Design of Subsea Well Intervention Systems using Non-Ferrous Alloys

API RECOMMENDED PRACTICE 17G3
FIRST EDITION, XXXX 2020
Contents

*It will be developed by API during editing*
Preface

This document is offered in hopes in bringing pragmatic practices for the utilization of titanium and aluminum in the oilfield and overcoming design issues seen in ferrous materials.

This document is not intended to be a standalone document from API 17G, rather an addendum to current engineering practices set forth by API 17G with the inclusion of titanium and aluminum alloys.

It is important to note that certain design guidelines will supersede some API 17G requirements due to the material properties of titanium and aluminum. These guidelines will be noted and emphasized for clarity and to resolve conflicting design and test procedures between the API 17G3 and the parent document.

It is necessary that users of this recommended practice be aware that additional or different requirements which can better suit the demands of a particular service environment, the regulations of a jurisdictional authority or other scenarios not specifically addressed in this RP, may be applied as required. This document is a recommended practice and it is not intended to replace sound engineering judgment.

One of the drivers for using titanium for the riser is the natural flexibility of titanium over traditional materials such as steel.

As demonstrated in Figure 1, from this side by side analysis of using steel vs. titanium to construct a tapered stress joint above the well control package, you find the titanium stress joint provides a 50% improvement in both wave height capacity (Hs), and vessel watch circle radius (Vessel offset).

This analysis was based on simulated North Sea currents and wave conditions, along with a water depth of 80 meters. All loads to the stress joint remain within the normal design limits.

\[FIGURE 1 Steel and Titanium Stress Joints\]
1 Scope

The scope of this document is to provide design guidelines for titanium and aluminum subsea intervention systems and components. For the purpose of the document, this equipment includes:

- Riser products and tubes
- Fasteners
- Seal Rings
- Pressurized Structural Components e.g. Tapered Stress Joints

This RP is intended to serve as a general guideline for titanium and aluminum subsea applications. Other subsea task groups and subcommittees (e.g. recommended practices, standards, and specifications) may elect to adopt a portion or all of the presented guidelines.

2 Normative References

The following referenced documents are indispensable for the application of this document:

API 5CRA Specification for Corrosion Resistant Alloy Seamless Tubes for Casing, Tubing, and Coupling Stock

API 17TR8 High-Pressure High-Temperature (HPHT) Design Guidelines

ASME BPVC Section VIII, Division 3: 2019 Edition DNV RP-F201

Design of Titanium Risers

Implement Russian Aluminum Drill Pipe and Retractable Drilling Bits Into the USA
Department of Energy, Aquatic, Maurer Engineering. August 1999 NACE

MR0175 Materials for use in H₂S Containing Environments

OTC 18624 Experience and Guidance in the Use of Titanium Components in Steel Catenary Riser Systems

3 Definitions, Acronyms, and Abbreviations

3.1 Definitions

For the purposes of this document, the following definitions apply in addition to those found in 17G:

3.1.1 Accidental Loading
A worst case scenario loading state determined by the operator

3.1.2 Alpha Case
A brittle phase found on the surface of titanium created when titanium is heated in air to approximately 1100F or higher.
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### 3.1.3 Corrosion-Resistant Alloy
Non-ferrous based alloy for which any one or the sum of the specified amount of the elements; aluminum, titanium, nickel, copper, cobalt, chromium, and molybdenum exceeds 50% mass fraction.

### 3.1.4 Fracture Toughness
Property of a material that measures the resistance to failure resulting from crack propagation.

### 3.1.5 Hydride
The anion of hydrogen, H−. Can cause embrittlement in titanium alloys.

### 3.1.6 Tensile Strength (Ultimate)
The maximum load before failing or breaking divided by the original cross-sectional area.

### 3.1.7 Yield Strength
Stress level, measured at both room temperature and elevated temperature, at which material plastically deforms and does not return to its original dimensions upon release.

### 3.2 Acronyms & Abbreviations
For the purposes of this document, the following acronyms and abbreviations apply:

- **CRA** Corrosion-Resistant Alloys
- **CTOD** Crack Tip Opening Displacement
- **FEA** Finite Element Analysis
- **FM** Fracture Mechanics
- **HIC** Hydrogen Induced Cracking
- **NDT** Non-Destructive Testing
- **PTFE** Polytetrafluoroethylene
- **SMYS** Specified Minimum Yield Strength
- **SCC** Stress Corrosion Cracking
- **SSC** Sulfide Stress Cracking
- **TS** Tensile Strength
- **YS** Yield Strength
4 Titanium Group

4.1 Objective

4.1.1 General

This section provides guidelines and requirements for use of titanium alloys for subsea intervention systems. Titanium grades provide high strength to weight ratio, low modulus of elasticity, and low marine and general corrosion rates. This section is a gap analysis to the main document and an informative tool in selecting the proper grade of titanium per project requirements.

