



Integrity of Connectors in Pipelines and Subsea Systems

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Summary

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Document control

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0.0	08/05/2025	First draft for client review
0.1	08/07/2025	Updated as per client comments
0.2	17/11/2025	Section 5.3.2 – Drawing of Collet connector added

List of abbreviations

Abbreviation	Description
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CRA	Corrosion Resistant Alloy
DNV	Det Norske Veritas
FEA	Finite Element Analysis
FEED	Front-End Engineering Design
FL	Flowline
FLET	Flowline End Termination
FMEA	Failure Modes and Effect Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
HCCS	Horizontal Clamp Connection System
HISC	Hydrogen Induced Stress Cracking
ILI	In-Line Inspection
ISO	International Organization for Standardization
MATIS	Modular Advanced Tie-in System
NDT	Non-Destructive Testing
OREDA	The Offshore and Onshore Reliability Data
PL	Pipeline
PLEM	Pipeline End Manifold
RAM	Reliability, Availability, and Maintainability
RIAD	Reliability and Integrity Assurance Documentation
ROV	Remotely Operated Vehicle
SQP	Standard Qualification Program
TQP	Technology Qualification Program
TRAR	Technical Risk Assessment Review
TRC	Technical Risk Categorisation
TRL	Technology Readiness Level
WD	Water Depth
XT	Christmas Tree

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Introduction

1. Introduction

Subsea pipeline connections enable connecting pipelines and spools to subsea equipment and also facilitate repairs and modifications. They are required to provide reliable and durable connection in various environments, critical for the safe and continuous operation of pipelines and subsea infrastructure.

The connections covered in this report consist of the following types: flanged connections, clamp hub connectors, collet connectors, proprietary connectors and gripping mechanical adapters. As such, the study of welded joints is not part of the scope of this report.

Since the early 20th century, subsea pipeline connection technology has steadily evolved. Industry maturity has led to improvements and refinement of existing connection technology through standardisation, material advancements, and manufacturing, building upon years of use cases and field-proven solutions.

As the industry develops in deeper water, subsea connection technology has been evolving to meet new challenges, such as higher pressures, higher temperatures and remote operability and maintainability. A wide array of connection systems and products have been developed to address demands for greater efficiency, safety, and adaptability in increasingly challenging sea environments. Diver-less installation and connection methods have become more common, especially in deep water where Remotely Operated Vehicles (ROVs) are used, as manual connections are not possible.

The selection criteria for subsea connections require careful consideration to ensure that the design and integrity of these connections are suitable throughout the operational lifespan.

1.1 Scope of Work

This study has been developed for Havindustritilsynet with the objective to assess the key requirements related to subsea connections through a detailed review of issues concerning the design, fabrication, installation, operation, and safety aspects of subsea connectors. The topics which will be addressed by this study are as follows:

- Description of different connection methods,
- Operational history and prevalence of connections internationally with focus on the British and Norwegian sectors,
- Study of available integrity event data for each connection type,
- Experience based analysis of different connections' safety level including evaluation of individual components which are barrier elements, the failure of which can lead to impairment/weakness of the connection, and
- Methods for risk evaluation as part of the selection of connection types.

Connections studied in this report are of the following types:

- Pipeline to pipeline
- Pipeline to structures (Manifolds, Risers, PLEMS and FLETs etc)
- Structures to equipment (Trees, Jumpers etc)

For reference, the original requirements, scope of work and objectives of this study are detailed in Appendix C.

Background

2. Background

Since the mid-nineties, the offshore industry has been moving into significantly deeper waters with a significant number of projects having been developed in water depths greater than 2000m. Figure 1 presents water depths of subsea oil and gas developments over time from 1950 to 2030 (2025 – 2030 estimated based on market data) [1]. As can be seen there has been a clear trend in increasing water depth since the 1990's with developments reaching water depths in excess of 3000m by the mid-2010's.

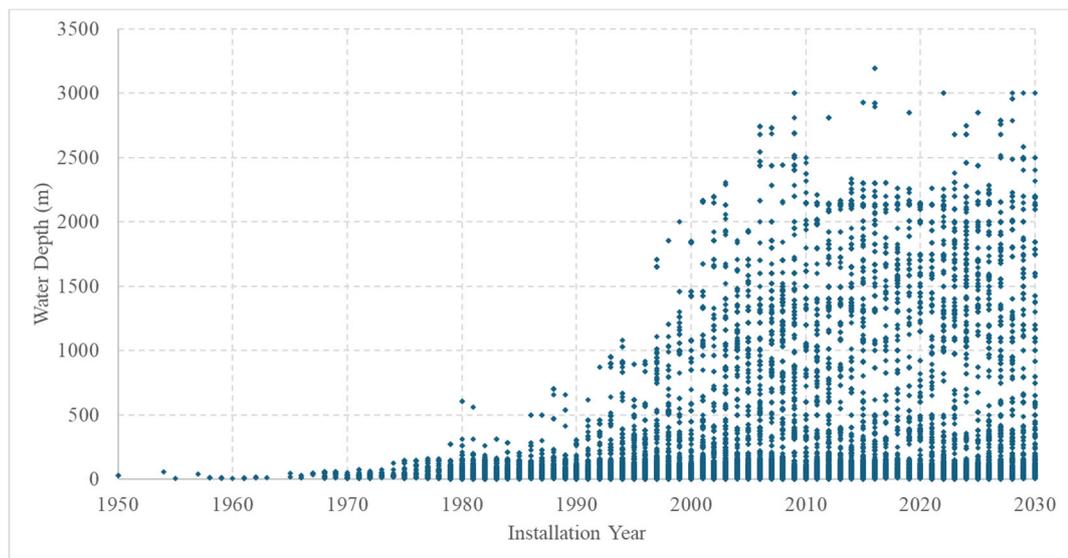


Figure 1 - Installation Year v Water Depth

In the early days of the oil and gas industry, subsea connection technologies were designed to be made-up with the support of subsea divers (e.g., standard bolted flanged connections).

As the industry has moved into deeper waters, advancements in subsea connection technologies have been required to allow connections between different elements of the subsea infrastructure to be made remotely in water depths inaccessible to divers.

With the development of technologies such as diverless connection systems and remotely operated vehicles (ROV), the industry has also taken advantage of these technologies to reduce construction risks such as risks associated with saturation diving.

To facilitate remote connections, the evolution of subsea connectors has resulted in a range of different solutions, often of a proprietary nature from different manufacturers. This report does not discuss the individual manufacturer solutions, however, presents general connection types and industry trends/experience with subsea connectors.

3. Estimated Prevalence of Subsea Connectors

To understand the general industry experience with subsea pipeline connectors, an effort has been made to estimate the lower-bound of the number of subsea pipeline connectors currently in-service and planned. Data from the S&P GLOBAL Offshore Fields Database [1] has been utilised to estimate the number of diver-assisted and diverless connectors. To estimate prevalence of the various connector types, a cut-off has been applied with the assumption that all connectors in water depth less than 200m are diver-assisted and all connectors in water depth greater than 200m are diverless. It is acknowledged that this is a simplified approach, however the general trends should hold. The number of connectors was determined by counting the number of pipelines, jumpers, and spools and applying the assumption that each unit has two associated connectors.

It should be noted that figures and estimates in this section are based on the above simplified approach and are used to demonstrate the relative prevalence of subsea connections and illustrate trends rather than report absolute numbers. It is acknowledged the statistics presented in this section are considered a conservative/lower bound estimate, supported by the fact that the underlying data used in this section does not account for connections within the envelope of manifolds and trees.

3.1 Global Perspective

Figure 2 below presents the estimated number of diver-assisted and diverless connectors installed and still in service globally since 1990.

As seen in Figure 2, the Gulf of Mexico and South America have the most experience with subsea connectors in general and most experience with deep-water diverless connectors.

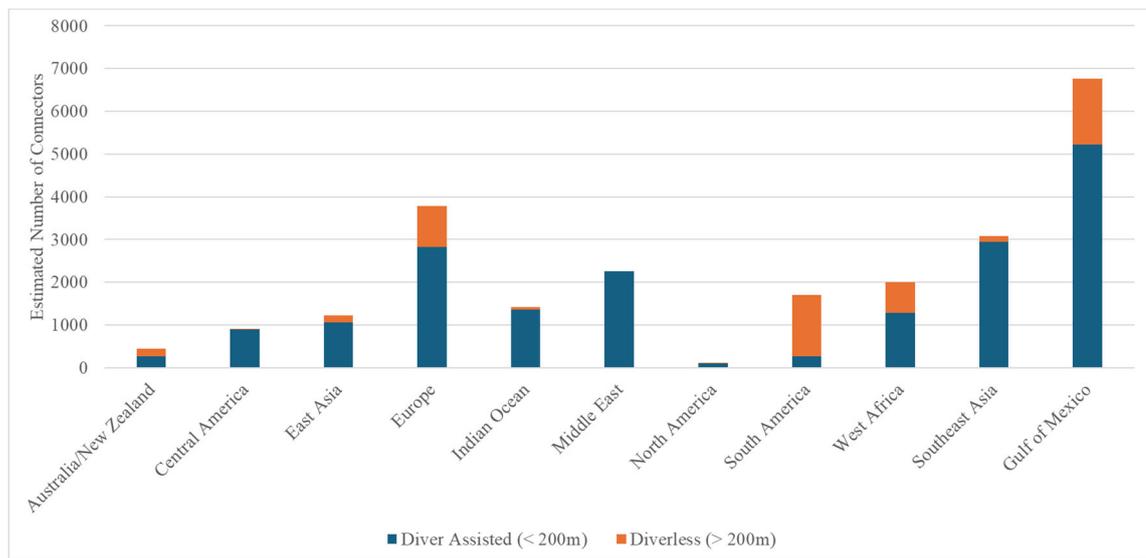


Figure 2 – Estimated number of in-service pipeline connectors installed globally since 1990

Looking forward to the next 10 years it is clear that a large proportion of projects will be in deeper waters requiring use of diverless technologies. The number of connectors expected in Europe makes up the largest proportion, but most connectors will be installed in shallower waters. South America will continue to focus on deep water developments.

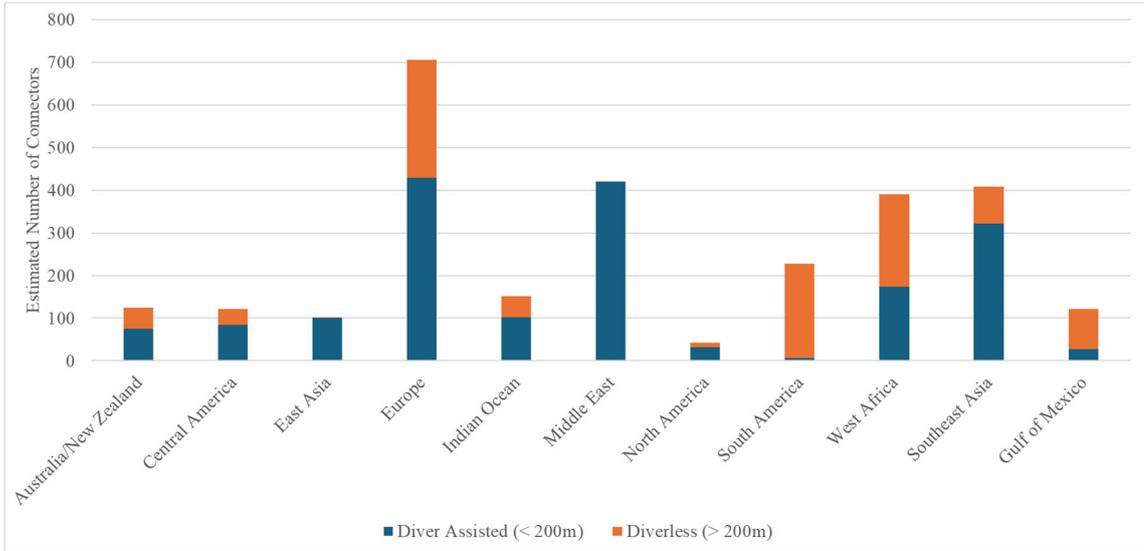


Figure 3 – Estimated number of pipeline connectors planned globally in next 10 years

3.2 North Sea Perspective

Most subsea developments in the North Sea have taken place and are planned in the Norwegian, British and Dutch Continental Shelves. A significantly smaller number of developments have taken place offshore Sweden, Ireland, Denmark and Germany and therefore the data for these countries are not presented here for ease of readability.

