

Guide to Materials Selection and Corrosion Control for Subsea Energy Equipment

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Contents

Foreword	XIII
Acknowledgements.....	XIV
Abbreviations.....	XIV
1 Introduction.....	1
2 Scope.....	3
2.1 Technical Guidance	3
2.2 Extent of Application	3
3 General Principles of Materials Selection and Corrosion Control.....	5
3.1 Reference Standards.....	5
3.2 The Need for Integrity.....	6
3.3 Equipment Criticality and Life-cycle Costing.....	7
3.4 Carbon and Low Alloy Steels	7
3.5 Applications of Corrosion Resistant Alloys.....	8
3.6 The Process-side Environment.....	8
3.6.1 Introduction	8
3.6.2 H ₂ S-Containing Environments.....	8
3.6.3 CO ₂ -Containing Environments.....	11
3.6.4 Chloride Ion Environments	11
3.6.5 Erosion	12
3.6.6 Chemical Treatment and Deployment.....	14
3.6.7 Mercury.....	15
3.6.8 Preferential Weld Corrosion.....	15
3.6.9 Other Considerations.....	16
3.7 The Seawater-side Environment.....	16
3.8 Hydrotesting and Commissioning Environments	17
3.9 Long Term Storage	18
4 Cathodic Protection	19
4.1 Introduction.....	19
4.2 Conventional Sacrificial Anode Design.....	19
4.2.1 Existing Practice.....	19
4.2.2 Deep Water Requirements.....	21
4.2.3 Renewable Energy Facilities	22
4.3 Low Voltage Cathodic Protection	23

4.3.1 Introduction	23
4.3.2 Diode Control.....	23
4.3.3 Low Voltage Anodes.....	23
4.3.4 Implications of Low Voltage CP.....	24
4.4 Anode Material Specifications.....	24
4.5 Impressed Current Design.....	25
5 Wellheads and Trees	27
5.1 Introduction.....	27
5.2 Relevant Standards.....	27
5.3 Major Components in Wellhead Equipment.....	27
5.4 Material Considerations	28
5.5 Material Options.....	29
5.5.1 Tree Body and Connector.....	29
5.5.2 Wellhead Housing, Casing Hanger and Seal Assemblies.....	30
5.5.3 Casing Hangers	30
5.5.4 Tubing Hangers	30
5.5.5 Valves and Chokes.....	30
5.5.6 Gaskets.....	30
5.5.7 Hydraulic Tubing.....	31
5.5.8 Flow Spools.....	31
5.6 External Corrosion Protection.....	31
6 Manifold Piping and Equipment.....	33
6.1 Introduction.....	33
6.2 Design Codes.....	35
6.3 Typical Fabrication	35
6.4 Duties	35
6.5 Materials Options for Piping and Vessels.....	36
6.6 Hub and Flange Connectors	37
6.7 Multiphase Pumps	38
7 Flowlines and Risers.....	41
7.1 Introduction.....	41
7.2 Service.....	41
7.3 Subsea Flowline Design.....	41
7.3.1 Flowlines from Trees to Manifolds (and between Cluster Trees)	41
7.3.2 Flowlines from Manifold to Processing Unit.....	42
7.4 Materials Options.....	42
7.4.1 Selection Factors.....	42
7.4.2 Flowlines Carrying Production Fluids.....	42
7.4.3 Flowlines Carrying Other Products.....	47

7.5 Installation of Subsea Flowlines	48
7.5.1 Installation Methods	48
7.5.2 Welding of Flowlines	55
7.5.3 Plastic-Lined Pipelines.....	57
7.6 Risers	58
7.6.1 General.....	58
7.6.2 Steel Catenary Risers (SCRs)	59
7.6.3 Titanium Risers and Stress Joints	60
8 Valves	63
8.1 Introduction.....	63
8.2 Standards	63
8.3 Materials Options.....	64
8.4 Subsea Wellhead Valves to API Specs 6A and 17D.....	64
8.5 Pipeline, Subsea Manifold and Flowline Valves.....	67
8.6 Erosion and Wear Resistant Materials	67
8.6.1 Introduction.....	67
8.6.2 Carbide Coatings.....	68
8.6.3 Electroless Nickel (ENP) and Hard Chromium Platings.....	69
8.7 Weld Overlaying of Duplex Stainless Steels	70
8.8 Valve Internals – Metallic.....	70
8.9 Valve Internals – Non-Metallic.....	70
8.10 Material Specifications and Testing	73
8.10.1 General Requirements	73
8.10.2 Valve Shell	73
8.10.3 Hardness	73
8.10.4 Impact Properties.....	73
8.10.5 Welding for Valve Fabrication and Installation	74
9 Fasteners and Gaskets	75
9.1 Introduction.....	75
9.2 Threaded Connectors	75
9.2.1 Scope.....	75
9.2.2 Low Alloy Steel Bolting.....	75
9.2.3 CRA Bolting	77
9.3 Circlips, Hub Connector Clamps and Other Connectors	80
9.3.1 Circlips.....	80
9.3.2 Hub Connector Clamps.....	80
9.3.3 Collet Connector Systems.....	80
9.4 RTJ Gaskets and Other Metallic Sealing Rings.....	81
9.4.1 RTJ Gaskets	81
9.4.2 Other Metallic Sealing Rings.....	81

9.5 Non-Metallic Seals.....	81
9.6 Bolt Tensioning/Controlled Torquing.....	82
10 Flexible Pipe	83
10.1 Introduction	83
10.2 Unbonded Flexible Pipe Construction	83
10.3 Materials Issues for Flexible Pipes.....	84
10.3.1 Annulus Environment.....	84
10.3.2 Tensile Armour Wires.....	85
10.3.3 Pressure Armour Wires.....	85
10.3.4 Fatigue Life Considerations of Reinforcement Wires	85
10.3.5 Internal Metal Carcass.....	86
10.3.6 Thermoplastic Inner Sheath.....	87
10.3.7 Anti-Wear Tapes.....	88
10.3.8 Thermoplastic Outer Sheath.....	88
10.3.9 Composite Reinforcement Wires.....	88
10.3.10 Thermal Insulation	89
10.3.11 Fibre Optics.....	89
10.3.12 End Fittings	89
10.4 Thermoplastic Composite Pipe.....	90
10.5 Bend Stiffeners	90
10.6 Flexible Pipe Integrity Management.....	90
11 Hydraulic Control and Chemical Injection Systems.....	91
11.1 Introduction	91
11.2 Materials Selection	91
11.2.1 Hydraulic Control System Fluids.....	91
11.2.2 Chemical Injection Systems	93
11.3 Tubing Connections.....	93
11.3.1 Introduction	93
11.3.2 Permanent Connections.....	94
11.3.3 Demountable Connections.....	94
11.4 Hydraulic and Chemical Injection Valves	95
11.5 Hydraulic and Chemical Injection Couplers	95
11.6 Tubing Design and Supports	96
12 Umbilicals	97
12.1 Introduction	97
12.2 Umbilical Design	98
12.2.1 Types of Umbilical	98
12.2.2 Umbilical Specifications	99
12.3 Materials Selection Considerations.....	99

12.3.1 Non-Metallic Hose Conduits.....	99
12.3.2 Metallic Tube Conduits.....	100
12.3.3 Umbilical Construction.....	101
12.3.4 End Terminations.....	101
12.3.5 Bend Stiffeners.....	102
12.4 Materials Problems.....	102
12.4.1 Service Experience.....	102
12.4.2 Non-Metallic Hoses.....	103
12.4.3 Metallic Tubes.....	104
12.4.4 Electric Cable Insulation.....	105
13 Instrumentation	107
13.1 Introduction.....	107
13.2 Materials Selection.....	107
13.3 Materials Problems Encountered.....	108
14 Protective Coatings and Insulation	109
14.1 Introduction.....	109
14.2 Protective Coatings.....	109
14.2.1 Surface Preparation.....	109
14.2.2 Selection of Coatings.....	110
14.2.3 Pipeline Field Joint Coatings.....	113
14.2.4 Inspection.....	115
14.3 Thermal Insulation.....	115
14.3.1 Introduction.....	115
14.3.2 Selection of Thermal Insulation Systems.....	116
14.3.3 Manufacturing and Installation Considerations.....	117
14.3.4 Thermal Insulation of Subsea Production and Process Equipment.....	119
14.3.5 System Qualification and Performance Verification.....	119
14.3.6 Inspection.....	120
14.3.7 Issues with Insulation Systems.....	120

Appendix A – Materials Selection and Corrosion Control for Offshore Renewable Energy Facilities.....	123
A.1 Introduction.....	123
A.2 Overview of Typical Facilities	123
A.2.1 Wind.....	123
A.2.2 Wave	124
A.2.3 Tidal.....	125
A.3 Standards.....	126
A.4 Materials Selection.....	127
A.4.1 Structures.....	127
A.4.2 Equipment.....	127
A.4.3 Fasteners	128
A.4.4 Cables.....	128
A.5 Corrosion Control	128
A.5.1 Coatings.....	129
A.5.2 Cathodic Protection	130
A.6 Specific Issues	131
A.6.1 Design.....	131
A.6.2 Fatigue.....	131
A.6.3 Steel Properties.....	132
A.6.4 Fabrication	132
A.6.5 Installaton	133
A.6.6 Cables.....	133
A.6.7 Coatings.....	133
A.7 Integrity Management.....	134
A.8 Future Developments	134
A.8.1 WTG Structures	134
A.8.2 Specific Materials Related Developments.....	135
Appendix B – Duplex Stainless Steels for Subsea Piping, Flowlines, and Associated Components (Excluding Fasteners).....	137
B.1 Introduction.....	137
B.2 Hydrogen Embrittlement and Cracking.....	138
B.2.1 Background	138
B.2.2 Mechanism	138
B.2.3 Cathodic Protection Potential	139

B.3 Summary and Recommendations	140
Appendix C – Weldable Martensitic Stainless Steels for Subsea Piping, Flowlines and Associated Components	143
C.1 Introduction	143
C.2 Background.....	143
C.3 Availability	144
C.4 Corrosion Resistance	144
C.5 Fabrication	144
C.6 Interaction with Hydrogen	145
C.6.1 Fabrication Hydrogen Cracking	145
C.6.2 Hydrogen Cracking from Cathodic Protection	145
Appendix D – CRA Clad and Lined Piping for Subsea Applications	149
D.1 General.....	149
D.2 Pipe	149
D.3 Manufacturing Procedure Specification (MPS)	150
D.4 Manufacturing Procedure Qualification Test (MPQT)	150
D.5 Components Other Than Pipe	152
Appendix E – Recommended Practice for the Automated Welding of Small Diameter CRA Tubing for Control and Chemical Injection	155
Appendix F – Automatic Ultrasonic Testing of Pipeline Girth Welds.....	157
References	161
EEMUA Publication: Feedback Form	170

