FOREWORD

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DNV Offshore Codes consist of a three level hierarchy of documents:

— Offshore Service Specifications. Provide principles and procedures of DNV classification, certification, verification and consultancy services.
— Offshore Standards. Provide technical provisions and acceptance criteria for general use by the offshore industry as well as the technical basis for DNV offshore services.
— Recommended Practices. Provide proven technology and sound engineering practice as well as guidance for the higher level Offshore Service Specifications and Offshore Standards.

DNV Offshore Codes are offered within the following areas:

A) Qualification, Quality and Safety Methodology
B) Materials Technology
C) Structures
D) Systems
E) Special Facilities
F) Pipelines and Risers
G) Asset Operation
H) Marine Operations
J) Wind Turbines

Amendments and Corrections

This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the “Amendments and Corrections” document located at: http://www.dnv.com/technologyservices/, “Offshore Rules & Standards”, “Viewing Area”.

The electronic web-versions of the DNV Offshore Codes will be regularly updated to include these amendments and corrections.
Introduction

This Recommended Practice (RP) provides general requirements for the design-, manufacture-, testing and certification processes for subsea gravity separators intended used for deepwater applications. In this context deepwater may be defined as water depths where the governing load is the external, rather than the internal pressure.

The objectives of this document are:

— to provide an internationally acceptable standard for the structural integrity of Subsea Separators
— to provide more exact design criteria when the external pressure is governing for required thicknesses of the design
— to serve as a technical reference document in contractual matters
— to serve as a guideline for the designers, suppliers, purchasers and regulators reflecting 'state-of-the art' as well as consensus on accepted industry practice
— to specify procedures and requirements for certification (or classification) of Subsea Separators intended used on deepwater installations.
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1. General

1.1 General

1.1.1 Introduction

This Recommended Practice (RP) provides general requirements for the design, manufacture, testing and certification processes for subsea gravity separators intended used for deepwater applications. In this context deepwater may be defined as water depths where the governing load is the external rather than the internal pressure.

This document provides recommended practice to achieve an acceptable overal safety level regarding the structural strength of the separators.

This RP has been developed for general world-wide application. Governmental legislation may include requirement in excess of the provisions of this standard depending on the intended installation.

Extracts from the requirement in the EU Directive Pressure Equipment, PED, EU Council Directive No. 97/23/EC are partly included, which need to be considered on subsea separators to be installed on one of the Continental Shelves within the EEA (European Economic Area).

The functionality of the separator is not covered by this Recommended Practice.

The main benefits of using this RP comprise:

— provision of subsea separator solutions for deepwater applications that are safe and feasible for construction
— specific guidance and requirements for efficient design analysis based on EN 13445, that satisfy the Pressure Equipment Directive (Applicable within EEA)
— application of a risk based approach where the magnitudes of the safety factors depend on consequence of failure (safety class methodology).

1.1.2 Objectives

This objective of this document is to:

— provide an internationally acceptable RP for the structural integrity of subsea separators
— provide more exact design criteria when external pressure is governing for the required thicknesses
— serve as a technical reference document in contractual matters
— serve as a guideline for designers, suppliers, purchasers and regulators reflecting state-of-the art and consensus on accepted industry practice
— specify procedures and requirements for certification or classification of Subsea separators intended used on deepwater installations.

1.1.3 Application and scope

This standard applies primarily to subsea production separators at deepwater installations within the petroleum and natural gas industries. At more ordinary water depths, existing practice, e.g. using the design by formulae (DBF) methodology in EN 13445-3, may provide feasible solutions. For deep water locations the design by analysis (DBA) approach provides consistent means to achieve more optimal designs with acceptable reliability. The design philosophy as focused on in this RP may also be utilised for ordinary water depths.

Connecting piping, foundation, anchoring and skids used for transportation, installation, etc. is considered outside the scope for this standard.

For others applications, special considerations may need to be agreed with the parties involved and according to the statutory regulations.

1.1.4 PED, particular compliance issues

This RP is essentially based on application of EN 13445, which is a harmonised standard and gives presumption of conformity with PED. However, this RP covers designs that were not in focus when PED was developed. In particular two issues have been addressed in this RP where PED does not provide a clear guidance, and additional considerations have been made in order to ensure that the essential safety requirements (Annex I of PED) are met. These issues relate to:

— application of safety class methodology
— proof test (pressure testing).

This RP provide explicit guidance on these issues as further described in Subsection 2.4 and in 6.8 respectively. Clarification of these issues may be of common interest within EU. Questions together with proposed answers (as reflected in these subsections) have been formulated and will be sent to the National Authorities for potential further processing in EU. A possible outcome is that this may end up as guidelines to PED.

1.2 How to use the RP

1.2.1 Users of the RP

The client (or purchaser) is understood to be the party ultimately responsible for the system as installed and its intended use in accordance with the prevailing laws, statutory rules and regulations.

The contractor is understood to be the party contracted by the client to perform all or part of the necessary work required to bring the system to an installed and operable condition.

The designer is understood to be the party contracted by the contractor to fulfill all or part of the activities associated with the design, and provides the main contribution to the design verification report.

The manufacturer is understood to be the party contracted by the contractor to manufacture all of part of the system.

The certification body is usually appointed by the client to perform independent certification.

1.2.2 Structure of this RP

The documents is organised as illustrated in the flowchart in Figure 1-1.

Section 1 contains the objectives and scope of the Recommended Practice. It further introduces essential concepts, definitions and abbreviations.

Section 2 provides the design philosophy which includes the safety philosophy and design format. In particular the concept of safety class is given and discussed in relationship to PED and the fully harmonised standard EN 13445.

Section 3 deals with the design criteria. Here the relevant load effects and material properties to be applied in the analysis are given together with a detailed description on how to carry out the design analysis.

Section 4 covers requirements to the base material, and covers aspects of manufacturing, chemical composition, properties, testing and resistance towards corrosion and Hydrogen Induced Stress Cracking (HISC) with particular focus on important parameters regarding use of clad and duplex steel and for the manufacturing of thick plates.

Section 5 contains requirements for the fabrication, testing and inspection of clad and duplex steel plates, whereas Section 6 covers such requirements for the separator.

Section 7 gives the certification process in terms of certification activities to be carried out by the certification body during design and fabrication. It also includes a list of documentation to be submitted by the manufacturer and designer for review and approval.
Section 8 on operation, maintenance and inspection addresses important issues to be addressed in preceding activities since the vessel is likely “never to be seen again” once it is installed. Note that installation aspects are not covered by this RP.

All users should go through Section 1 and 2 describing the scope of the RP and the design principles. The design analysis should be carried out by the designer according to Section 3, taking into account the design premises that are to be specified by the client and contractor. The contractor, manufacturer and certification body should consider Sections 5, 6 and 7, covering fabrication and certification.

1.3 Normative references
The following standards below include requirements that through reference in the text constitute provisions of this standard. Last revision of the references shall be used unless otherwise agreed. Other recognised standards may be used provided it can be demonstrated that these meet or exceed the requirements of the standards referred to herein and accepted by the involved parties as supplier, contractor, field operator, any third party or certifying authority/notified body.

Any deviations, exceptions or modifications to the codes and standards shall be documented for agreement or approval need to be given by the parties involved.

1.3.1 Offshore Standards
DNV-OS-F101, Submarine Pipeline Systems

1.3.2 Recommended Practices
DNV-RP-B401, Cathodic Protection Design

1.3.3 Other references
ISO/FDIS 2394 General Principles on Reliability of Structures

PD 5500 “Specification for Unfired fusion welded pressure vessels”
EN-13445-1, Unfired pressure vessels – Part 1: General
EN-13445-2, Unfired pressure vessels – Part 2: Materials
EN-13445-3, Unfired pressure vessels – Part 3: Design
EN-13445-4, Unfired pressure vessels – Part 4: Fabrication
EN-13445-5, Unfired pressure vessels – Part 5: Inspection and testing
ISO 15156-3, Petroleum and natural gas industries – Materials for use in H₂S-containing environments in oil and gas production – Part 3: Cracking resistant CRAs (corrosion resistant alloys) and other alloys
EN 10028-1, Flat products made of steels for pressure purposes - Part 1: General requirements.
EN 10028-6, Flat products made of steels for pressure purposes - Part 6: Weldable fine grain steels, quenched and tempered.


### 1.4 Definitions

**Clad component**: component with internal liner where the bond between base and cladding material is metallurgical. This includes corrosion resistant layer applied by weld overlay, hot rolling and explosion bonded plates.

**Corrosion allowance**: The amount of thickness added to the thickness of the component to allow for corrosion/erosion/ wear.

**Deepwater separator**: Subsea separators for deepwater applications. In this context deepwater may be defined as water depths where the governing load is the external rather than the internal pressure.

**Environmental loads**: Loads due to the environment, such as waves and current, wind.

**Failure**: An event causing an undesirable condition, e.g. loss of component or system function, or deterioration of functional capability to such an extent that the safety of the unit, personnel or environment is significantly reduced.

**Fatigue**: Cyclic loading causing degradation of the material.

**Fatigue Limit State (FLS)**: Related to the possibility of failure due to the effect of cyclic loading.

**Fracture Analysis**: Analysis where critical initial defect sizes under design loads are identified to determine the crack growth life to failure, i.e. leak or unstable fracture.

**Inspection**: Activities such as measuring, examination, testing, gauging one or more characteristics of an object or service and comparing the results with specified requirements to determine conformity.

**Installation**: The operation related to installing the separator, including tie-in.

**Limit State**: The state beyond which the separator or part of the separator no longer satisfies the requirements laid down to its performance or operation. Examples are structural failure or operational limitations.

**Load**: The term load refers to physical influences which cause for example stress, strain or deformation in the separator.

**Load Effect**: Response or effect of a single load or combination of loads on the structure, such as stress, strain and deformation.

**Load and Resistance Factor Design (LRFD)**: Design format based upon a limit state and partial safety factor methodology. The partial safety factor methodology is an approach where separate factors are applied for each load effect (response) and resistance term.

**Location class**: A geographic area classified according to the distance from locations with regular human activities.

**Lot**: A number of plates from the same heat, the same heat treatment batch and with the same thickness.

**Non-destructive testing (NDT)**: Structural tests and inspection of welds or parent material with radiography, ultrasonic, magnetic particle or eddy current testing.

**Offshore Standard (OS)**: Offshore Standard: The DNV offshore standards are documents which presents the principles and technical requirements for design of offshore structures. The standards are offerred as DNV’s interpretation of engineering practice for general use by the offshore industry for achieving safe structures.

**Operation, Normal Operation**: Conditions that are part of routine (normal) operation of the separator.

**Out of roundness**: The deviation of the perimeter from a circle. This can be an ovalisation, i.e. an elliptic cross section, or a local out of roundness, e.g. flattening. The numerical definition of out of roundness and ovalisation is the same.

**Ovalisation**: The deviation of the perimeter from a circle resulting in an elliptic cross section.

**Prior Service Life**: The duration that a component has been in service, since its installation. Duration is computed from the time of installation or production if relevant.

**Recommended Practice (RP)**: The publications cover proven technology and solutions which have been found by DNV to represent good practice.

**Residual Service Life**: The duration that a component will be in service, from this point forward in time (from now). Duration is computed from now until the component is taken out of service.

**Safety Class**: A concept adopted herein to classify the criticality of the subsea separator with respect to consequence of failure.

**Safety Class Resistance Factor**: Partial safety factor which transforms the lower fractile resistance to a design resistance reflecting the safety class.

**Service Life**: The length of time assumed in design that a component will be in service.

**Uncertainty**: In general the uncertainty can be described by a probability distribution function. In the context of this Recommended Practice, the probability distribution function is described in terms of bias and standard deviation of the variable.

### 1.5 Abbreviations and symbols

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
<td>Accidental Limit State</td>
</tr>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>COV</td>
<td>Coefficient Of Variance</td>
</tr>
<tr>
<td>CRA</td>
<td>Corrosion Resistant Alloy</td>
</tr>
<tr>
<td>DBA</td>
<td>Design By Analysis</td>
</tr>
<tr>
<td>DBF</td>
<td>Design By Formulae</td>
</tr>
<tr>
<td>DNV</td>
<td>Det Norske Veritas</td>
</tr>
<tr>
<td>EEA</td>
<td>European Economic Area</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>FLS</td>
<td>Fatigue Limit State</td>
</tr>
<tr>
<td>HPIC</td>
<td>Hydrogen Pressure Induced Cracking</td>
</tr>
<tr>
<td>LRF</td>
<td>Load and Resistance Factor Design</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-Destructive Examination</td>
</tr>
<tr>
<td>NDP</td>
<td>Norwegian Deepwater Program</td>
</tr>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing</td>
</tr>
<tr>
<td>PED</td>
<td>Pressure Equipment Directive (applicable within EEA)</td>
</tr>
<tr>
<td>PWHT</td>
<td>Post Weld Heat Treatment</td>
</tr>
<tr>
<td>RP</td>
<td>Recommended Practice</td>
</tr>
<tr>
<td>SLS</td>
<td>Serviceability Limit State</td>
</tr>
<tr>
<td>SSC</td>
<td>Stress Sulphide Cracking</td>
</tr>
<tr>
<td>TRB</td>
<td>Three roll bending</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>UO</td>
<td>Fabrication process for welded pipes</td>
</tr>
<tr>
<td>UOE</td>
<td>Pipe fabrication process for welded pipes, expanded</td>
</tr>
<tr>
<td>WSD</td>
<td>Working Stress Design</td>
</tr>
</tbody>
</table>
2. Design Philosophy

2.1 General

2.1.1 Objective

The purpose of this section is to present the safety philosophy and corresponding limit state design format applied in this RP.

2.1.2 Applicability

This section applies to subsea separators that are to be built in accordance with this RP. Note that the focus for this RP is the overall structural integrity of subsea separators in deep water where the static external pressure is the governing load condition. No design practice has yet been established for such conditions. At more shallow water depths, existing design practice governed by external overpressure according to existing rules. It is therefore recommended that the overall Safety Objective be followed up by more specific, measurable requirements. If no policy is available, or if it is difficult to define the safety objective, one could also start with a risk assessment. If no policy is available, or if it is difficult to define the safety objective, one could also start with a risk assessment. The risk assessment could identify all hazards and their consequences, and then enable back-extrapolation to define acceptance criteria, testing regime and areas that need to be followed up more closely.

In this Recommended Practice, the structural failure probability is reflected in the choice of safety class. The choice of safety class should also include consideration of the expressed safety objective. An overall safety shall be established, planned and implemented by company covering all phases from conceptual development until retrieval or abandonment.

Guidance note:

All companies have policy regarding human aspects, environmental and financial issues. These are typically on an overall level, but more detailed objectives and requirements in specific areas may follow them. Typical statements regarding safety objectives for a subsea separator may be:

- Consequences of such events for people, for the environment and for assets and financial interests.
- The impact on the environment shall be reduced to as low as reasonably possible.
- Statements such as those above may have implications for all or individual phases only. They are typically most relevant for the work execution (i.e. how the contractor executes the job) and for specific design solutions. Having defined the Safety Objective, it can be a point of discussion as to whether this is being accomplished in the actual project. It is therefore recommended that the overall Safety Objective be followed up by more specific, measurable requirements.
- If no policy is available, or it is difficult to define the safety objective, one could also start with a risk assessment. The risk assessment could identify all hazards and their consequences, and then enable back-extrapolation to define acceptance criteria, testing regime and areas that need to be followed up more closely.
- In this Recommended Practice, the structural failure probability is reflected in the choice of safety class. The choice of safety class should also include consideration of the expressed safety objective.

2.2.2 Systematic review

A systematic review or analysis shall be carried out at all phases in order to identify and evaluate the consequences of failure of the subsea separator, such that necessary remedial measures can be taken. The consequences include consequences of such events for people, for the environment and for assets and financial interests.

Guidance note:

A methodology for such a systematic review is quantitative risk analysis (QRA). This may provide an estimation of the overall risk to human health and safety, environment and assets and comprises:
- Hazard identification
- Assessment of probabilities of failure events
- Accident developments
- Consequence and risk assessment

It should be noted that legislation in some countries requires risk analysis to be performed, at least at an overall level to identify critical scenarios that might jeopardise the safety and reliability of the separator system. Other methodologies for identification of potential hazards are Failure Mode and Effect Analysis (FMEA) and Hazard and Operability studies (HAZOP).

