time for each make-up and break-out;

7) Targeted and achieved torques in each make-up;

8) Break-out torques for each break-out;

9) Torque-turn curves for all make-ups and break-outs;

10) Observations of connection seal and thread surfaces upon each break-out;

11) Photographs of at least one undamaged connection cleaned after break-out;

12) Photographs of the connections that were representative of the worst post-break-out conditions (with or without galling) of pin and box seal and thread surfaces;

13) Description and photographs of all occurrences of galling and performed repairs.

k) Results of Task 4.2 Thermal Cycle Test (the following list of reporting items is repeated from 14.4.10):

1) Identification of candidate connection specimens submitted for this test;

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2) Description of any excluded connections, as required in 14.2.6;

3) Calculated values for strain compensations S_{LCF}, L_{TTS} and S_{RI};

4) Overall description of the test set-up, including a schematic showing the test configuration, controlled strain interval, temperature control points, heating/cooling elements, and seepage detection points;

5) Photographs of the test set-up and specimen string(s) installed in the test frame;

6) Locations of installed thermocouples;

7) Determined effective string length;

8) Performed test frame and instrumentation checks;

9) For each load step executed per Table 24, at the beginning, midpoint, and end of that load step: date and time, cycle and load step number, measured temperatures, measured deformation within controlled elongation interval, average string strain, axial force, and applied internal pressure;

10) For each load step with a hold at stable conditions: hold duration, and average seepage rate in excess of 0,06 ml/min from each connection.

l) Results of Task 4.3.1 Bending Analysis (as performed according to D.5.3);

m) Results of Task 4.3.2 Bend Test (the following list of reporting items is repeated from D.5.9):

1) Identification of candidate connection specimens submitted for this test;

2) Description of any excluded connections, as required in 14.2.6;

3) Calculated values for the maximum test curvature and curvature increments;

4) Overall description of the test set-up, including a schematic showing the test configuration, curvature application and control elements, and seepage detection points;

5) Photographs of the test set-up and at least one bend test specimen installed in the test frame;

6) Performed test frame and instrumentation checks;

7) Ambient temperature during testing of each specimen;

8) For each load step executed per Table D.4: date and time, load step number, measured bending strains or lateral deflections, resultant curvature and dogleg severity, and applied internal pressure;

9) For each load step with a hold at stable conditions: hold duration, and average seepage rate in excess of 0,06 ml/min from each connection.

n) Results of Task 4.4 Limit-Strain Test (the following list of reporting items is repeated from 14.6.8):

1) Identification of candidate connection specimens submitted for this test;

2) Description of any excluded connections, as required in 14.2.6;

3) Calculated localized strain value and tensile strain threshold;

4) Average post-cycle strain ε_{TEa} used in testing;

5) Overall description of the test set-up, including a schematic showing the test configuration, and seepage detection points (if applicable);

6) Photographs of the test set-up and at least one limit-strain specimen installed in the test frame;

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7) Performed test frame and instrumentation checks;

8) Ambient temperature during testing of each specimen;

9) For each load step executed per Table 25 and Table 26: date and time, load step number, average specimen strain, axial force, and internal pressure (if applied);

10) For each load step with a hold at stable conditions: hold duration, and average seepage rate in excess of 0,06 ml/min from each connection;

11) Mode of failure and test termination conditions;

12) Description and photographs of specimen condition upon test termination.

o) Results of Task 4.5 As-Tested Configuration Analysis (as performed according to Clause D.7).

15.3 Reporting templates

It is recommended that the reporting templates be adopted by agreement between the assigner, the supplier and the evaluator.

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Annex A
(informative)

FEA modelling guidelines

A.1 Extent of guidelines

This annex provides general guidelines for finite-element (FEA) modelling, which apply to Task 2.2 Specimen Configuration Analysis described in 12.3 and supplementary analyses described in Annex D.

FEA is a numerical technique capable of simulating complex structures and loading conditions, and of solving highly nonlinear problems. The FEA methodology is based on analytically dividing a structure into many pieces (finite elements), with the behaviour of each individual element described by mathematical formulae. The behaviour of the entire structure is then predicted by simultaneously solving the formulae for all elements subject to appropriate boundary and load conditions. FEA allows for significant flexibility in the model geometry, external constraints and loading conditions. It is an efficient tool for conducting parametric investigations.

It is a challenging task to accurately represent tubular connection behaviour using numerical methods due to the physical nonlinearities in the system, such as contact, complex geometry and temperature dependent, elastic-plastic material behaviour. Due to mathematical complexity and computational limitations, numerical models necessarily are simplified representations of the actual physical system. Model simplifications need to be carefully chosen to ensure that all fundamental mechanics are considered.

Appropriate choices for FEA modelling parameters depend on the type of the simulated process and environment, and relate to many modelling aspects such as element types and formulations, kinematic assumptions, boundary conditions, loading sequence, and execution of the numerical solution. Given that multiple FEA software programs are available, with extensive libraries of elements available in each program, it is not practical to provide an analysis specification for each modelling parameter - such as, for example, “maximum element size”. Instead, these guidelines offer reasonable recommendations for analysing threaded connections in support of the modelling tasks of the evaluation procedure.

The complexity of the model development, combined with the diversity of available modelling tools and model simplification choices, creates an uncertainty in comparing FEA results from various evaluators. The following measures are taken to ensure a minimum level of consistency and quality in FEA results among various evaluation programs:

— Clause A.2 provides recommended methodology for development of FEA models that adequately represent a casing connection subjected to assembly and service loading typical of thermal oil recovery conditions;

— Clause A.3 provides recommendations for FEA benchmarking, which can be numerical examples verifying modelling assumptions and solution parameters adopted in an evaluation program, and comparing results obtained from the model used in that evaluation program to a set of established reference results.

The guidelines included in this document are mainly focused on axisymmetric modelling of a connection make-up and thermal cycling, as required in Task 2.2 Specimen Configuration Analysis, with some references made to non-axisymmetric modelling that is required in Task 4.3.1 Bending Analysis.