Figure 4 presents the estimated number of diver-assisted and diverless connectors installed and still in-service in the North Sea since 1990.

As can be seen the UK has the most experience with subsea connectors in general, however Norway has the most experience with deep-water diverless connectors.

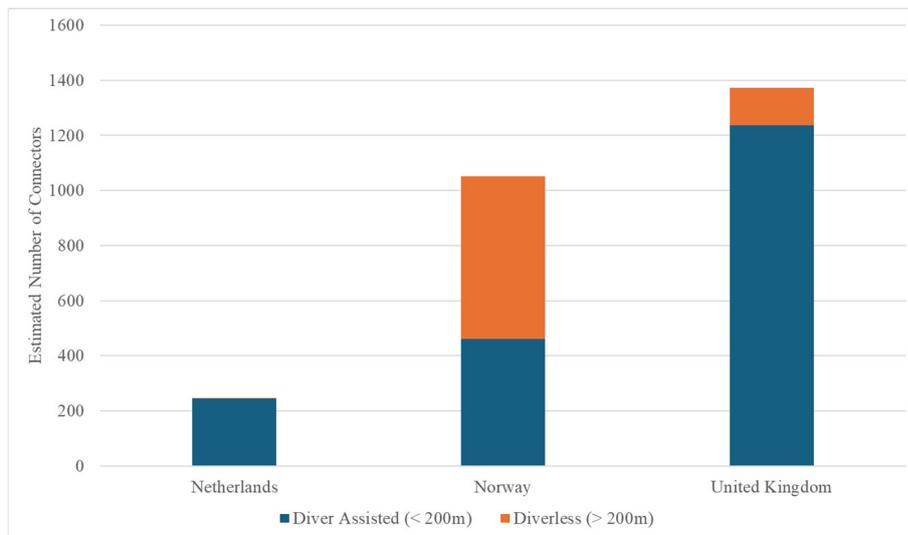


Figure 4 - Estimated number of in-service pipeline connectors installed in the North Sea since 1990

Looking forward to the next 10 years, it is clear that a larger proportion of projects will be in deeper waters requiring use of diverless technologies.

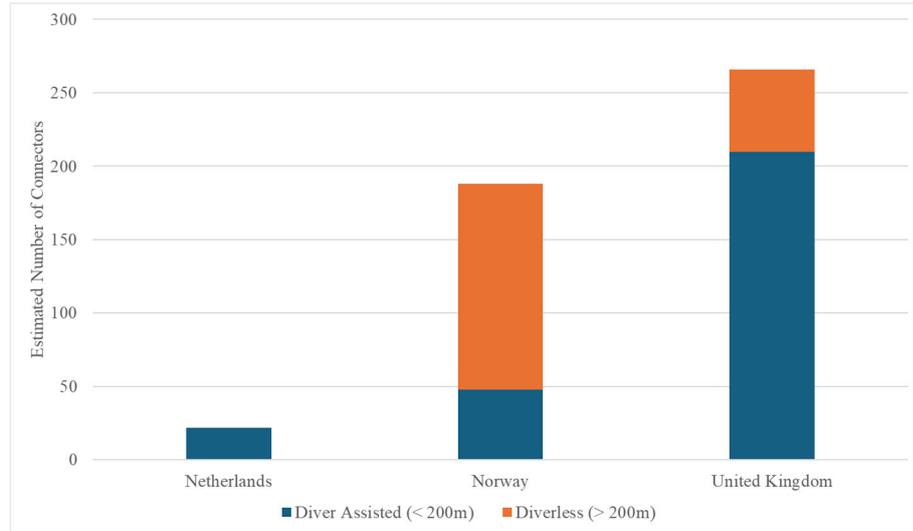


Figure 5 - Estimated number of subsea connectors planned in the North Sea in next 10 years

3.3 Prevalence Summary

As can be seen the industry now has significant experience with diverless connectors. Diver-assisted connectors remain by far the most common type of subsea connector in operation however the industry has a significant track record and experience with diverless connectors also.

Based on the simplified approach outlined in Section 3 it is estimated that there are over 18,000 diver-assisted connectors and over 5,000 diverless connectors currently in-service globally.

It is emphasised that these estimated numbers are lower bound and are based on a simplified estimation methodology as outlined in Section 3. The intention of the values reported is to demonstrate the relative prevalence of subsea connections and illustrate trends rather than report absolute numbers.

4. Subsea Connections – Configurations

Subsea connections are utilised between various subsea pressure containing equipment, such as XT's, manifolds, tie-in spools and pipelines.

Figure 6 below illustrates typical subsea systems and indicates the typical locations where subsea mechanical connections are required to connect different pieces of subsea production infrastructure.

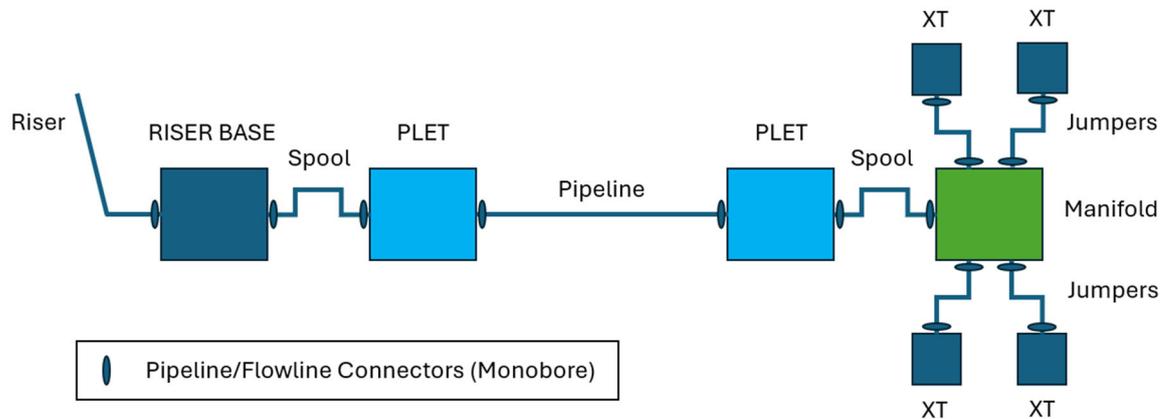


Figure 6 - Typical locations of Subsea connections

Subsea connections may be horizontal or vertical. Horizontal connections maintain the pipeline infrastructure close to the seabed and can be used for both rigid and flexible spools. Horizontal tie-ins can be made by diver-assisted mechanical connections or can be made utilising diverless connection systems in deeper water.

Vertical connections often use inverted U-shaped pipe spool/jumper geometries with connectors on each end, oriented downwards towards receiving connectors or 'Hubs'. The connecting piece is lowered to the seabed, and the connectors and hubs are 'mated,' activated, and usually provide a metal-to-metal seal. The sealing mechanism can be part of the connector or activated via tooling by a diver or ROV. Guides are typically present to assist with alignment.

5. Subsea Connection Types – Description and Evaluation of Critical Aspects

Subsea connections can be categorised into four main types, with various sub-types:

- **Flanged Connections:** Utilising metal gasket designs to create face-to-face contact, these connections adhere to API or ANSI/ASME codes and standards. These are discussed in Section 5.1.
- **Clamp Hub Connectors:** Similar to bolted flange connections, clamp hub connectors involve tightening a clamp to force the mating hubs together. These are discussed in Section 5.2.
- **Collet Connectors:** Widely used for jumper spool connections and wellhead connectors, collet connectors operate on a principle similar to hub and clamp connectors. However, they use a series of segments, or collets, activated by an annular locking cam ring. These are discussed in Section 5.3.
- **Mechanical Connectors:** These are more frequently used in deeper waters due to design and installation advantages. They employ either a mandrel or hub style interface, with actuating tools that are hydraulically or mechanically operated remotely. These are discussed in Section 5.4.
- **Gripping Mechanical Adapters:** These are used to create a non-welded connector on an open pipe end using similar principles and elements of both collet and mechanical connectors. Mechanically actuated rings apply a radial clamping and gripping force via internal collets or ball and taper technology around the diameter of the pipe. Pressure sealing is provided via seals/O-rings which are usually graphite or elastomeric material. These are discussed in Section 5.5.

5.1 Flanged Connections

5.1.1 Flanged Connections – Description

One of the most widely used, the flanged connection uses circular faces to make face to face contact, compressing between them a metal gasket to form a metal-on-metal seal, as the faces are bolted up these gaskets yield and compress and form the seal.

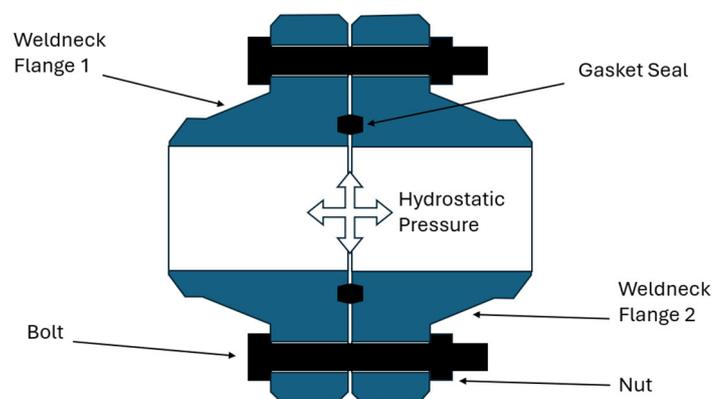


Figure 7 – Weld Neck Flange Connection

The typical weld neck flange (Figure 7) is well-known and commonly used worldwide. In Europe, particularly Norway, the use of the proprietary Compact flange has grown popular, owing to its low weight/compact dimensions, reliability and comparable strength [13].

Weld neck flange faces are fixed and although may allow limited misalignment, torsional misalignment is not possible owing to the fixed bolt-hole orientations. Therefore, the fixed bolt-hole positioning in weld neck flanges requires an extremely high precision in fabrication and installation to ensure the bolt holes are aligned.

The use of swivel ring flanges (Figure 8) can eliminate this torsional restriction, allowing the face itself to rotate around the neck, allowing for ease of bolt-hole alignment.