4.1.2 Application

Titanium grades are successfully used in intervention service when proper design, manufacturing, and heat treatments are used.

The essential requirements in the alloy selection, manufacturing, quality controls, and certification are outlined in clause 4.2.2.

Titanium alloys shall be annealed, solution treated and aged, or beta anneal conditioned to meet the mechanical properties for the application. These grades, denoted in Table 1, are corrosion resistant fulfilling NACE requirements.

Some of the titanium alloys suitable for subsea well intervention system are given in Table 1.

Typically use of titanium alloys is for tension stress joint, slick joint, riser joints, metal seals, keel joints, fasteners and tension ring.

Titanium grades for use in H₂S service shall include qualification with SSC testing. Specific application or other testing as appropriate may be used if agreed with the end user.
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**TABLE 1 Titanium Alloy Grades**

<table>
<thead>
<tr>
<th>Common alloy designation</th>
<th>UNS number(^a)</th>
<th>NACE MR0175 Service</th>
<th>Yield Strength(^b) (ksi)</th>
<th>Tensile Strength(^b) (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1</td>
<td>R50250</td>
<td>Yes</td>
<td>20</td>
<td>35</td>
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<tr>
<td>Grade 2</td>
<td>R50400</td>
<td>Yes</td>
<td>40</td>
<td>50</td>
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<td>Grade 5</td>
<td>R56400</td>
<td>No</td>
<td>120</td>
<td>130</td>
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<td>Grade 9</td>
<td>R56320</td>
<td>No</td>
<td>70</td>
<td>90</td>
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<tr>
<td>Grade 12</td>
<td>R53400</td>
<td>Yes</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Grade 19(^c)</td>
<td>R58640</td>
<td>Yes</td>
<td>110-170</td>
<td>115-180</td>
</tr>
<tr>
<td>Grade 23</td>
<td>R56407</td>
<td>No</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Grade 25</td>
<td>R56403</td>
<td>Yes</td>
<td>120</td>
<td>130</td>
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<tr>
<td>Grade 28</td>
<td>R56323</td>
<td>Yes</td>
<td>70</td>
<td>90</td>
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<tr>
<td>Grade 29</td>
<td>R56404</td>
<td>Yes</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Titanium 6246(^c)</td>
<td>R56260</td>
<td>Yes</td>
<td>135-165</td>
<td>145-175</td>
</tr>
</tbody>
</table>

\(^a\) Unified numbering system (UNS)  
\(^b\) Minimum Values  
\(^c\) Heat Treat Dependent

4.2 Design

4.2.1 General

Physical properties like modulus of elasticity, thermal expansion coefficient, thermal conductivity and thermal diffusivity should be considered at maximum operating temperature.

The maximum hardness of different grades shall comply with NACE MR0175 / ISO 15156-3

4.2.2 Design Considerations

Due to the differences in material properties between steel and titanium, as stated in section 4.10.4, one must take into consideration the following items when using titanium in subsea application:

- FEA Design Review
- Effects of YS/TS Ratio
- Modulus of Elasticity
- Surface Stresses (Residual/Applied)
- Localized Plasticity (Yielding)
- Material Substitutions (With Analysis)

Failure to address these issues and direct substitution with another material may result in catastrophic failure.
4.2.3 Prevention of Creep

Creep propagation is a design consideration when working with titanium alloys, including working at ambient temperatures at high loads. When used at elevated temperatures, a project specific document shall be issued to specify the minimum design and mechanical properties.

A project specific shall be established when using at design temperature. Strength correction to SMYS due to temperature effects is required.

Option 1 - Working stresses shall remain below 58% SMYS at operating temperature per ASME Section VIII Div. 2 to prevent creep propagation.

Option 2 - Manufacturer can test the material(s) specifically for the intended application and apply the following rules to define allowable stress and prevent creep. The normal design stress shall not exceed the lowest of the following:

- 67% of SMYS;
- 100% of the average stress required to produce a creep rate of 0.01%/1,000 hra, when tested at or above design temperature.

*ASME B&PVC Section II Part D, Appendix 1

4.2.4 FEA Design Verification

The objective for design verification is to confirm that the titanium equipment design is in compliance with its functional specifications and serviceability criteria, and the equipment has adequate protection against failure modes identified for specified equipment:

1) Global plastic collapse
2) Local failure due to excessive strain (local strain limit damage)
3) Ratcheting effects
4) Plastic collapse under the hydrostatic test condition
5) Fatigue assessment (life-cycle estimation)

The loads obtained from the functional specifications form the design basis for the titanium equipment, and shall include the applicable operating pressure, temperature, and external loads as well as the corresponding cyclic loadings (loading histogram) for significant events that are applied to the equipment.