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A.2 Modelling basis

A.2.1 Kinematic assumptions

Analyses requiring only axisymmetric geometry and loading should take advantage of the efficiencies offered by such models. Non-axisymmetric analyses shall be conducted using three-dimensional model formulations.

Some analytical options enhance results, although in some cases in exchange for additional computer-time consumption:

— large-strain behaviour (where plastic strains exceed 2 %) is not expected in a significant volume of the structure, so a large-strain formulation is not required but can be employed if available.

— a significant volume of the structure is expected to undergo post-yield deformation, causing material flow with nearly incompressible behaviour. Therefore, mixed formulation elements with pressure degrees of freedom should be used, if such elements are available, to accurately predict post-yield behaviour.

— large displacement formulation is recommended in order to capture any axisymmetric buckling behaviour, particularly in the pin nose region.

A.2.2 Constitutive material model

Material response shall be simulated with a temperature-dependent, elastic-plastic constitutive material model. Several constitutive material descriptions are required for the specimen configuration and make-up torque analysis: as-characterized, minimum-yield, maximum-yield and median-yield (see 12.2). The values for input parameters, such as the elastic modulus, initial yield strength and post-yield stiffness (strain hardening), shall be chosen so that the uniaxial material response predicted by the constitutive material model is representative of the material property data set (see A.2.3) specified for each analysis case. Available test data on the candidate connection material should be used to incorporate temperature dependency of the material properties (see A.2.3.3).

An isotropic strain-hardening rule should be used as a default. If there is material test data to support use of a different strain-hardening rule, then the choice of the different rule should be by agreement between the assigner, the supplier, and the evaluator. The choice of the strain-hardening rule, together with applicable technical justification, shall be documented in the evaluation report.

A.2.3 Material property data sets

A.2.3.1 Formulation of material property data sets

Eight material property data sets are defined to facilitate completion of the connection analyses in Task 2.2 Specimen Configuration Analysis. Table A.1 lists the defined material property data sets and provides guidance for selecting yield strength for each set. Table A.2 cross-references the defined sets to the analyses required in Task 2.2.

Each material property data set consists of the following properties:

— Temperature-dependent elastic modulus;

— Poisson's ratio;

— Coefficient of thermal expansion;

— Temperature-dependent yield strength;

— Temperature-dependent post-yield stress-strain curve.

Some of the above-listed properties are assumed the same in different material property data sets (see A.2.3.2), and some vary for different material property data sets (see A.2.3.3).

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A.2.3.2 Properties common to different material property data sets

The following properties are the same for each material property data set:

— Temperature-dependent elastic modulus;

— Poisson's ratio;

— Coefficient of thermal expansion.

Elastic modulus. The first choice for selecting temperature dependent elastic modulus is to measure modulus following ASTM E11. In the absence of measurements from specific elastic modulus tests, values measured from test data obtained in Task 2.1 may be used. Elastic moduli measured from tensile tests completed in Task 2.1 should be verified to be reasonable as the specified test method is not designed for high-accuracy measurement of elastic modulus. In the event the elastic moduli measured from tests completed in Task 2.1 are not suitable and representative test data is unavailable, temperature-dependent elastic moduli should be estimated using recognized temperature-dependence relationships for structural steels such as those found in NIST Technical Note 1907 and ECS Eurocode 3. When using such temperature dependence models, an ambient-temperature elastic modulus of 200 GPa to 205 GPa should be assumed.

Poisson's ratio. A Poisson's ratio of 0,3 shall be used unless there is sufficient material test data to support use of a different value. Use of a different value and the technical justification for such use shall be documented in the evaluation report.

Coefficient of thermal expansion. The magnitude of the average temperature-dependent thermal expansion coefficient (α_a) shall be assumed as determined in Task 2.1.

A.2.3.3 Formulation of material property data sets

The following properties are set-specific, i.e. different for each material property data set:

— Temperature-dependent yield strength;

— Temperature-dependent post-yield stress-strain curve.

Temperature-dependent yield strength. Table A.1 provides a list of eight defined material property data sets with cross-references to sources of temperature-dependent yield strength that need to be adopted for each set. The table indicates the basis for the ambient temperature and elevated temperature yield strengths and lists the clauses within this document that reference each material property data set.

Temperature-dependent post-yield stress-strain curve. The transition from elastic to post-yield stress-strain relationship depends on the assumed yield strength; consequently, the post-yield stress-strain curves vary among different material property data sets. However, all pin material property data sets have the same post-yield strain hardening behaviour ("shape") as measured from the pin as-characterized stress-strain curve. Likewise, all box material property data sets have the same post-yield strain hardening behaviour as measured from the box as-characterized stress-strain curve.

To accommodate connection analyses with 5 °C minimum temperature where test data at 5 °C specimen temperature is unavailable, the 5 °C material response can be assumed to be the same as the ambient-temperature material response.

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Table A.1 — Selection of yield strength for different material property data sets

Material property data set	Yield strength source		Reference clauses
	Ambient temperature	Elevated temperatures	
As-characterized pin	As-characterized from tensile tests	As-characterized	12.2.4.1
As-characterized box	As-characterized from tensile tests	As-characterized	12.2.4.1
Maximum-yield pin	Specified maximum yield strength	Thermal degredation function	12.2.4.2, 12.2.4.3
Minimum-yield pin	Specified minimum yield strength	Thermal degredation function	12.2.4.2, 12.2.4.3
Median-yield pin	See 12.3.6.2	Thermal degredation function	12.2.4.2, 12.2.4.4, D.3
Maximum-yield box	Specified maximum yield strength	Thermal degredation function	12.2.4.2, 12.2.4.3
Minimum-yield box	Specified minimum yield strength	Thermal degredation function	12.2.4.2, 12.2.4.3
Median-yield box	See Clause D.3	Thermal degredation function	12.2.4.2, 12.2.4.4, D.3

A.2.3.4 Selecting material data set for different analyses

Table A.2 provides guidance for selecting material property data sets for the pin and box in different analysis cases included in Task 2.2 Specimen Configuration Analysis.