List of Figures

Figure 1	Severe internal corrosion of a 316 SS-clad subsea pipeline caused by excessive exposure time to seawater hydrotest fluid.....	17
Figure 2	PTFE coated subsea fastener	20
Figure 3	Umbilical connection head showing severe corrosion of the carbon steel components.....	20
Figure 4	Subsea umbilical termination unit recovered after 10 years subsea, showing extensive wastage of the aluminium anodes but no corrosion of the steel structure	25
Figure 5	Typical subsea tree assemblies.....	27
Figure 6	Typical subsea tree components	28
Figure 7	Some typical subsea manifolds.....	33
Figure 8	Cluster manifold connected to eight satellite wells.....	34
Figure 9	Typical deep water production manifolds during fabrication.....	36
Figure 10	Non-recommended design of welded joint for low alloy steel manifold components.....	38
Figure 11	Option 1 for fabrication of low alloy steel components and valve bodies with C-Mn buttering layer, welded to C-Mn steel pup piece with C-Mn butt weld	39
Figure 12	Option 2 for fabrication of low alloy steel components and valve bodies with C-Mn buttering layer, welded to C-Mn steel pup piece with Alloy 625 butt weld	40
Figure 13	Installation of PLET from a J-lay vessel	50
Figure 14	Installation of a subsea flowline by reeling	51
Figure 15	Bundle installation by the controlled depth tow method.....	51
Figure 16	Cross-section through a typical pipeline bundle.....	52
Figure 17	Main riser concepts.....	59
Figure 18	Titanium allow taper stress joining for deep water steel catenary riser application.....	61
Figure 19	Typical construction of unbonded flexible piping for subsea application.....	84
Figure 20	Damaged flexible riser with reinforcing wires exposed.....	84
Figure 21	Typical umbilical cross-sectional arrangements.....	98
Figure 22	Typical umbilical bend stiffener.....	102
Figure 23	Brittle failures of super-duplex stainless steel umbilical tubing.....	104
Figure 24	Wind Turbine foundations	123
Figure 25	Aquamarine Oyster 800 wave energy convertor	124
Figure 26	Minesto tidal generator	125
Figure 27	Full bore fracture of super-duplex stainless steel manifold hub connector.....	138
Figure 28	Fractured super-duplex hub connector showing the nature of the hydrogen induced stress cracking, mainly in the ferrite matrix.....	140
Figure 29	Offshore pipelay of 13% Cr (UNS S 41426) pipeline	145
Figure 30	Cracking of 13% Cr pipeline at anode doubler plate attachment weld	146
Figure 31	Cross-section of butt weld in 316L SS clad X-65 pipe made with Alloy 625 consumables.....	149
Figure 32	Typical butt welds in hydraulic control tubing made by the automated GTAW process.....	156

List of Tables

Table 1	Relevant standards for subsea equipment.....	5
Table 2	CRAs commonly used in subsea equipment	10
Table 3	Typical generic valve materials for wellheads, manifolds and flowlines.....	66
Table 4	Recommended Charpy impact test requirements for subsea wellhead valves.....	74
Table 5	Typical subsea coating systems	112
Table 6	Field joint coating systems	114
Table 7	Typical subsea insulation systems	117
Table 8	Typical application ranges of subsea insulation systems.....	118
Table 9	Coating systems for offshore renewable energy structures.....	129

Foreword

Although subsea well completions, manifolds, flowlines and associated equipment have been used for around forty years, there is a continuing need for increased, up-to-date guidance and awareness of materials selection and performance, the reasons for which are expanded upon in the Introduction.

Accordingly, this Publication was developed by EEMUA's Materials Technology Committee (MTC), first published in 1999 as "Guidelines for materials selection and corrosion control for subsea oil and gas production equipment", updated in the Second Edition in 2004 and subsequently in the Third edition in 2012. Since then, further developments in subsea materials technology and operational experience have occurred, including the increasing application of offshore renewable energy facilities. These developments have been captured in this Fourth Edition which has been renamed Guide to Materials Selection and Corrosion Control for Subsea Energy Equipment.

A new Appendix A provides guidelines for materials selection and corrosion control for the offshore renewable sector. The information in the previous Appendix II is covered by the standard ISO 15156 / NACE MR-01-75, or has been incorporated into the main text.

The experience in this Publication has been drawn from leading energy and offshore engineering companies with input from materials and corrosion engineers with particular expertise in the subsea environment.

Extensive reference is made in the text to various industry, national and international codes and standards. As this Publication is intended as a guide and not a specification, such references are for guidance only. A comprehensive list of references is given in the References section.

Phrases such as 'at present' or 'currently' are used in the text to indicate conditions at the time of writing this Fourth Edition, i.e. 2019.

Abbreviations used in this Publication are listed in Abbreviations section.

Acknowledgements

The Association is grateful to the American Petroleum Institute, Azur Offshore Ltd, Saab Seaeye, Statoil and to Subsea 7 for kindly permitting the reproduction of various diagrams and photographs from publications of those organisations.

Abbreviations

AISI	American Iron & Steel Institute
AMS	Aerospace Material Specifications
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AUT	Automatic ultrasonic testing
BS(I)	British Standard(s Institution)
CP	Cathodic protection
CRA	Corrosion resistant alloy
CSA	Canadian Standards Association
CTOD	Crack tip opening displacement
DFF	
DFT	Dry Film Thickness
DN	Numerical designation of size of piping components which approximates to the nominal diameter, in mm, of the corresponding line pipe
DNVGL	Det Norske Veritas – Germanischer Lloyd
ECA	Engineering criticality assessment
EEMUA	Engineering Equipment and Materials Users' Association
EFC	European Federation of Corrosion
ELI	Extra low interstitial
EN	(European Standard)
ENP	Electroless nickel plating
EPDM	Ethylene propylene diene monomer
EPDT	Ethylene propylene diene termer
ERW	Electric resistance welded
FBE	Fusion bonded epoxy
FCAW	Flux cored arc welding
FFPM	ASTM designation for perfluoroelastomers
FJC	Field joint coating
FPM	ASTM designation for fluoroelastomers
FPSO	Floating production, storage and offloading (vessel)
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
HB	Brinell hardness
HDPE	High density polyethylene
HE	Hydrogen embrittlement
HESC	Hydrogen embrittlement stress cracking
HIC	Hydrogen induced cracking

HIP	Hot isostatic pressing(s)/pressed
HISC	Hydrogen induced stress cracking
HNBR	Hydrogenated NBR
HRC	Rockwell hardness 'C'
Hv	Vickers hardness
HVOF	High velocity oxy-fuel
IIW	International Institute of Welding
IOGP	International Association of Oil and Gas Producers
ISO	International Organization for Standardization
JIP	Joint Industry Project
LME	Liquid metal embrittlement
MDPE	Medium density polyethylene
MPQ(T)	Manufacturing procedure qualification (test)
MPS	Manufacturing procedure specification
MSS	Manufacturers' Standardization Society of the Valve & Fittings Industry
NACE	National Association of Corrosion Engineers
NACE MR	NACE Material Requirement
NACE TM	NACE Test Method
NBR	Nitrile-butadiene rubber
NDT	Non-destructive testing
NORSOK	Norsk Sokkels Konkuranseposisjon ('the competitive standing of the Norwegian offshore sector')
NPS	Nominal pipe size
NPT	[US] National pipe thread
P&NGI	Petroleum and Natural Gas Industries [includes petrochemical]
PD	(BSI) published document
PE	Polyethylene
PEEK	Polyether ether ketone
PEX	ASTM designation for cross-linked polyethylene (see also XLPE)
PiP	Pipe-in-pipe
PIR	Polyisocyanurate
PLEM	Pipeline end manifold
PLET	Pipeline end termination
PP	Polypropylene
PPS	Polyphenylene sulphide
PR	Performance requirement (level)
PREN/PREw	Pitting resistance equivalent number
PSL	Product specification level
PTFE	Polytetrafluoroethylene
PU	Publication
PUF	Polyurethane foam
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
PWC	Preferential weld corrosion
PWHT	Post-weld heat treatment
QA/QC	Quality assurance/control
ROT	Remotely operated tools
ROV	Remotely operated vehicle
RP	Recommended Practice
RTJ	Ring type joint

SAW	Submerged arc welding
SCC	Stress corrosion cracking
SCR	Steel catenary riser
SMAW	Shielded metal arc welding
SMYS	Specified minimum yield stress
SOHIC	Stress oriented HIC
Spec	Specification
SRB	Sulphate reducing bacteria
SS	Stainless steel
SSC	Sulphide stress cracking
Std	Standard
SUT	Society for Underwater Technology
SWC	Step-wise cracking
TFE/P	Tetrafluoro-ethylene/-propylene
TIG	Tungsten inert gas (welding)
TLP	
TOFD	Time of flight diffraction
TP	
TS	Tensile strength
TSA	Thermally sprayed aluminium
UNS	Unified Numbering System (<i>see ASTM E527</i>)
UTS	Ultimate tensile strength
UV	Ultra-violet (radiation)
WTG	
YS	Yield strength
XLPE	Cross-linked polyethylene (see also PEX)

1 Introduction

This EEMUA Publication is aimed at engineers and others involved in the design, specification, commissioning, operation, maintenance, repair or refurbishment of underwater oil and gas production equipment and related facilities. It is also intended to cover materials and corrosion control for offshore renewables facilities. It provides an overview of the current knowledge of the principles and practices of materials selection and corrosion control for these facilities. Guidance on the application of such knowledge is considered necessary because:

- Some expensive subsea materials-related failures have occurred over recent years.
- The complexity of subsea equipment is continually increasing: items such as multiphase pumps, separators and water injection facilities are becoming more commonly specified.
- The amount of hydrocarbons recovered from subsea developments is set to continue to increase in the future, hence the reliability of subsea equipment has become increasingly important for the producing companies.
- Deep water developments have become more common, and the performance of materials in such environments is not well understood and documented at present.
- Reservoir fluids from marginal fields may become increasingly corrosive/erosive.
- Relatively little detailed guidance is available in existing industry codes, standards, etc.
- The integrity of subsea equipment is paramount for protection of the environment.
- Growing business in offshore renewable energy can learn from the experience of the subsea business in the past.

At the time of this revision, some areas of subsea materials technology are continuing to evolve, hence the associated information in this EEMUA Publication should be supplemented or qualified by the latest knowledge and experience. In order to help readers maintain their knowledge up-to-date, EEMUA currently provides a 2½-day training course based on the Publication but incorporating the latest experience. This EEMUA course, in association with the Society for Underwater Technology (SUT), is held annually in the UK and at various locations around the world, subject to demand. A summary of the course is provided on the next page. See www.eemua.org for more details.

In order to assist with further updating of this Publication to ensure its continued relevance, EEMUA would welcome feedback from users of their experiences regarding materials performance in the subsea environment or renewable energy sector.

EEMUA Subsea Materials & Corrosion Frequently asked questions

Who runs Subsea Materials & Corrosion?

This course has been developed and is administered by the Engineering Equipment and Materials Users' Association (EEMUA), a European industry Association with headquarters in London. EEMUA's engineering guides, standards and training schemes are recognised and followed worldwide. See www.eemua.org.

The course is operated in association with the Society for Underwater Technology (SUT). The SUT is an international learned society actively promoting the development, dissemination, and exchange of ideas, information and technology arising from or related to the underwater environment. The Society brings together organisations and individuals from over 30 countries with a common interest in subsea technology, ocean science and offshore engineering. For more details, visit www.sut.org.uk.

The principal course presenters will be materials and corrosion specialists from major offshore/subsea operating companies; in addition, guest speakers are invited from equipment vendors and subsea contractors.

When and where will the courses be held?

Courses are planned at regular intervals in the UK. Courses elsewhere in the world may be organised from time to time, depending on demand. The language is English. For the latest details of all future courses, dates and locations, visit the EEMUA website www.eemua.org or contact EEMUA directly by phone or e-mail (see below).

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A Training Course from EEMUA in association with SUT

A two and half day training course for engineers and others involved in the design, specification, commissioning, operation, maintenance, repair or refurbishment of underwater oil and gas production equipment and related facilities



SUBSEA ENGINEERING

Materials selection
and corrosion control
for subsea oil and gas production equipment



2 Scope

2.1 Technical Guidance

This Publication sets out the principles and practices of materials selection and corrosion control and provides information on lessons learned in the industry. Key aspects of welding and fabrication are also discussed. However, it should not be seen as an alternative to the involvement of suitably qualified materials and corrosion specialists in subsea or renewable energy projects. Indeed, the complexity of some of the issues involved is such that the document cannot always provide definitive recommendations, and the requirement for expert advice on materials issues will remain.