2.2.3 Fundamental requirements

A separator shall be designed, manufactured, fabricated, operated and maintained in such a way that:
- With acceptable probability, it will remain fit for the use for which it is intended, having due regard to its service life and its cost, and
- With appropriate degree of reliability, it will sustain all foreseeable load effects, degradation and other influences likely to occur during the service life and have adequate durability in relation to maintenance costs.

---end-of-Guidance-note---

---end-of-Guidance-note---
Sub-sea separators in this RP are based on the conditions that the separators are built as cylindrical vessels with dished heads at each ends. If other type of separators are selected, they will be subject to special considerations.

The number of nozzles and penetrations through the vessel wall should be kept as low as possible in order to minimise the areas for potential leaks. If possible, flanged joints should be replaced by permanent welding or similar safe joining in order to avoid any leaks.

Dished heads should be of hemispherical type in order to give a smooth area between shell and heads and also to reduce possibility for buckling in any transition areas due the external pressure. Elliptical and torispherical heads should not be used for deep water separators.

In the case of shell and spherical head plates with different thicknesses, the design for the joint needs special considerations. Generally, centrelines in the middle of the shell- and spherical heads plates should merge theoretically together without any offset. For unequal thicknesses of the plates, the transition section should be machined with a minimum internal and external angle/slope. The thicker part of the shell or the heads should preferably be machined with a cylindrical part for performing required non-destructive testing of the final weld joint.

Horizontal vessels should be supported on two symmetrically located saddle supports equipped with stiffening rings continuously the whole circumference of the separator in order to reduce any local stress concentrations in the shell cased by supporting loads. Those stiffening rings will also give protection for any externally objects which might hit the separator during the installation- and/or operating phases. Any lifting pads/lugs should also be integrated into the stiffening rings or saddle supports if possible on order to reduce unnecessary welding on separator shell.

Note that in service, inspection will be impossible (or at least very limited) in very deep water.

In order to maintain the required safety level, the following requirements apply:

- The design shall be in compliance with this RP.
- Separators shall be designed by appropriate qualified and experienced personnel.
- The materials and products shall be used as specified in this RP.
- Adequate supervision and quality control shall be provided during design, manufacture and fabrication.
- Manufacture, fabrication, handling, transportation, installation and operation shall be carried out by personnel having the appropriate skill and experience. Reference is made to recognised standards for personnel qualifications.
- The separator shall be maintained and inspected in accordance with the design assumptions.
- The separator shall be operated in accordance with the design basis and the installation and operating manuals.
- Relevant information between personnel involved in the design, manufacture, fabrication and operation shall be communicated in an understandable manner to avoid misunderstandings.
- Design reviews shall be carried out where all contributing and affected disciplines are included to identify and solve any problems.
- Verification shall be performed to check compliance with provisions contained herein in addition to national and international regulations.

2.2.4 Installation and operational considerations

Operational requirements are system capabilities needed to meet the functional requirements. Operational considerations include matters which designers should address in order to obtain a design that is safe and efficient to install, operate and maintain. Operational requirements include operational philosophy, environmental limits, installation and retrieval, in-service operations, inspection and maintenance philosophy.

Safe operation of a separator requires that:

- The designer shall take into account all conditions which the separator will be subjected to during installation and operation.
- The operations personnel shall be aware of, and comply with, limits for safe operations.

2.2.5 Design principles

In this RP, structural safety of the separator is ensured by use of a safety class methodology, with the use of EN 13445 as a basis. The separator including interfaces, details and components, shall be designed according to the following basic principles:

- Since no (or very limited) in service inspection is possible, particular focus on robust design is essential, e.g. weld design (with focus on enabling proper NDT), nozzle design, material specifications, inspection and testing scope.
- The separator shall satisfy functional and operational requirements as given in the design basis.
- In addition to the use of comprehensive and detailed installation procedures, soft landing devices should be specially designed to accommodate installation forces.
- The separator shall be designed such that an unintended event does not escalate into an accident of significantly greater extent than the original event.
- Permit simple and reliable installation, retrieval, and be robust with respect to use.
- Provide adequate access for subsea (ROV) inspection and replacement (and maintenance/repair – as applicable).
- Nozzles and components shall be made such that fabrication and adequate inspection can be accomplished in accordance with relevant recognised techniques and practice.
- Design of structural details and use of materials shall be done with the objective to minimise the effect of corrosion, erosion and wear.
- The design should facilitate monitoring of its behaviour in terms of vibrations, fatigue, cracks, wear, erosion, corrosion, etc.

2.2.6 Quality assurance

The design format within this RP requires that the possibility of gross errors (human errors) shall be prevented by requirements to the organisation of the work, competence of personnel performing the work and the verification activities during the design, manufacture and fabrication phases and quality assurance during all relevant phases.

A quality system shall be established and applied to the design, manufacturing, fabrication, testing, operation and maintenance activities to assist compliance with the requirements of this RP.

2.3 Design format

2.3.1 Basic considerations

The design procedure and its format ensure that the safety objective is met. This is to keep the risk and the failure probability (i.e. probability of exceeding a limit state) below a certain level. Note that gross errors have to be prevented by a quality system that ensures proper organisation of the work and use of personnel with appropriate competence and verification.

The following design methods may be applied:

- Load and Resistance Factor Design (LRFD) method
— working stress design
— reliability based design.

2.3.2 Safety class methodology

This RP gives the possibility to design with different safety requirements, depending on the safety class to which the separator belongs. The separator shall be classified into a safety class based on the consequences of failure. The safety class depends on:

— the hazard potential of the fluid in the separator; i.e. fluid category
— the location of separator
— whether the separator is in operating or temporary state.

Fluids are divided into two groups in accordance with the classification given in Article 9 of PED.

Group 1 comprises dangerous fluids defined as:

— explosive
— extremely flammable
— highly flammable
— flammable (where the maximum allowable temperature is above flashpoint)
— very toxic
— toxic
— oxidizing.

Group 2 comprises all other fluids not referred to above.

**Guidance note:**

For a subsea production separator, the normal operating fluid contents are produced hydrocarbons, hence fluid group 1 applies.

Location is classified two areas:

— Location 1 is where no frequent human activity is anticipated.
— Location 2 is near human activity; e.g. within the platform safety zone. A horizontal distance of 500 m from the platform is suggested at shallow water depths, whereas a larger distance should be considered in deeper waters.

**Guidance note:**

Risk analysis considering release of hydrocarbons may be used to establish the location class. For a deepwater separator normally location category 2 applies.

The concept of safety class links acceptance criterion for the separator design with the potential consequences of failure defined in Table 2-1:

<table>
<thead>
<tr>
<th>Table 2-1 Classification of safety classes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Safety class</strong></td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>Medium</td>
</tr>
<tr>
<td>High</td>
</tr>
</tbody>
</table>

For normal use, the safety classes in Table 2-2 apply. Other classification may exist depending on the conditions and criticality of the separator. The operator shall specify the safety class to which the separator shall be designed, and although the consequences to life and environment may be low/medium, particular consideration should be made regarding the economic consequences before a safety class of medium or low is assigned.

<table>
<thead>
<tr>
<th>Table 2-2 Normal classification of safety classes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase</strong></td>
</tr>
<tr>
<td>Temporary</td>
</tr>
<tr>
<td>Operating</td>
</tr>
</tbody>
</table>

The concept of safety classes is not explicitly addressed in PED or in the EN 13445 code. The safety class concept is discussed in relationship to PED in 2.4.

2.3.3 Design by LRFD-method

This is a flexible format where each partial safety factor is intended to reflect the uncertainty in the parameter it is multiplied with. Typically different magnitudes of the partial safety factors for different types of loading associated with different degree of uncertainty applies. Typically load effects with associated partial safety factors are split into:

— pressure load effect
— functional load effect
— environmental load effect
— accidental load effect.

Similarly, several partial safety factors on the capacity side may be defined, reflecting uncertainty in the material properties and capacity calculation. The factor to distinguish between the different safety classes applies to the resistance, and is defined as a safety class resistance factor.

2.3.4 Working Stress Design (WSD)

The Working (allowable) Stress Design method is a design format where the structural safety margin is expressed by one central safety factor or usage factor for each limiting state.

**Guidance note:**

In the present RP, with focus on deep water, the dominating uncertainty is related to the capacity of the separator, whereas the loading governing for the main dimensions of the separator is practically deterministic (based on the static head). A single safety factor on the capacity is defined, whereas the load is applied with a safety factor of unity due to its deterministic nature. In this particular application the LRFD-method may therefore be equivalent to the WSD method.

The usage factor may be interpreted as an inverted weighted product of partial safety factors. The usage factor is also named Allowable Stress factor or Design Factor in some WSD codes and standards.

2.3.5 Reliability based design

As an alternative to the design formats specified in this standard, a probabilistic design approach based on a recognised structural reliability analysis may be applied provided that:

— The method complies with DNV Classification Note no. 30.6 or ISO 2394.
— The approach is demonstrated to provide adequate safety for familiar cases, as indicated by this standard.
— The target reliability level complies with the acceptance criteria defined herein; confer discussion in 2.4 on the “equivalent overall level of safety”.

The reasoning for pursuing a probabilistic design approach may be that:

— It is used for calibration of explicit limit states outside the scope of this standard.
— Physical properties for governing variables are know to be...
different from what was applied in the calibration performed herein.

The adequate probabilistic model is know to be different from what was applied in the calibration performed herein.

Guidance note:
Detailed analysis, inspection, testing, application of improved material quality, may reduce statistical uncertainty, model uncertainty and measurement uncertainty. This improved state of knowledge may then be utilized in the design process.

Suitably competent and qualified personnel shall perform the structural reliability analysis, and extension into new areas of application shall be supported by technical verification. As far as possible, target reliability levels shall be calibrated against identical of similar subsea separator designs that are known to have adequate safety based on this standard. If this is not feasible, the target safety levels shall be based on the failure type and safety class as given in Table 2-3.

Guidance note:
For subsea separators in very deep water, the annual probability of failure considering ULS is close to the probability of failure for the entire lifetime, if material degradation and corrosion is accounted for in the analysis. This is because the time dependent load is insignificant compared to the static. The application of Table 2-3 is therefore somewhat more conservative than for designs where e.g. time variant environmental loading is dominating.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

2.4 Safety Class Concept and PED

The concept of safety class is not addressed in PED nor part of the EN 13445 code. The “Essential Safety Requirements” of PED (Annex I, Section 7) allows for alternatives to the provisions given, provided that it can be demonstrated that appropriate measures have been taken to achieve an equivalent overall level of safety. Guideline 8/6 of PED states that adequate safety margins and deviations from a particular value can be justified by reduced risk in the respective failure mode, or by additional means to ensure no increase of the risk.

Guidance note:
The safety class concept as defined here should not be confused with the class of vessel (I, II, III and IV) based on pressure and volume as used in PED, This RP deals with large volumes and high pressures; i.e. class IV vessels. The safety class concept introduced in this RP is based on risk evaluations for this type of vessels.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

Table 2-3  Acceptable failure probabilities\(^{1)}\) vs. safety class

<table>
<thead>
<tr>
<th>Limit state</th>
<th>Probability bases(^{2)})</th>
<th>Safety class</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS(^{3)})</td>
<td>Annual</td>
<td></td>
<td>(10^{-1})</td>
<td>(10^{-1}-10^{-2})</td>
<td>(10^{-2}-10^{-3})</td>
</tr>
<tr>
<td>ULS</td>
<td>Annual</td>
<td></td>
<td>(10^{-3})</td>
<td>(10^{-4})</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>FLS(^{4)})</td>
<td>Annual</td>
<td></td>
<td>()</td>
<td>()</td>
<td>()</td>
</tr>
<tr>
<td>ALS</td>
<td>Annual</td>
<td></td>
<td>()</td>
<td>()</td>
<td>()</td>
</tr>
</tbody>
</table>

Notes:
1) The failure probability from a structural reliability analysis is a nominal value and cannot be interpreted as an expected frequency of failure.
2) The probability basis is failures per year for permanent condition, or for the actual period of operation for temporary conditions.
3) The failure probabilities for SLS are not mandatory. SLS are used to select operational and installation limitations and can be defined according to the operator’s preference. Note that exceeding a SLS condition requires a subsequent ALS design check.
4) The annual failure probability is usually considered in the last year of service life or last year before inspection.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

Risk is defined as the product of probability of a hazardous situation (here structural failure) and its associated consequences. This is illustrated in Figure 2-2.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

The risk may be reduced either by reducing the probability of structural failure or by reducing its consequences. A hazard with a “high” probability of occurrence in combination with “high” consequences is associated with a high risk, which is not tolerable. On the other hand, unlikely hazards with “low” consequences may be ignored. In between is the ALARP (As Low As Reasonably Practicable) region, where cost effective risk control options should be implemented.

The fully harmonised standard EN 13445 forms the basis for the design criteria in this RP. Since consequences of failure (or the concept of safety classes) are not explicitly addressed in EN 13445, it is reasonable to assume that the design criteria of EN 13445 also cover cases where the consequences associated with failure are “high”. In order to have an acceptable risk level the corresponding annual probability of occurrence must in these cases be “low”. Following Table 2-3, such a probability is likely to be in the order of \(10^{-3}\), and EN 13445 may be associated with the upper left corner of the risk matrix in Figure 2-2. The probability of failure is a controlled by the design criterion, and a change in the magnitude(s) of the (partial) safety factor(s) implies a change in the probability of failure.

Guidance note:
The consequences of structural failure of a subsea separator installed in deep water are to be evaluated with respect to life, environment and property, see also 2.3.2. Some comments are given as follows:
- consequences to life are likely to be low; i.e. no injuries of fatalities.
- consequences to environment are also likely to be relatively low, provided that the separator can be isolated so that limited or no releases from the connected pipelines are ensured. (Failure is most likely to occur in a near vacuum condition, and the spill of content will therefore be limited due to low filling). However, appropriate consideration of these consequences must be made in each individual case.
- consequences to property; i.e. costs related to loss of the separator itself, and costs related to the operation interruption and replacement. Appropriate considerations should be made by the operator. If the consequences to life and environmental are low, a cost benefit calculation may be performed to check if the safety factor corresponding to safety class low is cost effective or if a higher safety factor should be applied.

The risk matrix in Figure 2-2 Risk matrix includes a “combined consequence” on the vertical axis; i.e. a combination of consequences to life, environment and property.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

The risk level inherent in the EN 13445 code is assumed to fit into the risk matrix at high consequences and low probability.
Failure of a subsea separator is likely to be associated with lower consequences, and this allows maintenance of the same risk level for an increased probability of failure, see Figure 2-2. An increased probability of failure effectively corresponds to a reduction in the safety factor(s) of the design criterion. The safety class methodology is in terms of a safety class resistance factor that is to be multiplied with the partial safety factor for the material strength. The magnitude of the safety class resistance factor was calibrated using structural reliability analysis for different target safety levels. Background for these calculations may be found in Appendix A. Focus for the calculations is collapse due to external pressure, but the philosophy and the factors are also valid for designs in shallow water governed by the internal pressure, provided that a departure from high consequences can be justified. The value of the safety class resistance factor for the different safety classes are:

- 1.0 for safety class “high” (This corresponds to EN 13445)
- 0.93 for safety class “medium”
- 0.86 for safety class “low”.

The use of safety class methodology effectively maintains the safety level without increasing the risk, and complies with the essential safety requirements of PED.

It follows according to the ALARP principle that application of the resistance factor for a lower safety class, and hence acceptance of a higher failure probability, should be based on cost efficiency arguments. Possible causes may be fabrication limitations or installation aspects, making the more reliable design unduly costly or even unfeasible. Oppositely, if the potential savings for the more unsafe design are marginal, the safety factor for the higher safety class should be applied.

3. Design

3.1 General

This section provides procedures for limit state design checks of relevant failure modes for subsea separators in very deep water.

3.2 Material selection

Reference is made to EN 13445 and Section 4 of this RP.