Some choices of the material property data sets depend on execution of optional tasks. For example, if the box yield strength analysis (Task 2.2.4.2), then the strength of the median-yield material property data sets is dependent on the results of the pin yield strength analysis (see 12.3.6.2) and box yield strength analysis (see 12.3.6.3 and D.3).

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Table A.2 — Selection of yield strength for different material property data sets

Connection analysis	Clause	Connection component	Both pin and box are characterized		Pin and box materials assumed the same, only one material characterized (pin-box)	
			When optional box yield strength analysis is		When optional box yield strength analysis is	
			Omitted	Completed	Omitted	Completed
Nominal reference case	12.3.3	Pin	As-characterized pin		As-characterized pin-box	
		Box	As-characterized box			
Worst-case geometry configurations	12.3.4	Pin	As-characterized pin		As-characterized pin-box	
		Box	As-characterized box			
Seal taper analysis	D.2	Pin	As-characterized pin		As-characterized pin-box	
		Box	As-characterized box			
Pin yield strength analysis	12.3.6.2	Pin max. yield	Maximum-yield pin		Maximum-yield pin-box	
		Pin min. yield	Minimum-yield pin		Minimum-yield pin-box	
		Box	As-characterized box		As-characterized pin-box	
Box yield strength analysis	D.3	Pin	N/A	Median-yield pin	N/A	Median-yield pin
		Box max. yield	N/A	Maximum-yield box	N/A	Maximum-yield pin-box
		Box min. yield	N/A	Minimum-yield box	N/A	Minimum-yield pin-box
Make-up torque for sealability tests	12.3.7	Pin	Median-yield pin		Median-yield pin	
		Box	As-characterized box	Median-yield box	As-characterized pin-box	Median-yield box
Test versus production analysis	D.4	Pin	Based on selections determined in D.4.3			
		Box				

A.2.4 Boundary conditions

The model geometry should be chosen to employ appropriate and efficient symmetry boundary conditions.

In an axisymmetric analysis of a TC connection response to thermal cycling, the model boundaries in the axial direction should be at the centre of the coupling and at the centre of the pipe joint, as illustrated in Figure A.1a. For integral connections, there is no symmetry at the centre of the connection and model boundaries should be at the centres of the pipe joints on either side of the connection, as illustrated in Figure A.1b.

For modelling purposes, full pipe joints should be assumed to be 12,5 m (41 ft) long unless there is reason to differ, and at least half of that length shall be included in the model, the other half being simulated by means of the symmetry boundary conditions.

At all simulation times, the FEA nodes at the model boundaries shall be free to move in the radial direction. During simulation of make-up, the nodes on one model boundary (see Figure A.1) shall be axially constrained, and the nodes on the other model boundary (see Figure A.1) shall be appropriately constrained or loaded to best represent the anticipated make-up conditions. During the simulated thermal cycle, the nodes on both model boundaries shall be held stationary in the axial direction to simulate conditions of constrained thermal expansion with an effective free length of one pipe joint.

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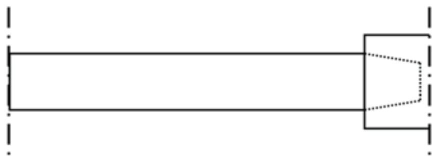
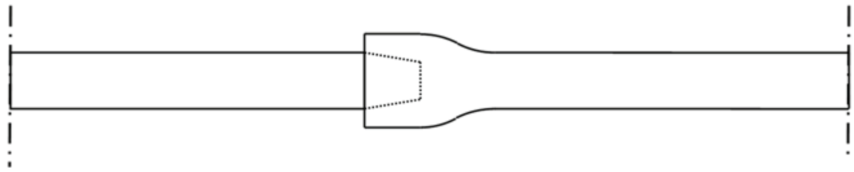


a) TC connection



b) Integral connection

Figure A.1 — Model boundaries and symmetry planes for connection models

A.2.5 Contact model

The model should accommodate contact conditions between mating surfaces in the pin and box. The model should assume frictionless contact characteristics for axisymmetric behaviour to simulate worst-case conditions for movement. Out-of-plane friction can be considered for evaluating torque characteristics.

The contact surfaces should have the minimum contact compliance necessary to enable solution convergence. The effect of contact surface compliance, if used, on the resultant solution should be evaluated. The contact surface compliance should be selected to have a minimal impact on selection of worst-case geometry, material sensitivity and make-up torque.

Where make-break behaviour is simulated, the sequence of contact shall be representative of that occurring in the candidate connection.

A.2.6 Element meshing

Meshing will depend on the kinematics of the continuum element type(s) chosen for the model. Elements using more nodes generally require fewer elements to provide a given level of accuracy. Mesh requirements also vary with the magnitude of stress gradients that need to be modelled. For example, the axial stress gradient over most of the joint length is very small, so long elements can be employed over that interval with only one element through the wall thickness. More elements are required in the threaded interval, particularly at the ends of the threaded interval because of high load transfer rates and the associated stress and strain gradients. Furthermore, element shapes and aspect ratios are more important in these regions because of the stress gradients and high shear stresses. A minimum mesh density of 2 by 2 quadrilateral elements with quadratic displacement field is suggested for a full-height buttress-type thread. If linear-displacement-field elements are employed, the minimum linear mesh density should be tripled (i.e. 6 × 6 elements per thread). The selected mesh density should be adequate to simulate the overall shear response of the thread to axial load transfer, but a detailed stress field assessment for individual threads is not required.

Mesh density requirements are much higher in regions where localized contact occurs, as is often the case with metal-to-metal seals. In such regions, the mesh shall be refined sufficiently to model the seal contact at make-up across several elements, so that the contact interval and stress can be assessed properly. The seal contact location will generally change over the course of thermal cycling; therefore, the refined mesh shall extend beyond the seal contact interval at make-up to include the region of seal contact during thermal cycling. The region of contact is usually well defined, allowing a localized mesh concentration to be applied. The mesh density along each contact surface and perpendicular to the contact surfaces should be comparable to properly capture the stress field in the region of contact.