There are many associated topics that could affect materials performance and equipment integrity that are not addressed in any detail in this document, for example:

- welding and cladding procedures,
- weld defect acceptance criteria,
- non-destructive examination requirements,
- QA/QC procedures during component manufacture,
- verification and validation testing of assembled equipment,
- chemical treatment of hydrotest fluids,
- methods of deployment of equipment to avoid seawater ingress, and
- subsea connection procedures to avoid or minimise seawater ingress.

2.2 Extent of Application

This Publication relates to equipment fully immersed in seawater installed at or above the seabed for oil and gas production, including water, gas and chemical injection systems and their associated controls – essentially everything from the wellheads downstream to the delivery point to the surface facilities. The equipment is that typically associated with subsea developments, using either tie-backs to fixed platforms, or an arrangement of rigid or flexible risers to floating production units which could be semi-submersibles or monohull vessels. Similarly, Appendix A covers those elements of renewable energy facilities that are predominantly immersed in seawater.

The emphasis is on the identification and discussion of those materials- and corrosion-related issues which are specific to subsea equipment and which are not usually encountered in offshore platform-based designs utilising dry completions.

Outside the scope are:

- drilling and downhole equipment;
- items used only for the deployment, retrieval or maintenance of the permanently installed facilities (though the materials used for such equipment should be subjected to review, based on the principles in this document. At least one serious incident is known to have occurred due to rapid galvanic corrosion of aluminium components in deployment equipment.

Failures of high strength fasteners used in lifting and deployment equipment have also been reported);

- structural items and steel fabrications (Ref ISO 13628-15); and
- topside equipment if not part of the subsea envelope, e.g. risers.

3 General Principles of Materials Selection and Corrosion Control

3.1 Reference Standards

The most relevant and useful reference documents which relate specifically to subsea materials selection and corrosion control are currently those listed below. Some are quite detailed and give clear materials requirements, but usually without supporting explanations. Others deal with materials rather more superficially.

Most of the relevant international documents have been issued as a suite of ISO standards, which are currently numbered as ISO 13628-1 to -15, Design and Operation of Subsea Production Systems – Parts 1 to 15. These have in general been developed from, and in many cases are identical to, the ANSI / API 17 series of documents, as listed in Table 1.

Table 1 Relevant standards for subsea equipment*

ISO	Equivalent ANSI/API
13628-1: General Requirements & Recommendations	RP 17A: Design & Operation of Subsea Production Systems (co-branded ISO 13628-1)
13628-2: Unbonded Flexible Pipe Systems for Subsea & Marine Applications	Spec 17J: Unbonded Flexible Pipe
13628-3: Through Flowline (TFL) Systems	RP 17C: TFL (Through Flowline) Systems (co-branded ISO 13628-3)
13628-4: Subsea Wellhead & Tree Equipment	Spec 17D: Subsea Wellhead & Tree Equipment
13628-5: Subsea Umbilicals	Spec 17E: Specification for Subsea Umbilicals
13628-6: Subsea Production Control Systems	STD 17F: Specification for subsea Production Control Systems (co-branded ISO 13628-6)
13628-7: Completion/workover riser systems	Spec 17G: Design and Operation of Completion/Workover Riser Systems
13628-8: Remotely Operated Vehicle (ROV) interfaces on subsea production systems	RP 17H: Remotely Operated Vehicles (ROV) Interfaces on Subsea Production Systems
13628-9: Remotely Operated Tool (ROT) intervention systems	
13628-10: Specification for Bonded Flexible Pipe	Spec 17K: Specification for Bonded Flexible Pipe
13628-11: Flexible Pipe Systems for Subsea & Marine Applications	RP 17B: Flexible Pipe (contains full text of ISO 10420 – withdrawn)
13628-15: Subsea Structures and Manifolds	

**Notes: Annex A to ISO 13628-1 includes descriptions of the various components of a subsea production system. It is a useful guide for those unfamiliar with such systems. Other relevant subsea documents include NORSOK Standard M-001 Materials Selection subsec. 5.6 'Subsea production and flowline systems'.*

Some guidance is also given in ISO 21457 'Materials selection and corrosion control for oil and gas production systems'. This was first published in 2010 and its scope includes surface and subsea facilities. Due to the breadth of its scope, the level of detail is limited. However, cross references to this ISO standard are made within this EEMUA Publication where appropriate.

Standards used for the offshore renewable energy sector are primarily DNVGL or Euronorm standards and are listed in Appendix A.

3.2 The Need for Integrity

Integrity, in the context of subsea equipment, usually means:

- reliable operability with minimal intervention, and
- no loss of containment of hazardous or toxic fluids.

Failure of subsea pressure boundary equipment by corrosion or cracking will usually result in some environmental impact – possibly serious in the case of hydrocarbons and chemicals. The feasibility of condition monitoring of equipment to prevent such incidents needs to be considered during materials selection. Subsea equipment, by its very nature, is far more difficult and expensive to inspect and maintain than its equivalent topside or onshore. This is particularly the case in deep water developments where divers cannot operate. Some equipment items, particularly in complex and compact assemblies such as manifolds, can only be properly inspected by retrieval to the surface. Currently available inspection and condition monitoring technologies include the following:

- general visual/ROV inspection,
- internal corrosion/erosion monitoring of flowlines and pipelines,
- corrosion monitoring of flowlines and pipelines with external techniques (ultrasonic, radiography, pulsed eddy current, magnetometry)
- sand detection,
- cathodic protection surveys,
- intelligent pigging of pipelines,
- ultrasonic thickness surveys of subsea equipment,
- external crack detection,
- bolt/stud crack detection,
- vibration/movement measurements,
- stress/strain monitoring, e.g. of dynamic risers and umbilicals,
- leak detection (visual, acoustic, laser),
- functionality testing of remotely actuated and ROV operated valves,
- monitoring of status of subsea sensors (temperature, pressure, sand, etc.),
- non-metallic materials degradation monitoring, e.g. textile rope or thermoplastic coupons,
- monitoring flexible piping annulus fluids,
- eddy current inspection of flexible pipe armour wires, and
- electrical resistance integrity tests for control system umbilicals.

Failure of non-pressure boundary equipment that impairs or even prevents operability can be equally expensive to correct, both in terms of the cost of intervention and the value of deferred or lost production. In this context, even small and seemingly minor items can become profoundly important if they fail in service, e.g. set screws mounting a hydraulic control valve onto a panel, or a circlip retaining an umbilical coupler in its mounting.

Fabrication and welding play an important role in equipment integrity and it is essential that appropriate and qualified procedures are in place for these activities. It is recommended that fabricators should be accredited to ISO 3834.

The overall picture is that increasing water depth and field life favour a trend towards a 'fit and forget' philosophy, where increasingly robust materials and designs are employed, and reliance on in-service inspection and monitoring is kept to a minimum.

3.3 Equipment Criticality and Life-cycle Costing

Methodologies for assessing equipment criticality usually combine the probability and consequence of failure, and these have been used for the selection of materials and for defining product reliability requirements in subsea projects as described, for example, in the Energy Institute Publication 'Guidelines for the management of integrity of subsea facilities'. Criticality assessments for subsea equipment require particular care because many items will have high consequences of failure, and meaningful discrimination into different grades of criticality can be difficult to achieve. Also, it is necessary to consider all feasible 'failure' modes – not just those associated with loss of containment, but all those possible causes of loss of functionality or operability.

Subsea equipment design, materials selection, fabrication, testing and installation all require attention to detail of a higher level than that traditionally associated with topside/onshore facilities. Appropriate integrity assurance processes should therefore be applied through all these stages, e.g. independent design verification, qualification of new designs/materials/fabrication methods, procurement QA/QC, materials certification and traceability.

Life-cycle costing for materials selection is recommended, though its application is likely to be limited to relatively few equipment items where realistic options exist for both 'high' and 'low' capital expenditure. The most common example is inhibited carbon steel versus corrosion resistant alloy (CRA) for flowlines, where the field life operating costs for the inhibitor injection and the associated corrosion monitoring and pipeline condition assessment can usually be estimated fairly accurately. Strategic replacement of equipment during field life should also be considered.

Guidance on the application of life-cycle costing may be found in ISO 15663-1.

3.4 Carbon and Low Alloy Steels

Carbon and low alloy steels are extensively used in subsea equipment. As described in this Publication, restrictions on hardness for welded and non-welded components are required to prevent external hydrogen embrittlement from cathodic protection.

Restrictions on yield strength for welded applications should also be considered. ISO 21457 and NORSOK M-001 both restrict the specified minimum yield strength (SMYS) of carbon and low alloy steels intended for welding to 560 MPa, but permit a higher SMYS, provided that documentation showing acceptable properties with respect to weldability and the properties of the base material, heat affected zone and weld metal is presented. It is recommended that information concerning the successful prior subsea application of specific higher strength steels should be sought as appropriate.

Subsea installation contractors may also place restrictions on the range of yield strength of pipe for reeled pipeline applications.

3.5 Applications of Corrosion Resistant Alloys

Table 2 (on page 10) provides a summary of the compositions, properties and application limits of the most commonly specified corrosion resistant alloys (CRAs) for subsea use. The following general recommendations are made:

- Copper base alloys should not be specified for pressure boundary equipment in hazardous duty.
- Free-machining grades should be avoided due to their relatively poor corrosion resistance, even for small items machined from bar stock.
- Consideration should be given to qualification of alloys of 0.2% proof strength above 827 MPa (120 ksi) in terms of their mechanical, corrosion and environmental cracking performance.
- Low carbon grades of austenitic stainless steels, including 'dual grade' alloys such as 316 / 316L, are recommended for welded applications.
- Austenitic and super-austenitic alloys used for pressure boundary equipment should be specified to be in the solution treated and water quenched condition, and free from any cold work intended to enhance their mechanical properties. Forced air or gas quenching of thin-walled components may also be satisfactory, subject to qualification.
- Caution is advised on the use of cast 6Mo alloys for components to be welded due to segregation and risk of cracking.
- Duplex stainless steels should be specified in accordance with ISO 17781, and procured in accordance with ISO 17882 and EEMUA Publication 218 'Quality requirements for the manufacture and supply of duplex stainless steels'.
- Alloy 718 forgings should comply with API Specification 6ACRA.
- Alloy 625 weld overlays should have:
 - A minimum of two layers.
 - A thickness of at least 3 mm at the final finished surfaces, including machined locations.
 - An iron content at the finished surfaces not exceeding 10% for resistance to crevice corrosion (5% iron may be considered appropriate for severe sour service).
 - The chemical analysis confirmed at the predicted end-of-life thickness location, when internal erosion is expected.

3.6 The Process-side Environment

3.6.1 Introduction

The principles of materials selection for process-side environments are similar to those for surface designs, except that a more conservative approach can often be justified for the reasons stated. Key considerations for materials selection applicable to all types of subsea equipment include:

- material availability in the required product form;
- weldability;
- project cost and schedule requirements;
- complexity and novelty of manufacture and fabrication;
- damage mechanisms during storage and transport, deployment, wet parking, hydrotesting, and commissioning, particularly with regard to the potential for seawater ingress;
- damage mechanisms during operations, including startup, shutdown and well treatments;
- predicted changes in reservoir conditions over the design life, e.g. souring; and
- any local content requirements and capability.