It is necessary that users of this document be aware of regulations from a jurisdictional authority that may impose additional or different requirements which better suit the demands of a particular service environment. Where API product standards exist with specific design factors for titanium equipment, these factors should be satisfied as a minimum. This document provides additional considerations in titanium equipment designs.
4.2.5 Validation

The design validation process is required to demonstrate that the equipment maintains the mechanical integrity and functionality/operability relative to its functional specifications. Design validation is defined in API 17G and Q1, and it should have the following components:

Validation of materials used for the design: Material properties, service and application limits used in the analyses should be based on test data or recognized sources/literature. Degradation mechanisms that should be considered in the material validation process may include, but not be limited to:

- Temperature
- Corrosion
- Fatigue
- SCC
- HIC
- Erosion/corrosion, and
- Other corrosion mechanism, etc.

4.2.6 Design Life

Design life and service life shall be specified, see API 17G Annex F. If the service life has not been specified, a minimum of five years shall be assumed.

4.2.7 FEA Design

FEA analysis should be done on titanium subsea equipment. Accidental loading should be applied for worst case scenario. Localized plastic yielding up to 2% shall be deemed acceptable.

Critical defect size shall be accounted for during FEA analysis. Critical defect size shall be determined for specific equipment.

4.3 Galvanic Corrosion Considerations

4.3.1 Internal Corrosion Resistance

Internal corrosion is primarily caused by galvanic coupling of titanium to a ferrous material or the presence of a corrosive material. Corrosive materials are discussed in section 4.10.3. Internal galvanic coupling can occur at elevated: H2S levels, free water levels, and temperatures. If these conditions do exist the operator must either isolate the titanium section with an insulated material or insert a galvanically compatible joint between the titanium and steel section. If a compatible joint is used adequate and appropriate inhibitors must be used in the riser fluid to prevent hydrogen embrittlement inside of the titanium riser.
4.3.2 External Corrosion Protection

External corrosion protection shall be provided by appropriate materials selection, coating systems, and cathodic protection.

Grades 1, 2, 5, 9 and 23 are prone to corrosion when service temperature exceeds 85°C (185°F).

Allowable coatings can be found in Table 2.

<table>
<thead>
<tr>
<th>Rubber Type</th>
<th>Max. Service Temp.</th>
<th>Water Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>~140°C (~284°F)</td>
<td>Medium - high</td>
</tr>
<tr>
<td>EPDM</td>
<td>120-140°C (248-284°F)</td>
<td>Low</td>
</tr>
<tr>
<td>Chlorobutyl</td>
<td>110-120°C (230-248°F)</td>
<td>Very low</td>
</tr>
<tr>
<td>Bromobutyl</td>
<td>100-110°C (212-230°F)</td>
<td>Very low</td>
</tr>
<tr>
<td>Butyl</td>
<td>~100°C (~212°F)</td>
<td>Very low</td>
</tr>
<tr>
<td>Chloroprene</td>
<td>90-100°C (194-212°F)</td>
<td>Medium</td>
</tr>
<tr>
<td>Natural Rubber</td>
<td>60-75°C (140-167°F)</td>
<td>Medium</td>
</tr>
</tbody>
</table>

4.3.3 Potential Galvanic Reactions

Hydrogen embrittlement is potential mode of failure when titanium is mechanically and electrically coupled to steel or carbon steel. Hydrogen absorption caused by galvanic reactions of these two metals can lead to embrittlement.

Hydrogen damage of titanium alloys is manifested as loss of ductility and/or a reduction in the stress-intensity threshold for crack propagation.

The connection between titanium and a cathodically protected steel structure can cause hydrogen embrittlement in the titanium structure.

To prevent embrittlement there must be a non-conductive barrier between the two materials and/or electrical isolation of the titanium component. This precaution can lead to a number of benefits including:

- Reduce risk of long term hydrogen embrittlement in the titanium component
- Eliminate galvanic interactions between titanium and steel components.
- Reduce the consumption rate of the sacrificial anodes coupled to the steel components.
4.3.4 Cathodic Corrosion Protection

Titanium alloys are safe from corrosion under -750 MV. Proper cathodic protection system shall be used. There are strategies to mitigate such corrosion.

The well intervention system shall have a cathodic protection system designed for the specified design life in accordance with DNV- RP-B401.

Cathodic-protection system design requires consideration of the external area of the equipment being protected. The equipment manufacturer shall be responsible for documenting the design basis of the cathodic protection system.

4.4 Fasteners

4.4.1 General

Closure bolting and critical bolting should be designed using the design verification requirements of API 17D. Bolt preload requirements should follow the guidelines of API 17D. Qualification, production and documentation of bolting should meet the requirements of API 20E.

The general guidelines for design validation are applicable to titanium alloys, as stated in 4.2.4, shall be used.