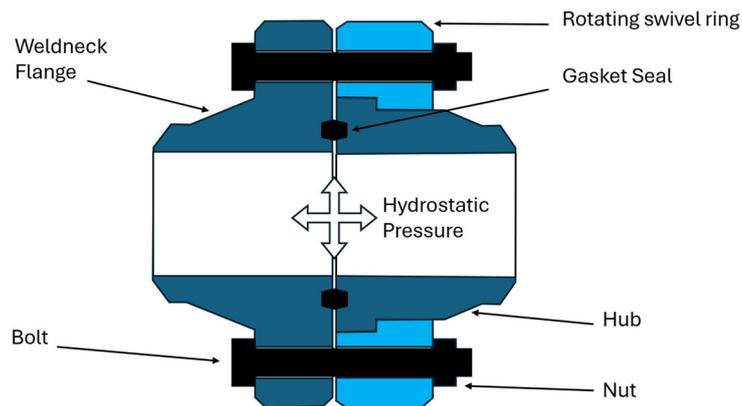


Figure 8 – Swivel Ring Flange Connection [14]

Misalignment flanges (Figure 9) can allow greater degree of misalignment before make-up, employing ball and socket-like connection that eases both axial and rotational restrictions.

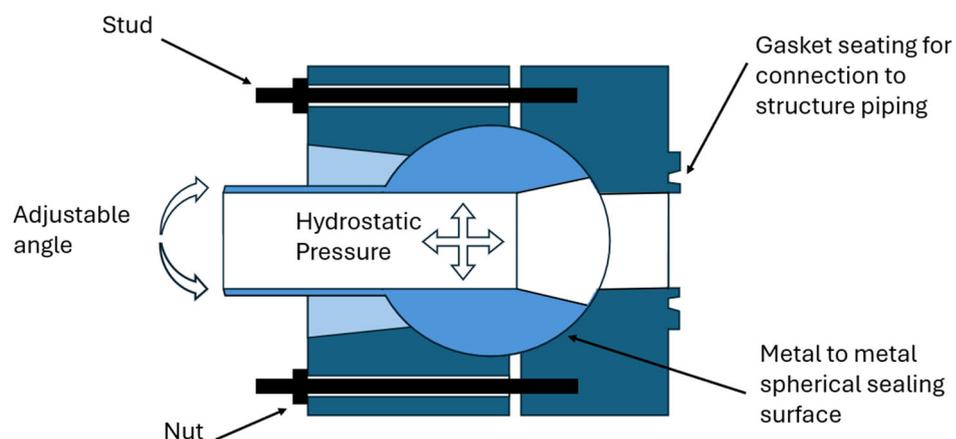


Figure 9 – Misalignment Flange Connection [15]

Appropriate gasket selection and correct gasket stress at installation ensures performance and reliability during service. Gasket materials can be metal, elastomers or composites, some gaskets with secondary or additional sealing are often made with different materials. Like other parts of the pipeline system these materials will need to resist corrosion from seawater and service/production fluids. Furthermore, welded inlays are often specified to ensure a corrosion resistant finish.

The gaskets must withstand internal and external pressures, demonstrating good recovery after compression but resisting further deformation to maintain seal integrity. With respect to loading, consideration should be given to the dynamic loads imposed by subsea wave, current and equipment activity and during installation. It should be ensured that the gasket can easily be installed or replaced – accuracy of alignment is of particular importance as misalignment can cause failure of the seal. Gaskets must be compliant with the relevant codes and standards, and relevant certification of proposed gasket materials must be verified.

After initial alignment, the flanges are brought together via stud/bolt and nut fasteners, usually employing a stud/bolt tensioning system which is made up by divers in shallow water depths. For deepwater applications, technologies exist which enable ROVs to perform make-up of conventional flanged connections. Two examples of diverless flange connection technology are discussed below:

- MATIS system: The MATIS system is an example of technology which uses pipe handling frames and flange alignment frames to mate flange surfaces and the insertion and tensioning tool performs the preloading operation.
- Brutus system: The BRUTUS system uses an axial force tool and a reaction tool which enable the flange faces to be pulled together and aligned. The bolt insertion and tensioning tool performs connections remotely by ROV and carries all bolts and nuts together with the bolt tensioning equipment.

5.1.2 Flanged Connections – Evaluation of Critical Aspects

5.1.2.1 Design Stage

At design stage, the following technical aspects determine safety level and reliability in respect of flanged connections:

1. Material selection: Flange, gasket and fastener materials must withstand the harsh subsea environment, external hydrostatic pressure, functional loads, corrosive internal fluids and design temperature extremes. For example, some applications involving corrosive internal fluids may require CRA cladding or weld overlay of the inside surface of the flange bore, and the improper application (or absence) of such CRA cladding/overlay can cause severe internal corrosion and subsequent flange failure.
2. Flange mechanical design: The mechanical design must ensure that the flange will withstand all forces due to internal pressure, external pressure, axial loads, bending loads and torsion loads and must ensure that all stresses are within allowable limits and that there are no excessive localised stress-concentrations which may lead to fatigue/cracking. This is generally achieved by appropriately selecting the flange type and pressure rating or by demonstrating, via analytical or FEA-based stress analysis, that the design adheres to established design standards (for example ASME Section VIII Div 1 [22] or Div 2 [23]). In case materials susceptible to Hydrogen Induced Stress Cracking (HISC) are used, then the design must demonstrate compliance with relevant industry standards (e.g. DNV-RP-F112 [24]). Correct bolt pre-tension must be specified to ensure the right joint compression and gasket seating stress.
3. Fastener and gasket selection: Selected fasteners must withstand all pressure loads, temperature loads and externally applied bending moments. Selected gaskets must be capable of maintaining a reliable seal under varying pressure and temperature conditions. The gasket grooves should be specified with welded CRA inlay to prevent corrosion within the gasket seat area. When specifying fasteners, it must be ensured that the appropriate grade of nut is

matched to the bolt/stud grade – this is to avoid issues due to incompatibility, such as thread stripping.

5.1.2.2 Manufacturing Stage

At manufacturing/fabrication stage, the following technical aspects determine safety level and reliability in respect of flanged connections:

1. Quality Control: Quality at manufacturing/fabrication stage must be controlled by implementing the requirements of the flange standards (such as ASME B16.5 [17]), and additionally the requirements of pipeline design standards (such as DNV-ST-F101 [8]).
2. Inspection and Testing: Inspection and testing must comply with the requirements of the flange standards (such as ASME B16.5 [17]), and additionally the requirements of pipeline design standards (such as DNV-ST-F101 [8]).

5.1.2.3 Installation Stage

At installation/hook-up stage, the following technical aspects determine safety level and reliability in respect of flanged connections:

1. Misalignment: To prevent excessive stresses, misalignment at the point of flange make-up must be within the limits defined at the design stage.
2. Stud/Bolt Tensioning: Improper tightening sequence and/or incorrect torque applied to fasteners may lead to inadequate or uneven gasket compression (or even bolt/stud failure) which can compromise the sealing performance.

5.2 Clamp Hub Connectors

5.2.1 Clamp Hub Connectors – Description

The clamp hub connector typically uses a two-half shell design, together with a metal ring or proprietary gasket for sealing, and a bolted clamp to clamp the two mating hubs together. Clamping pressure is normally applied by tensioning four bolts between the two half shells resulting in compression and activation of the seal. A typical clamp hub connector cross-section is shown in Figure 10.

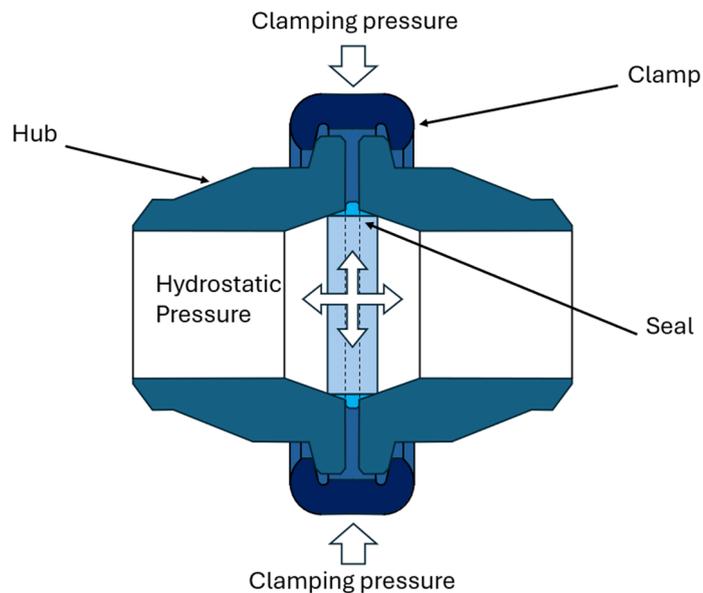


Figure 10 – Typical Clamp Hub Connector

Clamp hub connector requires a greater degree of axial alignment but eliminates the need for rotational (torsional) alignment completely. Requiring less fasteners than a standard welded flange connection, they can be quicker to install, make-up and remove, although in the latter case clamps in long service may be difficult to remove due to the existence of residual stress and friction.

5.2.2 Clamp Hub Connectors – Evaluation of Critical Aspects

As the clamp hub connector is similar in principle to the flanged connection, the technical aspects that determine safety level and reliability in respect of clamp hub connectors are broadly the same as those for flanged connections listed in Section 5.1.2. However, the following specific considerations apply to clamp hub connectors:

- Localised stresses at clamp interfaces and bolt hole regions
- Fatigue considerations due to cyclic bending moments
- Clamp hub connectors require alignment of the two halves of the clamp. This involves the following critical aspects:
 - machining accuracy and precision in manufacturing/fabrication is critical
 - this may make it challenging to achieve the correct fit of clamp halves subsea

5.3 Collet Connectors

5.3.1 Collet Connectors – Description

A collet connector has a receiving hub at one end of the connection and on the other end is a collet connector with a series of segmented collets that provide the clamping force. Once mated, the collet connector is activated by an actuator via an annular locking cam ring (actuator ring). Once actuated, the individual collets (or ‘fingers’) clamp-close around both hubs, hooking into the alternative mating ring and forming a full structural connection. While the gasket imparts a seal, the collet preload used for the clamping force provides strength equivalent to that of the pipe itself. A typical collet connector cross-section is shown in Figure 11.

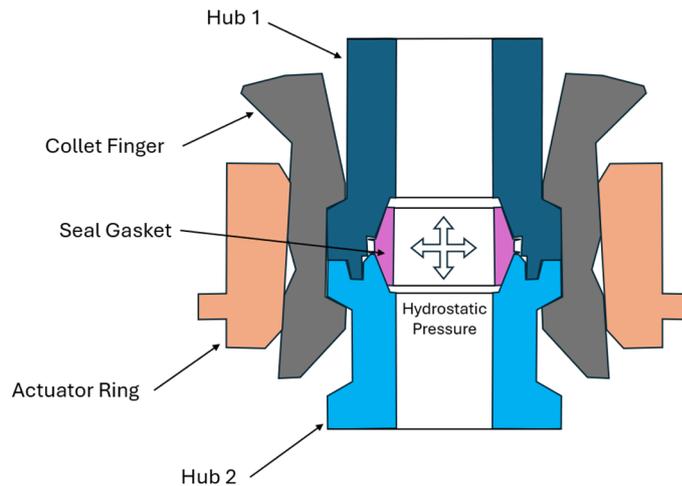


Figure 11 – Typical Collet Connector

The sealing preload can be regulated by the axial force on the actuator ring and friction between the actuator ring and collet fingers provides seal performance while said friction is self-locked [26]. Collet connectors can typically accommodate up to $\pm 2^\circ$ angular misalignment and ± 1.5 in axial offset.

Depending on whether the actuator is integral to the connector, there are broadly two types of collet connectors:

- Collet connectors with integral (self-contained) actuator
- Collet connectors without integral (self-contained) actuator – in this case, an external actuator is required.

