IEC TS 62600-2

Edition 2.0 2019-10

TECHNICAL SPECIFICATION

colour
inside

Marine energy – Wave, tidal and other water current converters –
Part 2: Marine energy systems – Design requirements

IEC TS 62600-2:2019-10(en)

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MARINE ENERGY –
WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

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FOREWORD

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8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-2, which is a Technical Specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

This second edition cancels and replaces the first edition published in 2016. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) The first edition published in 2016 was based on design methodologies developed by TC88. The second edition sets forth design conditions unique to marine energy converters.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
114/306/DTS	114/322/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International Standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 62600 outlines minimum design requirements for marine energy converters (MECs) and is not intended for use as a complete design specification.

Any of the requirements of this document may be altered if it can be demonstrated that the overall safety of the marine energy converter is not compromised. Compliance with this document shall be done in observance of applicable regional regulations.

MARINE ENERGY –
WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 2: Marine energy systems – Design requirements

1 Scope

This document provides design requirements to ensure the engineering integrity of wave, ocean, tidal and river current energy converters, collectively referred to as marine energy converters. Its purpose is to provide an appropriate level of protection against damage from all hazards that may lead to catastrophic failure of the MEC structural, mechanical, electrical or control systems. Figure 1 illustrates the scope of this document and critical interfaces with other elements of a marine energy converter installation.

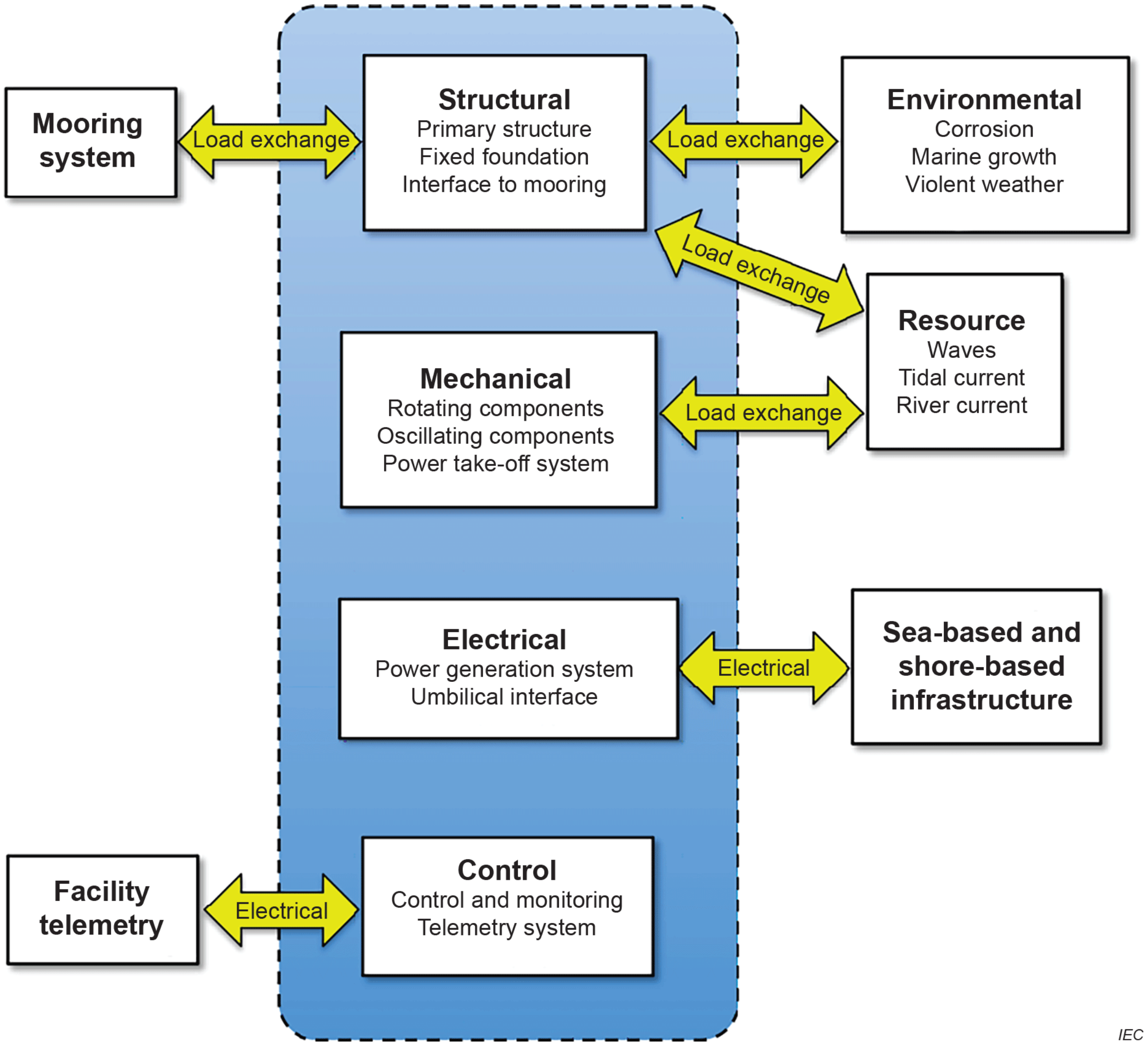


Figure 1 – Marine energy converter system boundary for IEC TS 62600-2 and interfaces

This document provides requirements for MEC main structure, appendages, seabed interface, mechanical systems and electrical systems as they pertain to the viability of the device under site-specific environmental conditions. This document applies to MECs that are either floating or fixed to the seafloor or shore and are unmanned during operational periods.

NOTE Refer to IEC 62600-10 for guidance on the design of moorings for floating MECs.

In addition to environmental conditions, this document addresses design conditions (normal operation, operation with fault, parked, etc.); design categories (normal, extreme, abnormal and transport); and limit states (serviceability, ultimate, fatigue and accidental) using a limit state design methodology.

Several different parties may be responsible for undertaking the various elements of the design, manufacture, assembly, installation, erection, commissioning, operation, maintenance and decommissioning of a marine energy converter and for ensuring that the requirements of this document are met. The division of responsibility between these parties is outside the scope of this document.

This document is used in conjunction with IEC and ISO standards cited as normative references, as well as regional regulations that have jurisdiction over the installation site.

This document is applicable to MEC systems designed to operate from ocean, tidal and river current energy sources, but not systems associated with hydroelectric impoundments or barrages. This document is also applicable to wave energy converters. It is not applicable to ocean thermal energy conversion (OTEC) systems or salinity gradient systems.

Although important to the overall objectives of the IEC 62600 series, this document does not address all aspects of the engineering process that are taken into account during the full system design of MECs. Specifically, this document does not address energy production, performance efficiency, environmental impacts, electric generation and transmission, ergonomics, or power quality.

This document takes precedence over existing applicable standards referred to for additional guidance. This document adheres to a limit state design approach utilizing partial safety factors for loads and materials to ensure MEC reliability in accordance with ISO 2394.

MECs designed to convert hydrokinetic energy from hydrodynamic forces into forms of usable energy, such as electrical, hydraulic, or pneumatic may be different from other types of marine systems. Many MECs are designed to operate in resonance or conditions close to resonance. Furthermore, MECs are hybrids between machines and marine structures. The control forces imposed by the power take-off (PTO) and possible forces from faults in the operation of the PTO distinguish MECs from other marine structures.

The document is applicable to MECs at the preliminary design stage to those that have progressed to advanced prototypes and commercial deployment. It is anticipated that this document will be used in certification schemes for design conformity.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60092-301, *Electrical installations in ships – Part 301: Equipment – Generators and motors*

IEC 60092-350, *Electrical installations in ships – Part 350: General construction and test methods of power, control and instrumentation cables for shipboard and offshore applications*

IEC 60204-1:2016, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11:2018, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for equipment for voltages above 1 000 V AC or 1 500 V DC and not exceeding 36 kV*

IEC 60228, *Conductors of insulated cables*

IEC 60364-5-54, *Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors*

IEC 60812, *Failure modes and effects analysis (FMEA and FMECA)*

IEC 61508 (all parts), *Functional safety of electrical/electronic/programmable electronic safety-related systems*

IEC 61643-11, *Low-voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power systems – Requirements and test methods*

IEC 61882, *Hazard and operability studies (HAZOP studies) – Application guide*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-201, *Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization*

IEC TS 62600-10, *Marine energy – Wave, tidal and other water current converters – Part 10: Assessment of mooring system for marine energy converters (MECs)*

ISO 2394, *General principles on reliability for structures*

ISO 12473, *General principles of cathodic protection in sea water*

ISO 17776, *Petroleum and natural gas industries – Offshore production installations – Major accident hazard management during the design of new installations*

ISO 19900, *Petroleum and natural gas industries – General requirements for offshore structures*

ISO 19901-1: 2015, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations*

ISO 19901-4*, Petroleum and natural gas industries – Specific requirements for offshore structures – Part 4: Geotechnical and foundation design considerations*

ISO 19901-6, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 6: Marine operations*

ISO 19902, *Petroleum and natural gas industries – Fixed steel offshore structures*

ISO 19903, *Petroleum and natural gas industries – Fixed concrete offshore structures*

ISO 31010, *Risk management – Risk assessment techniques*

DNVGL-OS-C301, *Stability and watertight integrity*

DNVGL-RP-C205, *Environmental conditions and environmental loads*

EUROCOMP, *Structural design of polymer composites*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 as well as the following apply.