The following precautions and measures should be taken when titanium alloy is used for fasteners:

a) Creep limit of titanium alloys should be considered when using for fasteners, bolts, studs and screws. Temperature and environment conditions have influence on creep strength.

b) Hydrogen embrittlement of titanium alloy may occur if these alloys are galvanic-coupled to certain active metals (e.g. carbon steel) in H2S containing aqueous media at temperatures above 80°C (176°F).

c) Some titanium alloys may be susceptible to crevice corrosion and/or SSC in chloride environments

4.5 Coatings

Coating selection is outside the scope of this document but barrier coatings should be non-conductive, tough, and durable. This has been achieved by employing well bonded rubber to the titanium. These coatings are normally 3-5 mm thick, but may be thicker in areas where abrasion is expected. They also readily bond to weight coatings and thermal insulation. Suitable rubbers should be selected, together with their maximum operating temperatures.

4.6 Metallic Seal Ring

Titanium grades 1, 2, and 12 shall be used for titanium seal ring applications.

4.7 Hardfacing, Metallic and Non-Metallic Coating

Any coating metallic or non-metallic used for application defined in Section 4.5 shall be qualified. Coating for corrosion resistance shall be qualified in actual environment and temperature range.
4.8 Ductility, Toughness and Hardness

To ensure ductile failure and avoid hydrogen embrittlement, mechanical properties of titanium alloys, shall meet the following requirements for base material, heat affected zone and weld metal:

a) The tensile properties limitation for titanium alloys are specified in Table 1

b) Charpy impact testing is neither required nor valid for titanium alloys.

c) Toughness of the alloy shall be evaluated with fracture mechanics testing. The alloys may be evaluated by $J_{IC}$, $K_{IC}$ or CTOD per ASTM E399. The requirement shall be specified by the purchaser using design criteria.

d) The maximum hardness to avoid hydrogen embrittlement under sour service and cathodic protection shall be limited by NACE MR0175/ISO15156

4.9 Fracture Mechanics

Fracture mechanics design method for fatigue assessment shall be based on ASME BPVC Section VIII, Division 3. Fracture Mechanics is an acceptable alternative to elastic plastic analysis when designing titanium components.

The fracture mechanics testing for titanium alloys and weldment shall be qualified and assessed as in Section 4.2.5.

The minimum fracture toughness value of CTOD shall be based on design requirements depending on actual operating temperature, yield strength and material thickness.

Fracture mechanics criteria shall be based on fracture toughness test parameters such as $K_Q$ or $K_{IC}$ per ASTM E399, $KEE$ per ASTM E992, and/or $K_J$ or $K_{1J}$ per ASTM E1820. Note that these high-strength titanium alloy riser components are often insufficiently thick to achieve valid $K_{IC}$ values (cannot meet plane-strain criteria) per ASTM E399 specification requirements. CTOD (ASTM E1290) and $K_Q$ (ASTM E399) tend to be highly dependent on test specimen thickness, such that these toughness values increase with increasing specimen thickness in these plastic alloys. Therefore, toughness specimen thickness should be maximized where possible, and/or utilize elastic-plastic fracture mechanics-based test values (e.g., $KEE$, $K_J$, JC) for more representative toughness results.

4.9.1 Fatigue Crack Growth Rate

When possible, fatigue crack growth data should be evaluated from test results in the intended environment since this can greatly affect the fatigue crack growth rate. Cyclic fatigue crack growth data, $da/dN$ vs. $\Delta K$, including threshold $K_{th}$ and environmentally assisted fracture toughness $K_{IEAC}$, may be determined by testing or by data that are determined to be as conservative as or more conservative than the actual material properties in the defined environment and loading conditions. Cyclic crack growth material properties for FM design are defined in API 579-1/ASME FFS-1, or BS 7910.
4.9.2 Environmental Effects

Environmental effects must be taken into consideration when modeling fracture mechanics and effective life cycle. Section 4.10.3 contains environmental considerations.

4.10 Titanium Selection

4.10.1 General

Titanium selection shall take into account internal and external fluids, loads, temperature, and possible failure modes. The selection of materials shall ensure that the requirements are met for all components in the subsea well intervention system.

Pressure containing, pressure controlling and/or primary load bearing components shall not be manufactured from cast materials.

Weld repair of pipes, forgings and fasteners is prohibited.

It shall be the responsibility of the end user to ensure that material specified and material properties are suitable for the operating conditions.

Titanium Grade 23, 25, 28 and 29 are primarily used for tension stress joint, slick joint and tension ring. Other titanium alloys as fit may be used for other components as described in Table 1 with due qualification.

4.10.2 Sour Service

Table 1 indicates which grades are suitable for sour service conditions. These grades shall be used where NACE standard is required.

It shall be the responsibility of the manufacturer to ensure materials for sour service are in compliance with ANSI/NACE MR0175/ISO 15156. Metallic material exposed to H2S-containing environments that do not comply with ANSI/NACE MR0175/ISO 15156 shall be documented and presented to the end user or third party integrator for approval.