Collet connectors are often used in jumper spool configurations and use funnels to guides to provide initial alignment. Once mated, internal hydraulic systems or ROV operated tooling actuate the closing of the collets.

5.3.2 Collet Connectors – Evaluation of Critical Aspects

5.3.2.1 Design Stage

At design stage, the following technical aspects determine safety level and reliability in respect of collet connectors:

1. Material selection: Hubs, collets, housing and seals materials must withstand the harsh subsea environment, external hydrostatic pressure, functional loads, corrosive internal fluids and design temperature extremes.
2. Mechanical design: Collet fingers must engage securely and deliver the required compression without localised stress concentrations which may later lead to cracking. The mechanical design must ensure that the connector and actuator will withstand all forces due to internal pressure, external pressure, axial loads, bending loads and torsion loads and must ensure that all stresses are within allowable limits and that there are no excessive localised stress-concentrations which may lead to fatigue/cracking. This is generally achieved by demonstrating, via FEA-based stress analysis, that the design adheres to established design standards (for example ASME Section VIII Div 1 [22] or Div 2 [23]). In case materials susceptible

to Hydrogen Induced Stress Cracking (HISC) are used, then the design must demonstrate compliance with relevant industry standards (e.g. DNV-RP-F112 [24]).

3. Seal Design: Design of metal-to-metal seals and any elastomeric/secondary seals must withstand all pressure loads, temperature loads and externally applied bending moments. Seal design must account for expected misalignment at the time of make-up and ensure a reliable seal under varying pressure and temperature conditions.
4. Actuator: Actuator must be designed to provide the required actuation force and must be reliable and repeatable in engaging and disengaging the collet fingers.

5.3.2.2 Manufacturing Stage

At manufacturing/fabrication stage, the following technical aspects determine safety level and reliability in respect of collet connectors:

1. Quality Control: High accuracy and precision are required in machining and surface finish during manufacturing/fabrication.
2. Inspection and Testing: In addition to NDT and pressure testing, a system level test is required to ensure that the actuator assembled to the connector performs as expected. Installation procedures (including installation tooling) should be tested as part of a system integration test at manufacturing stage.

5.3.2.3 Installation Stage

At installation stage, the following technical aspects determine safety level and reliability in respect of collet connectors:

1. Misalignment: To prevent uneven collet loading and sealing issues, misalignment at the point of make-up must be within the limits defined at the design stage and subsequently tested at the manufacturing (factory acceptance) stage.
2. Installation procedures (including installation tooling) must be well defined and must accommodate practical ROV limitations and variations in environmental conditions at the seabed.
3. Post-installation testing must confirm seal performance.

5.4 Proprietary Connector Systems

There are several proprietary diverless connector systems available on the market which are usually large self-contained subsea connection solutions and/or items. Provided by a range of manufacturers and designers, the technologies involved often incorporate those already discussed previously. The design, features and application of technology is varied across these products, however this report will discuss the most common features available in most connector systems.

5.4.1 Proprietary Connector Systems – Description

Connector Systems are proprietary connections which are horizontally or vertically oriented and are actuated hydraulically or mechanically by remote techniques.

The main elements of Connector Systems are listed below:

a) Clamp Connector

The clamp connector assembly is the primary component of the mechanical connector that joins two sections of subsea infrastructure, such as pipelines or umbilicals. It is designed to create a secure, leak-proof seal that can withstand high pressures (up to 15,000 psi) and harsh conditions. Clamp connectors are engineered to be robust and reliable, ensuring the integrity of the subsea system. They often feature metal-to-metal primary seals and elastomeric secondary seals to ensure a tight fit and prevent leaks. Connectors may also include features for electrical and hydraulic connections, enabling the transmission of power and control signals.

b) Hub and Receiver

The connector receiver serves as the fixed point (typically situated on a subsea structure) where the subsea connector attaches. The hub is typically mounted on a support structure that provides stability and alignment, ensuring it remains securely in place. The support structure is designed to withstand high pressures and strong currents.

c) Actuator

The connector actuator is a mechanism that facilitates the engagement and disengagement of the connector. It can be operated remotely using a Remotely Operated Vehicle (ROV) to ensure a precise and safe connection. The actuator applies the necessary force to lock the connector in place, ensuring a secure and stable connection. Actuators are typically hydraulic or electric, providing the force needed to engage the connector under high-pressure conditions.

d) Soft-landing System

A soft-landing system gently guides and positions subsea equipment, such as connectors, onto the hub or other subsea structures. This helps to prevent damage to the equipment and the subsea infrastructure during installation. The soft-landing system typically includes features like dampers or cushioning mechanisms to absorb impact forces. Soft-landing systems may use hydraulic or pneumatic controls to ensure smooth and controlled descent, minimizing the risk of impact damage. These systems are crucial for the precise placement of heavy and delicate subsea components.

e) Connector Override Tool

The connector override tool is a device used to manually operate the connector in case of actuator failure or other issues. This tool allows for the manual engagement or disengagement of the connector, providing a backup method to ensure the connection can be made or released as needed. Override tools are designed to be used by ROVs, featuring interfaces that allow for easy manipulation in deep-sea conditions. They are essential for maintaining operational

flexibility and ensuring that connections can be managed even in the event of primary system failures.

5.4.2 Proprietary Connector Systems – Evaluation of Critical Aspects

5.4.2.1 Clamp Connector

The following technical aspects determine safety level and reliability in respect of the clamp connector:

- **Protection of Mating Hub:** The connector must be designed to ensure that it does not permanently deform the mating hub during the connection process. This is crucial to maintain the integrity and functionality of the hub for future connections and disconnections. The design should incorporate features that distribute the connection forces evenly to prevent excessive localized stress and deformation.
- **Seal Protection:** During both deployment and retrieval, the connector should protect the seals and seal surfaces. This involves using protective covers or barriers that shield the seals from physical damage and environmental contaminants.
- **Retention of Metal-to-Metal Seal:** The connector must retain its metal-to-metal seal throughout the installation and operation phases. The design should ensure that the seal remains intact and effective under varying operational and accidental conditions.
- **Mechanical Load Management:** The mechanical loads imposed on the connector must be within the limits identified at design stage and also must not exceed the limits of the connector receiver structure or the connected piping.

5.4.2.2 Hub and Receiver

The following technical aspects determine safety level and reliability in respect of the receiver:

- **Self-Contained Assembly:** The hub and receiver assembly should be designed as a complete unit that can be independently tested before being connected with other subsea components. Independent testing ensures it meets all necessary specifications and performance criteria, reducing the risk of issues during installation. This testing typically includes pressure, mechanical load, and functional testing to simulate operational conditions.
- **Weldability and Load Transfer:** The hub must be weldable to the subsea pipeline or equipment, using materials and design practices that facilitate secure and reliable welding under subsea conditions. Common materials include high-strength, corrosion-resistant alloys like duplex stainless steel or Inconel. The design should ensure the receiver can transfer overloads into existing structures, incorporating features like load transfer pads or gussets to distribute forces evenly and prevent localized stress.
- **Protection of Mating Hub:** The connector receiver should protect the mating hub during installation and retrieval. This involves incorporating design features that shield the hub from physical damage and environmental exposure, such as guide funnels, bumpers, and protective covers. Additionally, the receiver should minimize the ingress of debris and marine growth, which can affect the connection's integrity.
- **Material Selection:** The materials used for the connector receiver should be selected based on their mechanical properties, corrosion resistance, and compatibility with the subsea environment. Common materials include duplex stainless steel, super duplex stainless steel, and nickel-based alloys. These materials offer high strength, excellent corrosion resistance, and good weldability, making them suitable for harsh subsea conditions.

- **Sealing Mechanisms:** The connector receiver should have reliable sealing mechanisms to ensure a leak-proof connection. This may include metal-to-metal seals, elastomeric seals, or a combination of both. Metal-to-metal seals provide high-pressure containment and long-term reliability, while elastomeric seals offer flexibility and additional sealing integrity.
- **Hydraulic and Electrical Interfaces:** For connectors that include hydraulic or electrical interfaces, the receiver should accommodate these. This may involve integrating hydraulic couplers, electrical connectors, and control lines into the receiver design. These interfaces should be protected from mechanical damage and environmental exposure to ensure reliable operation.
- **Installation and Retrieval Considerations:** The connector receiver should be designed for easy installation and retrieval using Remotely Operated Vehicles (ROVs) or other subsea handling equipment. This includes features like alignment guides, ROV-friendly interfaces, and clear visual indicators to assist with positioning and engagement

5.4.2.3 Actuator

The following technical aspects determine safety level and reliability in respect of the actuator:

- **Ease of Recovery:** Connector actuators are designed to be easily recoverable from the seabed whenever possible. This feature helps to minimize the amount of equipment left in the field area, reducing clutter and potential obstacles for other operations. Easy recovery can be facilitated by incorporating features such as ROV-friendly interfaces, quick-release mechanisms, and clear visual indicators to assist with retrieval.
- **Integral Actuator Design:** The actuator is integrated with the connector, it must be designed to prevent accidental unlocking due to impact, vibration, or thermal loads. This is crucial to ensure the stability and security of the connection under various operational conditions. The design should include robust locking mechanisms that can withstand these forces.
- **Backup Locking Mechanism:** For actuators with self-locking mechanisms, an additional backup lock should be provided. This secondary lock acts as a fail-safe to ensure that the connector remains securely locked even if the primary locking mechanism fails. The backup lock should be designed to engage automatically and be capable of withstanding the same operational stresses as the primary lock

5.5 Gripping Mechanical Adapters

5.5.1 Gripping Mechanical Adapters – Description

Gripping mechanical connectors are proprietary connections which can be horizontally or vertically oriented and are actuated mechanically or hydraulically by remote techniques. These connectors are generally used to make a connection to an open pipe end. They are often used when a pipeline has been cut to allow tie-in of a new pipe to facilitate repair or repurposing. Gripping mechanisms vary between manufacturers but are typically either by collet ring or ball and taper.

The main elements comprising the gripping mechanical adapters are:

a) Gripping Mechanism

The collet grip element in the receiving end of the connection provides the clamping force. Once mated, the collet Grip is activated by an internal annular cam or alternative system for impressing the radial collet around the pipe and providing the gripping force.

In the Ball and Taper variety spherical balls roll up the tapers in the mandrel part of the connector pressing into the connecting pipeline resulting in a multipoint grip, trying to remove the pipe in this instance causes the balls to roll further up the taper, increasing the gripping strength. There are a few variations of the ball and taper gripping system, but the technology and mechanisms are similar. [31]

b) Seals

The Seals or O-rings providing leak tight sealing are typically provided in dual configuration to allow an annulus seal test after installation.

c) End termination

There are a variety of end connections available depending on purpose of use, including flanged end, end cap for pipe termination, or in coupling configurations gripping mechanisms can be provided on both ends to facilitate two open ended pipes to be connected.