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A.2.7 Loading sequence

The axisymmetric analyses include cases with one connection make-up only, cases with one connection make-up and one thermal cycle, and cases with two make-ups and one thermal cycle.

Upper-bound temperature condition and lower-bound temperature condition are defined as the connection analysis solution steps at which contact stresses and seal contact stress intensities are recorded for use in the tables in 12.3. The upper-bound and lower-bound temperature conditions are identified in Table A.3 and Figure A.2.

Table A.3 illustrates the load path that shall be applied for the analysis cases with one make-up and one thermal cycle. The load path for the cases with a single make-up will consist only of the first load step shown in Table A.3. The load path for the cases with two make-ups shall involve all steps included in Table A.3 plus additional two load steps after the first make-up simulating connection break-out (unloading) and the second make-up.

The magnitudes of temperature and pressure loads simulating the thermal cycle shall be based on the selected ASL. The sequence of the pressure and temperature changes in Table A.3 assumes that changes in casing's internal pressure precede changes in temperature (see rationale in 6.5.7), and that the well cools back to the original temperature (which occurs, for example, when the well is shut down for an extended period soon after the start of thermal operation). As an example, Figure A.2 graphically illustrates a loading path for ASL-240.

Table A.3 — Simulation of thermal cycle load path

Operating point	Simulation step	Temperature	Internal pressure
Connection assembly (make-up)	1	T_{lb}	0
Commence steam circulation	2	T_{lb}	$p_{SS}(T_{ub})$
Heat to maximum temperature	3	T_{ub}	$p_{SS}(T_{ub})$
Upper-bound temperature condition			
Shut-off steam circulation	4	T_{ub}	0
Cool to minimum temperature	5	T_{lb}	0
Commence steam circulation	6	T_{lb}	$p_{SS}(T_{ub})$
Lower-bound temperature condition			

Prior to the application of internal pressure and temperature change, the net axial force at the end boundaries of the model shall be zero (or negligible). Due to the fixed axial displacement at the model boundaries, axial loads will be induced by the Poisson's effect during application of internal pressure and by the constrained thermal expansion during the thermal cycle.

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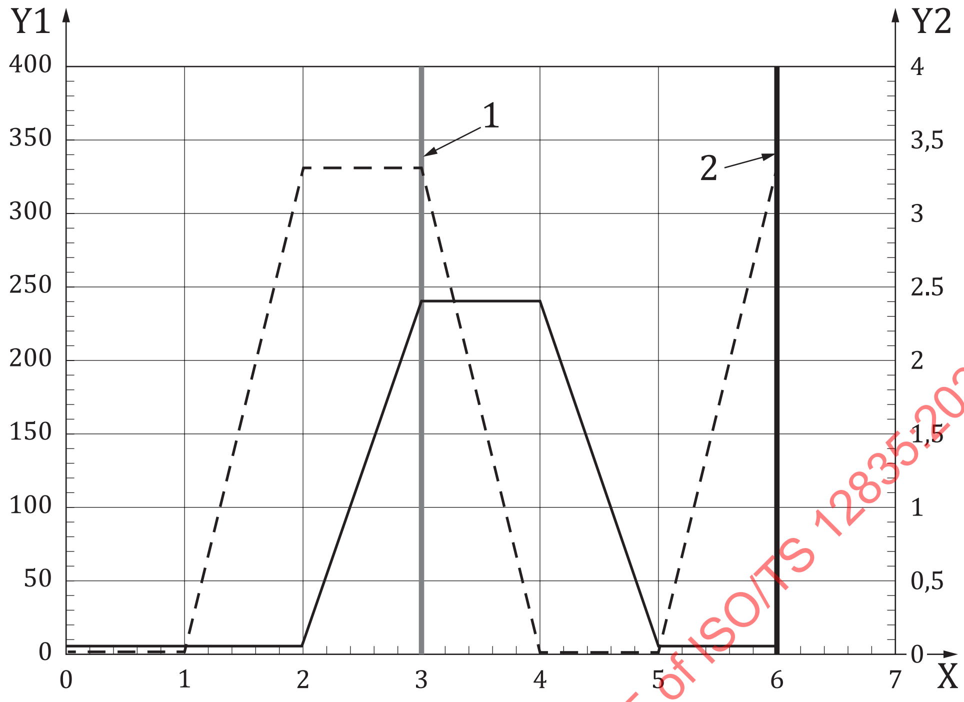

Key

X	simulation time
Y1	temperature, °C
Y2	pressure, MPa
1	upper-bound temp. condition
2	lower-bound temp. condition
————	temperature, °C
- - - - - -	internal pressure, MPa

Figure A.2 — Example of load path graph for ASL-240

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Temperature load shall be applied uniformly to all model elements.

Temperature and pressure load increments (simulation time step size) should be sufficiently fine to ensure accurate numerical solution convergence. Numerical results at each load step should be saved to adequately describe the progression of the applied load path.

A.2.8 Simulation of make-up to a target torque

Numerical simulations of connection make-up shall be performed to prescribed target torques. To meet that requirement, pin and box contact forces and torque shoulder interferences shall be reconciled with the supplier's connection make-up specifications, sample make-up curves, and friction coefficients representative of lubricated connection surfaces (coated and/or covered by a thread compound).

A.2.9 Calculating casing string low and high stiffness lengths from FEA results

Determination of strain compensation factors (see Clause B.1) for full-scale connection testing requires calculation of the connection equivalent high-stiffness length, L_{stiff}, from FEA results using the finite element model from 12.3.