3.6.2 H₂S-Containing Environments

3.6.2.1 Relevant Standards

Documents describing options for dealing with H₂S in the produced fluids include:

- ISO 15156/NACE MR0175 (the NACE MR is co-branded),
- NACE Report 1F192,
- EFC Publications 16 and 17,
- NACE TM0177, and
- NACE TM0284.

It should be recognised that ISO 15156/NACE MR0175 is primarily intended to reduce the risk of sulphide stress cracking, although other hydrogen related mechanisms such as hydrogen induced cracking (HIC) and stress oriented hydrogen induced cracking (SOHIC) are now included in the scope. The impact of H₂S in combination with CO₂ as a wet gas also needs to be considered especially for carbon steel systems.

3.6.2.2 Sulphide Stress Cracking (SSC) Resistance of 13% Cr and Duplex/Super-duplex Stainless Steels

For carbon or low-alloy steels, the cost impact of using 'sour-resistant' grades is usually minimal. Hence they are often specified for environments containing even low H₂S levels, i.e. below the thresholds for SSC as defined in the above documents. For CRAs with only limited 'sour resistance', however (e.g. weldable 13%Cr steels and duplex/super-duplex stainless steels), the need to use a different alloy composition for sour service is likely to have a significant cost impact.

'Sour service' limits for the weldable 13%Cr and duplex/super-duplex stainless steels are somewhat complex. Such materials may fail sour service testing in the 'standard' conditions used for carbon/low alloy steels (as defined in NACE TM0177 and associated documents). The susceptibility to SSC is a function of the temperature, H₂S level, pH and chloride content of the transported water.

H₂S limits for some grades of 13%Cr and duplex/super-duplex stainless steels in specific process conditions are given in ISO 15156 / NACE MR0175, NACE Report 1F192 and NORSOK Standard M-001. Manufacturers of such grades might also recommend sour service limits, and many users have their own guidelines.

The effects of operations such as welding and plastic straining (e.g. during pipe reeling) on SSC resistance need to be considered.

In cases of doubt, particularly for those materials with uncertain SSC resistance, 'sour service' materials testing of parent material and representative welds under the actual or predicted environmental conditions (or under a 'worst case' estimate of conditions) at a load close to yield should be made. A conservative approach to materials selection is recommended where conditions are considered marginal between different classes or grades of steels/alloys. Alternatives such as carbon steel clad or lined with a high alloy CRA (e.g. Alloy 625) should be considered.

Table 2 CRAs commonly used in subsea equipment

Generic Type	Common Name	UNS	Typical Composition				Typical Properties, MPa ¹		Typical Min Design Temp °C	PREN ² /PREW (min)
			Cr	Ni	Mo	Others	Min YS	Min TS		
Austenitic Stainless Steels	316L SS	S31603	18	12	2.5		205	515	-196	22.6
	Nitronic 50	S20910	20.5	12.5	2.25	Mn, Nb, N	380	690	-196	28.6
Super-austenitic Stainless Steels	6Mo	S31254	20	18	6	N	300	650	-196	42.2
	904L	N08904	21	25	4.5	Cu	220	490	-196	32.2
	Alloy (Sanicro) 28	N08028	27	31	3.5	Cu	215	550	-196	35.9
Precipitation-Hardened Aust. SS	Grade 660	S66286	15	25	1.25	Al, Ti, V, B	585	895	-29	16.8
Duplex Stainless Steels	Nitronic 19D	S32001	19.7	16	0.06	Mn, N, Cu	450	620	-50	22
	2Cr Duplex	S31803	22	5.5	3	N	450	620	-50	30.56
	25Cr Super-duplex	S32550	25	5.5	3	N	600	760	-50	32.25
	25Cr Super-duplex	S32750	25	7	3.5	N	550	800	-46	37.75
	25Cr Super-duplex	S32760	25	7	3.5	N, Cu, W	550	750	-46	37.45
	25Cr Super-duplex	S32974	25	7	3.2	N, Cu, W	550	800	-46	36.75
	410 SS	S41000	12.5	0	0		380	585	-10	11.5
Martensitic Stainless Steels	F6NM	S42400	13	4	0.5		620	790	-46	13
	Super-13%Cr (weldable)	Apex IV	11-13	2.5-6	1-3		500	600	(Note 3)	
Nickel Base Alloys	Alloy (Incoloy) 825	N08825	21	42	3	Cu, Ti	175	515	-196	27.8
	Alloy (Incoloy) 925	N09925	21	44	3	Cu, Ti, Al	810	1210	-196	27.8
	Alloy (Inconel) 625	N06625	22	60	9	Fe, Nb	415	825	-196	46.4
	Alloy (Inconel) 718	N07718	19	53	3	Fe, Al, Ti, Nb	1030	1275	-196	26.2
	Alloy (Inconel) X-750	N07750	16	75	0	Fe, Al, Ti, Nb	895	1275	-196	14
	Alloy (Inconel) 725	N07725	21	57	8	Fe, Al, Ti, Nb	895	1200	-196	42.1
	Alloy (Hastelloy) C-22	N06022	21	55	13.5	Fe, Co, W	310	690	-196	65.5
	Alloy (Hastelloy) C-276	N10276	16	55	16	CO, Fe, W, V	280	690	-196	64
	Alloy (Hastelloy) C-4	N06455	6	63	16	CO, Fe, Ti	275	690	-196	60.2
	Alloy (Monel) 400	N04400	0	66		Cu	195	480	-196	n/a
Cobalt Base Alloys	Elgiloy	R30003	20	16	7	Co	1510	2500	-196	n/a
Copper Base Alloys	MP35N	R30035	20	35	10	Co	380-1950	900-2000	-196	n/a
	Ni-Al-Bronze	C95800		4.5		Cu, Al, Fe	300	650	-196	n/a
Titanium Alloys	High Strength Cupronickel	C72420		15		Cu, Al, Fe, Mn	430	710	-196	n/a
	Grade 5 Ti-6Al-4V	R56400					830	895	-604	n/a
	Grade 12 Ti-0.3Mo-0.8Ni	R53400					345	483	(Note 4)	n/a
	Grade 19, Beta-C	R58640					896-1170	965-1240	-604	n/a
	Grade 23, Ti-6Al-4V ELI	R56407					758	827	(Note 4)	n/a
	Grade 29, Ti-6Al-4V-0.1Ru	R56404					758	827	(Note 4)	n/a

Table 2 Footnotes

¹ Dependent on heat treatment condition.

² $PREN = \%Cr + 3.3\%Mo + 16\%N$ (The other frequently used equation is for PREw which also accounts for presence of tungsten. $PREw = \%Cr + 3.3(Mo\% + 0.5W\%) + 16\%N$).

³ Typically from $-20^{\circ}C$ to $-46^{\circ}C$, dependent on grade.

⁴ From ANSI-ASME Codes. Good low temperature fracture toughness: dictated by design code.

⁵ 25Cr super-duplex stainless steels are commonly specified to have a minimum PREN/PREw of 40 for general application, and 42 for umbilical tubing.

⁶ 22Cr duplex stainless steels are commonly specified to have a minimum PREN/PREw of 35.

3.6.2.3 HIC-Resistance of Carbon and Low Alloy Steels

Recommendations to deal with hydrogen-induced cracking (HIC), stress oriented HIC (SOHIC) and stepwise cracking (SWC) are made in ISO 15156 Part 2 and EFC Publication 16, and need to be considered for **any** level of H_2S in the produced fluids. A test method for assessing the susceptibility of materials to HIC is NACE Standard TM0284 (HIC).

The probability of HIC can be minimised by steel chemistry control and by avoiding plate steels for fabricated items, e.g. valve bodies, longitudinally welded pipe.

3.6.3 CO₂-Containing Environments

Documents providing guidance for the use of carbon and low alloy steels in wet CO₂ environments include EFC Publication 23 and NORSOK Standard M-506. Some users have generated their own predictive models for CO₂ corrosion that differ mainly in terms of the effects of protective scaling at elevated temperature, stream velocity, and algorithms for pH prediction. Effects of organic acids should be taken into account in corrosion prediction modelling and in any testing for corrosion inhibitor selection.

The main value of these documents and models will be for the prediction of CO₂ corrosion rates, and thereby the assessment of the viability of using carbon or low alloy steels for subsea equipment. The more conservative approach to subsea materials selection often results in higher alloy materials being selected.

The corrosion performance of the higher alloys in CO₂-containing environments should be considered in terms of both general corrosion or localised corrosion, especially in high temperatures and/or high salinity waters. Intergranular corrosion associated with sensitisation of the weld HAZ of 'lean' grades of weldable 13Cr alloys has also been observed (see Appendix C).

3.6.4 Chloride Ion Environments

300-series austenitic stainless steels in the as-welded or cold worked condition are well known to be highly susceptible to chloride stress corrosion cracking (SCC) at metal temperatures above about $50^{\circ}C$. Due to their low strength properties, these alloys find relatively little application for subsea pressure containment equipment other than for hydraulic control/chemical injection tubing (see Section 11.2.1).

Although duplex stainless steels have far superior resistance to chloride SCC, very high concentrations of chloride ions in combination with elevated temperatures ($70^{\circ}C$ to $140^{\circ}C$) can lead to failures. Several such incidents in topsides process equipment have occurred, either due to internal or external induced cracking. External induced failures are reviewed in a report by the UK

Health and Safety Executive (website www.hse.gov.uk – search Research Report 129). For subsea facilities this mechanism will be prevented by the CP, although needs to be considered for above water riser sections should the protective coating fail.

The internal failures were associated with water flashing downstream of control valves in the gas–condensate systems of HP/HT plant, allowing internal deposition of very corrosive high chloride solids (S. Huizinga, et al., NACE 2005, Paper 05474). The process conditions that led to these failures are unlikely to be experienced subsea but should nevertheless be checked in HP/HT developments where duplex stainless steel is proposed for flowlines or manifold piping.

Where doubts about the suitability of duplex stainless steel in HP/HT environments exist, consideration should be given to more chloride SCC-resistant materials such as Alloy 825 or carbon steel internally clad with Alloy 625.

3.6.5 Erosion

3.6.5.1 General

Erosion can be defined as the wastage that occurs by mechanical removal of material from surfaces due to the impact of liquid droplets and/or solid particles. It will need to be considered for all production scenarios, but especially for equipment handling high velocity multiphase streams or when solids production is expected.

Guidance is available in a number of documents, including ISO 13703, API RP 14E and DNV RP-O501. Predictive models to evaluate erosion rates by solids (e.g. sand) have been developed in a number of joint-venture projects, including those run by the University of Tulsa's 'Erosion-Corrosion Research Center' and by AEA Technology. A predictive model has also been developed by DNVGL (DNVGL RP-O501), whilst the GB Health and Safety Executive has published guidance on the avoidance of erosion of piping elbows on its website (Research Report 115 obtainable from www.hse.gov.uk).

3.6.5.2 Types of Erosion Damage

Erosion damage can be essentially categorised as four main types:

- i) **Pure erosion by liquid droplet or gas bubble impact in a non-corrosive fluid.** In a multiphase flow regime, droplet impact is possible in annular mist flow (the corollary to this would be bubble impact in bubbly flow, although this is significantly less damaging) and can result in the mechanical removal of material (i.e. erosion). In practice, droplet erosion is generally only a problem in multiphase systems with very high mixture velocities. For gas-condensate systems DNV RP-O501 recommends a maximum velocity of 70 to 80 m/s. Another approach to derive maximum allowable velocities is that of API RP 14E, using company-specific 'C' constants derived by testing and/or experience.
- ii) **Pure erosion by solid particle impact in a non-corrosive fluid.** This mechanism could apply to very low corrosivity or dry gas, gas-condensate or oil systems where corrosion is not a problem. Production rate is highly relevant here because, typically, doubling the production rate will result in an order-of-magnitude increase in erosion rate. Sand content and erosion rate, however, are generally in direct proportion, except for very high sand contents when energy losses occur due to inter-particle collision.

iii) Erosion-corrosion by a corrosive fluid in the absence of solids. Most oil and/or gas production systems will exhibit some corrosivity. In the absence of solids, enhanced erosion-corrosion wastage can occur due to the removal of protective corrosion product layers or corrosion inhibitor films by the fluid flow, with consequent corrosion of the newly exposed surface.

iv) Erosion-corrosion by a corrosive fluid containing solids. In solids-containing fluids, there can be synergy between the erosion and corrosion rates, e.g. due to the removal of protective corrosion scales or inhibitor films, such that the resultant damage can be significantly enhanced. However, as a rule of thumb, if the expected erosion rate is an order of magnitude less than the expected corrosion rate, or vice versa, then synergistic effects between them are likely to be minor.