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

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Symbols and abbreviated terms

For the purposes of this document, the symbols and abbreviated terms given in IEC TS 62600-1 as well as the following apply.

d	water depth
f	wave spectrum frequency
f_d	material property design value
f_k	material property characteristic value
f_P	wave spectrum peak frequency
f_E	elastic buckling stress
f_y	specified minimum yield stress
F_d	load design value
F_k	load characteristic value
g	gravitational acceleration
h	ice thickness with a 50-year return period
H_1	extreme wave height with a return period of 1 year
H_5	extreme wave height with a return period of 5 years
H_{50}	extreme wave height with a return period of 50 years
H_b	breaking wave height
H_{EWH}	extreme wave height
H_{OWH}	operational wave height
H_{rated}	device rated wave height
H_{m0}	significant wave height
$H_{m0,\ OSS}$	significant wave height of the operational sea state
H_{mn}	significant wave height with a return period of *n* years

I	turbulence intensity
K	turbulent kinetic energy
MEC	marine energy converter
REC	river energy converter
s	slope of beach floor
S	pseudo response spectrum
SWL	still water level
T	wave period
T_P	peak wave period
TEC	tidal energy converter
U_{bw}	breaking wave current velocity
U_{in}	cut-in velocity for a TEC
U_{rated}	device rated current velocity
U_{out}	cut-out velocity for a TEC
U_{ss}	sub-surface current velocity
U_w	wind-generated current velocity
V	10 min mean wind speed
$V_{1\text{-}hour}$	1 h mean value of wind speed at 10 m height above SWL
V_5	extreme wind speed with a return period of 5 years
WEC	wave energy converter
z	height above still water level
σ_c	ice crushing strength
σ_U	standard deviation of the current velocity
$\sigma_{U,c}$	characteristic standard deviation of mean current velocity at a specified probability distribution
γ	damping ratio
γ_f	partial load safety factor
γ_m	partial material safety factor
ω	angular frequency
λ	slenderness parameter; wave length

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the integrity and safety of the structural, mechanical, electrical and control systems of a MEC are given in the following clauses. This specification of requirements applies to the design, manufacture, installation, operation and maintenance of MECs.

A common characteristic of all MEC devices that distinguishes them from other marine devices is the requirement to determine loading and response due to interaction with power take-off (PTO) and control systems.

The design process for MECs is illustrated in Figure 2. The process is iterative and shall incorporate load and load effect calculations for the complete MEC, including the support structure, foundation or moorings, mechanical and electrical elements. The structural design of a MEC shall be regarded as completed when its structural integrity has been verified based on the limit state analyses described in Clause 7.

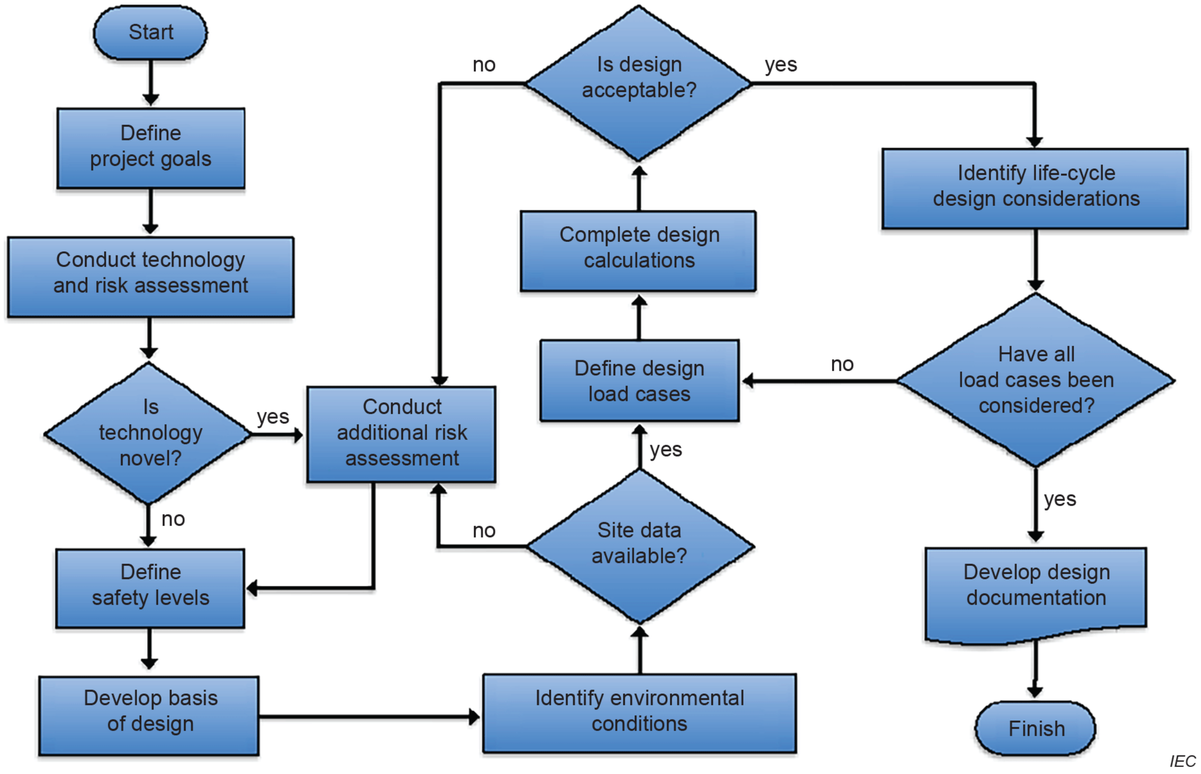


Figure 2 – Design process for a MEC

Verification of the adequacy of the design shall be made by calculation and/or by testing. If test results are used in this verification, the environmental conditions during the test shall be shown to reflect the characteristic values and design situations defined in this document.

5.2 Design objectives

Design objectives shall be established to outline the design targets and project requirements. They may include safety, integrity, environmental impact, functionality, operability, efficiency, reliability, lifecycle and availability targets. These objectives should take into account the needs of all MEC stakeholders. The design objectives should consider all phases of the project, including manufacturing, transport, installation, operation, maintenance and decommissioning.

5.3 Technology assessment

As a part of MEC technology development, a technology assessment shall be carried out. The first stage of this will be to break down the MEC technology into distinct elements or components that can be individually assessed for their maturity. This system decomposition is achieved through a structural and/or functional breakdown of the overall system into subsystems, equipment and components down to the smallest element/sub-component that can be assessed. The technology will be then assessed for two aspects:

- degrees of novelty; and
- application area.

For degrees of novelty, it is necessary to decide for each element/sub-component which category it falls into:

- verified;
- limited field history; or
- new or unverified.

For the application area, it is necessary to decide for each element/sub-component which category it falls into:

- known; or
- new.

From this, the technology class can be established using Table 1.

Table 1 – Technology classes

Application area	**Technology degree of novelty**		
	Verified	**Limited field history**	**New or unverified**
Known	1	2	3
New	2	3	4

The technology classes indicate the following levels of maturity.

a) No new technical uncertainties.
b) New technical uncertainties.
c) New technical challenges.
d) Demanding new technical challenges.

Verified technology operating in a known application is considered technology classified as Class 1. No new technical uncertainties. Verified technology shall be documented in accordance with recommended practices and relevant international standards. All other classes reflect varying levels of technology novelty.

All systems and phases (from manufacturing to decommissioning) should be considered. New technologies (Classes 2-4) have increasing degree of technical uncertainty and shall be subject to qualification in addition to traditional certification processes. Verified technology covered in Class 1 can utilize traditional certification procedures in place with third-party classification entities. Class 2 items normally require only additional design studies to mitigate the added risk. Class 3 and 4 items normally require testing in addition to design studies.