4.10.3 Environmental Conditions

4.10.3.1 Methanol

Methanol is often used in hydrate dissolution subsea. Dry methanol (99%) should never contact titanium alloy metal surfaces to avoid stress cracking problems. Water is a highly effective inhibitor. DNV RP-F201 provides the minimum water percentages needed to prevent damages to the titanium.

4.10.3.2 Hydrofluoric Acid

Hydrofluoric acid (HF) reacts with titanium therefore HF should not be used with bare titanium surfaces. Inhibitors or coatings shall be used to prevent critical damage to the titanium tubular.

4.10.3.3 Hydrochloric Acid

Hydrochloric acid (HCl) also reacts with titanium therefore HCl should not be used with bare titanium surfaces. Inhibitors or coatings may be used to prevent critical damage to the titanium tubular.
4.10.4 Material Considerations

4.10.4.1 Stress Strain Considerations

It is highly likely that titanium will be coupled with a dissimilar metal in subsea application. For this reason titanium components shall be designed in such a way that in accidental loading state all components shall maintain structural integrity. Annex A; Figure 1 shows the stress-strain curve for both steel and titanium. Titanium tensile strength is also its ultimate strength whereas with steel there is a range of plasticity before ultimate tensile stress.

4.10.4.2 Coefficient of Thermal Expansion

The relatively low thermal expansion coefficient of titanium must be taken into account during the design process as it is roughly half that of steel. Therefore the direct substitution of titanium into a design where thermal expansion has not been accounted for will be invalid.

4.10.4.3 Ductile-Brittle Transition

High strength titanium alloys do not exhibit the classic “ductile-to-brittle” transition behavior as service temperature decreases. A gradual, monotonic increase in alloy strength and modulus, along with a subtle decrease in ductility and toughness occur with decreasing temperatures down to the cryogenic range.

4.10.4.4 Wear Resistance

Titanium alloys show poor wear resistance in systems that involve rotating and sliding components. Compared to a steel-steel couple the wear of titanium- titanium was around 15 % higher.

4.11 Manufacturing and Fabrication Requirements

4.11.1 General

The guidelines and requirement as stated in section 4.2.2 shall be followed for qualification of material and manufactures, material specification, limitations, manufacturing procedure and qualification.

Fabrication and manufacturing requirements and standards can be found in API 17G. Depending on the manufacturing process stress can be introduced that could negatively affect the performance of the piece. Design features normally found in steel, such as undercuts, that depend on a degree of localized yielding are not acceptable.

Due to a buildup of alpha case on both the exterior and interior of the tubular surfaces the alpha case must be either physically or chemically removed. If the alpha case is not removed it can lead to cracking or early failure of the equipment. Chemical milling is preferred as it removes the least material subsequently increasing the usable life of the equipment.

Hydride embrittlement can occur during both fabrication and field use. Gaseous hydrogen and hydrogen introduced cathodically can cause embrittlement. Temperature, pH, and titanium grade must all be taken into account during design to avoid hydride embrittlement.

4.11.2 Weldments

Gas Tungsten Arc Welding is the preferred method for welding titanium intervention equipment. Inspection of weldments can be carried out the same way as traditional ferrous materials with the exception of magnetic particle as titanium is non-magnetic.

More details on welding can be found in DNV RP-F201.
4.12 Non-Destructive Testing

4.12.1 General

All components for subsea intervention system will require non-destructive testing. The requirements and qualification shall be per API 17G Clause 8.6. The NDT shall be performed in accordance with the written procedure and quality plan. When possible, 100% volume shall be inspected.

Non-destructive testing (NDT) shall be performed using a combination of methods capable of detecting surface and subsurface imperfections that would classify the material being inspected as rejectable.

All non-destructive testing of forgings and weldments shall be performed in accordance with written defined procedures and acceptance criteria.

All NDT shall be detailed in a test report documenting the techniques and parameters of the test. The report shall contain sufficient information such that the testing can be reliably repeated.

4.12.2 Weldments

All fatigue critical weldments shall be subjected to 100% high definition radiography in addition to ultrasonic inspection.

The weldments with higher dynamic loadings shall be identified, and extended NDT of these welds shall be considered. Extended NDT can take place in the form of spot checks performed by other qualified operator.
5 Aluminum Group

5.1 Objective

5.1.1 General

This section provides guidelines and requirements for use of aluminum alloys for subsea intervention systems. Aluminum provides a low modulus, low weight system as compared to steel systems.

5.1.2 Application

Aluminum alloys are successfully used in low pressure, <10 ksi, service with proper design and manufacturing. Determination of a specific alloy shall be designated per project requirements.

The design basis for aluminum application shall be API TR-8, where fracture mechanics play an important role, irrespective of the load or pressure.

The essential requirements in selecting manufacturing, quality controls and certification are outlined in Section 5.2.

Aluminum alloys shall be corrosion resistant fulfilling NACE MR0175 requirements.