3.6.5.3 Likely Locations and Nature of Erosion

Guidelines for identifying the likelihood, locations and nature of erosion are set out below.

- In the absence of solids, erosion is unlikely to be a problem unless flow rates are very high (>80 m/s). Wastage is most likely to be corrosion dominated.
- Solids erosion is by far the most aggressive damage mechanism. Severe erosion problems are therefore most likely to be associated with entrained solids.
- Erosion is most likely to occur at changes in flow direction, e.g. bends, tees, at or downstream of constrictions or valves (especially chokes).
- Eroded surfaces will generally be shiny and relatively free from deposits. They also appear relatively smooth, due to the polishing effect of the erosion damage.
- Where erosion pits are formed, they exhibit a characteristic sharp-edged appearance, either as a tear-drop shape (with the narrow end upstream) or as a horseshoe shape.

3.6.5.4 Alleviating Damage by Erosion

Possible methods for alleviating the effects of damage by erosion include:

- Designing out erosion by removing the solids (downhole sand screens, gravel packs, in-line sand removal equipment, etc.), reducing the flow velocity (e.g. by increasing pipe diameter, using 'dual' lines), giving close attention to manifold piping design, eliminating sharp bends, using target tees (NB: not universally effective and not normally beneficial for liquid systems, only really useful for gas systems) and erosion-resistant valve designs. API RP 14E, ISO 13703 and DNVGL RP-O501 give further guidance on some of these aspects.
- Using erosion-resistant materials for solid-particle containing conditions. Carbon steels, stainless steels and nickel-base CRAs are often not suitable for duties where erosion by solid particles is a problem. Suitable materials are often very hard e.g. proprietary cobalt-base alloys, tungsten carbide or ceramics, but are not a universal panacea: even those materials will experience erosion under severe conditions. Alternatively, very soft elastomeric coatings or liners are possible options, but it needs to be demonstrated that they are resistant to the production fluids and operating temperatures. As yet, there is no extensive experience with non-metallic materials in such service.
- For nominally solids-free production (less than one pound of solids per thousand barrels of liquid (1 pptb) for liquid flow, or 0.1 lb of solids per MMscf (millions of standard cubic feet) of

gas for gaseous flow, consider the use of erosion corrosion resistant materials. The higher alloy CRAs are generally more erosion corrosion resistant than carbon steel or 13Cr steel as they do not suffer from the same levels of synergistic erosion corrosion. However, care should be taken when selecting CRAs for erosion corrosion resistance, accelerated corrosion rates could occur for CRAs if the passive film is removed by solids erosion and the environment does not enable the passive layer to rapidly reform.

- When internal CRA cladding is specified, erosion studies should be made to demonstrate that adequate CRA thickness, typically at least 1 mm, will remain for the design life of the component.

3.6.5.5 Use of 'C-Factors'

Recently there has been a move away from the use of the API RP 14E equation together with the material- or application-specific C-factors, due to the fact that this methodology does not account for many of the major factors that affect erosion, such as fluid viscosity, solid particle size and concentration, flow regime, etc. In addition, the method can prove either overly conservative (for liquid flow) or non-conservative (for gas flow) if C-factors are selected to try to cover the full range of mixture densities. However, the API RP 14E approach can provide a useful 'order of magnitude' evaluation tool for totally solids-free or nominally solids-free conditions as long as the severe limitations in its use are realised and appropriate C-factors are generated for the materials/fluids/conditions under consideration.

The 'C-factor' constants recorded in API RP 14E are generally considered to be somewhat conservative, both for carbon steel and for CRAs, and higher values are utilised by many designers/users. Typical values which have been used for nominally solids-free or totally solids-free conditions, derived from both laboratory testing and field experience, are:

- carbon or low-alloy steel – 135 (gas or multiphase) or 250 (liquid only);
- 13Cr stainless steels – 300 (gas, multiphase or liquid); and
- CRAs (i.e. super-austenitic stainless steels, duplex stainless steels, nickel alloys) – 350 (gas or multiphase) or 450 (liquid only).

For absolutely solids free, single-phase gas conditions no erosional velocity limit is imposed, although velocities may be constrained by noise/vibration limits.

3.6.6 Chemical Treatment and Deployment

Chemical treatments are frequently adopted for flow assurance and/or the control of corrosion or scaling in subsea producing systems, e.g.:

- corrosion inhibition/pH modifiers,
- scale inhibition,
- hydrate inhibition,
- wax control,
- asphaltine control,
- flow improvers.

Earliest consideration should be given in system design to the range of expected chemical treatments, understanding how the required chemicals will interact with the materials they contact (metals and elastomers) and how they will behave with one another when mixed.

The compatibility between treatment chemicals should be established before their final selection and use, since any potential incompatibility may result in neutralisation of one (or more) of the products' active ingredients, or in precipitation and blockage ('gunking').

If the range of chemicals or their compatibility with each other is not known at the design stage, installation of dedicated injection facilities for each chemical type is advised. The use of shared distribution and injection facilities is not recommended unless mixing and compatibility trials on the designated chemicals demonstrate no adverse interaction or precipitation. (See also Chapter 12 for recommendations for transport of chemicals by umbilicals).

The rheology of the chemicals at ambient temperature and seabed pressure and temperature needs to be understood when designing the pumping, delivery and distribution systems. Required flow rates, including chemical suppliers' minimum advised rates, need to be considered when sizing umbilical cores and specifying pumps. Distribution, injection facilities and flow measurement devices need to cater for any rheological changes between the point of supply and injection.

Suitable redundancy in the supply system may be necessary in order to achieve required chemical availability.

3.6.7 Mercury

Mercury and associated mercury compounds can be detrimental to certain materials. Mercury can occur naturally as a contaminant in well production fluids. The likelihood of its presence should be recognised at the earliest possible stage of design to avoid potentially susceptible materials being specified.

It is generally accepted that mercury needs to be present in the liquid form for damage to occur. Attack can be by amalgamation or by liquid metal embrittlement (LME).

Alloys 400 and K500 fail by LME as a result of mercury adsorption onto their surface. Type 304 and 304L austenitic stainless steels, Alloy 600 and 9% nickel steel have also been shown to be susceptible to LME when subjected to high loads and plastic strain in laboratory testing. In the same tests there was no indication of LME in austenitic stainless steel types 321, 316, and 316L, and Alloy 800.

Whilst unalloyed titanium is considered immune to damage by mercury, it is known that aluminium and copper alloys are affected. Caution should therefore be exercised if titanium alloys containing aluminium and/or copper are proposed for duty in systems that may contain mercury. Testing of these alloys to establish immunity or susceptibility is advised.

3.6.8 Preferential Weld Corrosion

Preferential weld corrosion (PWC) is the dissolution of metal associated with welds. It is a selective form of attack that corrodes the weld metal and/or heat affected weld zones rather than adjacent parent material. PWC rates of attack in carbon steel can be high: up to 12 mm/year have been observed in the laboratory and in the field. Since it is a selective form of attack, PWC should not be mitigated by additional design corrosion allowances, particularly for piping and flowlines.

PWC is a particular concern with carbon and low alloy steels used for transporting produced hydrocarbons with entrained water and CO₂ that have been welded with consumables depositing around 1% Ni weld metal. Preferential corrosion of welds containing increased levels of Si, or alloyed with Cr or Mo, can also be expected, although the effect may be less pronounced. Service

experience indicates that gas and gas condensate production systems are more prone to PWC damage than oil systems. However, Ni-containing weld metal is beneficial for produced water and water injection lines.

Guidelines have been developed to reduce the risk of PWC in carbon and low alloy steels, including the selection and deployment of inhibitors (Ref: SPE publication SPE-87552-MS and EFC Publication 39).

3.6.9 Other Considerations

Key additional considerations for materials selection include:

- Internal corrosion at locations of low flow where deposits might form and where corrosion inhibitors and biocides are unlikely to be effective.
- Internal corrosion due to water drop-out at low points.
- Localised pitting or general corrosion in CRAs at elevated temperatures (especially for 13% Cr and duplex/super-duplex stainless steels).
- Corrosivity of internal fluids encountered during installation and operational transients (e.g. workovers), including chemical treatments and seawater entry.
- The effects of gas lift operations on corrosion.
- Specification and reliability of facilities for the treatment of reservoir injection fluids e.g. gas dehydration, water treatment, or for other applications e.g. flowline bundle heating.
- Materials availability, ease of fabrication and track record in the intended application.

3.7 The Seawater-side Environment

Most metallic materials for subsea use require a combination of protective coatings and cathodic protection (CP) to avoid general or localised seawater corrosion, and, in some cases, chloride ion SCC. Materials that can be considered, for design purposes, to be inherently resistant to corrosion in seawater (although even this resistance is only retained up to certain temperature limits) are Alloy 625 and other nickel-base alloys of equal or higher pitting resistance equivalent number (PREN/PREw), or titanium.

For optimum corrosion resistance, duplex stainless steels, most austenitic stainless steels and nickel alloys should be used in the solution treated and water quenched condition with microstructures confirmed free from undesirable precipitates (e.g. carbides, sigma phase), taking account of the effects of welding or other fabrication procedures. However, some grades of austenitic stainless steels and nickel alloys are used in the precipitation hardened condition, e.g. UNS S66286 and N07718.

Certain grades of austenitic stainless steels such as UNS S21800 have been formulated primarily for wear and galling resistance as opposed to corrosion resistance, and have particularly low PREN values. They are sometimes offered in the cold worked condition for enhanced strength, e.g. for hydraulic couplers, and may even receive a heat treatment that results in sensitisation. Failures by pitting and stress corrosion cracking have been reported on items manufactured in these types of alloys due to exposure to non-submerged marine environments prior to deployment.

External chloride SCC of duplex stainless steels due to the concentration of chlorides on unprotected high temperature surfaces is generally unlikely to be a problem on painted or insulated subsea components additionally protected by CP. Nevertheless a theoretical risk will exist for HP/HT installations, e.g. at crevices, and so a detailed risk assessment should be made where duplex stainless steels are proposed for such developments.

The corrosivity of the seawater and/or mud at the seabed will depend on factors such as oxygen content, bacterial activity, temperature, currents and salinity. These factors will normally only affect the design of the CP system and the selection of protective coatings, and not materials selection as such.

Materials for raw seawater injection schemes need to be designed in seawater resistant materials and/or using carbon steel with robust internal protective coatings or linings. External CP is not effective in controlling internal corrosion.

Avoidance of external hydrogen embrittlement of carbon or low alloy steels and CRAs induced by CP systems will represent an important part of materials selection and specification, and is discussed in detail in the equipment-specific sections and appendices of this Publication.