5.5.2 Gripping mechanical connectors – Evaluation of Critical Aspects

5.5.2.1 Design Stage

At design stage, the following technical aspects determine safety level and reliability in respect of gripping mechanical connectors:

1. Material selection: Hubs, collets, housing, tension bolts, mechanical actuation elements and seals materials must withstand the harsh subsea environment, external hydrostatic pressure, functional loads, corrosive internal fluids and design temperature extremes.
2. Mechanical design: Adequately sufficient and accurate data on surface finish and diameter tolerance at the cut end of the pipe is important in ensuring The gripping collets and mandrels must engage securely and deliver the required compression without localised stress concentrations which may later lead to cracking. The mechanical design must ensure that the connector and actuator will withstand all forces due to internal pressure, external pressure, axial loads, bending loads and torsion loads and that all stresses remain within allowable limits ensuring that there are no excessive localised stress-concentrations which may lead to fatigue/cracking. This is generally achieved by demonstrating, via analytical calculations or FEA-based stress analysis, that the design adheres to established design standards (for example ASME Section VIII Div 1 [22] or Div 2 [23]). In case materials susceptible to Hydrogen Induced Stress Cracking (HISC) are used, then the design must demonstrate compliance with relevant industry standards (e.g. DNV-RP-F112 [24]).
3. Seal Design: Metal-to-metal seals and any elastomeric/secondary seals must be designed to withstand all pressure loads, temperature loads and externally applied bending moments. Seal design must account for expected misalignment at the time of make-up and ensure a reliable seal under varying pressure and temperature conditions.
4. Actuator: The actuator must be designed to provide the required actuation force and must be reliable and repeatable in engaging and disengaging the gripping elements.

5.5.2.2 Manufacturing Stage

At the manufacturing/fabrication stage, the following technical aspects determine safety level and reliability in respect of gripping mechanical connectors:

1. Quality Control: High accuracy and precision are required in machining and surface finish during manufacturing/fabrication.
2. Inspection and Testing: In addition to NDT and pressure testing, a system level test is required to ensure that the actuator assembled to the connector performs as expected.

5.5.2.3 Installation Stage

At the installation stage, the following technical aspects determine safety level and reliability in respect of gripping mechanical connectors:

1. Misalignment: To prevent uneven gripping element loading and sealing issues, misalignment at the point of make-up must be within the limits defined at the design stage and subsequently tested at the manufacturing (factory acceptance) stage.
2. After activation there should be a verifiable confirmation that the internal cam has activated the gripping collet correctly or that the individual ball and taper mechanical elements have correctly engaged with the pipe. In both cases care should be taken to ensure the radial forces are within the identified limits to limit compressive damage to the connecting pipe.
3. Installation procedures must be well defined and must accommodate practical ROV limitations and variations in environmental conditions at the seabed.
4. Post installation testing must confirm seal performance.

6. Subsea Connections – Requirements

6.1 Functional Requirements

Subsea connection systems must meet the following functional requirements:

- **Functional Loads:** Connections must withstand the worst expected combination of design pressure and minimum and maximum design temperature
- **Externally Applied Axial Loads and Bending Moments:** Connections must withstand the worst expected axial loads and bending moments, for example axial load and bending moment on a connector due to pipeline end expansion at the location of a FLET.
- **Fatigue Life:** Connections must be able to endure the expected cyclic loading over service life.
- **Misalignment:** Connections must accommodate flowline/pipeline/jumper misalignment or metrological misalignment to the required extent, without sacrificing integrity
- **Material Compatibility:** Connection materials must be suitable for both environmental conditions and the conditions of service (fluid, sour service etc). In addition, connection materials must be compatible with the flowline/pipeline materials that are being connected.

6.2 Design Requirements

Connections must be designed to withstand the required functional, environmental, and accidental loads over the intended lifetime. Connections must demonstrate the required safety, reliability and accessibility for inspection and maintenance. The design should account for worst-case scenarios, such as pressure separation, external pressure and externally applied axial loads and bending moments, ensuring all seals are qualified for various pressures, temperatures, and fluids. Redundant seals are required unless metal-to-metal seals are used. Qualified procedures must be defined for correct installation of subsea connections.

A summary of the primary standards and guidance which are referenced in the design and qualification of subsea connections is provided in below.

Table 1 - Applicable Design Guidelines

Standard Number	Standard Title	Contents	Applicable To
American Petroleum Institute (API)			
API Spec 17D [4]	Specification for Subsea Wellhead and Tree Equipment	Requirements for flange end and API clamp connections applicable to connecting to subsea equipment, refers API Spec 6A [5] for material requirements.	API Flanges API Clamps
API RP 17R [6]	Recommended Practice for Flowline Connectors and Jumpers	Requirements and recommendations for subsea flowline	Flange (No-Diver assist) Clamp Mechanical Proprietary

		connectors and jumpers	
API TR 17TR7 [7]	Verification and Validation of Subsea Connectors	Requirements and recommendations for the verification and validation of subsea connectors.	General
Det Norske Veritas (DNV)			
DNV-ST-F101 [8]	Submarine Pipeline Systems	Provides reference to recommended design standards for connectors and flanges, some additional requirements for manufacture, testing and reference to Qualification (via TQ)	Flanges Mechanical Connectors Repair clamps and couplings
International Organization for Standardization (ISO)			
ISO 13628-1 [9]	Petroleum and natural gas industries – Design and operation of subsea production systems – Part 1: General requirements and Recommendations	High level guidance and reference to other codes for design of connectors. General requirements	Flange Clamp
ISO 13628-7 [10]	Petroleum and natural gas industries – Design and operation of subsea production systems – Part 7: Completion/workover riser systems	Design and functional requirements and detailed requirements for analysis also includes Qualification requirements for connectors	Flange Clamp Mechanical Proprietary

6.3 Material Requirements

Materials selected for connections must meet the functional, mechanical, and environmental demands of their intended use. Critical components should avoid castings, and high-contact stress areas like threaded connections must consider galling. Non-metallic materials should be evaluated for service compatibility, mechanical properties, and resistance to environmental factors such as high-pressure extrusion, thermal cycling, and rapid gas decompression. For sour service, materials must comply with ISO 15156, ensuring resistance to sulphide stress cracking and hydrogen-induced cracking. Qualification testing is required for materials in sour service, focusing on their ability to withstand operational stresses and deliver the expected fatigue performance.

Corrosion protection is a key focus, both internally and externally. Internally, considerations include the corrosiveness of handled fluids, with mitigation strategies like coatings, inhibitors, and flushing systems. Externally, where required, components may be coated and provided with cathodic protection to withstand marine environments. External coatings shall be durable and resist mechanical damage,

ensure electrical continuity, and prevent galvanic corrosion. Overall, the materials and protective measures must be carefully selected to ensure the integrity and longevity of subsea connections.

6.4 Qualification and Certification Requirements

Connections are subject to a higher threshold of qualification than simple welded joints where qualification is covered by basic quality assurance. This is in part due to the variations in connection technologies and readiness of such technologies in the context of a specific project or application. Connections must be qualified to prove that design and functional requirements of any given connection are met, reducing risk and ensuring reliability. Qualification and reliability assurance strategy are discussed further in Section 10.

Please refer to Appendix B for further details on qualification considerations.

The process of certifying equipment for offshore use is critical to ensure that said equipment meets regulatory requirements, a process often supported by third-party bodies that involves technical support, design reviews, testing and survey. This process provides assurance that equipment is fit for installation, safe and reliable in use and will function as intended.

The design and qualification of subsea connectors is initially performed to satisfy a pre-defined design life. For in-service connectors where a life extension is required, the original design and qualification of the connector should be reviewed in the context of the requirements of the life extension. Focus should be made to time dependent degradation mechanisms such as corrosion and fatigue and whether the operating history or future operation will impact these aspects.

6.5 Installation / Make-Up Requirements

The make-up of connections must be assessed throughout all project phases, including installation, testing, and operation. During installation, connections must deliver sufficient gasket sealing pressure to maintain seal integrity under installation and operational stresses, including under cyclic pressures, temperature changes and dynamic loads. Where applicable, adequate clearance for future seal replacement should be provided.

Connections must be assembled by qualified personnel using a qualified procedure to achieve the specified preload without overloading. The combined stresses, including operational and residual stresses from alignment and installation, must be carefully managed to ensure long-term connection performance and integrity.

6.6 Testing Requirements

The connection assembly must be capable of verifying, through testing, that the required seal performance has been achieved, and that the connection is fully actuated or clamped into position as designed. Hydrostatic testing must be performed during manufacture, at factory acceptance stage, and post-connection to ensure the integrity and functionality of connections under operational conditions.

7. Comparative Evaluation of Failure Modes

Table 2 presents a comparative evaluation of subsea connection failure modes. These failure modes may be realised during the in-service operating phase of the connector. Any failures found during pressure testing are assumed to be rectified as part of the pre-commissioning process.

Table 2 – Comparative Evaluation of Subsea Connection Failure Modes

Connection	Failure Modes
Flanged Connections and Clamp Hub Connectors Clamp Hub Connectors	<ul style="list-style-type: none"> • Leakage failure may occur due to: <ul style="list-style-type: none"> ○ Lack of gasket pre-load due to incorrect tightening of bolts ○ Loss of gasket pre-load due to gasket creep, bolt stress relaxation (e.g. temporary loss of bolt tension due to differential thermal expansion, permanent loss of bolt tension due to creep, etc) ○ Incorrect bolt tightening sequence and/or incorrect bolt torque ○ Poor gasket selection, or poor gasket manufacturing quality ○ Corrosion at sealing surfaces ○ Excessive misalignment leading to uneven gasket stress distribution • Stress failure may occur due to: <ul style="list-style-type: none"> ○ Overstressing, poor material selection / material specification, manufacturing defects ○ Incorrect stress analysis • Fatigue failure in flanged connections can occur due to alternating pressure, temperature and external loads • Bolt failure may occur due to: <ul style="list-style-type: none"> ○ Poor material selection / material specification leading to degradation in service due to corrosion, stress corrosion cracking, HISC, etc ○ Uneven stress distribution due to excessive misalignment between flanges ○ Overstressing of bolts during installation or uneven tightening of bolts

Connection	Failure Modes
Collet Connectors	<ul style="list-style-type: none"> • Leakage failure may occur due to: <ul style="list-style-type: none"> ○ Lack of actuator driving force, inadequate or uneven collet engagement, collet failure, actuator failure ○ Excessive misalignment ○ Poor seal design, or poor seal manufacturing quality ○ Corrosion at sealing surfaces ○ Excessive misalignment leading to uneven seal stress distribution • Stress failure may occur due to: <ul style="list-style-type: none"> ○ Overstressing of collets due to uneven engagement, poor material quality, manufacturing defects ○ Poor material selection / material specification leading to degradation in service due to corrosion, stress corrosion cracking, HISC, etc ○ Excessive misalignment between flanges leading to uneven stress distribution ○ Incorrect stress analysis • Fatigue failure in collet connectors can occur due to alternating pressure, temperature and external loads • Actuator failure may occur due to loss of hydraulic pressure / electric signal, or due to long term corrosion, fouling and wear.
Mechanical Connectors	<p>Failure modes vary based on specific technologies adopted by mechanical connector vendors. Typical failure modes are:</p> <ul style="list-style-type: none"> • Improper material selection / material specification in the form of corrosion, stress corrosion cracking, HISC etc of materials for the hub, porch, receiver, seals, stroking tool, override tool, etc leading to cracking or leakage failure • Incorrect or inadequate FEA leading to overstressing or localised stress concentrations leading to stress and fatigue failure • Poor seal design or poor seal manufacturing quality leading to leakage failure • Stroking tool failure may lead to incorrect connector engagement • Manual override tool failure may lead to inability to emergency-disconnect • Insufficient factory / site acceptance testing may hide faults

The failure modes listed in Table 2 are not exhaustive and it is recommended to consult manufacturers for subsea connectors during the procurement phase to document the possible failure modes for their connection systems and to identify any indicators of degradation which can be inspected for in-service. It is also recommended that any in-service failures are reported to the manufacturers.