5.4 Risk assessment

The purpose of a risk assessment is to provide further information regarding technology uncertainties to support the development of the technology. While performing the risk assessment the following shall be carried out:

- definition of risks reflecting the level of acceptance of the risks to success compatible with the phase of technology development and requirements from authorities and other stakeholders;
- identify, where possible, relevant standards for components and sub-systems;
- assess maintenance, condition monitoring and possible concept modifications to reduce the risks to an acceptable level;
- define consequences and technology classes that are in line with the range of events and failures for the technology; and

- in lieu of data obtained from the specific application or the technology, the probability of the event / failure to be used during the risk assessment can be derived from relevant data from other industries, provided that an assessment of the impact of the new application in the marine renewables sector is taken into account.

A risk assessment can be done using a number of techniques such as (but not limited to):

- failure mode effects and criticality analysis (FMECA) – guidance on FMECA can be found in IEC 60812;
- hazard identification study (HAZID) and hazard and operability study (HAZOP) – guidance on HAZID and HAZOP can be found in ISO 17776 and IEC 61882, respectively; and
- structured what if technique (SWIFT), which is described in ISO 31010.

The process shall be carried out based on (but not limited to) the following:

- design objectives;
- technology assessment;
- detailed drawings of items subject to review;
- drawings and descriptions of control and safety systems;
- material specifications;
- outline of fabrication procedures;
- outline of installation procedures; and
- outline of inspection and maintenance procedures.

5.5 Safety levels

The appropriate safety level shall be selected with due regard to possible consequences of failure.

The assessment of the consequences of failure shall cover all phases of MEC installation, operation, maintenance and decommissioning and shall consider:

- risk to life and injury;
- environmental impact, e.g. pollution due to fluid releases and risk to marine life;
- economic consequences, e.g. cost of repair, cost due to loss of power generation; and
- loss of public reputation and other political and societal consequences.

Three safety levels for MECs depending on the consequences of failure are defined in Table 2 along with associated target probabilities of failure.

Table 2 – Safety levels

Safety level	Definition	Target probability of failure
SL1	High risk to human life and/or injury, significant environmental impact and/or very high economic or political consequences	$< 10^{-5}$ per year
SL2	Risk of human injury, significant environmental impact and/or high economic or political consequences	$< 10^{-4}$ per year
SL3	Low risk of human injury and minor environmental and economic consequences	$< 10^{-3}$ per year

The requirements in this document, including partial safety factors for loads and materials, have been derived to comply with the target probability of failure for safety level 2 (SL2). Other safety levels may be appropriate depending on project particulars.

Safety levels shall be considered while defining redundancy or safety features for the equipment and systems. Different safety levels may be required for different sub-systems/components of the same MEC depending on consequences of their failure. Higher levels of safety might be required for critical sub-systems and components depending on their consequences of failure.

The safety level of a MEC shall satisfy local regulations where the device is designed to operate. To achieve this, SL1 may need to be selected for the MEC design.

When failure of a MEC does not imply risk of human injury and environmental impact and may only cause minor economic consequences, SL3 may be selected, subject to compliance with local regulations. Safety requirements for the MEC, including partial safety factors, shall be agreed upon between the manufacturer and the customer.

5.6 Basis of design

The basis of design defines the technical framework for a project, the intended operational environment for the MEC and the associated parameters to be adopted for design. The basis of design is also a key input to the technology qualification process (see 5.3). Typically, a basis of design would include the following information:

- governing project description, general requirements, deployment duration, targets and objectives;
- reference assumptions (e.g. datums, legislation and regulations);
- site definition (e.g. location, water depth);
- environmental conditions (e.g. water levels, currents, wave conditions, turbulence, wind); and
- seabed characterisation (e.g. geotechnical, bathymetry).

The basis of design shall be applicable to all stages of MEC development, subject to refinement as operational data becomes available. In addition to being a design governance document, a key objective of the basis of design is to promote consistency across design activities of a project and to manage updates in light of new information.

5.7 Environmental conditions

A MEC shall be designed to safely withstand the environmental conditions defined in the basis of design. The environmental conditions described in Clause 6 include waves, currents, water level, wind, sea ice, marine growth, seismic forces and seabed conditions. These conditions apply to the MEC when it is deployed.

5.8 Life cycle considerations

Clause 12 considers design conditions when the MEC is not operationally deployed. This includes inspection and maintenance operations, where it is anticipated that personnel will be required to work on the MEC. Other life cycle MEC phases include fabrication, transportation, installation and decommissioning.

Specific load cases addressed in Clause 12 include safe lifting and handling of the MEC; stability; watertight integrity; inspection and maintenance operations; and metocean limits for life cycle operations.

5.9 Load definition and load combinations

Clause 7 defines the load cases that MECs are expected to experience when deployed. Design load cases used to determine the structural integrity of the MEC shall be calculated from the following combinations:

- normal design situations and normal external conditions;

- fault design situations when the MEC is operating with a single major system failure and appropriate environmental conditions; and
- normal design situations and extreme environmental conditions.

Clause 7 also defines MEC design limit states and loading partial safety factors.

5.10 Limit state design

The performance of a MEC or part of it shall be designed with reference to a specified set of limit states beyond which the MEC no longer satisfies the design requirements. Ultimate, fatigue, serviceability and accidental limit states are defined in 7.3.4.

A MEC and its components shall be designed, constructed and maintained so that they are suited to their intended use for the design service life. In particular, the MEC and its components shall:

- withstand extreme actions likely to occur during construction and anticipated use (ULS requirement);
- perform adequately during normal operation (SLS requirement);
- not fail under repeated actions (FLS requirement); and
- provide an appropriate level of robustness to avoid accidental failure (ALS requirement)

5.11 Partial safety factors

This document applies partial safety factors for loads and materials to support limit state design. Limit states are the acceptable limits for the safety and serviceability requirements of the structure before failure occurs. The design of MECs by this method will ensure that they will not reach limit states and will not become unfit for the use for which they are intended.

Partial safety factors for loads are given in Clause 7 and for materials in Clause 9. Partial safety factors for loads and materials shall be calibrated in the same engineering model to ensure that appropriate values are derived for design calculations. To achieve design loads and material strength for design calculations, the characteristic load and material strength are modified by the partial safety factor for loads and materials, respectively. The characteristic load for a given limit state is defined as the value below which not more than a prescribed percentage of test results may be expected to fall.

Model testing and prototype tests may also be used to support analytical design methods, as specified in ISO 2394.

To ensure safe design values, the uncertainties and variability in loads and materials are taken into account by partial safety factors as defined in formulas (1) and (2).

$$F_d = \gamma_f F_k \tag{1}$$

where:

F_d is the design value for loads acting on the MEC for the given design load case;

γ_f is the partial safety factor for loads;

F_k is the characteristic value for the load;

$$f_d = \frac{f_k}{\gamma_m} \tag{2}$$

where:

f_d are the design values for material properties;

γ_m are the partial safety factors for material properties;

f_k are the characteristic values of material properties.

5.12 Structural modelling and analysis

Structural analysis is the process of determining the action effects in a structure, or part thereof, in response to a given set of actions. Action effects required for the design of MECs typically include the following:

- internal section forces, which shall not exceed the strength of the section;
- displacements and vibrations, which shall be within acceptable limits; and
- support reactions, from which the required foundation or mooring capacity can be determined.

The number, types and extent of analyses to be performed shall cover all stages of the lifetime of the MEC. However, if it can be demonstrated that particular stages in the design service life of a component of the MEC do not govern its design, such stages need not be analysed for that component. In general, refer to ISO 19902 for structural design equations.

6 Environmental conditions

6.1 General

The environmental conditions described in this clause shall be considered in the modelling, analysis and prediction of environmental loads on MECs. The most important environmental phenomena for most MECs, waves, currents, and water level, are discussed in 6.2. Other conditions, such as wind, ice, earthquake, soil conditions, temperature, and marine growth, are discussed in 6.3.

The marine conditions for load and safety considerations are divided into the normal marine conditions that are statistically expected to occur more frequently than once per year, and extreme marine conditions that are expected to occur less frequently than once per year i.e. defined as having return periods greater than one year. Load cases associated with normal and extreme conditions are prescribed in Clause 7. ISO 19901-1 provides additional guidance for the determination of environmental conditions and their relevant parameters.