The stiffness of the casing system is found by applying a small elastic unload upon completion of the thermal cycle to load step 6 as per Table A.3 and Figure A.1 and Figure A.2. To calculate the high-stiffness interval, it is assumed that the casing system consists of two parts, one part with stiffness equal to the stiffness of the pipe body and a second part that is rigid (has infinite stiffness). With the

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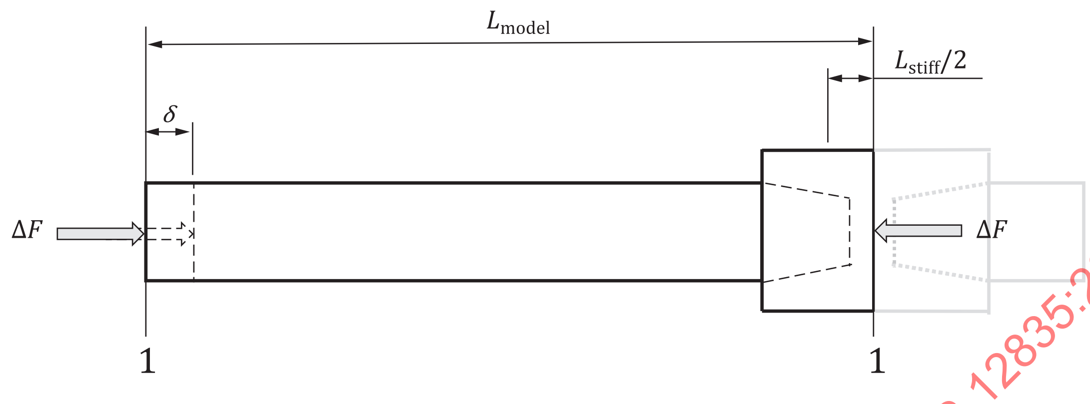
calculated casing string stiffness and the known elastic stiffness of the nominal pipe body, the length of high stiffness interval can be calculated.

A schematic illustrating the basis for calculation of the high-stiffness interval is shown in Figure A.3.



Key

1 line of symmetry

Figure A.3 — Schematic for calculation of high-stiffness interval

The length of the high stiffness interval in a coupled connection is then calculated by:

$$L_{stiff} = 2 \cdot \left(L_{model} - E \cdot A_{pipe} \frac{\delta}{\Delta F} \right) \tag{A.1}$$

where

L_{stiff}	is the length of the high-stiffness interval;
L_{model}	is the length of the connection model;
E	is the elastic modulus of the pipe body;
A_{pipe}	is the full cross-section area of the pipe body;
ΔF	is the change of axial force on the full pipe cross-section area corresponding to axial displacement δ.

Length of the high-stiffness interval of an integral connection can be calculated in the same way, but without the factor of 2 on the right side of Formula (A.1).

Studies of sensitivity of the resulting length change of the model to the applied force increment have shown that, even when elastically unloading the connection model, the response might not be linear because of changing contact conditions within the connection. For this reason, engineering judgement should be used when selecting the magnitude of the force increment and displacement.

A.2.10 Reporting

Modelling assumptions adopted for the evaluation program shall be documented in the evaluation report, including the assumptions that are consistent with the modelling guidelines described in A.2.1 to A.2.9, and any additional assumptions adopted by agreement between the assigner, the supplier and the evaluator as stipulated in 12.3.2.

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The modelling results shall be documented in the evaluation report according to reporting requirements for various modelling tasks specified in 12.3 and 15.2. In general, modelling results of primary importance for each competed analysis are:

— Table of seal contact stress intensity, maximum seal contact stress, maximum thread contact stress and axial pin-tip force at solution steps 1, 3, 5 and 6 as listed in Table A.3.

— Contour plots of von Mises stress, axial stress and accumulated equivalent plastic strain in and near the connection at solution steps 1, 3, 5 and 6 as listed in Table A.3.

— Plot of seal contact stress as function of axial distance from the pin tip vertex at solution steps 1, 3, 5 and 6 as listed in Table A.3.

— Thread contact stress at full make-up (solution step 1), including distribution and peak stress.

— Plots of seal contact stress intensity and pin tip axial force as functions of temperature using results at all solution steps and sub-steps.

A.3 FEA benchmarking cases

It is recommended that the scope and procedure for FEA benchmarking be determined by agreement between the assigner, the supplier and the evaluator.

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Annex B
(informative)

Derivations of formulae - Strain compensation factors

B.1 Background

As explained in 9.1, total axial strain in a thermal well cemented casing string typically remains zero or nearly zero during a thermo-mechanical cycle. However, distribution of the total axial strain in a field configuration will almost always be different from a test configuration. In the field configuration, couplings (or integral connections) are separated by pipe lengths usually much longer than those that can be included in a thermal cycle test. Those length differences lead to increased pipe-body mechanical strain in the test configuration (i.e. in the specimen string) compared to the field configuration, if the test's loading control imposes zero total strain. The reasons for such over-straining are described below.

Coefficients of thermal expansion of the casing pipe and coupling stock do not differ substantially, if those components have the same nominal material grade. For practical purposes, those components can be assumed to expand equally, or have equal thermal-expansion strains, if exposed to a change in temperature while not mechanically loaded.

Contrary to the thermal-expansion strains, distribution of mechanical strains will, in most cases, be non-uniform due to strength and stiffness contrasts that exist between the pipe and couplings, where the pipe has lower stiffness than the couplings' central regions (or integral connections' upset regions). Under an axial load, the pipe is at higher axial stress than the couplings' central regions, and deforms correspondingly more. When the pipe in a well or in a testing assembly yields while the couplings' central regions typically remain elastic, the majority of incremental mechanical strain will occur in the pipe. Transfer of strain from the stiffer regions to less stiff regions has been called strain localization. The degree of strain localization in the pipe will depend on connection geometry, material properties of the pipe and coupling stock, and the ratio of the total pipe length to the sum of the stiffer sections' lengths.

Some of the foregoing variables are more significant than others, and some are not directly addressed during testing. Differences in material properties of the pipe and coupling stock (or integral connections' box regions) have insignificant effect if the connections' stiff regions remain elastic, and have otherwise little effect if the stiff regions' cross-sectional areas are appreciably larger than the pipe's cross-sectional area. Variability in material strength and cross-sectional area along a testing assembly's pipe segments is ignored, despite being present, because such variability is present in the downhole casing, too. The key variables, to match pipe strains during testing to pipe strains in the field, are temperatures, pressures, and the ratios of pipe length to stiffer section lengths.