Due to the complex geometry of subsea mechanical connectors and the lack of accessibility to inspect certain connector types it may not be possible to directly inspect the connector, but indications of the connector condition may be made from inspection of the upstream and downstream connected parts, i.e., performance of CP system or level of corrosion of similar materials.

Some connector systems may depend on a single element to maintain a leak-free seal. For example, certain proprietary diverless clamp connectors may rely upon a single locking screw to maintain the clamping force on

the hubs. These single point of failure elements may not be readily inspectable during the service life and therefore the design and qualification of these elements is of particular significance.

8. Subsea Connection Selection Considerations

Table 3 presents a comparative evaluation of subsea connection subsea connection selection considerations.

Table 3 – Comparative Evaluation of Subsea Connection Selection Considerations

Parameter	Flanged Connections	Clamp Hub Connections	Collet Connections	Connection Systems
Installation misalignment	<p>Require tight linear and angular misalignment tolerances</p> <p>Swivel ring flanges allow flexibility in orientation of bolt holes, hence eliminating torsional pipe stresses and the need for control of pipe orientation</p>	<p>Do not tolerate axial and out-of-plane misalignments as well as flanged connections</p> <p>No need for control of pipe torsional orientation, eliminating torsional pipe stresses</p>	<p>Can accommodate angular misalignment, the collet system ensures a tight and accurate fit</p>	<p>Can tolerate slight angular and translational misalignments.</p> <p>Horizontal connections may result in stressing of the pipe during make-up due to horizontal stroking.</p>
Procurement lead time	Short procurement time, especially due to standard available flanges		Longer procurement time, especially due to project-specific requirements	

Parameter	Flanged Connections	Clamp Hub Connections	Collet Connections	Connection Systems
Connection make-up time	Longest connection time due to number of fasteners, connection time increases with flange size	Shorter connection time compared to flanged connections, due to lower number of fasteners Can be difficult to disconnect – divers may have to hammer or use a special tool, to strip the clamp halves of the hubs, particularly if they have been subsea for a considerable length of time	No fasteners involved, short connection time	
Cost	Low material and fabrication cost, but high offshore installation cost due to longer connection time		High material and fabrication cost, but low offshore installation cost due to short connection time	
Deepwater / Diver-less friendly	No, typically require diver intervention	No, typically require diver intervention	Yes	Yes
Ability to disconnect, park and re-connect in-situ	No			Yes
Capability Range	Technology proven across a large range of sizes, pressures and temperatures	Proven range depends on manufacturer. Review of technical risks and technological readiness levels is recommended, see Section 10.		

9. Failure Statistics and Trends

A comparative analysis has been conducted on the reliability of connections versus other subsea equipment, such as pipelines, based on data available from the OREDA project [14]. The OREDA project (*The Offshore and Onshore Reliability Data*), a collaborative initiative comprising several oil and gas companies along with the Norwegian Petroleum Directorate, has been systematically collecting reliability data from a wide range of equipment, both topside and subsea, since 1983 [14]. The data compiled by the OREDA project is restricted to generic information, with detailed specifics not disclosed due to confidentiality and anonymity agreements. Nevertheless, valuable insights can be derived from the statistical data concerning failure modes and failure rates.

The particular dataset utilised is from OREDA@Cloud Phases VI-XII Data v 3.7.4.3, with the subsea data corresponding to information gathered from 2000 to 2017. As illustrated in the subsequent sections, the reported failures associated with loss of containment for subsea connections are lower compared to associated subsea equipment such as valves, piping, and flowlines. This trend is logically sound given that, provided the connections are correctly designed and installed, these components typically possess greater thickness than the connecting pressure-containing parts and are more frequently manufactured from superior materials such as stainless-steel alloys.

The failure statistics and trends outlined in the subsequent sections have been derived from the OREDA dataset. Since OREDA reports both functional failures (such as blockages) and structural failures (leading to a loss of containment), the data has been processed for this study, focusing solely on failures involving loss of containment (e.g., leakage or burst).

9.1 Flowline Connections – Failure Statistics

Table 4 presents the failure rates of flowline and pipe (body) alongside the failure rates of flowline connections which result in loss of containment. As can be seen the mean failure rate per unit per year of flowline connections is approximately five times lower than that of the flowline (pipe body).

Table 4 - Failure Rates - Flowline Connections

Description	No. Units	Mean Failure Rate /unit/year
Flowline & Pipe	1587	5.18 E-06
Connections (Flowline)	1278	1.04 E-06

The associated failure mechanisms leading to loss of containment for flowline connections are presented in an extract of the data available in the OREDA database as presented. The most common failure mechanisms identified were material and mechanical failures.

It is notable that the mechanical failures of connections were only associated with external leakage of utility fluids rather than process fluids suggesting that the failure resulted in a leak of fluid such as hydraulic fluid rather than hydrocarbons. Furthermore, no catastrophic structural failures of the connections were reported as all failures involved leakages. In contrast, burst failure modes were found in flowline and pipe body data.

Despite the dataset containing over 1200 units, as referenced in Table 4, there were only 8 reported incidents contributing to the failure distribution shown in .

Table 5 - Flowline Connection Failure Mechanisms (OREDA extract)

	Buckling	External Leakage Process	External Leakage Utility	Other	Structural Failure	
	BUC	ELP	ELU	OTH	STD	ΣTot
Corrosion				1		1
Leakage		1				1
Material failure - general		4				4
Mechanical failure - general			2			2

9.2 Manifold Connections – Failure Statistics

Table 6 presents the failure rate of manifold piping and valves alongside the failure rate of the connections associated with the manifold. As can be seen the mean failure rate per unit per year of the manifold connections is approximately four times lower than the mean failure rate of the manifold piping and approximately five times lower than the manifold process valves.

Table 6 – Failure Rates – Manifold Connections

Description	No. Units	Mean Failure Rate /unit/year
Manifold Piping	737	4.75 E-06
Manifold Process Valves	3266	6.89 E-06
Connections (Manifold)	1769	1.35 E-06

The associated failure mechanisms leading to loss of containment for manifold connections are presented in an extract of the data available in the OREDA database as presented. The most common failure mechanisms reported were leakage and material failure. For manifold connections, failure mechanisms such as breakage and looseness are reported in addition to mechanical failure, material failure and leakage. In all cases, regardless of the reported failure mechanism, the resulting failure mode is leakage for all reported failures resulting in loss of containment.

Table 7 - Manifold Connection Failure Mechanisms (OREDA extract)

	Combined /common Cause	External Leakage - Process	External Leakage - utility	Other	
	COM	ELP	ELU	OTH	ΣTot
Breakage		1			1
Leakage		4	1		5
Looseness		2			2
Material failure - general		2			2

9.3 Subsea Connections – Failure Mechanisms Summary

The reported mechanisms for subsea flowline and manifold connection failures reported in the OREDA database are listed below:

- Mechanical Failure
- Leakage
- Corrosion
- Material Failure
- Looseness
- Breakage

It is challenging to draw definitive conclusions from the data as details of each case and the root cause of failure are not known. However, it can be observed that leakage of process or utility fluids is the common failure mode among all reported failures. This suggests that burst or rupture type failures have not been documented, possibly limiting the severity of containment loss.

A significant proportion of failures are attributed to material failure, which may involve factors such as inappropriate material selection, underestimation of loads, manufacturing or quality issues, and problems during assembly.

Improved sealing technology, geometries, materials, and thorough validation can reduce failure risks but must be backed by post-installation verification, inspection and monitoring strategies, and feasibility of replacement and repair.

Whether the reported failures could have been avoided through in-service inspection is unknown; however, recommendations regarding in-service integrity management and inspections are provided in Section 11.

10. Connection Reliability, Technical Risk Assessment and Qualification Strategy

10.1 Approach

API RP 17N provides a framework in the form of the DPIEF reliability assurance cycle (loop) where DPIEF stands for the following steps:

- Define – goals, requirements, technical risks, accountability, and priorities
- Plan – activities, resources, deliverables, schedules, roles and responsibilities
- Implement – plans, tasks, and verification activities
- Evaluate – reliability, availability, and maintainability (RAM) analysis results against objectives, qualification test results, inspection and integrity monitoring results, and residual risks that cannot be eliminated.
- Feedback – lessons learned, technical risk assessment review (TRAR), and reliability and integrity assurance documentation (RIAD)

The DPIEF framework can be applied at each stage of the lifecycle of a connection, including:

- Feasibility
- Concept Selection
- FEED
- Detailed Design
- Manufacture, Assembly, Testing, Installation and Commissioning
- Operations
- Decommissioning

API 17N identifies the following four activities that should be updated continuously throughout each stage of the lifecycle, as an integral part of the DPIEF loop:

- **Statement of goals and requirements:** These are statements that direct project and operations teams on what needs to be accomplished. Selected goals and requirements should be specific and clearly defined, measurable, and realistically achievable within the specified time frame.
- **Technical Risk Categorisation (TRC):** This is a formal risk assessment that allows consideration all sources of technical uncertainty to qualitatively define risk due to each technical uncertainty. This is further discussed in Section 10.2.
- **Technology Readiness Level (TRL):** A TRL indicates the level of maturity (state of readiness) of a technology for a specific application.
- **Reliability and Integrity Assurance Document (RIAD):** The RIAD provides evidence-based record of activities undertaken to address technical risks and uncertainties.

10.2 Qualification Strategy

API RP 17Q recommends that the adopted path and the level of effort in qualification of the connection should be defined by combining outputs from the following:

- A TRC assessment which defines the technical uncertainty and the risk to the connection itself and to the wider system in which the connection is used.
- A technology readiness level (TRL) assessment which defines the level of maturity (state of readiness) of the technology and equipment used in the connection.

10.2.1 Technical Risk Assessment

The objective of the technical risk assessment is to qualitatively assess all sources (and the level) of technical uncertainty and provide a qualitative “score” to each technical uncertainty based on the deviation from prior experience.

API RP 17N provides a Technical Risk Categorisation (TRC) framework which enables performance of a technical risk assessment by conducting a systematic review of the sources and levels of uncertainty in order to qualitatively define the risk involved.

Note: Other industry standards such as ISO 20815 and DNV-RP-A203 use alternative risk categorization and novelty assessment schemes.

In the pre-operation phases of a project, the TRC process informs the qualification strategy by performing the following:

- 1) the TRC process identifies what has changed in terms of technology and application, compared to previous successful projects.
- 2) the TRC process is an opportunity to assess failure modes.
- 3) multiple technology options can be assessed simultaneously using the TRC process to perform a comparative analysis.

Table 8 presents a format for TRC in accordance with API RP 17N, highlighting the various risk categories and associated focus areas for each risk category. Table 8 also lists a set of typical questions to be asked in assigning a TRC score to each risk category.

The TRC presented Table 8 should be performed for each relevant element/component of the connection, such as hubs, receivers, gaskets, tooling, pressure caps, etc). Furthermore, the TRC should be performed for each stage of the lifecycle, from feasibility to decommissioning, as outlined in Section 10.1.

Qualitative ranking of risk for each component of the connection against each risk category is assigned in the following form:

- A – very high risk
- B – high risk
- C – medium risk
- D – low risk.