6.2 Primary environmental conditions

6.2.1 General

Primary environmental conditions shall be used for the development of MEC modelling, unless site-specific secondary environmental conditions are more severe and likely to occur. The conditions defined in this section are used to compose the design load cases covered in Clause 7.

6.2.2 Waves

6.2.2.1 General

Waves are considered a primary influence on loading for WECs and some TECs. Characteristics of the site, including the combination of wave heights, periods and directions should be considered.

6.2.2.2 Operational sea state (OSS)

The Operational Sea State (OSS) is characterized by a significant wave height (H_{m0}), a peak period (T_p) and a wave direction. For use in DLCs, OSSs shall be defined as those sea states likely to occur within a 1-year period. Where available, regional or site-specific data shall be used to specify spectral shape and directional distributions.

6.2.2.3 Operational wave height (OWH)

The Operational Wave Height (OWH), H_{OWH}, shall be derived from analysis of appropriate measurements and/or hindcast data for the site of deployment of the MEC and defined as the single most likely wave height. Consideration shall be given to the range of wave periods (T) appropriate to the operational wave height. Design calculations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

The wave periods, T, in combination with the operational wave heights, H_{OWH}, may be assumed to be within the range given by:

$$11{,}1\sqrt{\frac{H_{m0,OSS}}{g}} \leq T \leq 14{,}3\sqrt{\frac{H_{m0,OSS}}{g}} \tag{3}$$

where:

$H_{m0,OSS}$	is the significant wave height of the operational sea state in metres;
g	is gravitational acceleration in m/s^2; and
T	is the wave period in seconds.

Formula (3) is appropriate only for deepwater waves. Water is considered 'deep' for a wave, if the water depth is greater than one-half of the wavelength of the wave. See Annex D for more information on shallow water hydrodynamics and breaking waves. The full dispersion relation shall be solved for waves falling in the intermediate regime.

Short-term stationary irregular sea states shall be described by a wave spectrum that represents the power spectral density function of the vertical sea surface displacement. Where possible, site-specific spectra should be used. When site-specific-spectra are unavailable, idealized spectra can be used. The most frequently used spectra for wind-generated seas are Pierson-Moskowitz (PM) spectra for a fully developed sea, and the JONSWAP spectra for a developing sea. Standard wave spectrum formulations are given in Annex C. The Ochi-Hubble spectrum based on superposition of two modified PM spectra or the Torsethaugen double peak spectral model based on sea state and swell may also be appropriate. Information on swell spectra can be found in ISO 19901-1.

6.2.2.4 Extreme sea state (ESS)

The designer shall consider extreme stochastic sea states for 50-, 5-, and 1-year return periods. The return period is the average period between occurrences of a particular value being exceeded. When possible, the spectral parameters (H_{m0}, T_p, *etc.)* should be determined via a contour approach, where a plot of H_{m0} versus T_p for various return periods establishes contour lines (see DNV RP 205). Alternatively, the one-dimensional significant wave height distribution can be used to define three extreme significant wave heights (H_{m50}, H_{m5}, and H_{m1}, respectively). For both a contour and one-dimensional approach, historical measurements should be used if available. Alternatively, hindcast data can be used if historical measurements are unavailable. If a one-dimensional approach is taken, a wide range of the remaining spectra parameters can be based on empirical relations given in formula (3). Design calculations shall be based on values of peak spectral period that result in the most onerous loads acting on the MEC.

6.2.2.5 Extreme wave height (EWH)

The extreme wave height (H_{EWH}) is the largest single wave height for a given return period. As with the ESS, EWH shall be considered for 50-, 5-, and 1-year return periods. The values of H_{50}, H_5, H_1 and the associated wave periods may be determined from a one-dimensional probabilistic analysis of historical measurements or hindcast data. Alternatively, the designer may assume the following based on the Rayleigh distribution of wave heights assuming a three-hour storm.

$$H_n = 1{,}86 H_{mn} \tag{4}$$

Here, H_{mn} is the significant wave with a return period of n years. Thus, H_n is the corresponding extreme wave height. The general form of (4) for a period t and zero crossing period T_z is:

$$H_n = \frac{H_{mn}}{2}\sqrt{\ln}\left(t / T_z\right) \tag{5}$$

Extreme wave height shall be considered in design calculations for the range of deepwater waves periods given in formula (3).

The extreme wave heights H_{50}, H_5, H_1 and the associated wave periods for shallow water sites shall be determined from analysis of appropriate site-specific measurements. In the absence of measurements, H_{50}, H_5 and H_1 shall be assumed equal to the breaking wave height if the breaking wave height is less than the values of H_{50}, H_5 and H_1 determined from the Rayleigh distribution given by formulae (3) and (4). See Annex D for more information on breaking waves.

The computations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

6.2.3 Sea currents

6.2.3.1 General

The most common categories of sea currents are: wind generated currents, tidal currents, circulational currents, loop and eddy currents, soliton currents, and longshore currents. The total current velocity is the vector sum of all components at a given position in the water column. The designer shall determine whether sea currents may be neglected for calculation of fatigue loads considering site characteristics and MEC geometry.

6.2.3.2 Sub-surface currents

In the absence of other data, the sub-surface current velocity, U_{SS} (z), profile may be characterized by a simple power law over the water depth, d, as a function of height below SWL, z:

$$U_{SS}(z) = U_{ss}(0)\left\{\left(z+d\right)/d\right\}^{\frac{1}{7}} \tag{6}$$

The 1-year, 5-year and 50-year return periods of the sub-surface velocity, U_{SS} (0), may be determined from analysis of measurements of tidal, storm surge, wind generated and wave induced surf currents. If the current velocity is of significant importance to the design, current velocity measurements shall be carried out at the MEC deployment site.

6.2.3.3 Wind-generated near-surface currents

Wind-generated current may be characterized as a linear distribution of velocity, $U_w(z)$, reducing from the surface velocity $U_w(z)$ to zero at a depth of 20 metres (m) below the static water level SWL:

$$U_W(z) = U_W(0)\left\{\left(1+z\right)/20\right\} \tag{7}$$

The wind generated current velocity at the sea floor will be non-zero at sites where the water depth is less than 20 m. The wind generated sea surface current velocity may be assumed to be aligned with the wind direction and may be determined from:

$$U_W(0) = 0{,}01 V_{1-hour}\left(z = 10\mathrm{m}\right) \tag{8}$$

where $V_{1\text{-}hour}$ (z = 10 m) is defined as the 1 hour (h) mean value of wind speed at 10 m height above SWL.

The 1-year, 5-year and 50-year return periods of $V_{1\text{-}hour}$ (z = 10 m) may be determined from analysis of site measurements.

6.2.3.4 Tidal currents

Tidal currents are often magnified by topographical features, such as headlands, inlets and straights, or by the shape of the seabed when water is forced through narrow channels. Strong tidal currents may exist in inlets and straits in coastal regions (see IEC 62600-201).

6.2.3.5 Operational current model (OCM)

The operational current model includes the appropriate site-specific combination of wind-generated currents and breaking wave surf induced currents, if any, associated with operational wave conditions.

6.2.3.6 Extreme current model (ECM)

The extreme current model is defined as the appropriate site-specific combination of sub-surface currents, wind generated currents and breaking wave surf induced currents, if any, associated with peak spring tides.

6.2.3.7 Turbulence

Marine tidal current turbulence generated by sea bed material, ripples, bed forms, changes in bathymetry, waves and swell, ambient environment, and vortices shed from the blades and support structure shall be considered in determining frictional drag, flow separation, thickness of boundary layers, extent of secondary flows, and the spreading of jets and wakes. Flow fluctuations caused by turbulence will vary with current velocity. The three vector components of the turbulent current velocity are defined as:

– streamwise: along the principal direction of the flow;

– transverse: horizontal and normal to the streamwise direction, and

– vertical: normal to both the longitudinal and transverse directions.

Turbulence intensity, I, a measure of current flow variability, is given as:

$$I = \frac{u'}{\overline{U}} \tag{9}$$

where:

u' is the standard deviation of the streamwise, transverse and vertical turbulent current velocity;

$\overline{U}$ is the mean current velocity over a set period of time, usually taken as 10 min.

For the normal turbulence model (NTM), the current velocity shall be defined as the 50 % percentile in the probability distribution of the standard deviation u' of the 10 min mean current velocity at a specific point in the water column. The 95 % percentile in the probability distribution of the standard deviation u' shall be used for the extreme turbulence model (ETM).