Recommended alloys for subsea intervention can be found in Table 3. These alloys were selected on the basis of yield strength, minimum 50 ksi. Application of an aluminum alloy with yield strength below 50 ksi may be viable under proper engineering practices and design criteria.

Typical use of aluminum alloys is riser components and other tubular products. Use of aluminum in seals is not recommended due to potential localized yielding of the material.
### TABLE 3 Aluminum Alloys

<table>
<thead>
<tr>
<th>Alloy and Temper</th>
<th>UNS number</th>
<th>Yield Strength(^b) (ksi)</th>
<th>Tensile Strength(^b) (ksi)</th>
</tr>
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<tbody>
<tr>
<td>2014-T6, T651(^*)</td>
<td>A92014</td>
<td>58</td>
<td>70</td>
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<td>2024-T3(^*)</td>
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</tbody>
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\(^*\) Denotes Commonly Used Alloy  
\(^b\) Minimum Values

#### 5.2 Design

##### 5.2.1 General

Physical properties such as modulus of elasticity, thermal expansion coefficient, thermal conductivity and thermal diffusivity should be considered at maximum operating temperature.

Creep propagation is a design consideration when working with aluminum alloys. A project shall take elevated temperatures, and the associated reduction in Sy into consideration as part of the design. Working stresses shall follow Sm/Sy ratio guidelines with adjustments based upon operating temperature per ASME Section VIII Div. 2, Part D (Materials) to prevent creep propagation.

##### 5.2.2 Design Considerations

Due to the differences in material properties between steel and aluminum, as stated in section 5.9.4, one must take into consideration the following items when using aluminum in subsea application:

- FEA Design Review
- Effects of YS/TS Ratio
5.2.3 Prevention of Creep

Creep propagation is a design consideration when working with aluminum alloys, including working at ambient temperatures at high loads. When used at elevated temperatures, a project specific document shall be issued to specify the minimum design and mechanical properties.

A project specific shall be established when using at design temperature. Strength correction to SMYS due to temperature effects is required.

Option 1 - Working stresses shall remain below 45% SMYS at operating temperature per ASME Section VIII Div. 2 to prevent creep propagation.

Option 2 - Manufacturer can test the material(s) specifically for the intended application and apply the following rules to define allowable stress and prevent creep. The normal design stress shall not exceed the lowest of the following:

- 67% of SMYS;
- 100% of the average stress required to produce a creep rate of 0.01%/1,000 hra, when tested at or above design temperature.

a ASME B&PVC Section II Part D, Appendix 1

NOTE Extreme, and Accidental load limits will remain as defined within API 17G, with their relative position with respect to the Normal load limit.

5.2.4 FEA Design Verification

The objective for FEA design verification is to confirm that the aluminum equipment design is in compliance with its functional specifications and serviceability criteria, and the equipment has adequate protection against failure modes identified for specified equipment:

1) Global plastic collapse

2) Local failure due to excessive strain (local strain limit damage)

3) Ratcheting effects

4) Plastic collapse under the hydrostatic test condition
5) Fatigue assessment (life-cycle estimation)

The loads obtained from the functional specifications form the design basis for the aluminum equipment, and shall include the applicable operating pressure, temperature, and external loads as well as the corresponding cyclic loadings (loading histogram) for significant events that are applied to the equipment.

It is necessary that users of this document be aware of regulations from a jurisdictional authority that may impose additional or different requirements which better suit the demands of a particular service environment. Where API product standards exist with specific design factors for aluminum equipment, these factors should be satisfied as a minimum. This document provides additional considerations in aluminum equipment designs.

5.2.5 Validation

The design validation process is required to demonstrate that the equipment maintains the mechanical integrity and functionality/operability relative to its functional specifications. Design validation is defined in API 17G and Q1, and it should have the following components:

1) Validation (testing/qualification) of a component and/or system under development.

2) Validation of the design method: Model predictions (i.e. stress or thermal FEA, fatigue analysis, fracture mechanics, etc.) should be validated by measurements and testing. Historical validation processes can remain valid if they can be documented, demonstrated as technically sound, and meet the equipment design requirements and service conditions. Guidance for validation of FEA is provided in ASME V&V 10-2019, Guide for Verification and Validation in Computational Solid Mechanics.

3) Validation of materials used for the design: Material properties, service and application limits used in the analyses should be based on test data or recognized sources/literature. Degradation mechanisms that should be considered in the material validation process may include, but not be limited to:

   - Temperature
   - Corrosion
   - Fatigue
   - SCC
   - HIC
   - Erosion/corrosion, and
   - Other corrosion mechanism, etc.

5.2.6 Design Life

Design life and service life shall be specified, see API 17G Annex F. If the service life has not been specified, a minimum of five years shall be assumed.
5.2.7 FEA Design

FEA analysis should be done on aluminum subsea equipment. Accidental loading should be applied for worst case scenario. No amount of localized yielding shall be deemed acceptable.