Table 8 – TRC assessment of connections

Risk Category	TRC Assessment Focus Areas	Example questions to be asked in assigning TRC Score
Reliability, Availability and Maintainability	<ul style="list-style-type: none"> • Reliability • Maintainability • Availability • Failure Modes • Technical Risk • Uncertainty 	<ul style="list-style-type: none"> • Do existing QA control measures assure the required reliability? If not, are one or more of the following required to achieve the desired reliability? <ul style="list-style-type: none"> ○ Tighter control over quality during manufacture, assembly, fabrication, installation ○ Change to design ○ Change to underlying technology • Has availability and maintainability been demonstrated through studies and/or through field data? • Has a dedicated FMECA been performed to assess potential failure modes and their effects on performance of the connection itself and the wider effects on the system (for example, manifold) within which the connection is used?
Technology	<ul style="list-style-type: none"> • Design Concept • Size • Material Selection and Corrosion • Envelope of limiting load and bending moment 	<ul style="list-style-type: none"> • Has the connection been previously sourced from the same supplier, manufactured at the same location, was to the same design/specification? If so, have there been any changes to the suppliers' supply chain which may be relevant? • Are there modifications which need to be made to a previously supplied and proven design? For example, changes to materials, geometry etc. Have such modifications been reviewed and a path to qualification identified? • Is this a novel design or technology requiring full qualification? If not a completely novel design, does the specific project application fall outside previously qualified limits?

Risk Category	TRC Assessment Focus Areas	Example questions to be asked in assigning TRC Score
Architecture / Configuration	<ul style="list-style-type: none"> • Connection Interfaces • Diver/ROV accessibility • Installation considerations • Inspection and maintenance considerations • Required tooling 	<ul style="list-style-type: none"> • Is the architecture within which the connection is used the same/identical to previously supplied specifications with no changes to interfaces (such as ROV interfaces) etc? • Compared to previously successful supply, are there changes to control system architecture and components such as hydraulic/electric actuators, control fluids, control system interfaces etc? • Are there modifications to architecture/configuration which need to be made to a previously supplied and proven configuration? Have such modifications been reviewed and a path to qualification activities identified? • Has the architecture/configuration of the connection been previously successfully supplied by the supplier?
Environment	<ul style="list-style-type: none"> • Technical challenges specific to field location • Water depth • Seabed conditions • Environmental loads • Fluid composition • Pressure and Temperature Loads 	<ul style="list-style-type: none"> • Is the project pushing boundaries compared to previously successful supply, such as water depth, pressure limits, temperature limits, fluid composition, environmental loads etc? • Have risks emanating from pushing the above boundaries been assessed and adequately addressed?
Organisation	<ul style="list-style-type: none"> • Project location • End user (Company) • Contractor • Supply chain 	<ul style="list-style-type: none"> • Is the project for a new end user (Operator), executed by a new contractor, involves new technical personnel, involves new suppliers or involves changes to supply chain?

10.2.2 Technology Readiness Level (TRL) Assessment

Technology readiness level (TRL) was originally developed for NASA as a metric to measure the maturity and usability of an evolving technology and has been increasingly adopted across many industries. A TRL indicates a technology's current state of readiness and helps decision-makers to decide whether and when to integrate a technology into a larger system.

API RP 17Q provides a framework for performing the TRL assessment as a semi-quantitative assessment where the TRL for a given element/component of the connection is achieved based on performing qualification activities that meet the technical and functional requirements. API RP 17Q defines seven levels of technological readiness as follows:

- TRL 0 – Basic Research (Basic R&D, paper concept)
- TRL 1 – Concept Development (Development of concept as a paper study or R&D experiment)
- TRL 2 – Concept Demonstration (Experimental proof of concept using physical model tests)
- TRL 3 – Prototype Development (Prototype functional, performance and reliability tested)
- TRL 4 – Product Validation (Product validated and tested)
- TRL 5 – System Integration Testing (System interface tested)
- TRL 6 – System Installation and Commissioning (System installed and tested)
- TRL 7 – Field Proven (System field proven)

10.2.3 Qualification Path Selection

API RP 17Q identifies three qualification paths depending on the assessed TRC and TRL:

- Technology Qualification Program (TQP): TQP identifies the qualification activities necessary to qualify the technology based on Qualification FMECAs (Q-FMECAs). A Q-FMECA identifies threats and weaknesses, based on which analysis and testing activities can be defined and assigned the appropriate priority.
- Standard Qualification Program (SQP): SQP utilises qualification activities prescribed/recommended within existing standards (for example, API standards) applicable to the technology.
- Proven Technology: In the case of $4 \leq \text{TRL} < 7$, the technology is categorised as proven technology, meaning that no further qualification activity is required, and the technology is ready for implementation.

API RP 17Q recommends that the qualification program be decided based on the TRC/TRL qualification matrix, which is reproduced in Figure 12.

		Technology Readiness Level (TRL)																
		System Operation		System Installation / Commissioning		System Integration Testing		Product Validation		Prototype Development		Concept Demonstration		Concept Development		Basic Research		
		TRL7 Achieved	7	TRL6 Achieved	6	TRL5 Achieved	5	TRL4 Achieved	4	TRL3 Achieved	3	TRL2 Achieved	2	TRL1 Achieved	1	TRL0 Achieved	0	
Technical Risk Categorization (TRC)	Very High	A	7	See Section 5.12	6	See Section 5.12	5	See Section 5.12	4	TQP	3	TQP	2	TQP	1	R&D	0	R&D
	High	B	7		6		5		4	TQP / SQP	3	TQP / SQP	2	TQP	1	R&D	0	N/A
	Medium	C	7		6		5		4	SQP	3	SQP	2	TQP / SQP	1	N/A		N/A
	Low	D	7		6		5		4	N/A		N/A		N/A		N/A		N/A

Figure 12 – TRC/TRL Correlation Matrix

11. Connection Integrity Management

11.1 Approach

For connection integrity management in the operations stage, the API RP 17N [32] double DPIEF loop approach may be used (also see DPIEF approach outlined in Section 10.1). The double DPIEF loop is reproduced in Figure 13, and has the following components:

- Normal Operations Loop:
This loop applies to the periodic/regular integrity management activities, such as close visual inspection at pre-defined intervals.
- Corrective Actions Loop:
This loop is activated whenever remedial measures or corrective actions are required.

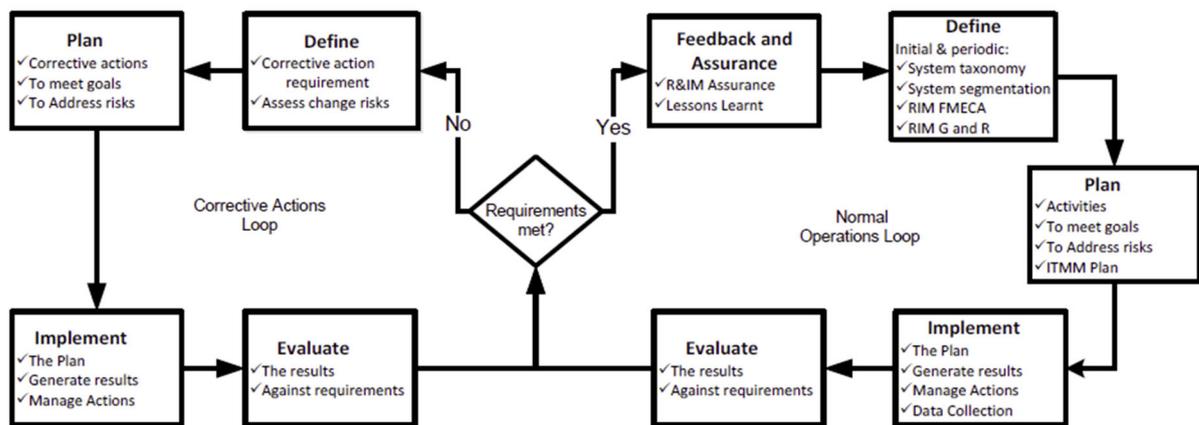


Figure 13 – Double DPIEF Loop in Operations Stage

11.2 Pillars of Connection Integrity Management

Following are the pillars of integrity management of connections [33]:

- Engineering stage shall ensure correct material selection, mechanical design, material specification, definition of manufacturing and installation procedures and specifications
- Manufacturing, Testing and Installation stage shall cover the required material quality, manufacturing accuracy and precision, in-manufacturing inspections, post-manufacturing testing, factory acceptance testing, site acceptance testing, and post-installation testing.
- In-service Inspection shall cover the required inspections at the designated intervals, such as close visual inspection, cathodic protection inspection, etc.
- Qualified Personnel shall be available at all stages of the lifecycle
- Qualified Equipment shall be available at all stages of the lifecycle

11.3 Defining the inspection regime

Typically, subsea inspection regimes are based on Risk Based Inspection (RBI) methodologies where the type and frequency of inspection is defined based on the existing condition, the degradation mechanisms/rates and the criticality of failure of each type of subsea equipment.

For subsea connectors, the inspection methods available are quite limited but include:

- General and close visual inspection
 - These surveys are conducted by diver or remotely via ROV and involve visually inspecting the connector for signs of damage, degradation, signs of leak and checking of any indicators.
- Cathodic protection survey

Unlike subsea rigid pipelines where technologies such as inline inspection (ILI) are available to detect and measure degradation such as corrosion and movement, it is not possible to inspect connectors in such detail due to high thickness of components and the inherent variation and complexity of geometries of proprietary connectors.

Therefore, where accessible, inspections should focus on any non-redundant parts which may become a single point failure source, such as locking screws. These types of elements should be inspected as far as possible for any signs of degradation such as cracking.

The methodology outlined in Appendix A can be used to identify higher risk elements of connectors.

11.4 Life Extension

When connectors approach the end of their design life, and there is a requirement to operate beyond the original design life of the equipment, a life extension study should be performed. The connectors are only one element of the subsea systems subject to life extension, and the general life extension approach applied to the adjoining subsea infrastructure is equally applicable to the subsea connectors. Life extension guidance and requirements can be found in NORSOK U-009 [34] and ISO 12747 [35].

Specific considerations for subsea connectors when performing life extension include but are not limited to the following:

- Evaluation of connector condition
 - The connector should be inspected for any signs of leakage to confirm that the seal is intact and functioning.
 - The connector and supporting structure should be inspected for signs of degradation including metal loss and cracking.
 - Fasteners such as bolts and screws should be inspected for signs of degradation such as cracking.
 - Any position indicators should be checked to confirm correct positions are maintained.
 - Coating and cathodic protection should be confirmed to be adequate for the extended life.
 - Compatibility of the connector with the transported fluids should be checked to confirm that the historical and future transported fluids are compatible with the connector

materials and that no new degradation mechanisms result from the transported fluids. For example, souring of the transported fluids could result in an increased risk of cracking if not accounted for during design.

- Evaluation of static loads acting on the connector
 - The loads acted upon the connector over the previous service life and the expected loads over the extended life should be evaluated and compared to the design capacity.
 - Settlement of the supporting structure or of connected infrastructure should be considered as this could result in increased bending loads acting on the connector.
 - Operating pressure and temperature should be reviewed to ensure the connector has been operated within its design capacity.
- Evaluation of cyclic loading acting on the connector
 - The number of load cycles to which the connector has been subjected during its service life should be estimated and compared with the design fatigue capacity.
 - The number of load cycles expected during the extended life should be estimated and it should be confirmed that the connector can withstand these cycles in addition to the cycles experienced during the design life.