The turbulent kinetic energy, K, can be estimated by:

$$K = \frac{2}{3}\left(u'\right)^2 \tag{10}$$

Site-specific spectral densities of the current speed data show how the energy of the current turbulence is distributed between different frequencies. Acoustic Doppler Current Profilers (ADCP) used to characterise the flow conditions of a tidal turbines sites generally give conservative estimates of turbulence. Acoustic Doppler Velocimeters (ADV) give more accurate speed readings but their location in the current stream is critical.

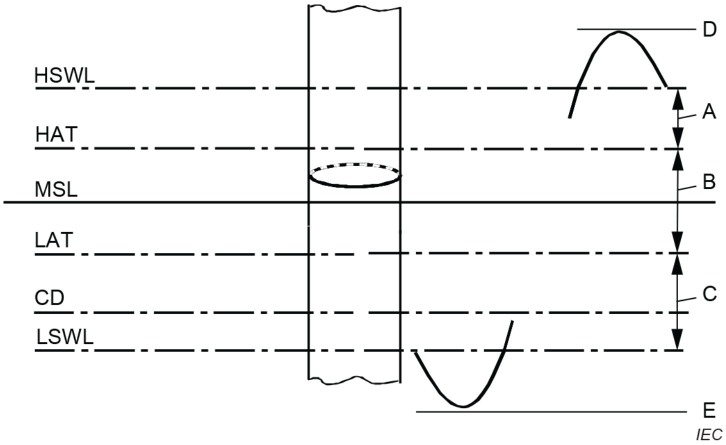
When measured current data are insufficient to establish site-specific spectral densities, turbulence models are to be used. The turbulence model shall include the effects of varying current speed, shears and direction and allow rotational sampling through varying shears. IEC 62600-201 provides guidance on use of turbulence modeling for power performance projection, which however, may be insufficient for determining the long-term spectral component of turbulence necessary to estimate TEC fatigue loading.

NOTE Modeling of turbulence intensity, I, and turbulent kinetic energy, K, in highly energetic current fields is an area of ongoing research, especially in regions affected by TEC operation. [Kilcher, et al., 2016, see Bibliography]

6.2.4 Water level

6.2.4.1 General

The variation in water level at the site shall be taken into account in the calculation of the hydrodynamic loading of MECs. The designer may assume a constant water level equal to the mean still water sea level (MSL) for ultimate load cases involving operational wave conditions (OSS and NWH). Different water levels are illustrated in Figure 3.



HSWL	highest still water level	A	positive storm surge
HAT	highest astronomical tide	B	tidal range
MSL	mean sea level	C	negative storm surge
LAT	lowest astronomical tide	D	maximum crest elevation
CD	chart datum (often equal to LAT)	E	minimum trough elevation
LSWL	lowest still water level		

Figure 3 – Definition of water levels

6.2.4.2 Normal water level range (NWLR)

The normal water level range shall be assumed equal to the variation in water level with a return period of 1 year. The normal water level range may be assumed to be equal to the variation between highest astronomical tide (HAT) and lowest astronomical tide (LAT) in the absence of site-specific data to characterize the long-term probability distribution of water levels.

6.2.4.3 Extreme water level range (EWLR)

The following extreme water level ranges shall be used if the long-term joint probability distribution of water level is not available:

- highest still water level (HSWL) with a return period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level (LSWL) with a return period of 50 years, based on an appropriate combination of lowest astronomical tide and negative storm surge; and
- water level associated with the maximum breaking wave load.

6.3 Secondary environmental conditions

6.3.1 General

Secondary environmental conditions shall be considered when the potential exists for significant MEC loading at the deployment site.

6.3.2 Breaking waves

A breaking wave is a wave whose amplitude reaches a critical level that causes large amounts of wave energy to be transformed into turbulent kinetic energy. The effect of breaking waves shall be assessed, if necessary, for a given site during the design of the MEC. Annex D provides guidance for modelling breaking waves based on site conditions and presents an empirical model of the distribution of wave heights for shallow water (see also DNV-RP-C205).

6.3.3 Breaking wave-induced surf currents

Surf currents generated by the forces of breaking waves along the coast shall be considered when the MEC is to be sited near a breaking wave zone.

Numerical methods (e.g. a Boussinesq model considering fully coupled wave and current motions) can be used for the estimation of the breaking wave induced surf currents. The breaking wave current velocity U_{bw} at the location of breaking waves is given as:

$$U_{bw} = 2s\sqrt{gH_B} \tag{11}$$

where:

H_B is the breaking wave height; and

s is the beach floor slope.

A method for estimating breaking wave height based on the site characteristics is presented in Annex D.

6.3.4 Wind conditions

The wind regime for load and safety considerations is divided into the normal wind conditions that occur more frequently than once per year and extreme wind conditions, which are defined as having 1-year (V_1), 5-year (V_5), and 50-year (V_{50}) return periods. Wind conditions may be ignored if the exposed device area above the waterline is insignificant.

6.3.5 Sea and river ice

Loading on an MEC due to sea or river ice can be critical in some areas. Ice may form in areas where subfreezing temperatures can prevail. Ice may exist in these areas as first-year ice, multi-year floes, first-year and multi-year pressure ridges, and/or ice islands. In these locations, ice features will influence the design and construction of MECs.

RECs need to consider the spring freshet 'wall of ice'. A site-specific assessment of the occurrence and properties of the ice shall be undertaken prior to the design of the support structure. The following parameters shall be determined from the assessment:

- ice thickness, h, with a 50-year return period;
- ice crushing strength, σ_c;
- risk of current or wind induced ice floe;
- risk of forces induced by fluctuating water level; and
- frequency of ice concentration.

NOTE Ice capable of disrupting the harvest of tidal power currently occurs in the Bay of Fundy, Nova Scotia. Recommendation has been made for deployment of tidal current harvesting devices in the headwaters of the Bay of Fundy to be designed for 30 % cover by 15 cm thick ocean ice in 100 m floes. (National Research Council Canada report CR-2006-01)

6.3.6 Earthquakes and tsunamis

Seismic forces shall be considered for sites that are determined to be seismically active. Additional consideration shall be given to the design of MECs that are being deployed at sites where tsunami have been known to occur. This design condition is beyond the scope of extreme sea states covered by this document.

6.3.7 Marine growth

The designer shall consider the influence of marine growth on the dynamic and hydrodynamic characteristics of MECs through the added mass of the growth, increased outer dimensions and potential changes to surface roughness. The thickness of marine growth is site-specific and depends on location, time of year, water temperature, member orientation, depth in water column and structure age (or time since removal of growth). Where available, site-specific data shall be used to establish the expected extent of marine growth.

6.3.8 Seabed movement and scour

The foundation or mooring of the MEC may be influenced by seabed movement and scour. The analysis of seabed movement and scour, and the design of appropriate protection shall conform to the requirements of ISO 19901-4.

6.3.9 Other environmental conditions

Other environmental conditions that can influence MEC survivability include: air temperature, humidity, air density, solar radiation, rain, hail, snow and ice, chemically active substances, mechanically active substances, salinity causing corrosion, suspended particles, lightning, and water density, viscosity, acidity and temperature. The probability of simultaneous occurrence of climatic conditions shall be taken into account.

7 Design load cases

7.1 General

This clause provides instructions for defining load cases and determining design loads. This process is illustrated in Figure 4, which contains a flow chart showing the load evaluation procedure described in this document.