3.3 Loads and load effects

The differential pressure due to the static external pressure and the internal design pressure or a vacuum condition is normally the dominating and governing load. Self-weight and support conditions should also be considered.

Evaluation of potential accidental loading, such as dropped object or fishing gear snagging, should be made.

3.4 Resistance

Reference is made to Section 3.7 Design criteria of this RP.

3.5 Limit states and failure modes

The following limit state categories are defined:

- Serviceability Limit State (SLS) corresponding to criteria limiting or governing for the normal operation (functionality) of the separator.
- Ultimate Limit State (ULS) corresponds to the maximum structural resistance before failure.
- Accidental Limit State (ALS) is an ULS, but consider infrequent (accidental) load.
- Fatigue Limit State (FLS) is an ULS condition accounting for accumulated cyclic load effects.

The present RP covers ULS only, which is defined as the limit state corresponding to the maximum load carrying capacity. In principle, SLS, ALS and FLS also need to be checked. Generally for subsea separators in very deep waters, these limit states are unlikely to be governing. However, an evaluation of potential dropped objects or other rare events should be evaluated related to ALS. Fatigue due to environmental loading is normally not an issue, however, potential fatigue of particular structural components and interfaces to pipes due to variation in operational loads or VIV should be considered if relevant.

Several failure modes may be relevant for the ULS. The Design by Analysis – Direct Route of EN 13445-3 Appendix B describes the following:

- Gross Plastic Deformation (GPD)
- Progressive Plastic Deformation (PD)
- Instability (I)
- Fatigue failure (F)
- Static equilibrium (SE).

The most critical design check for structures covered by the present RP is identified to be gross plastic deformation or instability, which in both cases leads to collapse of the subsea separator. It is the ability to sustain the external (static) pressure load that is governing, and this depends essentially on the actual compressive yield strength in the hoop direction and the initial ovality of the separator. (Ref. OMAE 2003-37219) If the separator is built from plate, an evaluation of the actual compressive yield strength in the circumferential direction of the separator is recommended. This must be carried out through un-axial compressive tests with round bar specimen (i.e. not flattened).

Progressive plastic deformation and fatigue do normally need to be evaluated since the load is completely dominated by the static head. Static equilibrium relates to stability of the separator as a unit when installed. In this context the support conditions of the separator are relevant, which is outside scope of the present RP. However, a compatible and proper interface with the support structure design must be ensured. These design checks are not further considered in this RP.

3.6 Calculation methods

Several calculation methods may be applicable according to EN 13445-3; i.e. design by formulae, design by analyses, design by fracture analysis or design by experimental methods. The present RP focuses on the use of design by analysis as an alternative, or as a complement to design by formulae.

At more ordinary water depths, existing practice, e.g. using the design by formulae (DBF) methodology in EN 13445-3, may provide feasible solutions. For deep water locations the design by analysis (DBA) approach provides consistent means to achieve more optimal designs with acceptable reliability. The design philosophy as focused on in this RP may also be utilised for ordinary water depths.

3.7 Design criteria

3.7.1 General

The vessel shall be designed according to a recognised design code. This RP focuses on use of the PED harmonised standard EN 13445 Unfired Pressure Vessels.

EN 13445 Part 3 describes three different design methods; one method for design by formulae (DBF), and two methods for design by analysis (DBA).

EN 13445 Part 3 Annex B Design By Analyses – Direct route is the method that has been in focus during the development of this RP. A non-linear analysis is carried out, taking into account the geometrically imperfections and a non-linear material model used. The relevant failure mode is simulated in the analysis. This Annex B describes a method for design which is an alternative to DBF or DBA-Annex C of EN 13445-3. Annex B may also be a compliment to DBF for load cases that is not covered by that route, for load combinations not covered by DBF and for cases where the manufacturing tolerances are exceeded.

DET NORSKE VERITAS
EN 13445-3 Annex C, Design by Analysis/Stress Categorisation covers the same principles for design as the principles found in ASME VIII Div. 2 Appendix 4. A linear analysis is basis for this approach, and the actual failure mode is therefore not physically simulated as accurately as using Annex B. The stress categorisation route can also be rather cumbersome in some cases. This RP does not give any guidance on how to apply Annex C.

**Guidance note:**

It is found that for shells subjected to external load, the use of Annex B will result in less required shell wall thickness compared to other design methods or codes. One reason is that the partial safety factor when using DBA for pressure loading $\gamma_P$ may be set equal 1.0, since external pressure is an action with a natural limit. The effective safety factor following the DBF route is higher.

---end-of---Guidance---note---

### 3.7.2 Guidance for EN 13445-3, Annex B

Finite element analysis shall be carried out using recognised and well documented software for analysis of non-linear response with the capability of including the possible weakening effect of geometrically non-linearity, ref. Chapter B.7.1.

**Guidance note:**

Different element types may be used. The use of 8-noded shell elements is a recommended alternative, modelled in the mid-plane of the wall thickness. The number of elements around the circumference may typically be in the order of 40. Assumptions of symmetry may be employed if relevant.

---end-of---Guidance---note---

The designer shall perform sensitivity studies to ensure that the choice of element type and mesh density is appropriate. The analysis thickness should be used (ref. EN 13445-3 Figure 3-1; i.e. defined as the nominal thickness minus the tolerance and corrosion (or erosion) allowance. In general no structural strength shall be attributed to the cladding, however, exemption to this may be made in special cases as indicated in EN 13445-3 Annex B.7.3.

The minimum required wall thickness for a vessel subjected to external pressure is normally found by the design checks Gross Plastic Deformation (B 8.2) or Instability (B 8.4). The applicable constitutive material law depends on the design check. For Gross Plastic Deformation and Instability, a linear-elastic ideal-elastic plastic law applies.

**Guidance note:**

The finite element model shall include initial out-of-roundness, implemented as a perfectly elliptic shape. The out-of-roundness is to be calculated as the difference between the largest and the smallest diameter divided by the mean diameter, which is equivalent to the deviation from the mean radius divided by the mean radius. In case the vessel is found to have out of roundness greater than this after manufacturing, the analysis shall be re-calculated with the new geometry input.

**Guidance note:**

An initial out of roundness of 0.5% is considered to be a realistic value for use in design; however, a lower (or higher) value may be used depending on the precision of the manufacturing process. In any case it needs to be verified that the final product is within the applied value.

EN13445-3 Annex D and E may be used to determine out of roundness measures. Local deviations from the design shape does not need to be modelled, but should satisfy the requirements of Annex D. Ovality (departure from the true circle of cylinders) shall be included in the finite element model along the full length of the separator. The modelled ovality shall be equal to, or greater than, the value obtained from measurements made according to Annex E.

---end-of---Guidance---note---

Usually the applied pressure on a shell finite element model refers to the mid plane diameter. The results in terms of pressure capacity from the finite element analysis shall then be corrected for the difference in diameter of the finite element model (mid plane diameter) and the real vessel outside diameter. A scaling factor equal to MD/OD ((Mid plane Diameter)/(Outer Diameter)) applies to the FE result. The external pressure acts on the outer surface which is greater than the modelled mid plane surface.

Most finite element software utilise von Mises yield criterion and this is accepted as long the difference between Tresca and von Mises yield condition is taken into account. Tresca yield condition, ref. Chapter B.7.4, shall be accounted for by reducing the material strength parameter by a factor $\sqrt{3}/2$ in the failure mode Gross Plastic Deformation Design Check (GPD-DC).

**Guidance note:**

Although the EN code states that this factor is to be applied to the material strength parameter, it is considered conservative and appropriate to apply this factor to the capacity itself. In cases when the elastic buckling capacity is important for the ultimate capacity, a certain reduction in the yield stress (material strength parameter) will not lead to a comparable reduction in the capacity, hence the difference between Tresca and von Mises may be underestimated.

---end-of---Guidance---note---

It is possible to adopt the partial safety factors for testing also for operation/design, ref. EN 13445-3 Annex B.7.5.1. However, due to the limited experience from design and operation of subsea separators at great depths, the partial safety factors in EN 13445-3 Annex B Table B.8-1 and Table B.8-2 should be used.

The partial safety factor $\gamma_R$ may be set at 1.0 for external pressure, as found in Table B.8-1. Internal overpressure shall have a partial safety factor $\gamma_R$ equal 1.2. The design strength parameter $R_{MD}$ is calculated by RM divided by $\gamma_R$ as found in Table B.8-2.

The design check Instability (EN 13445 Annex B.8.4) may become the dimensioning design check for wall thickness, at least if the separator is not subjected to tests as called for in EN13445-5 with external pressure. The partial safety factor $\gamma_R$ shall be 1.5 if the tests can not be performed, with tests a value of 1.25 applies.

The design shall, in principle also be subjected to the three remaining design checks Progressive Plastic Deformation (B.8.3), Fatigue (B.8.5) and Static Equilibrium (B.8.6). These may not be relevant or dimensioning, see also discussion in Section 3.5.

---end---of---Guidance---note---

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---
4. Materials

4.1 Application

The requirements in this section are applicable for the base material only. For manufacturing of the clad steel material, consisting of the backing material and a thinner layer cladding metal, reference is given in Section 5, “Fabrication, testing and inspection of clad steel plates”.

4.2 Normative references

The requirements in this section are supplementary to EN 13445. In case of conflict between EN 13445 and the requirements stated in this section, the most stringent shall apply.

4.3 General requirements

4.3.1 Type of materials

The base material shall be carbon-manganese (C-Mn) steel with maximum SMYS of 555 MPa, or ferritic-austenitic (duplex) stainless steel type 22 Cr or type 25 Cr. The selected base material shall be intended for pressure vessel applications. When possible, it is recommended to use one of the steels in EN 10028 modified as per this document.

4.3.2 C-Mn steel with SMYS > 555 MPa

C-Mn steels with SMYS > 555 MPa are not covered by this document. If applicable, qualification according to DNV-RP-A203, Qualification Procedures for New Technology, is recommended. The qualification testing should be based on fracture mechanics testing under simulated operational conditions.

4.3.3 Corrosion

Resistance towards external corrosion and Hydrogen Induced Stress Cracking (HISC) is covered in 6.3.

4.4 Material manufacturing

4.4.1 Manufacturing Procedure Specification (MPS)

It is required that the Contractor/manufacturer of the vessel prepares a Manufacturing Procedure Specification (MPS), see 6.4.1. This MPS shall address the important factors influencing the quality and reliability of the production. The material manufacturer shall ensure that all relevant requirements in this MPS are fully complied with.

4.4.2 General requirements

All manufacturing of plate shall be performed following the sequence of activities and within the agreed allowable variations of the qualified MPS. The manufacturing practice and the instrumentation used to ensure proper control of the manufacturing process variables and their tolerances shall be described in the MPS.

The following requirements shall apply for the manufacturing:

- the mill shall have proper control of start and finish rolling temperature, rolling reduction and post-rolling cooling rate (i.e. accelerated cooling)
- plate thickness shall be controlled by continuously operating devices
- heat treatment shall be controlled by calibrated temperature measuring devices
- plate edges shall be cut back sufficiently after rolling, to ensure freedom from defects.

---end-of-Guidance-note---

Stiffeners must be attached in such a way that they add/increase capacity for critical failure modes. When designing for the failure mode instability/collapse due to external pressure, outside stiffeners should be properly welded to the shell to effectively increase the resistance.

For fabrication processes which introduce cold deformations giving different strength in tension and compression, a fabrication factor, α fab, shall be determined. If no other information exists, maximum fabrication factors for a separator manufactured by the UOE or UO processes are given in Table 3-1. These factors also apply to other fabrication processes which introduce similar cold deformations such as three roll bending (TRB). The factor shall be applied to the yield strength in compression.

The fabrication factor may be improved through heat treatment, if documented.

3.8 Design details

Reference is made to EN 13445-3 Chapter 9: “Openings in shells”, EN 13445-4 Fabrication and EN 1708-1 “Recommended Weld Details”.

Guidance on specific details for separators:

<table>
<thead>
<tr>
<th>Table 3-1 Maximum fabrication factor, α fab</th>
<th>UO &amp; TRB</th>
<th>UOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>α fab</td>
<td>0.93</td>
<td>0.85</td>
</tr>
</tbody>
</table>

- nozzle to shell/head connections
- connections for internal and external stiffening rings and other attachments
- joining of lined components
- access openings: number and sizes
- lugs for lifting and transportation.
4.5 Material requirements

4.5.1 Steelmaking

4.5.1.1 C-Mn steel

All steels shall be made by an electric- or one of the basic oxygen processes. C-Mn steel shall be fully killed and made to a fine grain practice. Details and follow-up of limiting macro, as well as micro, segregation shall be given in the MPS.

For steel to be used for sour service, special attention to impurities and inclusion shape control shall be required. Details of the inclusion shape control treatment shall be given in the MPS.

4.5.1.2 Ferritic-austenitic stainless steel

As specified in 4.5.1.1. Additionally, ferritic-austenitic stainless steels shall be refined by argon oxygen or vacuum oxygen decarburization before casting.

4.5.2 Chemical composition

4.5.2.1 C-Mn steel

The chemical composition shall be agreed prior to start of production.

The chemical composition shall ensure the intended heat treatment response, and that the required mechanical properties are obtained.

The following general requirements with respect to chemical composition shall apply:

- sulphur ≤ 0.010% on cast analysis
- phosphorous ≤ 0.020% on cast analysis
- max. Carbon Equivalent, i.e. CE, shall be as specified in Table 4-1.

The carbon equivalents shall be calculated according to the equations below:

\[ CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15} \]

\[ P_{cm} = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + \frac{5B}{15} \]

It is recommended to use the latter formulae, i.e. \( P_{cm} \), for carbon-manganese steels with carbon content < 0.18%.

If sour service applies, the required modifications in ISO 15156 shall be fulfilled.

<table>
<thead>
<tr>
<th>SMYS</th>
<th>245</th>
<th>295</th>
<th>360</th>
<th>415</th>
<th>450</th>
<th>485</th>
<th>555</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE</td>
<td>0.36</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
<td>0.39</td>
<td>0.41</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**NOTE:**

Local brittle zones (LBZs) can be formed in the HAZ of C-Mn micro alloyed steels. These areas tend to exhibit very low cleavage resistance, resulting in low CTOD values. The LBZs are associated with the sections of the HAZs that are experiencing grain coarsening. These zones have a predominantly bainitic structure, with a large amount of martensite/austenite (M/A) constituents (BI-microstructure). The M/A constituents, as opposed to ferrite/carbide aggregate such as pearlite, may have a detrimental affect on the material's toughness. This should particularly be kept in mind when selecting the chemical composition for steels with SMYS > 450 MPa. In order to improve HAZ toughness, it is essential to refine the grain size and suppress the formation of bainite with M/A constituents.

For material to be quenched and tempered, the content of hardening elements Cr, Mo, Cu and Ni shall be sufficient to obtain the desired microstructure in the centre of the component. The selected chemical composition shall have adequate hardening ability to ensure through thickness hardening of the respective component.

4.5.2.2 Ferritic-austenitic stainless steel

The chemical composition shall be agreed prior to start of production.

The chemical composition shall ensure the intended heat treatment response, and that the required mechanical properties are obtained.

If not otherwise agreed the types 22 Cr and 25 Cr duplex stainless steels shall comply with the chemical compositions specified in EN 10028-7, as applicable, with the following limitations:

- sulphur ≤ 0.020% on cast analysis
- phosphorous ≤ 0.03% on cast analysis
- \( PRE = %Cr + 3.3%Mo + 16%N \geq 40 \) for type 25 Cr.

If sour service applies, the required modifications in ISO 15156 shall be fulfilled.

4.5.3 Mechanical properties

The material selected shall have appropriate properties for all operating conditions which are reasonable foreseeable.

If the selected material specification does not specify appropriate properties, the minimum values shall be agreed with the material manufacturer and included in the MPS, see Section 6.4.1.

4.5.3.1 Strength and ductility

The selected materials should have mechanical strength vs. ductility as specified in Table 4-2 and Table 4-3.

Attention is made to the relation between yield- and tensile strength in both longitudinal and transverse direction.
4.5.3.2 Properties at elevated temperatures

If elevated temperature properties for the steel is not included in the applicable material specification the minimum values shall be agreed with the material manufacturer and included in the MPS, see Section 6.4.1. The proposed de-rating effects of the yield stress, in Figure 4-1 below, may be used as guidance for establishing elevated temperature properties.