In the expressions shown in 14.4.5, a casing string or a testing assembly is assumed to include only two stiffness values: pipe with comparatively low stiffness, and high-stiffness components such as central regions of couplings or integral connections. In the threaded portions of the connections, axial stiffness changes gradually, and the character of that variation is specific to the connection design. The evaluation procedure requires that FEA be used (see 12.3 and A.2.9) to assess the geometry and load transfer mechanism for each candidate connection and determine the associated stiffness variation. Based on those findings, each varying-stiffness interval is to be divided into two sub-intervals. One such sub-interval can be treated as having "low" axial stiffness, such that its length can be added to the unthreaded part of the casing pipe (or segment) length. The other sub-interval can be treated as having "high" axial stiffness, and its length can be added to that of the coupling's or integral connection's central region.

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B.2 Assumption summary

The following assumptions are used in the derivation of strain-length compensation factors:

a) Coefficients of thermal expansion of pipe body and coupling stock are not significantly different.

b) Geometry and material properties of casing pipe are consistent, and geometry and material properties of the connections are also consistent.

c) Mechanical strain in the stiffer sections (coupling centre sections or upset sections) is neglected, i.e. it is assumed that the mechanical strain in the pipe body is much higher than the mechanical strain in the stiffer sections.

d) A connection's length can be divided into two component lengths: a high-stiffness sub-interval and a low-stiffness sub-interval.

e) Typical length of casing joints in the well is assumed at 12,5 m (41 ft). The longer the assumed joint length, the larger the S_{LCF}, and the smaller the S_{RI} (i.e. less strain is applied in the thermal cycle test).

B.3 Formulae for casing string low and high stiffness lengths

Derivation of formulae for high-stiffness and low-stiffness portions of a casing string assumes that the specimen string used in the thermal cycle test contains the same number of connections as a simulated portion of a downhole casing string. The following nomenclature is adopted:

a) A casing string typical of downhole well installations is referred to as the field configuration;

b) A specimen string used in a thermal cycle test is referred to as the test configuration.

Similarities of, and differences between, the two configurations listed above are illustrated in Figure B.1 and Figure B.2. Figure B.1 illustrates the field and test configurations for a threaded- and-coupled connection. Figure B.2 illustrates the same configurations for an integral connection. In each figure, the portion of the schematic above the symmetry axis refers to the field configuration; and the portion of the schematic below the symmetry axis refers to the test configuration.

The specifications for the thermal cycle test allow testing specimen strings composed of either a single connection specimen, or two connection specimens, or four connection specimens (refer to 4.1 and 5.1 for definitions of connection specimens for threaded-and-coupled and for integral connections, and refer to 14.4.6.1 for allowable test configurations). The schematics in Figure B.1 and Figure B.2 should be interpreted to correspond to the chosen test configuration, with one, two or four connection specimens in series. The field configuration simulated by the chosen test configuration should be interpreted to contain the same number of couplings or integral connections as the specimen string. The couplings/ integral connections are connected by casing pups in the test configuration, and by full-length casing joints in the field configuration.

As discussed in Clause B.1, it is assumed that an analysis of the candidate connection has been performed, and based on the results of that analysis, each threaded interval has been divided into two discreet sub-intervals. The length of each high-stiffness sub-interval is added to the length of the associated coupling's centre section or integral connection's upset section, and the resultant combined length of the stiff section is referred to as L_{stiff} in Figure B.1 and Figure B.2. Correspondingly, the length of each high-stiffness sub-interval in a threaded portion is subtracted from the pin tip-to-pin tip length of the casing joints and pups. The adjusted pipe-body lengths are considered to be the low-stiffness portions of the casing string:

L_{joint} is the low-stiffness joint length, i.e. joint pin tip-to-pin tip minus the high-stiffness length

L_{pup} is the low-stiffness pup length, i.e. pup pin tip-to-pin tip minus the high-stiffness length

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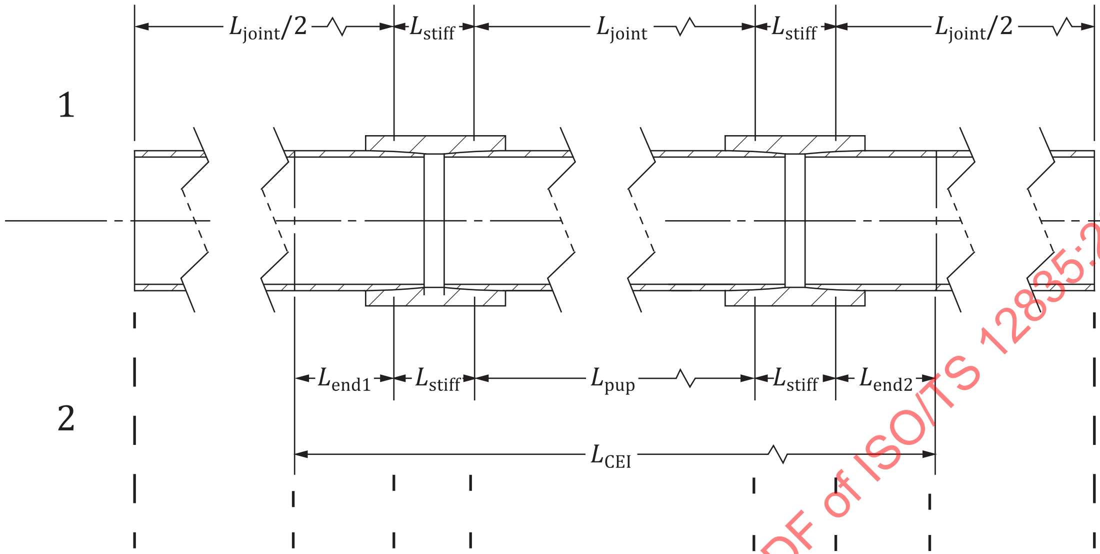
The length of each end pipe segment in the field configuration is assumed to be half the length of a typical casing joint. The length of each end pup in the test configuration, L_{end1} and L_{end2}, is assumed to conform to the requirements for the end segments that have to be included in the controlled elongation interval (see 14.4.6.2). The total length of the casing string in the test configuration corresponds to the length of the controlled elongation interval, L_{CEI}.