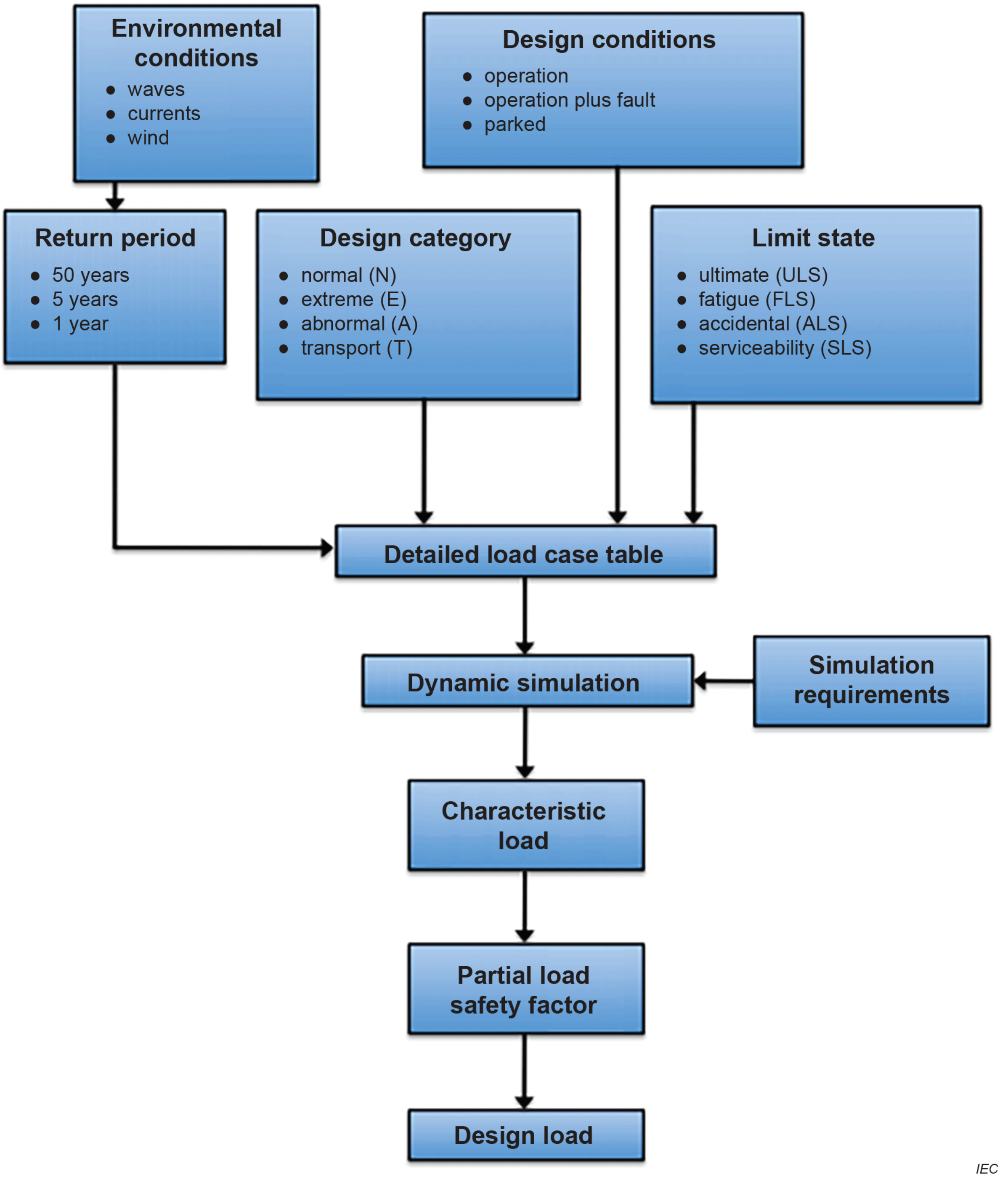


Figure 4 – Process for determining design loads via load cases

7.2 Load categories

The loads listed in Table 3 shall be considered in all design calculations when appropriate based on specific MEC site and geometry.

Table 3 – Types of loads that shall be considered

Environmental (see DNV-RP-C205 for additional guidance)	Hydrostatic	The result of still water pressure acting on the immersed surfaces of a body can be statically analyzed.
	Hydrodynamic	Dynamic loads that are caused by water flow and its interaction with the immersed body depend on the water kinematics, water density, dynamic viscosity, water depth, the shape of the immersed structure, and hydro-elastic effects.
	Wave	The interaction of waves with the MEC shall be analyzed using a relevant wave theory to calculate wave kinematics parameters, such as water particle velocities and accelerations at MEC components. For submerged components of the MEC, periodic pressure variations from passing waves shall be considered.
	Breaking wave	Breaking wave impact loads can lead to dynamic magnification, depending on the duration of the impact relative to the natural period of the structure. In the case where a MEC is installed close to the shoreline, fatigue loading due to breaking waves shall be considered. Since the analysis of breaking wave loads contains many uncertainties, model tests are recommended for the evaluation of the loads.
	Wave slamming	Wave slamming is the result of passing wave interaction with MEC components, usually normal to the surface of the structure.
	Green water	Green water is a term used to describe the overtopping of a body of seawater during severe wave conditions. Structural members exposed to green water shall be designed to withstand appropriate design head pressures.
	Currents	Currents represent water flowing around a structure that produce variable pressures and flow paths. Currents may contain turbulence, which can impose significant loading on the MEC. Cavitation can also impose additional loads on the structure and shall be considered. Dynamic loads that are caused by currents and their interaction with immersed bodies depend on the water kinematics, water density, dynamic viscosity, water depth, the shape of the immersed structure, and hydro-elastic effects.
	Vortex shedding	Vortex shedding creates oscillating loads behind a non-streamlined shape determined by the geometry of the structure and the velocity of the currents and waves.
	Aerodynamic	The quasi-static and dynamic loads that are caused by the interaction of airflow with the MEC's components above the water surface are determined by average wind speed, turbulence intensity, density of the air and the aerodynamic shape of the MEC's components above the water surface and their interactive effects, including aero-elastic effects.
	Seismic	Seismic loads include direct loads generated by seabed movements and fluid loads caused by the seismically induced fluid motions, such as tsunamis.
	Topside icing	Topside icing can cause stability and structural issues caused by icing of the structure above the waterline.
	Ice	Fast sea or river ice cover and/or dynamic loading caused by wind and current induced motion of ice floes can cause significant impact or fatigue loading.
Operational (see ISO 19901-6)	Construction	Unique construction loads occur during fabrication, assembly, transportation and installation of the MEC.
	Actuation	Actuation loads occur during normal operation and control of the MEC. The interaction of the MEC control system with the motion of the structure shall be considered in the control system design and load analysis.
	Maintenance	Unique loads can occur during maintenance work, such as locking of rotational components.
	Gravitational and inertial	Gravitational and inertial loads are caused by gravity, vibration, rotation and seismic activity.
	Vessel impact	Vessel impact force is determined by vessel size, mass, speed, and incident angle.
	Debris impact	Damage can occur from floating debris, such as fishing nets and plastic waste that may include large entrained masses, such as floating logs, chemical debris and fuel slicks.

7.3 Design situations and load cases

7.3.1 General

The design life of a MEC can be represented by a set of load cases covering the various conditions that the MEC may experience. As shown in Figure 4, load cases shall be determined from the combination of environmental conditions (Clause 6), design categories 7.3.3) and design conditions (7.3.7). In this subclause, the derivation of such design load cases for a MEC is described. Subclause 7.3.2 describes the combination of environmental conditions.

All relevant load cases with the corresponding probability of occurrence shall be considered in conjunction with the behaviour of control and safety systems.

The combination of extreme environmental conditions shall be performed in a way that results in the global extreme environmental action on the structure with the combined specified return period of 50 years.

7.3.2 Interaction with waves, currents, wind, water level and ice

If there is no project site information available about the combination of the extreme environmental conditions, the return periods as stated in Table 4 can be used to derive environmental combinations for a 50-year return period. The adverse directional alignment of wind, waves and currents shall be considered. Note that a worst-case directional alignment may not necessarily be the co-alignment of wind, current and waves.

Table 4 – ULS combinations of uncorrelated extreme events

Environmental combination ID	**Environmental event and return period (years) to define characteristic value of corresponding load effect**					
	Waves	**Current**	**Water level**	**Wind**	**Ice**	**Dominating event**
1	50	5	50	5	–	Ground swell
2	5	50	50	5	–	Sea currents
3	–	5	NWLR	5	50	Sea ice
4	50	5	50	50	–	Wind swell
5	-	50	50	5	-	River current

7.3.3 Design categories and conditions

Normal, extreme, abnormal, and transport and erection design categories for a MEC are defined in Table 5. These categories and associated design conditions (see 7.3.7) represent conditions that shall be considered for various load cases.

Table 5 – Design categories and conditions

Design category	Design condition
Normal	Normal operation, including stops and starts Normal operation plus fault Parked/idling Parked/idling plus fault
Extreme	Parked/idling Parked/idling plus fault Survival (or normal if that is survival strategy) Survival plus fault
Abnormal	Earthquake/tsunami Parked/idling plus major fault Survival plus major fault Rare ULS fault conditions Accidental events
Transport and erection	Installation Maintenance Decommissioning

7.3.4 Limit states

7.3.4.1 General

The structural performance of a whole MEC or part of it shall be described with reference to a specified set of limit states beyond which the MEC no longer satisfies the design requirements. The following limit states shall be considered.