**NOTE:** These de-rating curves are conservative compared to EN 10028.

4.5.3.3 Toughness

Minimum toughness requirements should be based on one of the following methods:

- Toughness values specified in Tables 4-1 and 4-2
- Using Method 2 in EN 13445-2, Annex B
- Fracture mechanics.

**Method a:**

The required toughness is specified as a function of the strength.

---

**Figure 4-1**

Proposed de-rating values for yield stress

---

**Table 4-2 Mechanical properties for carbon-manganese steels 1)**

<table>
<thead>
<tr>
<th>Type</th>
<th>SMYS (MPa) (T+L)</th>
<th>SMTS (MPa) (T)</th>
<th>YS (Rt0.5) UTS (Rm) Max. (σ0.2) (T)</th>
<th>Maximum Hardness (HV 10)</th>
<th>Elongation A5 min. % (T+L)</th>
<th>Charpy V-notch energy (KVT) minimum J (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>245</td>
<td>370</td>
<td>0.90</td>
<td></td>
<td>270</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>290</td>
<td>415</td>
<td>0.90</td>
<td></td>
<td>270</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>360</td>
<td>460</td>
<td>0.90</td>
<td></td>
<td>270</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>415</td>
<td>520</td>
<td>0.92</td>
<td></td>
<td>270</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>450</td>
<td>535</td>
<td>0.92</td>
<td></td>
<td>270</td>
<td>18</td>
<td>45</td>
</tr>
<tr>
<td>485</td>
<td>570</td>
<td>0.92</td>
<td></td>
<td>300</td>
<td>18</td>
<td>50</td>
</tr>
<tr>
<td>555</td>
<td>625</td>
<td>0.92</td>
<td></td>
<td>300</td>
<td>18</td>
<td>56</td>
</tr>
</tbody>
</table>

**Notes**

1) T = transverse direction, L = longitudinal direction.
2) The actual yield strength in longitudinal direction shall not exceed SMYS by more than 120 MPa.
3) SMTS in the longitudinal direction can be 5% less than the required values in transverse direction.
4) The YS/UTS ratio in the longitudinal direction shall not exceed the maximum specified value in the transverse direction by more than 0.020 for standard material, and more than 0.030 for sour service material.
5) The KVL values (when tested) shall be 50% higher than the required KVT values.
6) For thickness ≤ 40 mm the Charpy-V impact test temperature shall be T = TMDT-20°C (MDT = minimum design temperature).
   For thickness > 40 mm the Charpy-V impact test temperature shall be agreed upon.

**Table 4-3 Mechanical properties for ferritic-austenitic stainless steels 1)**

<table>
<thead>
<tr>
<th>Type</th>
<th>SMYS (MPa) (T+L)</th>
<th>SMTS (MPa) (T)</th>
<th>YS (Rt0.5) UTS (Rm) Max. (σ0.2) (T)</th>
<th>Maximum Hardness (HV 10)</th>
<th>Elongation A5 min. % (T+L)</th>
<th>Charpy V-notch energy (KVT) minimum J (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 Cr</td>
<td>450</td>
<td>620</td>
<td>0.90</td>
<td>290</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>25 Cr</td>
<td>550</td>
<td>750</td>
<td>0.90</td>
<td>330</td>
<td>15</td>
<td>45</td>
</tr>
</tbody>
</table>

**Notes**

1) T = transverse direction, L = longitudinal direction.
2) The actual yield strength in longitudinal direction shall not exceed SMYS by more than 120 MPa.
3) The YS/UTS ratio in the longitudinal direction shall not exceed the maximum specified value in the transverse direction by more than 0.020.
4) The KVL values (when tested) shall be 50% higher than the required KVT values.
5) For thickness ≤ 40 mm the Charpy-V impact test temperature shall be T = TMDT-20°C (MDT = minimum design temperature).
   For thickness > 40 mm the Charpy-V impact test temperature shall be agreed upon.
NOTE: For thickness above 40 mm the impact test temperature and/or the required impact toughness should be based on agreement. Increasing thickness requires higher toughness properties.

Method b:
Method 2 in EN 13445-2, Annex B, concerns technical requirements developed from fracture mechanics and operating experience. The method is valid for carbon-, carbon-manganese- and low alloy steels with SMYS ≤ 460 MPa, and for duplex stainless steels with thickness ≤ 30 mm.

Method c:
Fracture mechanic analyses should be performed as specified in EN 13445-2, Annex B, in method 3. This will ensure that the acceptance criteria used for Non Destuctive Testing (NDT) are adequate for a higher material utilisation. Possible problems related to NDT of thick plate will be easy to solve since the maximum allowable defect size will be determined by the analysis. Ultrasonic testing must be specified since X-ray testing cannot be used to determine defect height. The uncertainty in sizing and probability of detection must be established (this may be time consuming and costly). Method 3 is applicable for all steels covered by this document.

Method 3 will include fracture toughness Crack Tip Opening Displacement (CTOD) testing (that takes through thickness variations into account) to provide data that can be used to determine calculate NDT acceptance criteria and impact test criteria.

CTOD testing shall be carried out at minimum design temperature.

4.6 Material testing

The mechanical and corrosion testing shall include the testing shown in Table 4-5 as applicable.

All tests shall be performed as specified in the selected material specification if not otherwise specified in the MPS.
If neither the material specification nor this document or the MPS, specify sampling, test methods, the testing should be based on recognised standards, e.g. ISO-, EN, ASTM standards.

NOTE: The tensile test, impact tests, hardness tests, pitting corrosion test and metallographic examination shall be performed by the material manufacturer. The remaining tests shall be performed by the material manufacturer or by the contractor. If not otherwise agreed it is in the responsibility of the contractor.

4.6.1 Chemical analysis

The steel shall be subject to both heat analysis and product analysis as follows:
— heat analysis shall be carried out on each melt
— product analysis shall be performed on one randomly selected plate from each test unit.

The chemical analyses shall be performed as specified in the selected material specification, if not otherwise specified in the MPS.

The content of the following elements shall be determined and reported: C, Mn, Si, P, S, Cu, Ni, Mo, Cr, Al, Nb, V, Ti, N, B. Other elements for controlling the material properties may be added, subject to agreement. When scrap material is being used for production of C-Mn steel, the content of the elements As, Sb, Sn, Pb, Bi and Ca shall be checked once during MPQT, see 6.4.2, and reported. Limitations on amount of scrap metal shall be stated in the MPS.

If the value of any elements at the product analysis, or combination of elements fails to meet the requirements specified by the MPS, a re-test consisting of two specimens shall be made.

The re-test specimens shall be sampled from two additional plates from the same heat. If one or both re-tests still fail to meet the requirements, the heat should be rejected.

4.6.2 Mechanical testing

The mechanical testing shall be carried out on each separately rolled plate and shall as minimum contain:
— tensile testing transverse to rolling direction
— one set of Charpy V impact testing in transverse to rolling direction with notch perpendicular to the surface.

The mechanical testing shall be performed as specified in the selected material specification, if not otherwise specified in the MPS.

NOTE: In 4.3.1 it is specified that steels selected shall be intended for pressure vessel applications. It is therefore assumed that the test sampling is convenient. If any doubt, the test sampling should be especially checked and considered for each material specification / material data sheet.

Table 4-4 Mechanical- and corrosion testing

<table>
<thead>
<tr>
<th>Type of test</th>
<th>C-Mn steel</th>
<th>Duplex steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test</td>
<td>Mandatory</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Charpy V-notch test</td>
<td>Mandatory</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Hardness test</td>
<td>Mandatory</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Fracture toughness test</td>
<td>3)</td>
<td>3)</td>
</tr>
<tr>
<td>Strain ageing test</td>
<td>4)</td>
<td>4)</td>
</tr>
<tr>
<td>Weldability testing</td>
<td>5)</td>
<td>5)</td>
</tr>
<tr>
<td>SSC test</td>
<td>6)</td>
<td>6)</td>
</tr>
<tr>
<td>Pitting corrosion testing</td>
<td>NA</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Metallographic examination</td>
<td>NA</td>
<td>Mandatory</td>
</tr>
</tbody>
</table>

Notes:
1) All testing shall be performed in accordance with 4.6, if not otherwise specified in the MPS.
2) Shall be performed under the responsibility of the material manufacturer and included in Type 3.2 Material Certificate.
3) The contractor. shall specify whether this test (CTOD-testing) is relevant or not, see 6.6.2.8. If relevant, the contractor. shall specify whether the test shall be carried out under the responsibility of the material manufacturer or the contractor.
4) The contractor. shall specify whether this test is relevant or not, see 6.6.2.9. If relevant, the contractor. shall specify whether the test shall be carried out under the responsibility of the material manufacturer or the contractor.
5) The contractor. shall specify whether this test is relevant or not, see 6.5.2.7. If relevant, the contractor. shall specify whether the test shall be carried out under the responsibility of the material manufacturer or the contractor.
6) The contractor. shall specify whether this test is relevant or not, see 6.4.4. If relevant, the contractor. shall specify whether the test shall be carried out under the responsibility of the material manufacturer or the contractor.
7) Mandatory for duplex stainless steel, type 25 Cr. If applicable for type 22 Cr, the test conditions shall be agreed upon.

4.6.3 Hardness test

Hardness testing is required. Unless sour service is specified, the hardness shall comply with Table 4-1 and Table 4-2, as applicable.

If sour service is relevant the acceptance criteria shall be as specified in ISO 15156.

4.6.4 SSC test

If sour service is applicable, Stress Sulphide Cracking (SSC) test is required unless the material is listed in ISO 15156.
When applicable, the test should be carried out according to ISO 15156.

4.6.5 Pitting corrosion testing
Corrosion testing according to ASTM G48, method A, shall be performed in order to confirm adequate manufacturing procedures affecting the microstructure of ferritic-austenitic stainless steel, type 25 Cr.

The maximum allowable weight loss is 4.0 g/m² for solution annealed material tested 24 hours at 50°C.

4.6.6 Metallographic examination
Metallographic examination shall be conducted at 400X magnification for ferritic-austenitic (duplex) stainless steels. The material shall be essentially free from grain boundary carbides, nitrides and inter-metallic phases. The ferrite content shall be measured according to ASTM E562. The ferrite content shall be within the range 35-55%.

4.6.7 Re-testing
If one of the tests fails to meet the requirements, two additional re-tests shall be performed on samples taken from the same test unit. Both re-tests shall meet the specified requirements. The test unit shall be rejected if one or both of the re-tests do not meet the requirements.

4.7 Non-destructive testing and workmanship

4.7.1 General
Non-destructive testing shall be performed as specified in Table 4-5.

4.7.2 Visual examination and workmanship
Full visual testing, i.e. 100%, on both sides of the plates is required. The visual inspection shall be carried out as specified in the selected material specification.

4.7.3 Ultrasonic examination
Full ultrasonic testing, i.e. 100%, of plates for laminar imperfections is required. The visual inspection shall be carried out as specified in the selected material specification.

4.7.4 Repair of defects
Surface defects may be repaired as specified in the selected material specification. Repair welding is not permitted.

NOTE: Surface grinding may introduce cold working and hardness inconsistencies with the service requirements, i.e. sour service. In such cases, hardness testing may be required in order to permit grinding.

<table>
<thead>
<tr>
<th>Table 4-5 Non-destructive testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of test 1)</td>
</tr>
<tr>
<td>Visual inspection</td>
</tr>
<tr>
<td>Ultrasonic testing</td>
</tr>
</tbody>
</table>

Notes: 1) All testing shall be performed in accordance with 4.7, if not otherwise specified in the MPS.

4.8 Material certification
The base materials shall be delivered with type 3.2 inspection documents according to EN 10204.

NOTE: Type 3.1 inspection document according to EN 10204:2004 may be accepted provided there are no doubt that the applicable requirements for inspection documents in the Directive 97/23/EC are fulfilled, ref. the Directive 97/23/EC Annex I Ch. 4.3 and PED Working Group “Pressure” Guideline No. 7/2.

5. Fabrication, Testing and Inspection of Clad Steel Plates

5.1 Application
The requirements in this section are applicable for fabrication of clad steel plates when carbon-manganese steel is the base material.

5.2 Normative references
The requirements in this section are supplementary to EN 13445. In case of conflict between EN 13445 and the requirements stated in this section, the most stringent shall apply.

5.3 Manufacturing of clad steel materials

5.3.1 Manufacturing Procedure Specification (MPS)
It is required that the contractor of the vessel is preparing a Manufacturing Procedure Specification (MPS), see 6.4.1. This MPS shall address all factors which are influencing on the quality and reliability of the production. The clad steel plate manufacturer shall ensure that all relevant requirements in this MPS are fully complied with.

5.3.2 General requirements
Clad steel materials can be manufactured by any manufacturing process which guarantees a metallurgical bond between the base metal and the cladding. The cladding material shall be selected based on the corrosion resistance required by the internal environment. Materials selection for cladding, the associated hardness criteria, and requirements to manufacturing and fabrication shall comply with NACE MR0175/ISO 15156 (latest edition). The same applies to welding consumables for weldments exposed to the internal fluid.

Overlay welding should be carried out in minimum two passes to control substrate dilution and total cover of the backing steel.

The cladding thickness shall not be less than 2.5 mm.

5.3.3 Qualification of cladding procedure
Before cladding commences the cladding procedure shall be qualified. The procedure should be qualified according to EN 13445-2, Annex C. Additionally, one extra tensile test of the clad metal is required to prove an elongation after fracture A₅ of at least 12%.

The required tests are specified in Table 5-1. Alternative cladding procedure qualification tests may be used provided equivalency.

5.4 Fabrication testing

5.4.1 General
Methods and procedures for mechanical- and corrosion testing shall be according to recognised industry standards, if not otherwise specified in 5.4.2 to 5.4.8 or in the MPS.

The mechanical- and corrosion testing shall include the testing
shown in Table 5-1 as applicable.

<table>
<thead>
<tr>
<th>Table 5-1  Fabrication tests of clad steel plates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of test</strong></td>
</tr>
<tr>
<td>Tensile test</td>
</tr>
<tr>
<td>Charpy V-notch test</td>
</tr>
<tr>
<td>Hardness test</td>
</tr>
<tr>
<td>Metallographic examination</td>
</tr>
<tr>
<td>Shear strength test</td>
</tr>
<tr>
<td>Bend test</td>
</tr>
<tr>
<td>Pitting corrosion test</td>
</tr>
<tr>
<td>Ultrasonic examination</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) All testing shall be performed in accordance with 5.4 if not otherwise specified in the MPS.</td>
</tr>
<tr>
<td>2) The contractor shall specify whether this test is relevant or not.</td>
</tr>
</tbody>
</table>

5.4.2 Tensile test

One set of tensile tests is required for each plate. One set of tensile tests consists of two tensile tests as follows:

— One test from the full clad plate which is to have a tensile strength \( R_m \) not less than derived from the following formulae:

\[
R_m = \frac{S_1 R_{m1} + S_2 R_{m2}}{S} \text{ (N/mm}^2\text{)}
\]

- \( R_{m1} \) = min. tensile strength of base material
- \( R_{m2} \) = min. tensile strength of cladding metal
- \( S \) = nominal thickness of the clad plate \( (S_1+S_2) \)
- \( S_1 \) = nominal thickness of the base metal
- \( S_2 \) = nominal thickness of the cladding metal

— One test of the base metal after removal of the cladding metal. The test is to satisfy the requirements for the base material.

Tensile test pieces are to be of the flat type. The test pieces are normally to have the full thickness of the plate. Where the thickness of the plate is more than 50 mm, or if necessary for the capacity of the testing machine, the thickness of the test piece may be reduced by machining. On single clad plates, both sides of the test piece are to be machined to maintain the same ratio of cladding metal to base steel as in the plate, but the cladding metal does not need to be reduced to less than 3 mm.

**NOTE:** In the case of clad steels where the cladding has lower ductility than that of the base metal, a tensile test on the cladding after the base has been removed shall show an elongation after fracture \( \Delta A \) of at least 12%.