Occasionally, it is necessary to specify materials with inherent resistance to marine fouling, e.g. for exposed valve stems that could damage stem seals or packing during operation. Copper-base alloys are particularly suitable, and various high strength versions are available including the precipitation treated cupro-nickels and copper-beryllium alloys.

For raw seawater handling equipment, super-duplex stainless steels (PREN/PREw > 40), some super-austenitic stainless steels and some copper-base alloys have good resistance to internal corrosion for restricted (i.e. lower) operating temperatures. Care is required with chlorine or hypochlorite injection in raw seawater injection schemes as this can greatly increase the water corrosivity, further restricting the operating temperatures for these materials.

3.8 Hydrotesting and Commissioning Environments

Care is required in the specification and control of hydrotesting media and any other transient environments in order to avoid internal corrosion and fouling. Many grades of stainless steel used for internal components are not resistant to localised pitting and crevice corrosion in raw seawater, refer to Figure 1., which shows severe corrosion of the 316L cladding and underlying carbon steel of a subsea pipeline after 6 months exposure to untreated seawater.

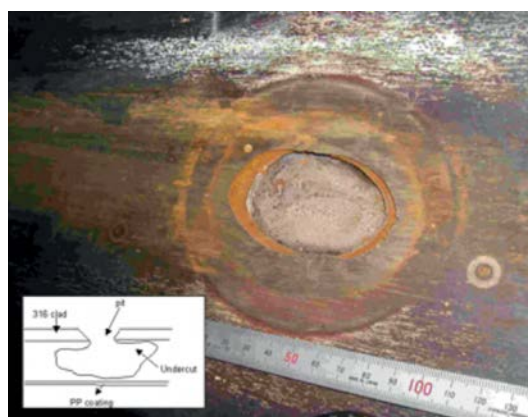


Figure 1 Severe internal corrosion of a 316 SS-clad subsea pipeline caused by excessive exposure time to seawater hydrotest fluid

The use of fresh water is preferred for hydrotesting, especially CRA equipment, but it is often difficult or impractical. Where seawater is used for hydrotesting, chemical treatment is required using biocides and oxygen scavengers.

During subsea installation of equipment it is possible that some seawater ingress will occur during deployment. Therefore, the potential time of exposure of CRA's that are not fully resistant to the seawater environment, should be limited by dewatering and inerting as soon as possible after installation as part of the commissioning scheme. Typical maximum exposure times used by some operators are 2 days for austenitic stainless steel (e.g. 316L), 7 days for 13Cr stainless steel, and 10 to 14 days for duplex stainless steels (PREN/PREw<40).

Some assemblies such as manifolds can be deployed after filling with treated fluids, such as glycol-based control fluids of the type described in Section 11.2.1 or a glycol-water mix.

In all cases attention should be paid to adequate venting during deployment to minimise the volume of trapped air since this will promote corrosion. This may require the use of relief valves at the high points of the manifold pipework.

3.9 Long Term Storage

There may be circumstances when subsea pipelines or equipment are installed in advance of the main field development and require preservation for months or even years (so-called 'wet parking').

Manifolds, tie-in spools and associated equipment are normally filled with a glycol based control fluid (refer 3.8) or a glycol-water mix. This is not feasible for long carbon steel pipelines which should be filled with seawater filtered to 50 μ m and treated with biocide. It is important to ensure that the chemical vendor has data to demonstrate that the specified biocide concentration will remain active over the proposed period of storage, and to take samples before and after storage to confirm the absence of bacterial activity.

4 Cathodic Protection

4.1 Introduction

Subsea installations require corrosion protection, usually by external coatings in conjunction with a sacrificial anode CP system. A well designed and installed CP system will normally protect against all the following forms of external attack:

- general corrosion of carbon and low alloy steels;
- crevice corrosion, e.g. at screwed and flanged connections (flange protectors are not necessary and are not recommended);
- galvanic corrosion at the junctions of dissimilar metals;
- chloride ion SCC of austenitic stainless steels;
- pitting corrosion of stainless steels; and
- bacterial corrosion.

The protective coating reduces the amount of sacrificial anode material required to protect the structure, and enhances the uniformity of the spread of protection.

4.2 Conventional Sacrificial Anode Design

4.2.1 Existing Practice

CP designs for structures or pipelines immersed in seawater have usually followed either DNVGL RP-B401 or NACE SP0176. For the North Sea and Norwegian Sea the NORSOK Standard M-503 has also been applied. ISO 15589-2 is now the recommended cathodic protection standard for carbon and stainless steel subsea pipelines, and is also applicable to retrofits, modifications and repairs made to existing pipeline systems.

These practices are based upon the premise that effective long term CP is reliant upon the build-up and maintenance of calcareous deposits upon the structure being protected. Specific current density requirements at three distinct stages in the structure's life – initial, mean and final – are identified and used to derive an appropriate CP design. High initial current densities are required to promote the rapid formation of the calcareous deposits and minimise the mean current density requirements thereafter. In the case of sacrificial anode systems, it is the mean current density that determines the overall anode weight. Minimising the mean current density requirement limits the additional weight of the anode system on the structure.

The 'final' current density takes into account the additional current density required to re-polarise the structure if the effectiveness of the established calcareous deposits and fouling layers is reduced during storms. The DNVGL RP gives guidance on these three current density requirements with respect to climatic region, while the NACE RP assigns values to specific coastal, country or sea locations. Neither document makes specific reference to deep water, yet the industry consensus is that the guidelines are applicable to water depths down to 300 m.

Subsea equipment is usually constructed from many different materials which are not resistant to seawater corrosion and which depend upon CP for their integrity. While it is not necessary for CRAs to be polarised to the same negative potentials as carbon steel, it is normally impractical to electrically isolate them from the main steel structure. It is therefore necessary to ensure that all metallic components are electrically continuous. Typical practices include the use of continuity straps, fan disc washers beneath bolt heads, the removal of paint from contact surfaces, and welding. Electrical continuity checks are necessary for almost all components that are not connected directly to the main structure by welding. The maximum recommended resistance is 0.1 ohm. Particular attention should be paid to items which, by their design, are either 'loose' or are required to move, e.g. ROV-operated valve stem extensions. Electrical continuity checks of subsea valves should be done in the open, half-closed and closed positions.

Figures 2 and 3 illustrate the consequences of failing to ensure electrical continuity. Severe corrosion has developed due to lack of electrical continuity with the associated structure and consequently no cathodic protection. PTFE coated fasteners are not recommended for this reason, as also explained in Section 9.2.2.4. In Figure 3 there was lack of electrical continuity with the cathodic protection system due to non-removal of paint beneath fasteners.



Figure 2 PTFE coated subsea fastener



Figure 3 Umbilical connection head showing severe corrosion of the carbon steel components

The phenomenon of hydrogen generation on cathodically protected structures is well understood. The rate of reduction of hydrogen ions to atomic hydrogen at the surface of a metal increases logarithmically with a linear negative change at potentials below -800 mV versus Ag/AgCl/seawater. While there is a tendency for hydrogen atoms to combine to form hydrogen gas, the reaction is slow and the atoms have time to diffuse into the metal. The presence of H_2S , due to microbial activity, further promotes hydrogen charging.

Charging can induce hydrogen embrittlement (HE) in many high strength steels, stainless steels and non-ferrous alloys (e.g. nickel alloys). Factors that usually determine the likelihood of HE and cracking taking place are:

- The material's microstructure and hardness.
- Applied and residual stresses, and whether these are static or dynamic.
- Excessively negative potentials.

Cracking has occurred with many different materials including high strength steels (>700 MPa yield strength), Alloy K500 polarised to potentials more negative than -900 mV, and both duplex and super-duplex stainless steels polarised to about -1000 mV. This may drive the selection of alternative materials depending on the circumstances. While HE of titanium due to galvanic coupling with a less noble metal is a well-known phenomenon, there have been no reports of titanium alloys suffering HE subsea.

4.2.2 Deep Water Requirements

Seawater environments change with depth, geographical location and season in a way that can have a significant effect on current density requirements for CP. Oxygen solubility is usually less than in shallower waters, but remains significant; temperatures are lower, fouling is less, seawater velocity, salinity and pH are variable. In some deep water locations of the world the oxygen content and velocity of the water at the seabed can be surprisingly high due to descending cold polar currents.

Perhaps most importantly, the solubility of calcium carbonate is higher in deep water. Calcareous deposits do not form as readily, nor are they as persistent as in shallow waters. The analysis of seawater properties for the determination of CP current density requirements has proved to be virtually impossible, and so, to date, these requirements for deep water structures have been mainly developed by empirical means, using test assemblies deployed at the specific water depths of interest. On some occasions, retrospective data have been collected using CP monitoring systems installed on a deep water platform or installation.

Measurements have confirmed that initial current densities required for the effective polarisation of bare steel in deeper waters are often 1.5 to 2 times those recommended for shallower waters. The two most influential aspects are the poorer quality of the calcareous deposits and the increased hydrostatic pressure. Poor quality calcareous deposits mean that the metal surface is more accessible, and more hydrogen can be generated. The kinetics of the hydrogen ion reduction reaction itself are not directly affected by changes in pressure, but the subsequent combining of hydrogen atoms to produce hydrogen gas, which competes with the entry of atomic hydrogen into the metal, will be retarded. Opportunities for hydrogen diffusion into the metal would appear to be greater in deep water, though whether this increases the susceptibility of materials to HE *per se* is not clear. Some users take the view it does not, hence they do not distinguish between deep water and shallow water in defining maximum limits for material strength and hardness.

Laboratory studies have shown that increases in the corrosion rate of carbon steel with increasing hydrostatic pressure can be ascribed to the effect of pressure upon the kinetics of the oxygen reduction reaction. The kinetics of the iron dissolution reaction is not affected, and thus the electrical potential at which iron is immune from corrosion in seawater is the same regardless of water depth. It follows that the same potential criteria for the protection of carbon steel in shallow waters (-800 mV versus Ag/AgCl/seawater in aerobic conditions, -900 mV in anaerobic conditions) are also applicable in deep water. In the absence of any definitive knowledge regarding the effect of water depth upon the growth of sulphate reducing bacteria (SRB), it would be appear prudent at present to adopt the same approach to the risk of SRB proliferation on the seabed or beneath fouling deposits.

There is a dilemma associated with the use of CRAs connected to carbon steel in adequately protecting the latter from general corrosion without inducing HE in the former. The following are seen as key areas in the quest for the level of equipment reliability which deep water exploitation demands (see also Appendices B and C):

- The use of component designs which are simple in relative terms and avoid the need for complex geometries as far as possible in order to ensure uniformity of CP.
- The adoption of low maximum allowable global stresses, well below the specified minimum yield stress, and minimisation of stress concentrations (e.g. due to poor fit-up, doubler plates, sharp changes in section, etc.).
- Assurance that materials are supplied with optimum heat treatment and microstructure.
- The more widespread use of durable, highly insulating protective coatings on CRAs and high strength steels to minimise hydrogen entry.
- Guidelines on the design current densities to be used on deep water structures to avoid the application of unnecessarily high current densities. *(Note: in practice, cathode potentials during early operating life will be close to open circuit anode potentials due to the general adoption of high quality coatings. Therefore, reductions in design current density alone may not result in significantly lowered risk of HE damage.)*
- Assurance that interaction between sacrificial anode CP systems for subsea equipment and impressed current CP systems for FPSOs or other surface facilities does not result in overprotection, increasing the risk of HE.
- Further investigations into the use of low voltage CP using diodes or alternative anode compositions.

Further guidance is provided in NACE Report 7L192.

4.2.3 Renewable Energy Facilities

CP design for offshore renewable energy facilities is similar to existing practice for offshore oil and gas facilities with some important differences which are described in Appendix A. One key difference is the need to assess requirements for CP for internal protection of monopile structures.