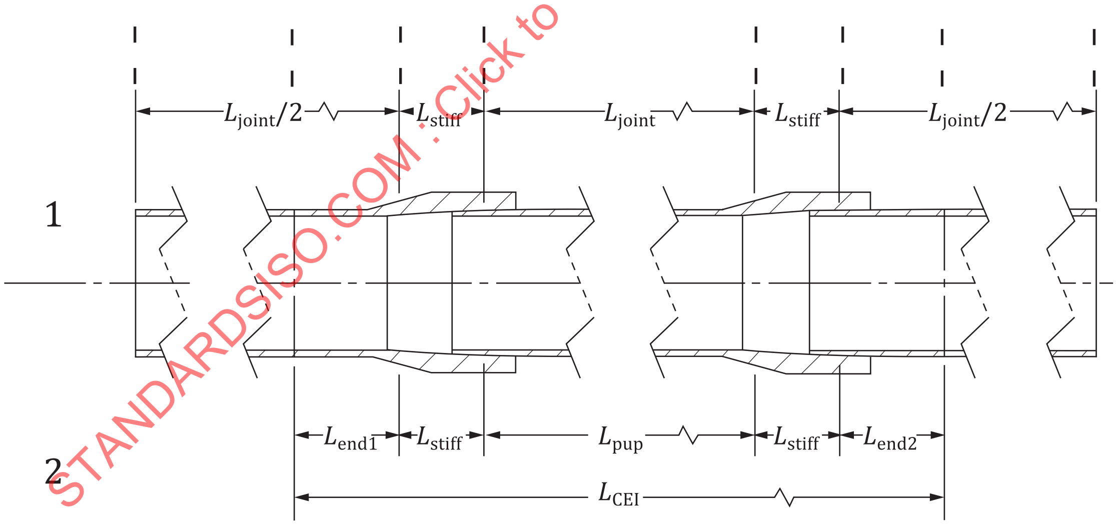


Key

1 field configuration

2 test configuration

Figure B.1 — Field and test configurations for threaded-and-coupled connections



Key

1 field configuration

2 test configuration

Figure B.2 — Field and test configurations for integral connections

The following derivation assumes that the number of the connection specimens in the specimen string is N, where N can be 1, 2 or 4.

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For either a threaded-and-coupled connection or an integral connection, the low-stiffness length L_{LS}^{test} of the specimen string in the test configuration is given by Formula (B.1):

$$L_{LS}^{test} = L_{end1} + \sum_{i=0}^{N-1} \left(L_{pup}\right)_i + L_{end2} = L_{end1} + (N-1) L_{pup} + L_{end2} \tag{B.1}$$

The high-stiffness length of the specimen string in the test configuration is given by Formula (B.2):

$$L_{HS}^{test} = \sum_{j=1}^{N} \left(L_{stiff}\right)_j = N \cdot L_{stiff} \tag{B.2}$$

The low-stiffness length of the field string is given by Formula (B.3):

$$L_{LS}^{field} = \left(\frac{1}{2}\right) L_{joint} + \sum_{i=0}^{N-1} \left(L_{joint}\right)_i + \left(\frac{1}{2}\right) L_{joint} = N \cdot L_{joint} \tag{B.3}$$

The high-stiffness length of the field string is equal to the high-stiffness length of the specimen string, as expressed in Formula (B.4):

$$L_{HS}^{field} = \sum_{j=1}^{N} \left(L_{stiff}\right)_j = N \cdot L_{stiff} = L_{HS}^{test} \tag{B.4}$$

B.4 General formula for strain-length compensation factor

The strain-length compensation factor (S_{LCF}) is introduced to account for the difference in the ratios of the low-stiffness length and the high-stiffness length in the field and test configurations.

To derive the strain compensation factor, first a general expression for thermal strain is assumed as in Formula (B.5):

$$\varepsilon_{thermal} = \alpha \cdot \Delta T = \frac{\Delta L_{therm}}{L_{therm}} \tag{B.5}$$

where

α	is the average thermal expansion coefficient corresponding to the temperature range ΔT;
ΔT	is the temperature range for which S_{LCF} is being applied;
L_{therm}	is the length subjected to thermal expansion/contraction.

For example, when S_{LCF} is applied to the temperature-range strain compensation (S_{RI}), the temperature range ΔT will be from the ASL lower-bound temperature to the ASL upper-bound temperature.

Next, a general expression for mechanical strain is assumed as in Formula (B.6):

$$\varepsilon_{mech} = \frac{\Delta L_{mech}}{L_{mech}} \tag{B.6}$$

where L_{mech} is the length that deforms appreciably under mechanical forces.

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Based on a fundamental assumption of tubular constraint in thermal wells, the total change in casing length is equal to zero. Consequently, the sum of the thermal length increment ΔL_{therm} plus the mechanical length increment ΔL_{mech} is equal to zero:

$$\Delta L_{therm} + \Delta L_{mech} = 0 \quad \text{(B.7)}$$

After substituting terms from Formula (B.5) and Formula (B.6), the resultant expression for the mechanical strain generated by constrained thermal expansion is given by Formula (B.8):

$$\varepsilon_{mech} = -\alpha \cdot \Delta T \cdot \frac{L_{therm}}{L_{mech}} \quad \text{(B.8)}$$

Formula (B.8) applies to mechanical strain in either field or test configuration. In the field configuration, the ratio between the thermal length L_{therm} and the mechanical length L_{mech} is close to 1, and so the mechanical strain is almost equal to the thermal strain. That ratio increases when short casing pups are substituted for full-length casing joints, and consequently the pipe-body mechanical strain in a test configuration is larger than in the field configuration. The purpose of introducing the strain-length compensation factor is to compensate for the above difference, and make the pipe-body mechanical strain in the test to be the same as the pipe-body mechanical strain in the field configuration. In order to achieve the above, we need to add a strain increment $\Delta\varepsilon$ to the mechanical strain in the test configuration, as shown in Formula (B.9):

$$\left(\varepsilon_{mech}^{test}\right)_{compensated} = -\alpha \cdot \Delta T \cdot \frac{L_{therm}^{test}}{L_{mech}^{test}} + \Delta\varepsilon \quad \text{(B.9)}$$

where $\Delta\varepsilon$ is additional strain applied to compensate for the difference in length between the field and test configurations.