5.4.3 Impact testing

Impact testing is required. The testing shall be carried out according to EN 13445-2, Annex C.

The impact test results shall comply with the requirements for the backing material.

5.4.4 Hardness testing

Hardness testing is required.

For both qualification testing and production testing the hardness measurements shall be performed as indicated in Figure 6-1.

**NOTE:** The hardness testing in the root area indicated on this Figure is not relevant.

If sour service is relevant the acceptance criteria shall be as specified in ISO 15156. Otherwise, the hardness requirements in Table 4-1 apply.

5.4.5 Metallographic examination

Metallographic examination of the weld metal and the HAZ of the cladding material shall be performed at a magnification of 400X. The microstructure shall be essentially free from grain boundary carbides, nitrides and inter-metallic phases.

5.4.6 Bend tests of cladding

The bend test pieces are to be bent 180°C round a former without showing signs of cracking or loosening of cladding metal from the base material. The diameter of the former is to be twice the plate thickness when the tensile strength of the plate is less than 490 MPa, and three times the thickness of the plate when the tensile strength is more than 490 MPa. Two bend tests are to be taken from each plate. On single clad plates, one test is to be bent with the cladding in tension and the other with the cladding in compression. On double clad plates, the test pieces are to be bent, so that both cladding metals are tested both ways.

5.4.7 Shear strength of cladding

One shear strength test is required from each plate. The test shall be carried out according to ASTM A 264, or another recognised standard. The shear strength shall be at least 140 MPa.

5.4.8 Pitting corrosion test

Pitting corrosion testing may be considered to confirm that the cladding process or a subsequent heat treatment has not affected the corrosion resistance of the cladding material. For this purpose, ASTM G48 method A, e.g. 24 hours at 50°C, of specimen machined from the cladding is adequate.

The test piece shall be machined to remove the carbon steel portion and are to contain the full weld and any heat affected zone in the corrosion resistant alloy.

5.4.9 Re-testing

If one of the tests fails to meet the requirements, two additional re-tests shall be performed on samples taken from the same test unit. Both re-tests shall meet the specified requirements. The test unit shall be rejected if one or both of the re-tests do not meet the requirements.

5.5 Non-destructive testing and workmanship

5.5.1 General

Non-destructive testing shall be performed as specified in Table 5-2.

5.5.2 Inspection and tolerances

EN 13445, Annex C, applies.

5.5.3 Surface crack examination

Full surface crack examination, i.e. 100%, of the cladding is required.

Crack like indications are not allowed.

5.5.4 Ultrasonic examination

Full ultrasonic testing, i.e. 100%, of clad plates to check for laminar imperfections and lack of bonding is required.

Laminar imperfections are not allowed.

Accept criteria for lack of bonding shall be based on EN 13445-2, Annex C, Ch. C.3.

5.5.5 Repair of defects

Minor surface defects and bonding defects may be repaired welded. However, the plate will be rejected without repair if:
a repair will cause a weakening of the plate
— a bonding defect exceeds 8 dm\(^2\), or several bonding defects amounting to more than 5% of the surface of the plate

5.5.6 Personnel qualifications

The personnel qualification requirements in EN 13445 applies.

**NOTE:** If the Directive 97/23/EC applies, the operator qualifications must also satisfy these criteria, i.e. qualified by a third-party organisation recognised in one of the Member State (ref. the Directive 97/23/EC Annex 1 Ch. 3.1.3).

### Table 5-2 Non-destructive testing

<table>
<thead>
<tr>
<th>Type of test 1)</th>
<th>C-Mn steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Surface crack inspection</td>
<td>Mandatory 2)</td>
</tr>
<tr>
<td>Ultrasonic testing</td>
<td>Mandatory</td>
</tr>
</tbody>
</table>

**Notes:**

1) All testing shall be performed in accordance with 4.7, if not otherwise specified in the MPS.

2) Magnetic particle examination for magnetic cladding, dye penetrant testing for non-magnetic cladding.

5.6 Inspection document

In order to prove the conformity to the applicable requirements, the manufacturer shall provide sufficient documentation. This should include, as relevant:

— material certificates of the plates
— cladding procedure
— welding procedure approvals
— welder/welding operator approvals
— non destructive testing operator qualifications
— non destructive testing reports
— destructive testing reports
— heat treatment information.

This information may be in the form of a component certificate.

6. Fabrication, Testing and Inspection of Separator

6.1 Application

The requirements in this section are applicable for fabrication, testing and inspection of subsea separators.

6.2 Normative references

The requirements in this section are supplementary to EN 13445. In case of conflict between EN 13445 and the requirements stated in this section, the most stringent shall apply.

6.3 Resistance to external corrosion and HISC

Cathodic protection

The need for application of Cathodic Protection (CP) shall be evaluated. This evaluation shall as a minimum take into consideration:

— the anticipated corrosion rate
— the design life
— external coating
— the maximum allowable wall-thickness reduction
— impact of connection to other systems.

If the outcome of such an evaluation is that CP is redundant, then CP may be omitted.

In case CP is required for corrosion control, the CP system shall be designed according to DNV RP B401, Cathodic Protection Design (latest revision).

HISC (Hydrogen Induced Stress Cracking)

CP will cause discharge of hydrogen atoms at the metal surface when this surface is in contact with seawater. Some of this hydrogen will become absorbed into the metal matrix. In combination with high tensile loads and/or high internal stresses, this hydrogen can cause Hydrogen Induced Stress Cracking (HISC) of susceptible materials. The risk for HISC can be reduced by application of a higher, i.e. less negative, anode potential than that produced by zinc-aluminium anodes. Omitting CP will eliminate the risk for HISC caused by discharged hydrogen.

If CP is not required, then no limitations on material strength are required with respect to HISC.

If CP is required, then the limitations of DNV RP B401 shall apply, i.e. maximum SMYS up to 550 MPa. This shall be required both for the welding metal and base metal. It is also proposed to include an upper limit on AYS, i.e. 650 MPa.

**NOTE:** Specific requirements for ferritic-austenitic (duplex) materials with respect to HISC are found in DNV RP F112.

Sour service

The selection of the C-Mn steel backing steel is, in ambient seawater conditions, normally not subject to any special sour service requirements. If, however, the external conditions are sour according to NACE MR0175/ISO 15156, the requirements of NACE MR0175/ISO 15156 and the supplementary requirements “S” of DNV OS-F101, shall apply for the backing steel.

**NOTE:** ISO 15156 addresses all mechanisms for cracking that can be caused by H\(_2\)S and related environments, including sulphide stress cracking, stress corrosion cracking, hydrogen induced cracking and stepwise cracking, stress-oriented hydrogen induced cracking, soft zone cracking and galvantically induced stress cracking (these terms are defined in the standard).

6.4 Manufacture of separator

6.4.1 Manufacturing Procedure Specification for separator fabrication (MPS)

Before production commences, the Manufacturer shall prepare an MPS. The MPS shall demonstrate how the specified properties may be achieved and verified through the proposed manufacturing route. The MPS shall address all factors which influence the quality and reliability of production. All main manufacturing steps from control of received raw material to shipment of finished product, including all examination and check points, shall be covered in detail. References to the procedures established for the execution of all steps shall be included.

The MPS shall be subject to agreement. The MPS should as a minimum contain the following information:

— plan(s) and process flow description/diagram
— project specific quality plan
— manufacturing process
— manufacturer and manufacturing location of raw material and/or plate
— raw material scrap content including allowable variation
— steelmaking process, casting process, alloying practice, rolling or working condition and heat treatment, including target values and proposed allowable variation in process parameters
— target values for chemical composition, including a critical combination of intended elements and proposed allowable variation from target values
— elevated temperature properties, if applicable
— forming process
— alignment and joint design for welding and production WPS

DE U G O R S K E V E R I T A S
— final heat treatment condition
— NDT procedures
— pressure test procedures
— list of specified mechanical and corrosion testing
— dimensional control procedures
— tracking procedures
— marking, coating and protection procedures
— handling, loading and shipping procedures.

For ordering of plates, and/or clad steel plates, the manufacturer must specify the relevant requirements and target values in the purchase order.

6.4.2 Manufacturing Procedure Qualification Test for separator fabrication (MPQT)

Each MPQT shall include full qualification of two plates from two different heats. The plates shall be subject to relevant cold deformation and heat treatment as specified in the MPS.

The type and extent of inspections and tests are specified in Table 6-1 and Table 6-2. The acceptance criteria for qualification shall comply with 6.5 and 6.6, and shall be specified in the MPS.

All tests shall be performed according to relevant ISO, EN or ASTM standards, unless otherwise specified in 6.4 and 6.5, or in the MPS.

NOTE: Additional testing may be required (e.g. weldability testing, analysis for trace elements for steel made from scrap, etc.) as part of the qualification of the MPS.

The validity of the qualification of the MPS shall be limited to:
— steelmaking practice
— deoxidation practice
— grain refining practice
— heat treatment
— material grade
— cladding procedure
— forming procedure (of vessel)
— fabrication facilities (for the vessel).

If one or more tests in the qualification of the MPS fail to meet the requirements, the MPS shall be reviewed and modified as necessary, and a complete re-qualification performed.

6.4.3 Plate forming

Relevant parts of EN 13445 apply.

The level of cold deformation shall be calculated and reported in the MPS.

6.4.4 Welding

Welding procedures, welding personnel, handling of welding consumables and the execution and quality assurance of welding, shall meet the requirements of EN 13445-4 and EN 13445-5.

Welding procedure qualification testing shall comply with EN ISO 15614-1, plus additional testing as specified in EN 13445-4, Ch.7.3 (Edition 2002).

Unless sour service applies the qualified welding procedure shall be limited to maximum hardness according to Ch.4, Table 4.2, for carbon-manganese steels. For duplex steels the maximum hardness shall be limited to 350HV10.

If sour service applies, maximum hardness shall comply with ISO 15156.

NOTE: For deep water applications the high water pressure may affect the formation and absorption of hydrogen. This may imply that using existing experience from more shallow water application of C-Mn steels in seawater under CP is non-conservative, and that additional margins in the specified maximum yield strength and hardness should be included.

6.4.5 Heat treatment

It is assumed that subsea separators fabricated from C-Mn steels will be heat treated after forming and welding.

If clad plates are used, the heat treatment procedure shall be suitable for the base material and the clad material.

6.5 Non-destructive testing

6.5.1 General

The separator shall be non-destructively tested according to EN 13445. The required inspections are summarised in Table 6-1.

See also 6.5.2 for further details.

6.5.2 Visual inspection

The separator shall be subject to 100% visual inspection of the outside and the inside in final condition.

Conditions and acceptance criteria in EN 13445 apply.

6.5.3 Magnetic particle inspection and ultrasonic examination

The finished product shall be subjected to non-destructive testing (NDT). Requirements for personnel, methods, equipment, procedures and acceptance criteria for NDT shall be in compliance with EN 13445.

When automated NDT equipment is used for the plates, a short area at the edges may not be tested. The untested areas shall be subjected to NDT during control of the finished separator. The extent of untested areas and description of the technique, sensitivity and parameters used for testing of the pipe ends shall be included in the MPS.

6.5.4 Correction of defects

The conditions and requirements in EN 13445 apply.

6.5.5 Personnel qualifications

The personnel qualifications stated in EN 13445 apply.

NOTE: If the Directive 97/23/EC applies, the operator qualifications must also satisfy these criteria, i.e. qualified by a third-party organisation recognised in one of the Member State (ref. the Directive 97/23/EC Annex 1 Ch. 3.1.3).

Table 6-1 Type and extent of non-destructive testing in connection with manufacturing procedure, qualification testing and fabrication testing 1)  

<table>
<thead>
<tr>
<th>Type of test</th>
<th>Method 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperfections in untested areas</td>
<td>UT+ST</td>
</tr>
<tr>
<td>Longitudinal imperfections in weld</td>
<td>UT</td>
</tr>
<tr>
<td>Transverse imperfections in weld</td>
<td>UT</td>
</tr>
<tr>
<td>Laminar imperfections in plate body and in area adjacent to weld seam 3)</td>
<td>UT</td>
</tr>
<tr>
<td>External surface imperfections in weld</td>
<td>ST</td>
</tr>
</tbody>
</table>

Notes:

1) All testing shall be performed in accordance with the requirements of EN 13445.
2) UT = Ultrasonic testing
   ST = Surface imperfection testing
   RT = Radiographic testing.
   Unless tested on plate prior to forming and assembly.
6.6 Fabrication testing

6.6.1 General

Fabrication testing is required for both the formed materials and for the production welds.

6.6.2 Type of tests

The fabrication tests to be carried out are specified in Table 6-2 and are further described in 6.6.2.1 to 6.6.2.11.

The sampling and the extent of the fabrication tests are specified in 6.6.3. See also Table 6-2.

6.6.2.1 Tensile testing

Tensile testing is required for both the formed material and for the weld. For tensile testing of the weld, both cross-weld tensile test and longitudinal tensile test are required.

The tensile testing shall cover the full thickness of the formed material and of the weld.

The tensile tests shall prove compliance with the base material specification (as modified in the MPS when relevant).

6.6.2.2 Impact testing

Impact testing is required for both the formed material and for the weld. For impact testing of the weld impact testing shall be carried out both in the weld metal, fusion line and in the heat affected zone.

For the formed materials two sets of Charpy-V impact testing is required.

For the welds four sets of Charpy-V impact tests are required, i.e. two sets 2 mm below the surface and 2 sets just below the mid-thickness (alternatively, in the root area).

The impact testing shall prove compliance with the base material specification (as modified in the MPS when relevant).

6.6.2.3 Hardness test

Hardness testing is required for both the formed material and for the weld. For hardness testing of the weld the tests shall be carried out at location as specified in Figure 6-1.

Unless sour service is relevant, maximum hardness shall be in accordance with Ch.4, Table 4.1, for carbon-manganese steels.

For ferritic-austenitic steels, maximum hardness shall be in accordance with Table 4.2 for the base material, and maximum 350 HV10 for the weld metal and HAZ.

If sour service is relevant the acceptance criteria shall be as specified in ISO 15156.

6.6.2.4 Metallographic examination

For carbon-manganese steel, metallographic examination of the weld metal and the HAZ in the root area of the cladding material, shall be performed at a magnification of 400X. The microstructure shall be essentially free from grain boundary carbides, nitrides and inter-metallic phases.

For ferritic-austenitic stainless steel, metallographic examination of the weld metal root, weld metal cap, and the HAZ in the root area of the cladding material, shall be performed at a magnification of 400X. The microstructure shall be essentially free from intermetallic phases after solution treatment. The ferrite content shall be measured according to ASTM E562. The ferrite content shall be in the range 35-65% in the weld and HAZ.

6.6.2.5 Macro examination

Macro examination applies for fabrication testing of welds. The testing and accept criteria shall conform to EN 15614-1.

6.6.2.6 Bend test

Bend testing applies for fabrication testing of welds. The testing and accept criteria shall conform to EN 15614-1.

6.6.2.7 Weldability testing

Weldability testing is required if not otherwise agreed. The testing shall be carried out in compliance with EN ISO 15614-1. The weldability testing may be carried out by the material manufacturer or by the contractor. If carried out by the material manufacturer this shall be specified in the MPS and the Purchase Order.

For carbon-manganese steels with SMYS $\geq 415$ MPa, the weldability testing / documentation shall, as minimum, include weld on bead Y-groove, and also fracture toughness tests of base material and HAZ. In addition, for carbon-manganese steels with SMYS $\geq 450$ MPa, metallographic examination should be conducted to establish the presence of LBZs (Local brittle zones, see Ch. 4.5.2). The maximum and minimum heat inputs giving acceptable properties in the weld zones, with corresponding preheat temperature and working temperatures, shall be determined.

For ferritic-austenitic stainless steel, the weldability testing / documentation shall determine the effect of thermal cycles on the mechanical properties, hardness and microstructure. The maximum and minimum heat inputs giving an acceptable ferrite/austenite ratio and a material essential free from intermetallic phases shall be determined. Allowances for repair welding shall be included.

For clad steel plates, the weldability testing / documentation shall determine the effect of thermal cycles on the mechanical properties, hardness and microstructure. The range of heat inputs giving acceptable properties shall be determined. Allowances for repair welding shall be included.