7.3.4.2 Ultimate limit state (ULS)

The ultimate limit state (ULS) places a structure at the cusp of failure, and typically corresponds to the maximum load-bearing capacity. ULS is to be analysed in extreme situations but with the model in normal or idling mode, with no failure. The following failure modes shall be considered when determining the ULS:

- loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning or capsizing);
- failure of critical components of the structure caused by exceeding the ultimate strength or the ultimate deformation of the components;
- transformation of the structural geometry (collapse or excessive deformation);
- loss of structural stability (buckling, etc.);
- loss of station keeping (free drifting); and
- sinking.

7.3.4.3 Fatigue limit state (FLS)

The fatigue limit state (FLS) generally corresponds to the effect of cyclic loading and includes the following states:

- cumulative damage due to repeated loads; and
- reduction of structural integrity beyond safety factor allowance.

7.3.4.4 Serviceability limit state (SLS)

Depending on the design and function, the serviceability limit state (SLS) is determined by various limiting values that are oriented towards normal use. Limits to be observed include:

- deformations or movements that affect the function of structural or non-structural components;
- excessive vibrations producing discomfort for maintenance personnel or affecting non-structural components or equipment (especially if resonance occurs);
- local damage (including cracking) that reduces the durability of a structure or affects the use of structural or non-structural components;
- corrosion that reduces the durability of the structure and affects the properties and geometrical parameters of structural and non-structural components; and
- motions that exceed the limitations of equipment.

7.3.4.5 Accidental limit state (ALS)

The intention of the accidental limit state (ALS) is to ensure that the structure can tolerate specified accidental events and maintain structural integrity for a sufficient period in order to repair or rescue the damaged MEC. The accidental limit state is to ensure that MECs are designed and manufactured such that they can sustain a limited extent of damage without a disproportionate level of failure so that failure of a single item does not lead to failure of the whole system.

7.3.5 Partial safety factors

Partial load safety factors are defined for the ultimate limit state for design categories (7.3.3) in combination with the load categories (7.2) in Table 6. These partial load safety factors, denoted as γ_f, take into account the probability of the load occurring and that certain limiting values will not be exceeded with a given probability. Thus, each partial load safety factor reflects the uncertainty of the loads and their probability of occurrence (e.g., normal and extreme loads), possible deviation of the loads from the characteristic values, plus the accuracy of the load model (e.g., gravitational or hydrodynamic forces).

If the loads of different origins can be determined independently of each other, the partial safety factors γ_f of the corresponding load and design category shall be applied for each load. In many cases, especially when unsteady loads lead to dynamic effects, the sources of loading cannot be determined independently of each other. In these cases, the most onerous partial safety factor γ_f of the corresponding load and design category shall be applied for the loads.

Partial load safety factors for fatigue, serviceability and accidental limit states are γ_f = 1,0.

Table 6 – ULS partial load safety factors γ_f for design categories

Load category	Unfavourable loads				Favourable loads[c]
	Design category				All design categories
	Normal (N)	**Extreme** (E)	**Abnormal** (A)	**Transport/erection** (T)	
Environmental	1,35	1,35	1,1	1,5	0,9
Operational	1,35/1,5[b]	1,35	1,1	1,5	0,9
Gravity	1,1/1,35[a]	1,1/1,35[a]	1,1	1,35	0,9
Other inertial forces	1,35	1,35	1,1	1,35	0,9

[a] For masses not being determined by weighing.

[b] For MECs working within ±5 % of whole-body or component structural resonance (see Annex B).

[c] Pre-tension and gravity loads that significantly relieve the total load response are considered favourable loads.

The partial load safety factors γ_f are intended to achieve a target safety level of SL2 and are based on the experience of the offshore oil and wind industries and have not yet calibrated for MECs. If a different target safety level is agreed upon between the manufacturer and the customer as per Clause 5, γ_f shall be adjusted accordingly.

In order to cope with the fact that the technology of many designs is new and yet unverified, the partial load safety factors in Table 6 may be increased accordingly.

7.3.6 Load case modelling and simulation

Once a set of load cases has been defined, a numerical model or experimental test can be utilized to determine characteristic loads. Numerical simulations and experiments shall have the ability to model devices that are comprised of rigid bodies, power take-off systems, and mooring systems. Simulations shall be performed in the time domain by solving the governing MEC equations of motion in six degrees-of-freedom. In addition to deterministic methods, stochastic representation of environmental conditions, such as turbulent flow and irregular waves, shall be considered, where appropriate.

When dynamic simulations or tests are used, the total period of load data for these cases shall be long enough to ensure statistical reliability of the estimated characteristic load effect.

- for load cases in the Normal and Extreme categories for TECs (e.g., power production), at least six 10 min stochastic realizations should be used for each mean current speed considered in the simulations. Constrained wave methods may be used for this purpose.
- for load cases in the Normal and Extreme categories for WECs, at least six 3 h stochastic realizations should be used for each sea state considered in the simulations. This requirement may be relaxed and shorter realizations may be assumed if the designer is able to demonstrate that the estimated extreme response is more conservative than that obtained with 3 h realizations. Constrained wave methods may be used for this purpose.
- for Abnormal and Transient load cases for both TECs and WECs (e.g. stopping procedures) at least six 10 min simulations should be carried out for each event at the given current speed and/or sea state.

7.3.7 Design conditions

7.3.7.1 General

Load partial safety factors are based on the combination of the design categories, design conditions and limit states for the design load case (DLC) matrix shown in Tables 7 and 8. For each design category (Normal, Extreme, Abnormal, and Transport), a set of design conditions (normal operation, parked, fault, etc.) and design load cases are defined. For each of these design load cases, limit states for consideration and environmental conditions are defined.

Tables 7 and 8 define a basic set relevant design load cases for WECs and TECs, respectively. However, if other realistic combinations lead to more severe loading, these shall also be considered.

The environmental conditions in Tables 7 and 8 may be represented by a set of discrete values provided that the resolution is sufficient to ensure accuracy of the calculation. In the definition of the design load cases (7.3.9.2 to 7.3.9.13), reference is made to the environmental conditions described in Clause 6.

In all design conditions, the designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for the fatigue damage associated with the long-term distribution of metocean parameters.

7.3.7.2 Normal operation (DLC 1.1 to 1.3)

In this design condition, the MEC is in operation and connected to the electrical grid. The assumed MEC configuration shall take into account any imbalance of the PTO unit, where relevant. The maximum mass and hydrodynamic imbalances specified for manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating conditions, such as orientation errors (e.g. for tidal energy converters) and control system delays, shall be taken into account in the analyses of operational loads.

This design condition includes loads resulting from wave loading and hydrodynamic turbulence (currents). Operational sea state (OSS) conditions shall be assumed for WECs and the turbulent current model (NTM) shall be considered for TECs.

For DLC 1.1, the significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site (typically represented with a scatter diagram).

For DLC 1.2 (TECs), the significant wave height and peak spectral period for the maximum permitted normal sea state during power production shall be selected. Wave direction shall be varied from 0° to 360° in 30° steps.

DLC 1.3 (TECs) embodies the requirements for maximum loading resulting from extreme turbulence conditions.

Table 7 – Design load cases for WECs

Design condition	DLC	Partial safety factor (limit state)	Wave conditions	Current conditions	Water level	Other conditions	Design category
1) Normal operation	1.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	OSS $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR		Normal
	Ice	1,35 (ULS) 1,00 (FLS)	No waves	OCM $U_{in} \leq U \leq U_{out}$	NWLR	Ice	Normal
2) Normal operation with fault	2.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR	Grid loss, grid failure, or fault in controller	Normal
3) Start procedures	3.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR		Normal
4) Normal shut down procedures	4.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR		Normal
5) Emergency shut-down procedures	5.1	1,35 (ULS) 1,00 (SLS)	NWH $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR		Normal
6) Parked/survival conditions	6.1	1,35(ULS) 1,00 (SLS)	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	EWLR	Wind: EWM ($V = V_5$)	Extreme
	6.2	1,10 (ALS) 1,00 (SLS)	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	EWLR	Wind: EWM ($V = V_5$) Grid loss	Abnormal
	6.3	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	OSS $H_{m0} = H_{rated}$	OCM $U = U_1$	NWLR		Normal
	Ice	1,35 (ULS)	ESS $H_{m0} = H_{m50}$	ECM $U = U_5$	NWLR	Ice: $h = h_{50}$	Normal
7) Parked plus occurrence of fault	7.1	1,10 (ULS) 1,10 (FLS)	ESS $H_{m0} = H_{m1}$	ECM $U = U_1$	EWLR	Wind: EWM ($V = V_1$)	Abnormal