4.3 Low Voltage Cathodic Protection

4.3.1 Introduction

The relationship between the quantity of hydrogen ions electrochemically reduced to hydrogen atoms at the metal surface and the electrochemical potential is logarithmic: for a unit change in potential there is a tenfold change in the rate of reduction. Limiting the generation of atomic hydrogen at the metal surface by controlling the applied CP potential represents, arguably, the most effective method of minimising HE risks.

The most negative potentials that can be achieved using conventional sacrificial anodes are governed by the open circuit potentials of the anodes themselves, typically a value of -1050 mV for zinc and -1100 mV for aluminium–zinc–indium versus Ag/AgCl/seawater. Potentials more negative than -900 mV are sufficient to cause embrittlement and crack propagation where the mechanical properties, applied loading conditions, and/or microstructure can lead to susceptibility to cracking. At potentials less negative than -800 mV the rate of the hydrogen reduction reaction and likelihood of HE cracking become negligible.

4.3.2 Diode Control

The current output of sacrificial anodes and, correspondingly, the potential of the structure, can be controlled using Schottky diodes that only allow current to pass when the voltage across the diode exceeds a certain limit. In the case of aluminium anodes and a controlled negative potential limit on the structure of -800 mV versus Ag/AgCl/seawater, this potential limit is 300 mV. Once the potential difference between the anode and the structure falls below this level, the Schottky diode becomes open circuit and current no longer flows between the anodes and the structure until the 300 mV difference is restored. For successful control of the potential of the entire structure at risk from HE, every anode needs to be connected to the structure via a Schottky diode. The structure needs to be electrically isolated from adjacent structures that have conventional CP systems, otherwise the CP system on the adjacent structure will override the control being imposed by the diodes. The establishment of permanent electrical isolation is often difficult offshore, particularly on complex subsea facilities, and therefore the use of diode controlled CP systems should be avoided.

Nevertheless, there have been several instances of the use of Schottky diode-controlled sacrificial anode CP systems to minimise the risk of HE of high strength steels, such as on simple pipeline systems or isolated steel structures. Reports indicate that in conjunction with protective coatings, dioded anodes have performed much as intended. On one bare structure a reluctance to achieve full polarisation has been reported, indicating that there is still much to be learnt about how these systems perform where high current demands are required.

Dioded anode designs should be qualified by testing to demonstrate their reliability under the intended operating conditions, particularly the design hydrostatic pressure for deep water.

4.3.3 Low Voltage Anodes

As an alternative to controlling the potential of conventional sacrificial anodes using diodes, work by the French navy has aimed at developing a commercial low voltage anode composition based upon aluminium. Initial studies indicated that an Al–0.1% Ga alloy, with an operating potential of -840 to -880 mV versus Ag/AgCl/seawater, is feasible. The composition of this alloy is patented. The same considerations about the need to isolate the structure from adjacent conventionally

protected structures would apply. There is little operating experience with these anodes under conditions likely to be encountered, such as high hydrostatic pressure, burial in marine sediments, or higher operating temperatures, and further research or qualification testing should be considered before selection of this option.

Carbon steel/iron anodes can be used to protect some CRAs, and this method has a history in seawater coolers. Whilst the adoption of such anodes would seem an attractive proposition, the lack of operational experience and field proven design data (particularly in deep water conditions) would indicate that further research and qualification testing would be required.

4.3.4 Implications of Low Voltage CP

There are three significant implications of using low voltage CP to prevent both corrosion and HE of materials subsea which need to be considered:

- **The formation of calcareous deposits.** Conventional CP designs for offshore structures are based upon the assumption of different current density requirements at different stages of the structure's life, and a high current density is desirable at the beginning to enable calcareous deposits to form rapidly. A major consequence of using potential-limiting or low voltage anodes is that, compared with a conventional sacrificial anode CP system, the actual current flowing to the structure is restricted, and calcareous deposit formation will occur at a slower rate. This has a fundamental impact upon CP design that, although not critical for coated structures, requires a reappraisal of the existing design rules where uncoated structures are concerned.
- **Sulphate reducing bacteria.** It is widely acknowledged that where there is a risk of SRB being active, the normally applied CP criterion in seawater of -800 mV versus Ag/AgCl/seawater for carbon steels needs to be adjusted to -900 mV. Such a move to more negative potentials is clearly in conflict with the need to limit CP potentials to prevent HE. This issue is likely to be more relevant on a bare structure than on one that is additionally protected from corrosion by a heavy-duty coating.
- **The effect upon crevice corrosion.** It is generally acknowledged that in seawater the spread of CP down crevices, such as those at bolted flanges, is sufficient to prevent crevice corrosion, providing that there is effective CP outside the crevice. The term 'effective CP' may be interpreted as measured potentials of typically -900 mV versus Ag/AgCl/seawater outside the crevice. With potentials limited to about -800 mV outside the crevice, there will be a higher risk of crevice corrosion, particularly where the crevice is formed between dissimilar metals.

4.4 Anode Material Specifications

Conventional aluminium-zinc-indium alloy anodes can have widely varying composition, particularly with respect to zinc, indium, iron and silicon contents, whilst still meeting the manufacturer's defined alloy specification. There is evidence that anodes may not perform satisfactorily across the widest conventional compositional range, particularly in deep water applications, or in hot operating conditions such as can occur on buried flow-lines. An optimised compositional range and performance requirements should be specified, based on proven satisfactory performance history under equivalent conditions, or on results of qualification testing under appropriate conditions.

Whilst there is little documented deep water data available relating to long term anode performance, there are indications that lower electrochemical capacity values may apply for anodes particularly in deep water, and when operated at low anodic current densities typical for well-coated pipelines or subsea equipment. Conservative design capacity values should be selected in the absence of long-term service or qualification data under similar conditions. Figure 4 shows the condition of a subsea unit that had to be recovered after about ten years subsea due to an electrical fault, which provided a rare opportunity to assess in detail the performance of the CP anodes.



Figure 4 Subsea umbilical termination unit recovered after 10 years subsea, showing extensive wastage of the aluminium anodes but no corrosion of the steel structure

4.5 Impressed Current Design

Impressed current CP design is not normally applied for subsea facilities and pipelines because of the requirement for a transformer/rectifier and inert anodes to deliver the current. Sacrificial anode CP design provides a simpler option for subsea. Impressed current CP design can be used where operation of a transformer/rectifier is feasible, such as for structures close to shore e.g. jetties, or for FPSO hulls. Impressed current CP has been used for steel jackets but is generally not favoured because of poor performance in the past due to lack of maintenance, over-protection and cable failures.

A recent development has been the application of a remote impressed current CP design for mature steel jacket structures where anode consumption would normally require retrofitting of sacrificial anodes. The anode(s) for the impressed current system are positioned a short distance (circa 100m) from the structure and effectively support the current delivered by the existing heavily consumed anodes. This approach requires detailed modelling and also consideration of the impact on adjacent equipment such as pipelines that are protected with sacrificial anodes. Continuous monitoring of potentials should be considered to ensure that over-protection does not occur.

5 Wellheads and Trees

5.1 Introduction

Wellhead and tree equipment can be used for hydrocarbon production, seawater injection (raw and treated), and a variety of chemicals for well treatment and gas lift operations. There may be a need for a change in the duty of a subsea tree during its lifetime, e.g. from production to injection, and this should be carefully considered at the design stage in order to ensure that the materials specified have the required properties and corrosion resistance.

Although valves and bolting form part of this equipment, they are separately dealt with in Chapters 8 and 9.

Typical subsea tree assemblies are shown in Figure 5.



Figure 5 Typical subsea tree assemblies

5.2 Relevant Standards

Relevant standards are ISO 10423 (API Spec 6A) and ISO 13628-4 (API Spec 17D). Supplementary requirements to API Spec 17D are given in IOGP S-561.

5.3 Major Components in Wellhead Equipment

The major components in wellhead equipment as shown in Figure 6 excluding bolting, are:

- tree connector,
- tree body,
- wellhead housing,
- casing hanger,
- tubing hanger,

- seal assemblies,
- valves and chokes, and
- flow spools.

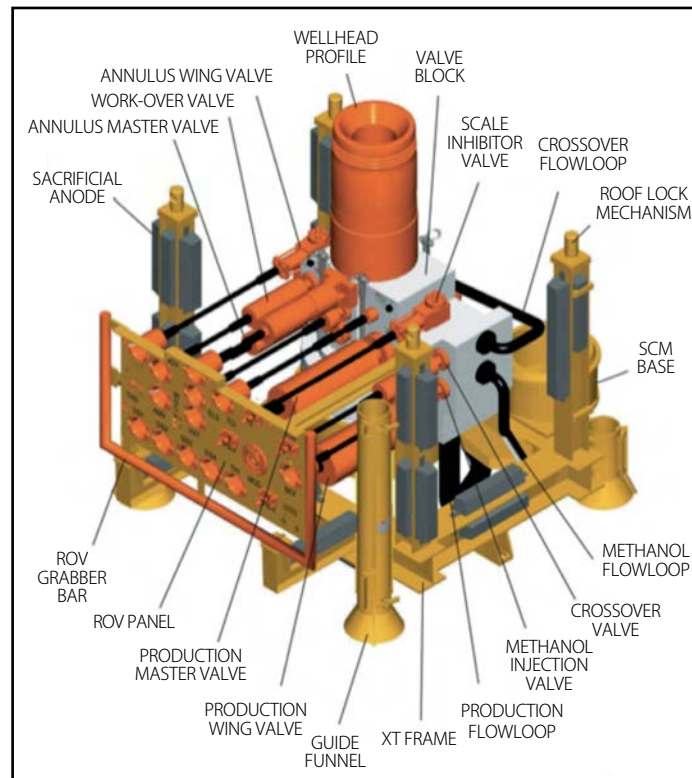


Figure 6 Typical subsea tree components

5.4 Material Considerations

The items listed in Section 5.3 are critical components, and careful consideration should be given to the specification of materials. It is recommended that all process-wetted materials other than bolting meet the requirements of ISO 15156/ NACE MR0175.

The ISO/API Product Specification Level (PSL) for subsea wellhead and tree equipment is typically 3, though ISO 13628-4 permits either PSL 2 or 3. The Temperature Classification is typically 'U', relating to an operating range of -18°C to 121°C . It should be noted that API Spec 17D requires all PSL 3 equipment to be impact tested regardless of temperature rating, the requirement being a minimum average of 20 J in the transverse direction at -18°C . However, to account for Joule-Thomson cooling IOGP S-561 requires impact testing at or below -46°C , with acceptance criteria to DNVGL RP-0034, for pressure-containing and pressure-controlling metal components downstream of the production choke and the choke body.

For subsea applications, PSL 3 with a gas test, in addition to the hydrostatic test, is recommended. This is referred to as PSL 3G.

Wellhead equipment should be corrosion resistant to the production and injection fluids in all internally process-wetted areas since, due to the complex geometry and turbulent flow, corrosion

inhibition cannot be relied upon to protect carbon and low alloy steels. It is also very unlikely that protective scales will form at the high velocities experienced in the trees, especially with chemicals being injected downhole.

Materials in direct contact with production fluids can be either inherently corrosion resistant or overlay welded with a CRA. This is a requirement in IOGP S-561.

Other material considerations are erosion, particularly if sand is produced, and the relatively large section thickness of many of the subsea components that will affect heat treatments and the attainment of suitable microstructures and mechanical properties. Preference should be given to the use of forged products for all high integrity components.

There are many 'minor' components, e.g. control line connectors, which if not correctly specified can lead to failure or malfunction of the equipment. It is therefore recommended that the materials properties and corrosion resistance of all components be considered.