6.6.2.8 Fracture toughness test (CTOD)

Fracture toughness testing is required of the base material and the weld metal.
The fracture toughness test should be carried out in general compliance with EN 13445-2 (2002) Annex B, or an equivalent method.

The measured fracture toughness of the base material and the weld metal, shall as minimum have a CTOD value of 0.20 mm when tested at the minimum design temperature.

The fracture toughness testing of the base material may be carried out by the material manufacturer or by the contractor. If carried out by the material manufacturer this shall be specified in the MPS and the Purchase Order.

NOTE: For clad steel plates, the testing shall be carried out by the contractor. The cladding material shall be removed prior to testing.

6.6.2.9 Strain ageing test

Strain ageing test is required for carbon-manganese steel if cold forming during subsequent manufacture exceeds 5%.

A test coupon shall be machined from the material. The orientation of the coupon shall be transverse to the rolling direction.

The test coupon shall be of either full or reduced wall thickness. The reduced (parallel) section of the coupon shall have a width and thickness sufficient to produce the required number of standard (full size) Charpy V-notch specimens needed for the test.

The test coupon shall be subjected to cold forming representative for that experienced by the plate during fabrication of the separator. After preparation the test coupon shall be aged at 250°C for one hour. Thereafter, the specified number of Charpy V-notch specimens shall be machined from the middle of the coupon. The orientation of the specimens shall be longitudinal to the coupon centreline, with the notch perpendicular to the surface of the test coupon.

Acceptance criteria: as specified for impact testing above.

Samples intended for strain ageing testing, if relevant, shall be taken from plates that have been subjected to the maximum cold deformation allowed.

The strain ageing test may be carried out by the material manufacturer or the contractor. If carried out by the material manufacturer this shall be specified in the MPS and the Purchase Order.

6.6.2.10 HPIC test

Hydrogen Pressure Induced Cracking (HPIC) test is required during production and qualification for sour service.

When applicable, HPIC testing during manufacturing shall be performed on one randomly selected plate from each of the three (3) first heats, or until three consecutive heats have shown acceptable test results. After three consecutive heats have shown acceptable test results, the testing frequency for the subsequent production may be reduced to one per casting sequence. The Ca/S ratio shall be greater than 1.5.

When applicable, the test should be carried out according to DNV-OS-F101, Appendix B300.

NOTE: For a material clad with an austenitic Corrosion Resistant Alloy (CRA), this testing is not considered relevant.

6.6.2.11 SSC test

If sour service is applicable, Stress Sulphide Cracking (SSC) test is required unless the material is listed in ISO 15156.

When applicable, the test should be carried out according to ISO 15156.

6.6.2.12 Re-testing

If one of the tests fails to meet the requirements, two additional re-tests shall be performed on samples taken from the same test unit. Both re-tests shall meet the specified requirements. The test unit shall be rejected if one or both of the re-tests do not meet the requirements.

If the HPIC tests during the subsequent testing fail (one test per casting sequence), three plates from three different heats of the last ten heats, selecting the heats with the lowest Ca/S ratio, shall be tested. Providing these three tests show acceptable results, the ten heats are acceptable. However, if any of these three tests fail, then all the ten heats shall be tested. Further, one plate from every heat following the initially failed heat shall be tested until the test results from three consecutive heats have been found acceptable. After three consecutive heats have shown acceptable test results, the testing frequency may again be reduced to one test per casting sequence.

NOTE: If the order consists of plates from less than three heats, testing of one plate from each heat is sufficient.

The Manufacturer shall investigate and report the reason for failure and shall change the manufacturing process if required. Re-qualification of the MPS is required if the agreed allowed variation of any parameter is exceeded.

### Table 6-2 Type of tests in connection with manufacturing procedure, qualification testing and fabrication testing

<table>
<thead>
<tr>
<th>Type of test</th>
<th>C-Mn steel</th>
<th>Duplex steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile test</td>
<td>1), 2), 3)</td>
<td>1), 2), 3)</td>
</tr>
<tr>
<td>Charpy V-notch test</td>
<td>1), 2), 3)</td>
<td>1), 2), 3)</td>
</tr>
<tr>
<td>Hardness test</td>
<td>1), 2), 3)</td>
<td>1), 2), 3)</td>
</tr>
<tr>
<td>Bend tests</td>
<td>1), 2), 3)</td>
<td>1), 2), 3)</td>
</tr>
<tr>
<td>Metallographic examination</td>
<td>1), 2)</td>
<td>1), 2)</td>
</tr>
<tr>
<td>Macro examination</td>
<td>1), 2)</td>
<td>1), 2)</td>
</tr>
<tr>
<td>Fracture toughness test</td>
<td>1)</td>
<td>1)</td>
</tr>
<tr>
<td>Strain ageing test</td>
<td>1), 4)</td>
<td>NA</td>
</tr>
<tr>
<td>Weldability testing</td>
<td>1), 4)</td>
<td>1), 4)</td>
</tr>
<tr>
<td>Pitting corrosion test</td>
<td>5)</td>
<td>1), 2), 3), 4)</td>
</tr>
<tr>
<td>HPIC test</td>
<td>1), 2), 3), 4)</td>
<td>NA</td>
</tr>
<tr>
<td>SSC test</td>
<td>1), 6)</td>
<td>1), 6)</td>
</tr>
</tbody>
</table>

**Notes**

1) Applies for the MPQT (qualification of the Manufacturing Procedure Specification)
2) Applies for fabrication testing of the production welds
3) Applies for fabrication testing of the formed plates
4) The test required may be carried out at the contractor. or at the manufacturer of the plate / clad plate. If carried out at the manufacturer of the plate / clad plate repetition of the test is not required. The contractor should specify in his purchase order and MPS if this test should be carried out by the material manufacturer or by the contractor.
5) See 5.4.8. If relevant, scope of tests to be agreed.
6) Applies for sour service if the selected material is not listed in ISO 15156.

### 6.6.3 Sampling and extent of fabrication tests

If not otherwise specified herein, the sampling and extent of fabrication tests shall be as described in EN 13445.

Methods and procedures for mechanical- and corrosion testing shall be according to recognised industry standards, and be referred to in the MPS.

### 6.7 Dimensions

The dimensional inspection shall be carried out as specified in EN 13445-5.

The acceptance criteria shall be defined in the design documentation.
6.8 Pressure testing

By pressure testing in this context is meant hydrostatic and/or pneumatic testing. Traditionally the purpose of such testing has been to verify structural integrity and leak-tightness of the pressure vessel. Additional effects from the load condition imposed by the hydrostatic pressure test have been redistribution of stresses at welded connections and corresponding beneficial effects on the mechanical properties for applicable load conditions.

Subsea separators for deepwater application are characterised by external pressure, governing the design, and heavy wall thicknesses. Furthermore, it is recognised that external pressure testing may not be practically feasible to carry out (due to size, or pressure rating for example).

It is considered possible and reasonable to confirm required capacity through comprehensive and detailed design analysis with a high degree of confidence. This should provide the substantiation and basis for omitting the external hydro-test. Such an approach requires particular focus on the manufacturing processes, i.e. welding procedure specifications to address an optimal thermal process including potential pre/post heat treatment of weldments to compensate for mechanical redistribution of stresses (normally obtained during hydro-test). In addition required efforts should be placed on defining and implementing state-of-art NDT processes as stipulated above.

It is considered reasonable to establish required confidence for leak-tightness through dedicated attention to welding procedures combined with state-of-the-art NDT as stipulated above. However, an internal pressure test (on land) to the same pressure as the external pressure during operation, alternatively a pressure rating of 1.10 times the external pressure, should be considered as means to obtain sound quality control. Additional safety factors (i.e. higher pressures) are, however, not expected to be required since the external pressure will tend to close defects while the internal pressure will tend to open the same.

Guidance note:
The value of 1.10 is selected in accordance with the EN 13445-5 section 10.2.3.3. The departure from the conventional standard hydrostatic test with a factor of 1.43 on the maximum allowable pressure is justified based on the last two paragraphs of EN 13445-5 section 10.2.3.3, where a value between 1.0 and 1.25 is indicated. Note that the external pressure is practically a deterministic value, and deserves a lower safety factor than e.g. the internal pressure for operational conditions. Note also that vacuum is the lower bound of internal pressure, which is not realistic in practice at any circumstances for a subsea separator in very deep water.

---end-of-Guidance-note---

6.8.2 Internal over-pressure
6.8.2.1 Structural failure
This should be tested on land, and be dependant on the design pressure versus the external pressure as criteria for defining the different levels that may be used. Basically this should constitute a pressure giving the same hoop stress utilisation as for a design condition with a certain safety margin

6.8.2.2 Leakage
Essentially same as for 6.8.1.2 Leakage. In this case the test pressure from EN 13445-5 should be applied directly; i.e. 1.43 (or other depending on temperature) times the maximum allowable (internal) pressure.

6.8.3 Conclusion – pressure testing
— It should be possible to avoid an external pressure test of a separator given that a capacity model is developed considering, in particular, the influence of out of roundness and residual stresses in very thick pipe wall.
— Any leakage from exterior will be better tested by an internal overpressure test which will tend to open defects rather than close them.
— The internal pressure test can be performed on land to a stress stage a certain factor higher than during design condition in place.
— Metal and other seals needs to be designed for the dominating external pressure, and adequate means to qualify such items, and confirm their adequacy for a particular application will be required. It is envisaged that this can be accomplished through relevant scaled testing.
— For water depths where it is not obvious if the internal or the external pressure is governing, the highest test pressure from either 6.8.1.2 Leakage or 6.8.2.2 Leakage shall be applied.

6.9 Inspection documents
The following documentation is required for formed and welded products which form part of the pressurised part of the subsea separator:
— test report from testing of production welds
— the original material certificates
— formed product test coupon results
— type and record of heat treatment
— markings.

7. Certification Process

7.1 Introduction
Subsea separators are generally considered as important and critical components due to the consequences in cases of any type of failures.

Subsea separators will therefore be subject to the highest certification category.

Independent certification body will be required.

The Certification Body should normally be appointed by the client.

7.2 Certification procedures
Certification procedure by the certification body should include the following activities as a minimum:

Design:
— design approval based on specified design condition, performed risk analyses and procedures for manufacturing and testing
— the design approval normally to be documented by a Design Verification Report.
**Fabrication activities:**

- pre-production meeting prior to start of fabrication in order to review the quality plan for fabrication and testing
- review and approval of fabrication and testing procedures
- follow-up visits during fabrication and testing
- review of fabrication and test records
- witness the final testing (internal testing and/or any external pressure testing) and load testing, if applicable.

Extent of survey may be decided on the basis of manufacturers QA/QC system, manufacturing survey arrangement and type of fabrication methods. The hold- and check-points during fabrication and testing should be agreed when the quality plan established by the manufacturer is reviewed in the pre-production meeting.

However, the independent survey shall not be accepted based on the QA/QC system established by the manufacturer alone.

After final inspection and testing, the Certification Body shall issue a ‘Certificate of Compliance’ for the separator covering the design, fabrication and testing.

**Guidance note:**
National Authorities might have specific requirements regarding the entity that is accepted used as independent Certification Authorities, and for certification processes etc. Extract from PED concerning the applicable certification procedure which will be applicable for Subsea Separators to be installed on an European Continental Shelf is outlined in Appendix B to this RP.

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### 7.3 Documentation requirements

The following documents reflect what typically should be submitted to the Certification Body by the “manufacturer”:

**Design Documentation (for review and approval):**

- technical data sheets for the separator
- project specification, pressure vessel class/category/module
- general arrangement drawing of the separator
- hazard analyses performed by the “manufacturer” for items to be taken into account for the design, manufacture and testing
- design pressure (internal and external) and max/min design temperature external nozzle loads
- environmental loading caused by e.g. forces due to current on the sea bed, load during operation and accelerations during transport as applicable
- accidental loading caused by e.g. earthquake-, explosion-, blow-out, anchor handling and any other objects which might hit the separator externally as applicable.

**Dimensional drawings (as far as applicable, the following items should be stated):**

- fabrication drawings of pressure retaining parts showing weld details and attachments welded to the pressure retaining parts
- welded connections
- welding procedure specifications
- attachments and supports
- bill of material with reference to material specifications for the various parts in the vessel, stating material standard, grade of material, type of material documentation
- information on heat treatment and testing of welds, extend of NDT
- hydraulic test pressure.

**Structural strength calculations report which should include the following items:**

- Structural strength calculations of subsea separator. In particular the calculation should include:
  - calculation of pressure retaining parts of the separator in accordance with applied standards/codes for the separator
  - calculation of nozzle reinforcement
  - local stresses on the shell at nozzle connection due to external nozzle loads
  - local stresses on the shell at saddles due to weight of the vessel and environmental loads
  - strength calculation of saddles
  - structural strength of lifting lugs and local stresses on the shell due to lifting loads
  - strength calculation of foundation bolts
  - fatigue assessments of the critical parts as applicable.

**Fabrication Documentation:**

- details regarding procedures for fabrication and forming
- details regarding procedures for welding, Welding Specification Procedure (WPS) and Welding Procedure Qualification Report (WPQR)
- details regarding production weld testing
- details regarding heat treatment due to forming or welding
- details regarding final strength testing of the vessel.

**The following should be checked out by the surveyor during fabrication and testing:**

- review and approval of the quality plan prepared by the manufacturer
- fabrication and forming according to approved documents
- status for approval of welding procedure qualification tests
- status for approval of welders and welding operators
- material according to approved documents and available documentation/certificates
- material traceability
- heat treatment (if performed)
- dimensional/out-of-roundness check
- qualifications of NDE operators
- qualification of NDE procedures
- quality records
- witnessing of final strength tests or load test (if applicable).

**Guidance note:**
When the separator is subject to CE-marking, the Notified Body in charge might need additional documentation from the manufacturer for the Conformity Assessment.

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### 8. Operation, Maintenance and Periodic Inspection

The design basis for separators typically requires that the vessel will operate for the design life without intervention or inspection (except for potential external ROV surveys including cathodic protection status).

The performance of the separator is, however, continuously monitored in terms of pressure, temperature, level control and to some extent quality of output - such as oil in water and water in oil for oil/water and gas separation. Another issue, which is field dependant, will be sand or solids build up, ultimately impacting the separation performance and having the potential of introducing wear mechanisms in the vessel.

These are all vital aspects that need to be carefully addressed and accounted for in design as well as fabrication and testing. Remedies under operation could, in addition to the above mentioned, typically be hydrocarbon leakage detection at vessel, and reasonably accurate means to measure solid accumulation and distribution in the vessel.
9. References

9.1 Codes and standards

DNV-OS-F101, Submarine Pipeline Systems
PD 5500 “Specification for Unfired fusion welded pressure vessels”
EN-13445-1, Unfired pressure vessels – Part 1: General
EN-13445-2, Unfired pressure vessels – Part 2: Materials
EN-13445-3, Unfired pressure vessels – Part 3: Design
EN-13445-4, Unfired pressure vessels – Part 4: Fabrication
EN-13445-5, Unfired pressure vessels – Part 5: Inspection and testing
DNV-RP-B401, Cathodic Protection Design
ISO 2394, General principles on reliability for structures
ISO 15156-1, Petroleum and natural gas industries – Materials for use in H2S-containing environments in oil and gas production – Part 3: Cracking resistant CRAs (corrosion resistant alloys) and other alloys.
EN 10028-1, Flat products made of steels for pressure purposes - Part 1: General requirements.
EN 10028-1, Flat products made of steels for pressure purposes - Part 6: Weldable fine grain steels, quenched and tempered.
ASME VIII div 2 Pressure vessels, alternative rules.

9.2 Papers and publications

Institute de Soundre, “Advanced design methodologies to exploit high strength steels for pressure equipment manufacture, Report No. 38234, dated 2001-09-19.
http://www.exxonmobil.co.im/Corporate/Newsroom/News-releases/xom_nr_040510.asp
DNV Classification Note no. 30.6 Structural Reliability Analysis of Marine Structures
APPENDIX A
SAFETY CLASS, CALIBRATION

A.1 Calibration procedure:
Calibration of partial safety factors for the collapse limit state has been performed by comparing results from a design analysis with results from a structural reliability analysis. The principle is illustrated in Figure A-1, and enables a quantification of the safety class resistance factors applicable for the different safety classes as described in 2.3.2. These factors apply to the capacity obtained using the direct route of EN 13445-3, Annex B.