5.3 Galvanic Corrosion Considerations

5.3.1 Internal Corrosion Resistance

Internal corrosion can be caused by both galvanic coupling and reactions with workover fluid.

Elevated chloride levels, free water levels, and temperature can increase the rate of corrosion due to galvanic coupling. If these conditions do exist the operator must either isolate the aluminum section with an insulted material or insert a galvanically compatible joint between the aluminum and base metal. Appropriate inhibitors must be used to protect the base metal from free hydrogen.

Environmental factors, outlined in section 5.9.3, may cause internal corrosion in aluminum riser systems. Chemical isolation using non-conductive coatings such as polymers or tar may prevent internal corrosion. A thick anodized layer may also be applied to the inner diameter to increase oxide protection.

5.3.2 External Corrosion Protection

External corrosion protection shall be provided by appropriate materials selection, coating systems, and cathodic protection. Subsea corrosion characteristics shall be used when testing corrosion.

5.3.3 Potential Galvanic Reactions

Hydrogen embrittlement is of little concern for aluminium components in a subsea riser system. Galvanic coupling presents a much larger risk due to the reactivity with steel.

The connection between aluminum and a cathodically protected steel structure can cause hydrogen embrittlement in the steel structure.

To prevent embrittlement there must be a non-conductive barrier between the two materials and/or electrical isolation of the aluminum component. This precaution can lead to a number of benefits including:

- Reduce risk of long term hydrogen embrittlement in the steel component
- Eliminate galvanic interactions between aluminum and steel components.
- Reduce the consumption rate of the sacrificial anodes coupled to the steel components.

5.3.4 Cathodic Corrosion Protection

The well intervention system shall have a cathodic protection system designed for the specified design life in accordance with DNV- RP-B401.

Cathodic-protection system design requires consideration of the external area of the equipment being protected. The equipment manufacturer shall be responsible for documenting the design basis of the cathodic protection system.

5.4 Coatings

Coating systems are outside the scope of this document but some material limitations apply. Coatings requiring fluid with pH levels above 9.5 shall not be used. Coatings, both internal and external, requiring heat treatment above 300°F for extended time shall not be used as these treatments can alter the material
properties of the aluminum.

Coatings should be non-conductive and may increase in thickness in areas where elevated corrosion rates are expected to occur.

Anodization may also be used to increase the oxide film protecting the riser. Increases in the oxide thickness allows for more corrosion to occur before contacting the alloy directly.

5.5 Hardfacing, Metallic and Non-Metallic Coating

No hardfacing or metallic coatings shall be used on aluminum riser systems. Non-metallic coatings used for subsea application as defined in section 5.4 shall be qualified. Coating for corrosion resistance shall be qualified in expected environment and conditions.

5.6 Valves and Actuators

Aluminum shall not be used for critical components for both valves and actuators. Items such as housings may be constructed of aluminum with proper qualification.

5.7 Ductility, Toughness and Hardness

To ensure ductile failure, material properties shall meet the following requirements for the base material, heat affected zone, and weld metal:

a) The tensile properties limitation for aluminum alloys are specified in Table 3

b) Charpy impact testing is neither required nor valid for aluminum alloys.

c) Toughness of the alloy shall be evaluated with fracture mechanics testing. The alloys may be evaluated by JIC, K1C or CTOD per ASTM E399. The requirement shall be specified by the purchaser using design criteria.

d) All corrosion properties shall meet NACE MR0175/ISO15156 requirements.

5.8 Fracture Mechanics

Fracture mechanics design method for fatigue assessment shall be based on ASME BPVC Section VIII, Division 3. Elastic-Plastic modeling must be used when dealing with aluminum alloys.

The minimum fracture toughness value of CTOD shall be based on design requirements depending on actual operating temperature, yield strength and material thickness.

Fracture mechanics criteria shall be based on fracture toughness test parameters such as KQ or K1C per ASTM E399. KEE per ASTM E992, and/or KJ or K1J per ASTM E1820. CTOD (ASTM E1290) and KQ (ASTM E399) tend to be highly dependent on test specimen thickness, such that these toughness values increase with increasing specimen thickness in these plastic alloys. Therefore, toughness specimen thickness should be maximized where possible, and/or utilize elastic-plastic fracture mechanics-based test values (e.g., KEE, KJ, JC) for more representative toughness results.

5.8.1 Fatigue Crack Growth Rate

Fatigue crack growth rate testing shall be in accordance with API 17TR8.

When possible, fatigue crack growth data should be evaluated from test results in the intended environment since this can greatly affect the fatigue crack growth rate. Cyclic fatigue crack growth data, da/dN vs. ΔK, including threshold Kth and environmentally assisted fracture toughness KIEAC, may be determined by
testing or by data that are determined to be as conservative as or more conservative than the actual material properties in the defined environment and loading conditions. Cyclic crack growth material properties for FM design are defined in API 579-1/ASME FFS-1, or BS 7910.