5.5 Material Options

5.5.1 Tree Body and Connector

Forged trees and connectors have been produced successfully in a number of materials:

- Low alloy steel, AISI 4130 and 8630, internally overlay welded with a suitable CRA, e.g. Alloy 625.
- ASTM A182 F22 (2¼%Cr 1%Mo steel), overlay welded with a suitable CRA, e.g. Alloy 625.
- AISI 410 (13%Cr stainless steel).
- ASTM A182 F6NM (13%Cr 4%Ni stainless steel).
- Duplex stainless steel.

It is unlikely that low alloy steel without weld overlay would be acceptable except in the most benign and short service conditions, or for treated seawater injection. Even in those conditions, seat pockets and seal areas should be overlay welded with Alloy 625 in accordance with Section 3.5, and trim should be in a suitable grade of stainless steel.

Although AISI 410 and A182 F6NM may have adequate corrosion resistance for many applications, consideration should be given to achieving the required impact toughness in thick section components, and to weldability. F6NM has higher toughness and superior weldability to type 410 stainless steel. Welds in type 410 stainless steel can have relatively poor toughness, even after PWHT.

Duplex stainless steel is not recommended for subsea tree bodies due to the risk of the formation of detrimental intermetallic phases in thick section forgings, with resultant deterioration of corrosion resistance and toughness.

Of the above listed materials, low alloy steel overlay welded with a suitable CRA, e.g. Alloy 625, represents the lowest risk option for subsea. The preferred low alloy steel is ASTM A182 F22, since this provides better through thickness hardenability in thick section forgings, and is especially recommended for pressure ratings above 689 bar (10,000 psi).

Requirements for low alloy steel forgings are given in DNVGL-RP-0034 Steel forgings for subsea applications and DNVGL-RP-B202 Steel forgings for subsea applications – quality management requirements.

Note: The designer should be aware that the mechanical properties determined for large section forgings on a qualification test coupon in accordance with API Specification 6A might only represent the near surface mechanical properties and not the bulk properties. If bulk section properties are required for design purposes, they should be measured at an appropriate depth into the forging section on a representative prolongation.

5.5.2 Wellhead Housing, Casing Hanger and Seal Assemblies

These are of thinner section than the tree bodies and can be manufactured in AISI 4130 or 8630. Any process-wetted areas and/or seal areas should be overlay welded with a suitable CRA, e.g. Alloy 625.

5.5.3 Casing Hangers

Casing hangers are usually manufactured in AISI 4130, 4140 or 8630, and under normal operating conditions do not come into contact with produced fluids.

5.5.4 Tubing Hangers

Tubing hangers should be manufactured from high strength CRA materials. Depending on the service, acceptable materials are:

- AISI 4130, 8630 or ASTM A182 F22 overlay welded with a suitable CRA, e.g. Alloy 625 in all wetted areas.

Note: the designer should be aware of the tendency for the formation of hard zones in the fusion boundary between low alloy steels and Alloy 625 (refer to Section 6.6).

- ASTM A182 F6NM.
- 25% chromium super-duplex stainless steel.
- Alloy 718 supplied in accordance with API Spec 6ACRA.

5.5.5 Valves and Chokes

The body and bonnets of valves and chokes are usually manufactured in either:

- AISI 4130 or 8630, with any process-wetted surfaces and seal areas being overlay welded with a suitable CRA, e.g. Alloy 625, and
- ASTM A182 F6NM.

Stems are typically in high strength CRA materials such as Alloy 718 hard faced with tungsten carbide. Gates are usually manufactured from ASTM A182 F6NM, AISI 4130 or AISI 8630 material and also hard faced: see Chapter 8.

5.5.6 Gaskets

Gasket materials in subsea hydrocarbon service may be manufactured in type 316 stainless steel, but Alloys 825 or 625 in the annealed condition are preferred for greater corrosion resistance. Where gaskets are to be used in ring grooves overlay welded with Alloy 625, it is recommended

that Alloy 625 or 6% molybdenum stainless steel gaskets in the annealed condition be used. For treated seawater injection, a 6% molybdenum stainless steel in the annealed condition is acceptable. For raw seawater injection, careful consideration needs to be given to ensuring adequate crevice and galvanic corrosion resistance of materials at the expected operating temperature.

5.5.7 Hydraulic Tubing

Solution annealed AISI 316 or if welded, 316L, stainless steel is commonly used, but for higher pressure and higher temperature applications Alloy 825 and Alloy 625 are recommended. Alloy 400 is also suitable provided it is not exposed to production fluids containing mercury. See also Chapter 11.

5.5.8 Flow Spools

Flow spools are usually manufactured from a CRA such as 22Cr duplex or 25Cr super-duplex stainless steel, with induction bends, all in the solution annealed condition (full component solution heat treatment and water quench). Carbon steel internally overlay welded with Alloy 625 or higher grade austenitic alloys will be required for sour conditions beyond the safe limits for 25Cr super-duplex.

Flow spools will incorporate butt welds, possibly with buttered joint faces, and hub or flange connectors: the fabrication guidance in Section 6.6 is applicable.

External coating of the completed spools is recommended in all cases; refer to Chapter 14.

5.6 External Corrosion Protection

Protective coatings and/or insulation in conjunction with CP, as discussed in Chapters 4 and 14, provide external corrosion protection.

6 Manifold Piping and Equipment

6.1 Introduction

Subsea manifolds transport, control and sometimes pump the co-mingled production fluids from the wellheads to the processing facilities, and/or the injection water or gas into wellheads. Manifolds typically comprise an assembly of piping, valves, control modules, instrumentation and associated fittings supported within a framework of structural steel. More recent designs may incorporate additional equipment items such as multiphase pumps and associated suction and discharge vessels. Some manifolds also serve as drilling templates, though recent trends have been to use 'cluster' manifolds for tying-in individual satellite wells to flowlines back to a processing facility. Towhead manifolds are used for bundled pipelines installed by towing. Typical manifold types are shown schematically in Figure 7.

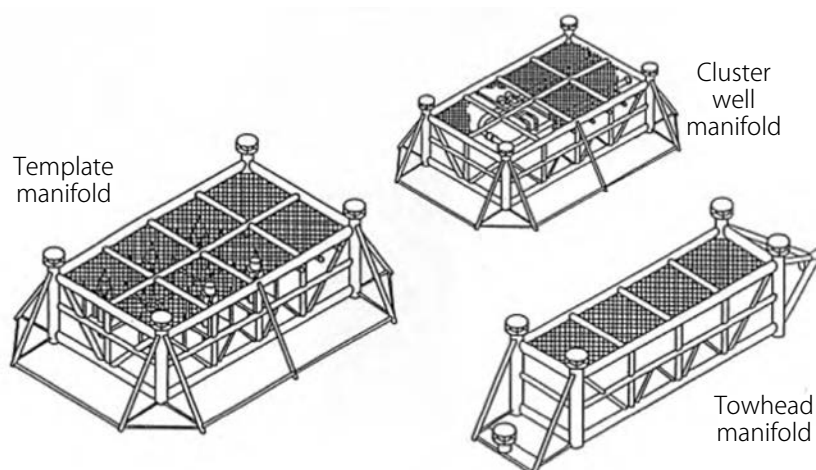


Figure 7 Some typical subsea manifolds

The requirements for materials and fabrication of manifold piping and fittings are extensively described in ISO 13628-15 and the recommendations made in this section are additional to these. The relevant sections of ISO 13628-15 are:

7	Materials and fabrication requirements to piping systems.....
7.1	General
7.2	Pipe and pipe fittings.....
7.3	Forged components.....
7.4	Chemical composition and weldability.....
7.5	Test sampling of base materials.....
7.6	Mechanical and corrosion testing of base materials.....
7.7	Non-destructive inspection of components
7.8	Fastener materials.....
7.9	Bending and forming operations.....
7.10	Overlay welding and buttering of components.....
7.11	Welding and non-destructive testing of piping systems

Supplementary requirements for piping including datasheets are given IOGP S-563.

Many different materials may be used for subsea manifold piping and equipment, based on a number of different manufacturing and construction techniques. Acceptable sources of materials include forgings, castings and hot isostatic pressings (HIP) from powder. Each product has benefits, but forgings and HIPped products are usually considered to have the highest integrity and should be the first choice material. Seamless or longitudinally seam welded pipe may also be used, with branch connections extruded from the main pipe-run by either hot or cold working. Where sour service is applicable to carbon and low alloy steel, a low sulphur, calcium treated and vacuum degassed grade should be used (see Section 3.6), especially for seam welded piping components.

ERW / HFI piping is not generally recommended for use in manifolds and the available thicknesses for the typical diameters of interest make it unlikely to meet design requirements. It is not permitted in ISO 13628-15.

Connections to the manifold from the wellheads, and from the flowlines to the processing facilities may be either flexible jumpers or rigid pipeline spools, made up by suitable flanged joints or proprietary connectors.

Figure 8 illustrates a cluster manifold connected to eight satellite wells, with flowlines to the processing facility.

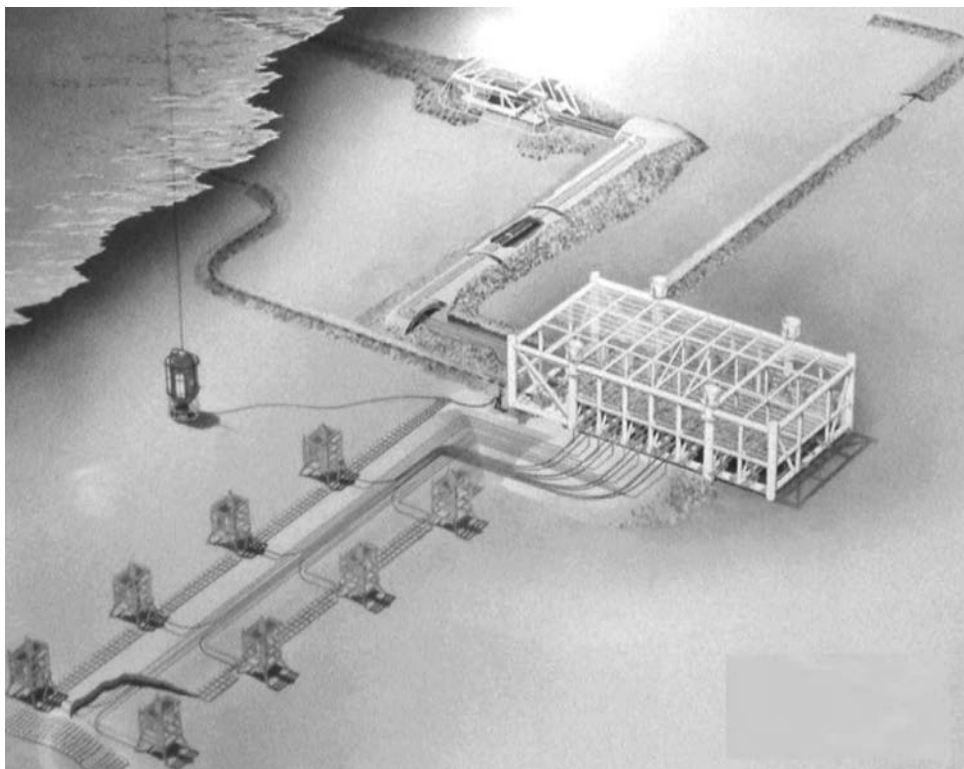


Figure 8 Cluster manifold connected to eight satellite wells

Auxiliary connections to the manifold may be made to facilitate injection of scale and/or corrosion inhibitor and sometimes H₂S scavengers, often via umbilicals, as described in Chapters 11 and 12.