![Figure A-1 Principle applied for calibration of safety class resistance factors.]

A description for Figure A-1 is given in the following:

**Design analysis:**
- select the geometry, use nominal dimensions with analysis thickness, ref. EN 13445-3 Figure 3-1
- material strength, assume yield strength (SMYS) and E-modulus.
- perform analysis to compute the characteristic pressure capacity, pc
- loop over a set of safety factors to obtain the design external pressure, pe.

**Reliability analysis:**
- Start with the external design pressure pe from the design analysis. Add an uncertainty factor (minor uncertainty for static pressure due to density and depth).
- Use the same geometry as in the design analysis, but with a probability distribution for the wall thickness. This uncertainty is rather low, with a mean value slightly higher than the nominal thickness.
- Use the yield strength distribution; assume the yield strength in the design analysis corresponds to the lower 5% fractile of this distribution. Apply uncertainty in the E-modulus. The uncertainty in E-modulus only affects the results where the elastic buckling capacity is important. For low D/t rations, this uncertainty has no effect.
- Apply a model uncertainty for the capacity calculations.
- Use PROBAN to compute the probability of failure.
- Display result in terms of probability of failure as a function of safety factor. Perform the design and reliability analysis for various geometries; i.e. D/t.

**Simplification:**
- In the ideal situation the DBA result using non-linear finite element analysis (FEA) (e.g. ABAQUS) should be applied both in the design analysis and within the reliability analysis. This is not possible due to excessive computational and programming effort, and a simplification is required.
- The second option would be to use non-linear FEA for the design analysis, and apply the response surface technique in the reliability analysis. That is to calculate the capacity by non-linear FEA for a representative grid of the random variables involved, and interpolate on these results in the reliability analysis. This would require a number of analyses per design, and is neither considered a feasible option within the project budget/scope.
- The third alternative is to replace the non-linear FEA both in the design analysis and in the reliability analysis with a simplified model that accounts for the effect of critical parameters and the defined uncertainties in an adequate way. In this case it may be acceptable that the actual capacity calculated for a particular design differ somewhat from a comparable non-linear result as long as the change in the capacity as a consequence of a change in the uncer-
ertainty parameters is reasonably well represented. Note that the calibration represents a comparison of results from a design and a reliability analysis, in which the same capacity calculation model is applied. For this reason the deviation from the actual non-linear result will be of approximately the same magnitude in both these analyses, and this deviation cancels out in the calibration of safety factors. In the present calibration this simplification has been employed, and the collapse equation for pipelines given in DNV-OS-F101 has been used. This formulation effectively accounts for the various uncertainties involved.

A.2 Limit state function:
The limit state formulation is collapse of a subsea separator due to external pressure. The formulation is given by:

\[ g(X) = X_{\text{mod}} \cdot p_{c,s} - p_{e,s} \]

Where

- \( X \) denotes the vector of stochastic variables
- \( X_{\text{mod}} \) is the model uncertainty; i.e. reflecting the ratio between the true capacity and the predicted capacity
- \( p_{c,s} \) is the stochastic collapse pressure capacity
- \( p_{e,s} \) is the (generally stochastic) external pressure

The probability of failure is calculated by integrating over the failure domain \( (g(X) < 0) \) using SORM (Second Order Reliability Method).

| Table A-1 Uncertainty modelling for the collapse limit state |
|-------------------------------------|------------------|------------------|
| Variable   | Description         | Distribution | Mean | COV |
| \( X_{\text{mod}} \)     | Model uncertainty | Normal       | 1.0  | 8%  |
| \( X_{p,e} \)     | \( p_{c,s}/p_e \)  | Normal       | 1.0  | 2%  |
| \( X_t \)         | \( t_s/t_1 \)      | Normal       | 1/(1-2CoV) | 1.04 | 2%  |
| \( X_y \)         | \( s_y/P_c \)       | Normal       | 1/(1-2CoV) | 1.111 | 5%  |
| \( X_E \)         | \( E_s/500 \)       | Normal       | 1.0  | 5%  |
| \( f_0 \)         | Ovality             | Fixed        | 1    | 0   |
| \( X_D \)         | \( (D_s-t_s)/(D-t) \)| Fixed        | 1    | 0   |

A.3 Summary of uncertainties

A brief summary of the uncertainties used in the structural reliability analysis is given in Table A-1. Subscript \( s \) indicates stochastic. For further details, reference is made to the pilot study by Hagen and Mørk (2003)

A.4 Calibration results

Based on the procedure as illustrated in Figure A-1 with the uncertainties as given in Table A-1 Uncertainty modelling for the collapse limit state, the probability of failure is calculated as a function of the safety factor. The results are given in Figure A-2, and different designs in terms of different \( D/t \) ratios have been analysed. Note that the difference in the results for different \( D/t \) ratios is due to the effect of uncertainty in the E-modulus which comes into effect only for \( D/t \) ratios greater than 20.

Here the main purpose is to quantify the difference in safety factor between safety classes, where the difference in failure probability between each safety class is assumed to be an order of magnitude. For this purpose the accuracy in the absolute value of calculated failure probability is not so critical. Using the recommended targets of \( 10^{-3}, 10^{-4} \) and \( 10^{-5} \) for consequence class low medium and high respectively, the corresponding partial safety factors from Figure A-1 are approximately 1.25, 1.35 and 1.45. Assume safety class high correspond to EN 13445-3 Annex B, the safety class resistance factors become:

- 1.0 for safety class “high” (This corresponds to EN 13445)
- 0.93 for safety class “medium”
- 0.86 for safety class “low” are obtained.

Note that the reference period for the probability of failure usually is one year, e.g. the tabulated values as given in DNV CN 30.6. In the present application the major uncertainty is practically time invariant, hence the annual probability of failure is close to the lifetime probability. For this reason it may be somewhat conservative to use the target levels as indicated in DNV CN 30.6 when considering lifetime probabilities.

![Figure A-2](image-url)  
Probability of failure versus safety factor.
APPENDIX B
DESIGN OF SUBSEA SEPARATOR
ACCORDING TO EN 13445-3 ANNEX B

The work presented in this appendix is collected from DNV report “Subsea Separator Structural Design Draft Recommended Practice”, which was commissioned by AS Norske Shell. The reason for including these results in this RP is to provide the reader with an illustrative example on how to use the Design by Analysis (DBA) methodology. Nevertheless, results from this analysis cannot be used directly by the designer. It is essential that a finite element analysis be performed for each specific design case.

B.1 Introduction
The scope of this study was to investigate if the required wall thickness obtained from DBA is lower compared to design by other codes. European Standard EN 13445-3 Annex B “Design by Analysis - Direct Route” has been the reference for DBA. This code opens for the use of finite element analysis as an alternative to design by formulae (DBF), and also DBA according to EN 13445 Annex C. EN 13445-3 Annex B may also be a compliment to DBF for load combinations not covered by DBF, and for cases where the manufacturing tolerances are exceeded. EN 13445-3 Annex C “Design by Analysis/Stress Categorisation” covers the same principles for design as the principles found in ASME VIII Div. 2 Appendix 4. The capacity of the separator vessel subjected to external pressure has been documented for Gross Plastic Deformation (GPD). It has been assumed that the final separator design, regardless of size, can be tested according to the requirements in EN13445-5 with external pressure. If this is not the case, the Instability design check (ID) may, depending on the material properties, become the most critical design check. With material properties as assumed in the present work the required wall thickness will be slightly higher with ID than that found by the GPD design check.

A number of parameters that influence the capacity of the vessel have been evaluated. These are wall thickness, Young’s modulus, yield stress, initial ovality, length/diameter (L/D) - ratio, head thickness and openings/nozzles. Furthermore, the geometry of the vessel has been varied. This was done to facilitate a comparison with other design studies, as for instance the design of a composite vessel.

It should be noted that corrosion allowance and manufacturing tolerances have not been included in this work.

B.2 Finite element model
The report describes three separator sizes; 50 000, 75 000 and 100 000 BPD. Due to the large depths at which the separator is to function, only a vessel of the smallest size is likely to meet the production and installation demands. Therefore, only the smallest size has been used in this study. For larger separator volumes very thick walls will most likely be required, preventing good control of material properties during the manufacturing process.

B.2.1 Separator geometry
The smallest vessel dimension found in /1/ (50 000 BPD) has been used as basis the calculations, with an inner diameter of ID = 2100 mm and length of L = 15600 mm.

All finite element models in this report have been generated with an initial ovality of 1%. This is twice the allowable tolerance when designing according to DBF. The rationale for use of 1% in this report is that there is little experience in manufacturing vessels with a high wall thickness. Hence it is assumed that the normal manufacturing tolerances will be exceeded when producing a separator to be installed at 3 000 m depth.

In this study initial ovality has been calculated as the difference between the largest and smallest diameter divided by the nominal diameter. The finite element geometry model was constructed with the largest/smallest diameter being 0.5% larger/smaller than the nominal diameter. In this way the initial ovality is a perfectly shaped elliptic shell. The finite element model thus has a predefined and natural way of buckling when subjected to external pressure. In order for the finite element model to produce reliable results, it is an essential requirement that it has a defined way of buckling. If the separator is modelled as a perfect (circular) cylinder, the capacity for external pressure may be over-estimated, thus leading to un-conservative results.

In a real case, the separator will not have a perfect circular shape after welding. In order to measure and analyse the welded structure, the procedures in EN13445-3 Appendix E “Procedure for calculating the departure from the true circle of cylinders and cones” and Appendix F “Allowable external pressure for vessels outside circularity tolerance” shall be applied. Special attention should be paid to the shape of vessels with high wall thicknesses after welding. All deviations from the nominal diameter of the production drawing should be evaluated, and in order to evaluate the possible reduction of capacity for external pressure, the finite element models should be updated with the real vessel shape.

The effect of cradles was not included in most of the analyses presented in this report. Cradles will increase the stiffness locally as long as they are fully welded to the shell. However, the steel weight of the separator will result in an unsymmetrical loading condition outside the cradles at the lower part of the shell. The effect of this is studied in B.4.9.

B.2.2 Material model
Material data for steel of quality P500QL2 (EN10028-6[1996]) was used in most of the analyses presented in this report, except when the effects of Young’s modulus (B.4.2) and yield stress (B.4.3) were evaluated. The choice of material in separator design situation is of course not limited to this quality only.

The specified minimum yield strength (SMYS) for P500QL2 is a function of plate thickness, see Table B-1. In the analyses the properties found for a plate thickness of 150 mm were used.

Figure B-1
Typical separator geometry.
The effect of temperature on the mechanical properties was not taken into account in any of the analyses. However, the de-rating effect of temperature must be included in a design situation.

According to EN13445-3 Annex B the material curve to be used should be linear elastic – ideal plastic, which excludes strain work hardening. Excluding strain hardening will for most applications be an assumption that gives a conservative result. However, when the failure mode is plastic collapse, ignoring strain hardening does not introduce any conservatism to the result. The plastic strain at the outer fibre at collapse is typically less than 3%. In such a case, the application of a linear elastic – ideal plastic material curve is absolutely necessary and can not be regarded as adding additional safety.

The Abaqus material input used is found in Table B-2.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>$R_{ef}$ (MPa)</th>
<th>$R_{m}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>500</td>
<td>590-770</td>
</tr>
<tr>
<td>100 mm</td>
<td>480</td>
<td>590-770</td>
</tr>
<tr>
<td>150 mm</td>
<td>440</td>
<td>540-720</td>
</tr>
</tbody>
</table>

According to EN13445-3 Annex B the material curve to be used should be linear elastic – ideal plastic, which excludes strain work hardening. Excluding strain hardening will for most applications be an assumption that gives a conservative result. However, when the failure mode is plastic collapse, ignoring strain hardening does not introduce any conservatism to the result. The plastic strain at the outer fibre at collapse is typically less than 3%. In such a case, the application of a linear elastic – ideal plastic material curve is absolutely necessary and can not be regarded as adding additional safety.

The Abaqus material input used is found in Table B-2.

<table>
<thead>
<tr>
<th>E-modulus</th>
<th>200 000 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisons ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield stress (SMYS)</td>
<td>440 MPa</td>
</tr>
<tr>
<td>Plastic strain at SMYS</td>
<td>0 (Abaqus input)</td>
</tr>
</tbody>
</table>

Von Mises yield criterion is implemented in most finite element software, and it is accepted to use as long as the difference between the Tresca and von Mises yield criteria is taken into account when calculating the allowable load. The difference between the two criteria is at maximum:

$$\sqrt{3}/2 = 1.155.$$

Since the plastic strain at collapse is low for a vessel under high external pressure, strain hardening of the material will have only marginal effect on collapse resistance. A strain of a few percent at the outer fibre is typical. Thus, compared with a material curve that includes strain hardening, the linear elastic–ideal plastic material curve is just slightly conservative when designing against external pressure.

### B.2.3 Element model

Abaqus element type S8R (8 node shell elements with reduced integration) were used for all analyses models.

The number of elements around the circumference was approximately 40, which was found to be a sufficiently fine element size. Refining the element density was found only to have marginal effect on the result, except for the increased solver time.

Cradles were not included in the FE models in this study, but must be included in a design situation.
B.2.4 Loads and boundary conditions

The finite element model was exposed to an evenly distributed external pressure load, and the load was incremented in steps of 0.001 MPa. The external pressure at the last converged increment was defined as the external pressure capacity (without safety factor).

An internal pressure of 0 bar (vacuum) was assumed for all cases with external over-pressure. The internal pressure will, however, probably never become lower than 10 bar (1 MPa).

To find the necessary wall thickness for internal over-pressure, analyses were carried out with an internal design pressure of 207 bar (20.7 MPa).

A three-plane symmetry was applied; hence only 1/8 of a model as illustrated in Figure B-3. Symmetry boundary conditions were assigned to nodes at the dividing lines between symmetry sections; i.e. no rotation about in-plane axes of the symmetry plane was allowed and neither was translation normal to the symmetry plane that defines the dividing line.

The local loads from the mass of the separator at the position of the cradles were not included in this study.

B.2.5 Software

The finite element software Abaqus 6.5-1 were used for all calculations. The models were created and meshed in Abaqus CAE and solved with Abaqus Standard static solver.

B.3 Calculation of allowable pressure

The finite element model can identify the failure mode due to elastic buckling (for high D/t) or plastic collapse (for low D/t) or a mixture of both. The load at the last increment at which convergence is achieved was used to calculate the capacity of the structure for external pressure. In this study, no solution method was implemented in order to continue the analyses past the point of collapse. If the behaviour of the shell past onset of buckling is to be studied in detail, the Riks method is one alternative.

B.3.1 Partial safety factors

Partial safety factors were applied on loads (external pressure) and on resistance (SMYS).

The partial safety factor γp for external pressure is found in EN13445-3 Annex B Table B.8-1. For actions with a natural limit (like water depth):

\[ γ_p = 1.0 \]

The partial safety factor for resistance γR is found in EN13445-3 Annex B Table B.8-2. For SMYS/Rm20 = 440 MPa / 540 MPa = 0.81, giving:

\[ γ_R = 1.5625 \cdot 0.81 = 1.27 \]

B.3.2 Calculation procedure

In a finite element model the mid plane diameter (MD) is one wall thickness larger than the inner diameter (ID) of the vessel. The external pressure is always applied to the mid plane, which is the plane of nodes of the shell elements. Subsequently, in this study the shell elements were positioned at the mid plane surface in the centre of the vessel wall. However, when a vessel is submerged in water the pressure will act at the outside diameter (OD). Because in an FE model the pressure acts on the plane of nodes, it is important to take the diameter difference into account. The allowable external pressure was thus reduced by the ratio between the two diameters, i.e. OD/MD.

There are other methods used to include the effect of the difference in diameter. Another way is to position the nodes of the finite elements at the outside surface of the vessel. In this case the loading surface will be correctly modelled, but the “stiffness” of the vessel is incorrectly represented because the diameter is larger than the nominal diameter. This would lead to very conservative estimates of the capacity.