As connectors are generally difficult to inspect, there is a heavy reliance upon the quality of the design, manufacture and qualification of the connectors. Life extensions are similarly heavily reliant upon these phases and the quality of the documentation. It is therefore recommended that Operators maintain robust records from the design, manufacturing and qualification phases to support in-service integrity assessments and life extension. Engagement with the connector manufacturer is also strongly recommended when conducting integrity evaluations (including defining inspection regimes and inspection tools) of in-service connectors due to the proprietary nature of some connection systems and the insights which can be provided by the manufacturer.

12. Conclusions and Recommendations

The integrity of connectors in pipelines and subsea systems is critical for the safe and continuous operation of offshore infrastructure. This report has provided an assessment of various types of subsea connections, including flanged connections, clamp hub connectors, collet connectors and proprietary connector systems. The study has highlighted the following key points:

- **Industry Experience:** The industry has significant experience with subsea connectors, including diverless connection technologies, which are essential for deep-water operations where manual connections are not feasible. However, although the industry has significant experience, detailed failure data for different connector types is not readily available in the public domain.
- **Design and Manufacturing:** The mechanical design and manufacturing quality of connectors play a vital role in ensuring their reliability and safety. Proper alignment, stress analysis, and quality control during manufacturing are essential to prevent failures.
- **Failure Modes:** Common failure modes for subsea connectors include leakage, material failure, mechanical failure, and corrosion. The report has identified that leakage is the most frequent failure mode.
- **Qualification and Testing:** Rigorous qualification and testing procedures are necessary to validate the performance of connectors under various operational conditions. This includes combined load testing, fatigue testing, and environmental testing.

Based on the findings of this report, the following recommendations are made to enhance the integrity and reliability of subsea connectors:

- **Collaboration with Manufacturers:** Engage with connector manufacturers to leverage their expertise in identifying potential failure modes and developing mitigation strategies. Manufacturers can provide valuable insights into the design, qualification, and maintenance of connectors.
- **Regular Inspections:** Establish a robust inspection regime, in collaboration with manufacturers, that includes regular visual inspections, cathodic protection surveys, and post-installation testing to detect and address potential issues early.
- **Life Extension Assessments:** Conduct life extension assessments for connectors approaching the end of their design life. This should include evaluating the condition of the connector, the loads it has been subjected to, and its compatibility with the transported fluids. Particular attention should be made towards components which are a single point of failure for the connector.

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Appendix A Example FMECA

FMECA Method

The FMECA (Failure modes, Effects and Criticality analysis) provides a systematic approach to evaluate connector item potential failures, assess them and their effects on the wider system operations and prioritize them according to their *Severity, Occurrence and Detectability*. *IEC 60812 -Failure modes and effects analysis (FMEA and FMECA)* provides a methodology for this assessment as well as tailoring the analysis for different applications. [36]

Manufactures and designers are best placed to produce the FMECA documentation and justify the metrics used in determining criticality. With this assessment in place customers can discuss the prioritization and potential mitigation recommendations in more detail.

Manufactures may have a tailored FMECA process to follow however this should, in general, contain the below (or similar) as a minimum:

1. Component or System Breakdown

Connector should be split into sub-units, systems and components (Clamps, Seals, Tension Bolts, hubs, Mechanical components etc)

2. Identification of Failure Modes

Determine how each of the above components could fail

3. Analysis of effects

Assess the effects of each failure (loss of containment, environmental release, leakage, incomplete or incorrect connection)

4. Calculation/Determination of Criticality

Evaluation of each failure mode to calculate a metric (an example being risk priority number, risk level etc). This should consider the severity (impact), occurrence (likelihood of failure), and likelihood of detection before failure.

5. Ranking of critical failure modes and recommendations

Using the criticality metric the failures can be ranked and potential mitigation such as design changes, maintenance or inspection regimes or monitoring can be prioritised.

FMECA Example Cases

By assigning metrics to each connector element for an identified failure mode, the criticality of each element can be established. The resultant prioritisation metric can be used to derive mitigating actions to provide assurance that the failure mode is avoided.

In the example below,

- **Severity Metric (Scale of 1 to 10):** Higher means more severe
- **Occurrence Metric (Scale of 1 to 10):** Higher means more frequent
- **Detection Metric (Scale of 1 to 10):** Higher means more difficult to detect
- **Prioritisation Metric = Severity Metric x Occurrence Metric x Detection Metric**

Connector Type	Element/Sub-Unit	Failure Mode	Effect	Severity Metric	Occurrence Metric	Detection Metric	Prioritisation Metric	Potential Action
Flanged Connections	Gasket	Seal degradation	Leakage	7	4	8	224	<ul style="list-style-type: none"> • Regular inspection • Design assessment (seal selection) • Robust installation procedures
	Bolts	Bolt loosening	Leakage	7	4	4	112	<ul style="list-style-type: none"> • Torque /installation verification • Locking mechanisms • Robust installation procedures
	Bolts	Bolt Fracture	Loss of structural integrity	10	3	8	240	<ul style="list-style-type: none"> • Design assessment (fatigue/HISC) • Robust installation procedures

Clamp Hub Connectors	Clamp body	Cracking	Loss of connection	10	5	4	200	<ul style="list-style-type: none"> • Design assessment (fatigue/HISC) • Regular inspection
	Seal ring	Seal degradation	Leakage	7	4	8	224	<ul style="list-style-type: none"> • Regular inspection • Design assessment (seal selection) • Robust installation procedures
	Locking mechanism	Failure to engage	Unsecured connection	3	4	1	12	<ul style="list-style-type: none"> • Pressure test • Install indicators • Robust installation procedures
Collet Connectors	Collet fingers	Fracture	Loss of grip	10	2	9	180	<ul style="list-style-type: none"> • Design assessment • Material selection review
	Seal	Seal extrusion	Leakage	7	4	8	224	<ul style="list-style-type: none"> • Design assessment • Qualification
Gripping mechanical connectors	Connector ring tapers	Galling	Material failure	8	2	9	144	<ul style="list-style-type: none"> • Design assessment • Qualification and FAT
	Locking mechanism	Failure	Disengagement under load	10	2	9	180	<ul style="list-style-type: none"> • Design assessment • Qualification and FAT

Appendix B Qualification Considerations

Scope

- **API 6A** [5] scope is limited to wellhead and Christmas tree equipment connectors with an emphasis on structural and pressure containment integrity. It covers traditional bolted flange connectors, hub, Metal to metal seal clamp connections and threaded connectors for use in lower pressure applications within this limited area.
- Providing for enhanced requirements for subsea environments specifically and including a wider range of subsea production connection, **API 17D** [4] also covers subsea pipeline connectors (Flowlines and export pipelines), jumper connectors and manifold connections, however the particular focus is on connection to Wellhead and tree equipment like API 6A [5].
- **API 17R** [6] broadens the scope of API6A [5] and API17D [4] to include Jumpers and a wider range of connections, with generalised validation requirements but refers to these specifications for design validation. Notably this document does not cover the particulars of diver assisted flanges or connections.
- **API17TR7** [7] this technical report provides guidance to support a detailed verification process in support of connector qualification, it is applicable to Hydraulic connectors, flanged connectors, radial bolt or “dog” type connectors, collet connectors and clamp connectors.
- **ISO 13628-7** [10] Covers pipeline connectors compliance and includes specifically guidance in the form of *Annex I (normative)* guidance on Qualification tests for connectors. It can be applied to flowline connectors, collet and clamp connectors and completion/workover riser connectors.

Design Qualification

- Common amongst the guidance is a design program that consists of calculations and FEA (Finite Element analysis) to establish structural strength, leak-toughness and fatigue performance under combined loading (pressure, axial, bending and torsion). **API 17D** [4] expands on this to include dynamic loads, considering those from installation, other equipment and flowlines and the effect of specific hydrodynamic forces and potential thermal stresses in subsea environments. Both **API17D** [4] & **ISO 13628-7** [10] address consideration of angular and axial misalignment in design and how this effects sealing.
- **API 17TR7** [7] builds on the verification process provides suggestion for a more rigorous combined-load analysis, including cyclic and fatigue loads over a long period of time. It also suggests the use of non-linear FEA to account for large deformation scenarios.

Material Qualification

- **API 6A** [5] lays the foundation for Material qualification and testing with reference to *NACE MR0175/ISO 15156* compliance and adds some detail around sour service. Depending on type and use, equipment is designated a PSL (product service level) that denotes the level of qualification required.
- **API 17D** [4], references *API6A* [5] but has some qualification requirements for HPHT (High Pressure High Temperature) applications (and as such references *API Technical Report 17TR8 - High-pressure High-temperature Design Guidelines*). Also adds some environmental testing to validate material properties in subsea conditions, for example resistance to Hydrogen embrittlement, fatigue and SCC (Stress corrosion cracking).

- In addition to the material qualification laid out in *NACE MR0175/ISO 15156*, **API 17TR7** [7] has additional recommendations for fatigue assessment and fracture toughness evaluation with a particular emphasis on correct environmental conditions for validity of qualification.
- **ISO 13628-7** [10] states that material Qualification should be considered.

Testing Qualification

- **API 6A** [5] focuses on qualification of pressure rating, and therefore on internal and external pressure containment by means of a hydrostatic proof test at a factored working pressure. As such Leak test qualification is conducted under static loads.
- **API 17D** [4], **API 17R** [6] & **API 17TR7** [7] elaborate with inclusion of combined load testing (torsion, bending, pressure and temperature), gas leak testing and Fatigue testing for dynamic loads to assess long-term durability. **API RP17R** [6] & **API 17TR7** [7] include some specific testing for pressure containment testing under bending and torsion conditions and some additional information for HPHT system connectors.
- **ISO13628-7** [10] includes guidance on validation for connectors under installation and operational pressures and collapse resistance. It also provides guidance on testing for connector resilience and degradation

Appendix C Original Report Requirements Specification

Goals of the project

Assessment and determination of experience base for the integrity of connections, welded and mechanical joints in pipelines and subsea facilities.

1. Brief description of the assignment

Connections between pipe to pipe and pipe to equipment can mainly be either welded or mechanically assembled ("non-welded"). Bolted flange connections are the most commonly used of the mechanical ones, but there are several variants that should be described in this assignment. Traditionally, welded connections are favoured. For design, installation or operational reasons, mechanical connections are used. We would like an overall assessment of the integrity of the various connections and what other factors are considered when choosing a solution.

Relevant topics, not restrictive:

- *Brief description of different connection methods.*
- *Estimate distribution in the Norwegian and British sectors.*
- *Integrity assessments at some of the largest operators.*
- *Experience base to analyse the security level of different connections.*
 - *Including assessment of individual components in connections or clamp connections that are assessed as barrier elements and which, in the event of a single point of failure, can lead to weakening of the connection.*
- *Operating history nationally and internationally.*
- *Relevant integrity incidents.*
- *Any methods used in risk assessments when selecting connection types.*

2. Background information

We work consciously to continuously improve our risk-based follow-up of activities, where follow-up of construction safety is central. Major accident risk is associated with structures with a hazard or accident indicator (DFU) in RNNP.

Pipelines and subsea installations are an important part of the Norwegian petroleum industry, and safe design and proper operation are key to achieving a sustainable industry.

The legal basis for the NFSA's follow-up is mainly Sections 11 of the Facilities Regulations on loads, load effects and resistance, and 12 on materials, Chapter II of the Management Regulations on risk reduction and Chapter IX of the Activities Regulations. The regulatory requirements are functional and the recognised standards for meeting the safety level are given in the guidance to the regulations.

3. Objectives of the project and expected impact

The aim is to reduce hazards and accident risk, identify risk elements, preventative measures relevant to the petroleum industry for accidents caused by failure of pipelines and subsea equipment.

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