5.8.2 Environmental Effects

Environmental effects must be taken into consideration when modeling fracture mechanics and effective life cycle. Section 5.9.3 contains environmental considerations.

5.9 Aluminum Selection

5.9.1 General

Aluminum selection shall take into account internal and external fluids, loads, temperature, and possible failure modes. The selection of materials shall ensure that the requirements are considered for all components in the subsea well intervention system.

Pressure containing, pressure controlling and/or primary load bearing components shall not be manufactured from cast materials.

Weld repair of pipes and forgings is prohibited.

It shall be the responsibility of the end user to ensure that material specified and material properties are suitable for the operating conditions.

Suitable alloys can be found in Table 3 with due qualification.

5.9.2 Sour Service

Aluminum alloys may be used as an alternative to steel in high H2S containing fluids. Fluid with sufficient electrolyte and significant H2S concentration will show a reduction in pitting corrosion.

Design specifications shall meet ANSI/NACE MR0175/ISO 15156 standards. Metallic materials exposed to H2S-containing environments that do not comply with ANSI/NACE MR0175/ISO 15156 shall be documented and presented to the end user or third party integrator for approval.

5.9.3 Environmental Conditions

5.9.3.1 pH

At pH levels between 7.0 and 9.5 corrosion rates are insignificant without substantial chloride concentration. Environments with pH levels above 10.5 will exhibit rapid corrosion rates.

5.9.3.2 Temperature

Aluminum riser systems shall not be subjected to environments exceeding 300°F. At temperatures above 250°F special design and operation considerations must be made to account for material properties at these elevated temperatures.

Aluminum’s material properties are permanently degraded by exposure to elevated temperatures. Time at temperature will determine the magnitude of the damage.
5.9.3.3 Erosion Corrosion

Considerations must be made if using fluid additives that may be abrasive to the riser system. Erosion corrosion is aided by large solids content and turbulent flows. In this environment the protective aluminum oxide layer is damaged leading to faster corrosion rates and ultimately failure of the equipment.

5.9.4 Material Considerations

5.9.4.1 Stress Strain Considerations

It is highly likely that aluminum will be coupled with a dissimilar metal in subsea application. For this reason aluminum components shall be designed in such a way that in an accidental loading state all components shall maintain structural integrity. It is important to note that aluminum tensile strength is also its ultimate strength whereas with steel there is a range of plasticity before ultimate tensile stress.

5.9.4.2 Coefficient of Thermal Expansion

Aluminum alloys have a much larger coefficient of thermal expansion as compared to steel. Therefore direct substitutions into steel systems are highly discouraged as dissimilarity in expansion may induce unnecessary loads.

5.9.4.3 Ductile-Brittle Transition

Aluminum alloys do not exhibit the classic “ductile-to-brittle” transition behavior. As service temperature decreases aluminum alloys display a slight increase in alloy ductility and toughness with decreasing temperatures.

5.9.4.4 Wear Resistance

Aluminum alloys exhibit hardness approximately 50% less than steel and will therefore wear at a higher rate as compared to a steel system.

5.9.4.5 High Temperature Affects

Irreversible changes in aluminum’s material properties occur at extended times and elevated temperatures which will not return to ambient levels.

5.10 Manufacturing Requirements

5.10.1 General

The guidelines and requirements stated in Section 5.2 shall be followed for qualification of material specification, limitations, manufacturing procedure, and qualification.

Fabrication and manufacturing requirements and standards can be found in Section 5.2. Depending on the manufacturing process stress can be introduced that could negatively affect the performance of the piece. Design features normally found in steel, such as undercuts, that depend on a degree of localized yielding are not acceptable.

5.10.2 Weldments

Gas Shielded Arc Welding is the preferred method for welding aluminum intervention equipment. Inspection of weldments can be carried out the same way as traditional ferrous materials with the exception of magnetic particle as aluminum is non-magnetic.

5.11 Non-Destructive Testing
5.11.1 General

All components for subsea intervention system will require non-destructive testing. The requirements and qualification shall be per API 17G Clause 8.6. The NDT shall be performed in accordance with the written procedure and quality plan. When possible, 100% volume shall be inspected.

Non-destructive testing shall be performed using a combination of methods capable of detecting surface and subsurface imperfections that would classify the material being inspected as rejectable.

All non-destructive testing of forgings and weldments shall be performed in accordance with written defined procedures and acceptance criteria.

All NDT shall be detailed in a test report documenting the techniques and parameters of the test. The report shall contain sufficient information such that the testing can be reliably repeated.

5.11.2 Weldments

All fatigue critical weldments shall be subjected to 100% high definition radiography in addition to ultrasonic inspection.

The weldments with higher dynamic loadings shall be identified, and extended NDT of these welds shall be considered. Extended NDT can take place in the form of spot checks performed by other qualified operator.
Annex A

Figures

Figure 1 – Stress Strain Curves of Steel and Titanium