Another option is “offset” modelling. If the software supports “offset shell elements” the nodes could be positioned at one side of the shell element (at OD) while the material of the element is positioned at correct ID and OD.

<table>
<thead>
<tr>
<th>Table B-3</th>
<th>Example of procedure for calculating allowable external pressure for a wall thickness of 100 mm and vessel inner diameter ID = 2100 mm. Partial safety factors were applied on analysis results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SMYS input in Abaqus.</td>
</tr>
<tr>
<td>2</td>
<td>Collapse pressure (from Abaqus) at last converged increment</td>
</tr>
<tr>
<td>3</td>
<td>Partial safety factor Table B.8-2 γR</td>
</tr>
<tr>
<td>4</td>
<td>Partial safety factor Table B.8-2 γp</td>
</tr>
<tr>
<td>5</td>
<td>Von Mises to Tresca conversion</td>
</tr>
<tr>
<td>6</td>
<td>Factor to reduce allowable pressure at outer diameter (OD) as a function of OD and mid plane diameter (MD) (From Table 16, initial OD and MD diameter for 100 mm wall thickness)</td>
</tr>
<tr>
<td>7</td>
<td>Allowable pressure (27.5·0.957) / (1.27·1.0·1.155) MPa</td>
</tr>
<tr>
<td>8</td>
<td>Water depth (assuming water density 1 025 kg/m³)</td>
</tr>
</tbody>
</table>

It was assumed in this study that the separator can be tested according to EN13445-5, and that the partial safety factor γR may be set to 1.25 for the Instability design check. Instability therefore did not become the dimensioning design check, and all results presented were thus a result of Gross plastic deformation (GPD). However, if the external pressure test can not be performed, the partial safety factor should be set to 1.5. Hence, Instability will be the most critical design check. The “equivalent GPD partial safety factor” is \(1.27 \cdot \sqrt{3}/2 = 1.47\); i.e. slightly lower than 1.5.

Note that the procedure described in Table B-3, differs somewhat from the procedure described in EN13445-3 Annex B, B 7.5.1. The code specifies that the partial safety factors γR shall be applied on the material strength parameter, RM, in this case the yield stress/SMYS. The resulting RM is to be used as input/yield stress in the finite element analysis. However, the procedure described in Table B-3 applies the safety factors and the Tresca/Mises factor on the finite element analysis result instead.

For elastic buckling it was found that if the factors were applied on the results, more conservative values for allowable external pressure or wall thickness were achieved. It is the opinion of the authors of this report that the conservative procedure described in Table B-3; should be used.

Hand calculations for pure plastic collapse of an infinitely long pipe were compared with the DBA results. For a very high thickness, i.e. a D/t of 13, almost the same capacity was obtained. This indicates that the plastic capacity was strongly dominating. It should be noted that the effect of the end domes was not accounted for in the hand calculations, whereas it may have a positive effect on the DBA result.
B.4 Results

Corrosion allowance and manufacturing tolerances were not included in any of the analyses.

B.4.1 Effect of wall thickness

In the capacity for external pressure is given as a function of wall thickness. The figure includes the results for DBA (green line) and DBF (blue line). The short black line shows the capacity from DBA with 4 external stiffeners. As can be seen from the results, wall thicknesses less than 120 mm are obtainable even at 3 000 m depth.

Separator geometry and material properties are given in Table B-6. The results are given in Table B-5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Wall thickness 80 mm</th>
<th>Wall thickness 100 mm</th>
<th>Wall thickness 120 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>mm</td>
<td>2100</td>
<td>2100</td>
<td>2100</td>
</tr>
<tr>
<td>Length (T/T)</td>
<td>Mm</td>
<td>15 600</td>
<td>15 600</td>
<td>15 600</td>
</tr>
<tr>
<td>SMYS</td>
<td>MPa</td>
<td>440</td>
<td>440</td>
<td>440</td>
</tr>
<tr>
<td>E-modulus</td>
<td>GPa</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Initial ovality</td>
<td>%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>mm</td>
<td>80</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Allowable ext. pressure DBA</td>
<td>MPa</td>
<td>11</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Equivalent pressure in bar</td>
<td>bar</td>
<td>110</td>
<td>180</td>
<td>250</td>
</tr>
<tr>
<td>Equivalent water depth</td>
<td>m</td>
<td>1 073</td>
<td>1 756</td>
<td>2 440</td>
</tr>
</tbody>
</table>

Figure B-4
Allowable external pressure as a function of wall thickness.
All other parameters are kept constant.
B.4.2 Effect of Young’s modulus
The effect of Young’s modulus when designing by analysis according to EN 13445-3 Annex B is illustrated in Figure B-5. Separator geometry and material properties are given in Table B-6.

Table B-6  Geometry and material properties for the model used to analyse the effect of the E-modulus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>2 000 mm</td>
</tr>
<tr>
<td>Length</td>
<td>12 000 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>120 mm</td>
</tr>
<tr>
<td>SMYS</td>
<td>440 MPa</td>
</tr>
<tr>
<td>Initial ovality of vessel</td>
<td>1%</td>
</tr>
</tbody>
</table>

Figure B-5
Effect of E-modulus on capacity against external pressure. Results from DBF are presented for comparison.

As expected the collapse capacity increased with increasing E-modulus. In general, the E-modulus becomes increasingly important with increasing D/t ratio and less important when the collapse is governed by plastic behaviour.

The capacity found by DBA is approximately 15% higher than the capacity calculated by DBF. The difference between DBF and DBA with a Young’s modulus of 200 GPa is 3.6 MPa, which corresponds to 36 bar, or approximately 350 m water depth.

B.4.3 Effect of SMYS
The effect of SMYS when designing by analysis according to EN 13445-3 Annex B is illustrated in Figure B-6. Separator geometry and material properties are given in Table B-7.

Table B-7  Geometry and material properties for the model used to analyse the effect of SMYS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>2 000 mm</td>
</tr>
<tr>
<td>Length</td>
<td>12 000 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>120 mm</td>
</tr>
<tr>
<td>E-modulus</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Initial ovality of vessel</td>
<td>1%</td>
</tr>
</tbody>
</table>
As expected the collapse capacity increased with increasing yield stress. In the present example a 25% increase in SMYS from 440 MPa gave an increase of 17% on the capacity.

**B.4.4 Effect of initial ovality**

The effect of initial ovality when designing by analysis according to EN 13445-3 Annex B is illustrated in Figure B-7.

Separator geometry and material properties are given in Table B-8.

| Table B-8 Geometry and material properties for the model used to analyse the effect of initial ovality. |
| Inner diameter | 2 000 mm |
| Length | 12 000 mm |
| Thickness | 120 mm |
| SMYS | 440 MPa |
| E-modulus | 200 GPa |
The collapse capacity decreased with increasing initial ovality. This was expected. The decrease was most significant at a relatively low ovality, e.g. less than 1%. When the ovality was increased from 0.5% to 1.0% a capacity reduction of 12% resulted. A 12% reduction of capacity approximately corresponds to a 7% increase in wall thickness.

B.4.5 Effect of vessel length

The effect of vessel length when designing by analysis according to EN 13445-3 Annex B is illustrated in Figure B-8.

Separator geometry and material properties were as given in Table B-9.

<table>
<thead>
<tr>
<th>Inner diameter</th>
<th>2 000 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovality</td>
<td>1%</td>
</tr>
<tr>
<td>Thickness</td>
<td>120 mm</td>
</tr>
<tr>
<td>SMYS</td>
<td>440 MPa</td>
</tr>
<tr>
<td>E-modulus</td>
<td>200 GPa</td>
</tr>
</tbody>
</table>

### Table B-10 Diameter and length for constant volume 50 000 BPD vessel.

<table>
<thead>
<tr>
<th>ID [mm]</th>
<th>Length [m]</th>
<th>Volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 300</td>
<td>13 600</td>
<td>63</td>
</tr>
<tr>
<td>2 100</td>
<td>16 800</td>
<td>63</td>
</tr>
<tr>
<td>1 900</td>
<td>20 900</td>
<td>63</td>
</tr>
</tbody>
</table>
Excluding cradles, supports and attachments an almost constant weight of 125 tons was found for the three vessel geometries given in Table B-10 at 3 000 m. At 1 500 m the weight was 86 tons.

The vertical part of the lines in Figure B-10 represents the burst limit state based on an inner pressure rating of 207 bar. These values were calculated by the DBF approach. Given a SMYS of 440 MPa and SMTS of 540 MPa the thicknesses for the three design geometries were found to be 92 mm, 101 mm and 111 mm. However, since these values were calculated with internal pressure as the dimensioning load, the DBF method was used. A consequence of this is that the wall thickness is governed by the SMTS. For a very high SMTS, e.g. 700 MPa, the corresponding required thicknesses will be reduced to 69 mm, 77 mm and 84 mm respectively. This effect will not be obtained with the use of DBA, since a linear-elastic ideal plastic material description is used. For this reason the DBF result may yield lower wall thicknesses than DBA for high SMTS.

By adding 4 outside stiffeners the shell thickness was reduced by 30-35 mm to approximately 112 mm, see Figure B-11. It therefore seems feasible to achieve wall thicknesses below 120 mm even for separators that are to be installed at 3 000 m depth. However, the benefit on weight due to reduced thickness was practically eliminated by the weight of the stiffeners.
No attempt was made to optimise the stiffener design. Nevertheless, a more optimum stiffener design may exist, potentially providing a slight weight reduction.

Figure B-11
Model of separator with totally four stiffeners (I-shaped). Only two stiffeners are visible in the figure, since there is symmetry about the centre of the model.

B.4.7 Effect of head thickness

The wall thickness for a semi-spherical head shape may be close to half that of the main shell when dimensioning for inner pressure. For other shapes the head walls will generally be thicker and may, depending on shell shape, be as thick as the shell.

The same is valid for external pressure. When dimensioning for external pressure, the capacity was not significantly influenced by a reduction of head wall thickness, see Table B-11 and Table B-12 below. Other head shapes were not evaluated.

<table>
<thead>
<tr>
<th>Table B-11</th>
<th>Capacity as a function of head wall thickness for D/t = 29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse pressure as function of head thickness</td>
<td>Head $t = 71$ mm</td>
</tr>
<tr>
<td>Vessel geometry: ID = 1 900 mm (OD = 2 042) L = 20 900 mm, $t = 71$ mm</td>
<td>10.247 MPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table B-12</th>
<th>Capacity as a function of head wall thickness for D/t = 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapse pressure as function of head thickness</td>
<td>Head $t = 150$ mm</td>
</tr>
<tr>
<td>Vessel geometry: ID = 2 300 mm (OD = 2 600) L = 13 600 mm, $t = 150$</td>
<td>31.118 MPa</td>
</tr>
</tbody>
</table>

B.4.8 Effect of openings

An opening will reduce the capacity of the structure unless the material that has been removed is replaced with material giving equivalent strength. In this study it was found that man ways and nozzles did not influence the buckling capacity if the man ways and nozzles had thick enough walls. However, as long as the ratio nozzle diameter / shell diameter is less than 0.3, ref. EN13445-3 Design by formulae, the thickness of a nozzle cannot be more than twice the thickness of the shell.

<table>
<thead>
<tr>
<th>Table B-13</th>
<th>Dimensions and wall thickness of openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man way</td>
<td>24” (600 mm)</td>
</tr>
<tr>
<td>Nozzles</td>
<td>4” (102 mm)</td>
</tr>
<tr>
<td>Nozzles</td>
<td>10” (254 mm)</td>
</tr>
</tbody>
</table>

In order to include the effects of end cap forces from external pressure, the man way was modelled with capped end. As long as the openings are modelled as described in Table B-13, the capacity was found to increase when openings were added. The model with openings is illustrated in Figure B-12.

<table>
<thead>
<tr>
<th>Table B-14</th>
<th>Capacity as a function of openings for a shell with ID 2300 and shell thickness $t = 150$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without any openings</td>
<td>31.1 MPa</td>
</tr>
<tr>
<td>With 4” nozzles and man way</td>
<td>31.2 MPa</td>
</tr>
<tr>
<td>With 4” and 10” nozzles and man way</td>
<td>31.7 MPa</td>
</tr>
</tbody>
</table>
B.4.9 Effect of gravity and cradle support

The finite element models used to produce the results in the previous chapters were modelled without taking mass or cradle support into account. The two factors have opposite effects on capacity for external pressure. Reaction forces from the mass will act locally at the cradle supports, and thereby reduce the capacity. The stiffness of the cradles, on the other hand, will increase the stiffness of the shell, leading to an increase in the capacity. In order to study the combined effect of the two factors, two different finite element models were compared, see Table B-15.

It was found that the collapse capacity was slightly increased when the model included cradle support, even when gravity was included. The cradle support was modelled with the same wall thickness as the separator shell, and was assumed to be fully welded to the shell.

<table>
<thead>
<tr>
<th>Table B-15</th>
<th>Comparison of models with and without gravity forces and cradle supports. Safety factors for material, Mises to Tresca conversion and the OD/MD - ratio were included.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1. Without mass and without cradle support.</td>
<td>Collapse load at last converged load increment</td>
</tr>
<tr>
<td>ID = 2 100 mm</td>
<td>23.9 MPa</td>
</tr>
<tr>
<td>L = 16 800 mm</td>
<td>and T = 95 mm.</td>
</tr>
<tr>
<td>Model 2. Including gravity forces and double thickness at cradle support.</td>
<td>24.5 MPa</td>
</tr>
</tbody>
</table>
B.5 Typical shape of vessel at time of collapse

When subjected to external pressure the thin walled structure deflected more than the thick shell before they collapse. The displacements at the time of collapse were between 6.1 mm \((t = 185 \text{ mm})\) and 23.2 mm \((t = 80 \text{ mm})\) in the inwards direction of the vessel wall. At the same time the largest diameter was increased by between 1.3 mm \((t = 185 \text{ mm})\) to 19.9 mm \((t = 185 \text{ mm})\), see Table B-16.

<table>
<thead>
<tr>
<th>Wall thickness, (t) mm</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>150</th>
<th>185</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial mid radius, smallest mm</td>
<td>1 084</td>
<td>1 094</td>
<td>1 104</td>
<td>1 119</td>
<td>1 137</td>
</tr>
<tr>
<td>Initial mid radius, largest mm</td>
<td>1 095</td>
<td>1 105</td>
<td>1 115</td>
<td>1 130</td>
<td>1 148</td>
</tr>
<tr>
<td>Initial OD/t (OD = outer diameter) ratio</td>
<td>28</td>
<td>23</td>
<td>20</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Reduction of smallest radius mm</td>
<td>23.2</td>
<td>15.7</td>
<td>10.8</td>
<td>7.7</td>
<td>6.1</td>
</tr>
<tr>
<td>Increase of largest radius mm</td>
<td>19.9</td>
<td>11.9</td>
<td>6.6</td>
<td>3.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

B.6 Effect of safety class concept

The concept of safety class was proposed in the draft Recommended Practice. It has been demonstrated that this concept complies with the PED requirements. However, a formal acceptance has not yet been obtained.

The concept is based on risk evaluation, where the basic assumption is that design according to the harmonised standard EN 13445-3 also covers design where the consequences of failure are high. If, while regarding life, environment and property, lower consequences can be documented at deep waters, a “safety class resistance factor” may be applied. This reduces the safety factor without a subsequent increase in risk, see Figure B-14.

The value of the safety class resistance factor for the different safety classes are:

- 1.0 for safety class “high” (This corresponds to EN 13445)
- 0.93 for safety class “medium”
- 0.86 for safety class “low”.

![Figure B-14 Risk Matrix](image)

The effect on design is illustrated in Figure B-15. It is seen that a reduction in wall thickness of approximately 5% or 7 mm was obtained while going from consequence class high to medium.

![Figure B-15](image)

**Effect of the safety class concept on design**

B.7 Conclusion

In this work it was found that DBA led to a reduction in wall thickness of at least 15 mm compared to DBF at a depth of 3 000 m. Furthermore, at this depth it is necessary to add stiffeners in order to the keep shell wall thickness of the separator below 120 mm. 120 mm is regarded as an upper limit for wall thickness in plates by some steel manufacturers, ref. DNV-Report 2003-1113.