This additional strain is adopted as S_{LCF}. Now the compensated mechanical test strain is set equal to the mechanical field strain, as given in Formula (B.10):

$$\left(\varepsilon_{mech}^{test}\right)_{compensated} = \varepsilon_{mech}^{field} \quad \text{(B.10)}$$

From Formulae (B.8), (B.9)and (B.10), the term $\Delta\varepsilon$ (adopted as S_{LCF}) can be determined as in Formula (B.11):

$$S_{LCF} = \Delta\varepsilon = \alpha \cdot \Delta T \cdot \left(\frac{L_{therm}^{test}}{L_{mech}^{test}} - \frac{L_{therm}^{field}}{L_{mech}^{field}} \right) \quad \text{(B.11)}$$

The following formulae relate the thermal and mechanical lengths for the field and test configuration used in Formula (B.11) to the low-stiffness and high-stiffness lengths previously discussed in Clause B.3.

L_{therm}^{test} is the thermal-expansion length in the test configuration (specimen string), which is equal to the controlled elongation interval, as defined in Formula (B.12):

$$L_{therm}^{test} = L_{LS}^{test} + L_{HS}^{test} = L_{CEI} \quad \text{(B.12)}$$

L_{mech}^{test} is the length assumed to be appreciably deforming under mechanical forces in the test configuration, which is somewhat shorter than L_{therm}^{test} and equal to the low-stiffness length given

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previously by Formula (B.1). This length is adopted as the effective string length L_{eff} (see 14.4.6.3) and given in Formula (B.13):

$$L_{\text{mech}}^{\text{test}} = L_{LS}^{\text{test}} = L_{\text{eff}} \tag{B.13}$$

$L_{\text{therm}}^{\text{field}}$ is the thermal-expansion length in the field configuration, which is assumed equal to the portion of the downhole casing string that is simulated in the test (with the same number of couplings or integral connections as the specimen string in the test), and is given by Formula (B.14):

$$L_{\text{therm}}^{\text{field}} = L_{\text{LS}}^{\text{field}} + L_{\text{HS}}^{\text{field}} \tag{B.14}$$

$L_{\text{mech}}^{\text{field}}$ is the length assumed to be deforming under mechanical forces in the well configuration, which is somewhat shorter than $L_{\text{therm}}^{\text{field}}$ and equal to the low-stiffness length of a casing string in a well (refer to Formula (B.3)), and is given by Formula (B.15):

$$L_{\text{mech}}^{\text{field}} = L_{\text{LS}}^{\text{field}} \tag{B.15}$$

B.5 Resultant formulae for strain compensations L_{TTS} and S_{RI}

Two strain compensations described previously in 14.4.5 are applied in the thermal cycle test: the lower-bound temperature strain compensation (L_{TTS}) and the temperature range strain compensation (S_{RI}). S_{LCF} is applied as an "offset" to the S_{RI} compensation, because the test string is subjected to constrained thermal expansion within the temperature range corresponding to the S_{RI} compensation. No strain-length factor is applied to L_{TTS}, because the test string is not subjected to constrained thermal expansion in the temperature range from T_{lb} to T_{lc}.

Based on the above, the strain-length compensating factor S_{LCFL} for L_{TTS} is zero:

$$S_{\text{LCFL}} = 0 \tag{B.16}$$

Based on Formula (B.11), the strain-length compensating factor S_{LCFS} for S_{RI} is given by Formula (B.17):

$$S_{\text{LCFS}} = (T_{\text{ub}} - T_{\text{lb}}) \cdot \alpha_{\text{a}} \cdot \left(\frac{L_{\text{therm}}^{\text{test}}}{L_{\text{mech}}^{\text{test}}} - \frac{L_{\text{therm}}^{\text{field}}}{L_{\text{mech}}^{\text{field}}} \right) \tag{B.17}$$

where α_{a} corresponds to the average thermal expansion coefficient in the temperature range from T_{lb} to T_{ub}.

Formula (B.18) describes the L_{TTS} strain compensation applicable in the test:

$$L_{\text{TTS}} = (T_{\text{lc}} - T_{\text{lb}}) \cdot \alpha_a \cdot \left(\frac{L_{\text{therm}}^{\text{field}}}{L_{\text{mech}}^{\text{field}}} \right) \tag{B.18}$$

where α_{a} corresponds to the average thermal expansion coefficient in the temperature range from T_{lb} to T_{lc}.

Formula (B.19) describes the S_{RI} strain compensation with the applicable strain-length offset S_{LCFS}:

$$S_{\text{RI}} = 10\% \cdot (T_{\text{ub}} - T_{\text{lb}}) \cdot \alpha_{\text{a}} \cdot \frac{L_{\text{therm}}^{\text{field}}}{L_{\text{mech}}^{\text{field}}} - S_{\text{LCFS}} =$$

$$= (T_{ub} - T_{lb}) \cdot \alpha_a \cdot \left[0{,}1 \cdot \frac{L_{\text{therm}}^{\text{field}}}{L_{mech}^{\text{field}}} - \left(\frac{L_{\text{therm}}^{\text{test}}}{L_{\text{mech}}^{\text{test}}} - \frac{L_{\text{therm}}^{\text{field}}}{L_{\text{mech}}^{\text{field}}} \right) \right] \tag{B.19}$$

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