Design condition	DLC	Partial safety factor (limit state)	Wave conditions	Current conditions	Water level	Other conditions	Design category
8) Transport, installation and maintenance	8.1	1,35 (ULS) 1,00 (SLS)	To be specified by the manufacturer				Transport
	8.2	1,10 (ULS) 1,00 (SLS)	ECM $U = \mathit{mean\ spring}_1$ flood, ebb, OE	ESS $H = H_{m1}$ 30° steps	EWLR	Locked state	Abnormal

The following abbreviations are used in Table 7:

ECM	extreme current model (see 6.2.3.6)
ESS	extreme stochastic sea state (see 6.2.2.4)
ETM	extreme turbulent current model (see 6.2.3.7)
EWH	extreme steady wave height (see 6.2.2.5)
EWM	extreme steady wind model (see 6.3.4)
EWLR	extreme water level range (see 6.2.4.3)
OSS	operational sea state (see 6.2.2.2)
NTM	normal turbulent current model (see 6.2.3.7)
OWH	operational wave height (see 6.2.2.3)
NWLR	normal water level range (see 6.2.4.2)

Table 8 – Design load cases for TECs

Design condition	DLC	Partial safety factor (limit state)	Current conditions	Wave conditions	Water level	Other conditions	Design category
1) Normal operation	1.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	NTM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0}$	MTL +/- Mean Range		Normal
	1.2	1,35 (ULS) 1,00 (SLS)	NTM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0,out}$ Wave direction 0° to 360° in 30° steps	MTL +/- Mean Range		Normal
	1.3	1,35 (ULS) 1,00 (SLS)	ETM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	OSS $H = H_{m0}$	MTL +/- Mean Range		Normal
2) Normal operation with fault	2.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	Grid loss, grid failure, fault in controller, i.e. faults triggering the control system	Normal
	2.2	1,10 (ULS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	Safety system relevant faults, short circuit, brake failure	Abnormal
	2.3	1,1 (ALS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	Accidental faults	Extreme

Design condition	DLC	Partial safety factor (limit state)	Current conditions	Wave conditions	Water level	Other conditions	Design category
3) Start procedures	3.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	TEC undergoing start-up	Normal
	3.2	1,35 (ULS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m0,out}$ Worst direction from DLC 1.2	MTL +/- Mean Range		Normal
4) Normal shut-down procedures	4.1	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	TEC undergoing shut-down	Normal
	4.2	1,35 (ULS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m0,out}$ Worst direction from DLC 1.2	MTL +/- Mean Range		Normal
5) Emergency shut-down procedures	5.1	1,35 (ULS) 1,00 (SLS)	OCM or NTM $U_{rated} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$ Worst direction from DLC 1.2	MTL +/- Mean Range	TEC undergoing emergency shut-down, rapid shut-down etc.	Normal

Design condition	DLC	Partial safety factor (limit state)	Current conditions	Wave conditions	Water level	Other conditions	Design category
6) Parked/ survival conditions	6.1a	1,35 (ULS) 1,00 (SLS)	ECM U = *peak spring* flood, ebb, OE	ESS $H = H_{m5}$ most probable direction(s)	EWLR	Wind: EWM ($V=V_5$)	Extreme
	6.1b	1,35 (ULS) 1,00 (SLS)	ECM U = *peak spring* flood, ebb, OE	ESS $H = H_{m50}$ most probable direction(s)	EWLR	Wind: EWM ($V=V_{50}$)	Extreme
	6.2	1,10 (ULS) 1,00 (SLS)	worst combination of current and wave from DLC 6.1a and 6.1b $U \leq U_{in}$, $U_{out} \leq U$ flood, ebb, OE	worst combination of current and wave from DLC 6.1a and 6.1b $H = H_{m0}$	EWLR	Wind: EWM ($V=V_5$) Grid loss for TEC with yaw system	Abnormal
7) Parked with fault	7.1	1,10 (ULS) 1,00 (SLS)	ETM U = *mean spring* worst direction from DLC 6.1a	ESS $H = H_{m1}$ worst direction from DLC 6.1a	EWLR	Wind: EWM ($V=V_1$)	Abnormal
	7.2	1,35 (ULS) 1,00 (FLS) 1,00 (SLS)	NTM $U_{in} \leq U \leq U_{out}$ flood, ebb, OE	NWH $H = H_{m1}$	associated tidal height	grid loss	Normal
8) Transport, installation and maintenance	8.1	1,35 (ULS) 1,00 (SLS)	To be specified by the manufacturer				Transport
	8.2	1,10 (ULS) 1,00 (SLS)	ECM U = *mean spring*$_1$ flood, ebb, OE	ESS $H = H_{m1}$ 30° steps	EWLR	Locked state	Abnormal

The following abbreviations are used in Table 8:

ESS	extreme stochastic sea state (see 6.2.2.4)
ETM	extreme turbulent current model (see 6.2.3.7)
EWH	extreme steady wave height (see 6.2.2.5)
EWM	extreme steady wind model (see 6.3.4)
EWLR	extreme water level range (see 6.2.4.3)
OCM	normal steady current model (see 6.2.3.5)
OSS	operational sea state (see 6.2.2.2)
NTM	normal turbulent current model (see 6.2.3.7)
OWH	operational wave height (see 6.2.2.3)
NWLR	normal water level range (see 6.2.4.2)
OE	maximum allowable orientation error

7.3.7.3 Normal operation with fault (DLC 2.1 to 2.3)

Any fault in the control system (including control induced failures that lead to uncontrolled excitations) as well as faults causing trigger of the safety system or any fault in the PTO unit (e.g. generator short circuit in electrical systems) that is significant to the MEC loading shall be assumed to occur during power production. It may be assumed that independent faults do not occur simultaneously. The designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for fatigue damage associated with the long-term distribution of metocean parameters.

For DLC 2.1, the occurrence of a fault in the control system shall be analysed. Exceedance of the limiting values of the control system (over-speed, stroke length limitation, etc.) shall be investigated. These faults shall be considered as normal events.

For DLC 2.2, the occurrence of faults triggering the safety system or faults in the PTO that are considered to be rare events shall be analysed. Exceedance of the limiting values for the safety system (over-speed, stroke length limitation, overpower, short circuit, vibrations, shock, runaway of the blade pitch, failure of a braking system, etc.) shall be investigated. These faults shall be considered as abnormal events.

If a fault causes an immediate shut-down or the consequent loading can lead to significant fatigue damage, the probable number of shut-downs and the duration of this extraordinary design condition shall be considered.

For DLC 2.3, accidental events are considered.

7.3.7.4 Start-up (DLC 3.1 to 3.2)

This design condition includes all events resulting in loads on the MEC during the transitions from any standstill or idling condition to power production.

For all start-up and shutdown procedures, the probable number of events shall be considered. Normal sea state (OSS) conditions shall be assumed for WECs and the turbulent current model (NTM) shall be considered for TECs and RECs. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site.

7.3.7.5 Normal shut-down (DLC 4.1 to 4.2)

This design condition includes all the events resulting in loads on the MEC during normal transitions from power production to a stand-by condition (standstill or idling).

If applicable, further shutdown procedures shall be taken into account due to site-specific requirements, such as shadow criteria or conditions for installation within a MEC array (curtailment strategy).

7.3.7.6 Emergency shut-down (DLC 5.1)

This design condition covers manual actuation of the emergency shutdown system. For this load case, the PTO unit shall be brought to a standstill (or idling in case of MECs without braking devices).

7.3.7.7 Parked during survival conditions (DLC 6.1 to 6.2)

For this design condition, the PTO is in standstill or idling mode. For some designs, the MEC may be operational and connected to the electrical grid. Extreme environmental conditions with a return period of at least 50 years shall be considered for this design condition.

Either the steady current model or the turbulent current model shall be used. If the turbulent current model is used for TECs, the response shall be estimated using a full dynamic simulation. If the steady current model is used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

Additionally, either regular waves or irregular sea state shall be considered. If a stochastic sea state is considered, the response shall be estimated using a full dynamic simulation. If regular waves are used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

Stochastic waves are recommended for global hydrodynamic loads and motions, with the appropriate control and PTO settings. Regular waves are more appropriate for specific phenomena, such as slamming and wave breaking.

The 50-year return period of the significant wave height for WECs and the 50-year return period of the mean current speed for the TECs shall be considered.

7.3.7.8 Parked during normal conditions (DLC 6.3)

For this design condition, the PTO unit is in stand-by mode (standstill or idling) in normal environmental conditions.

Irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each normal sea state shall be selected, together with the associated mean current speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The designer shall ensure that the number and resolution of the normal sea states considered are sufficient to account for fatigue damage associated with the long-term distribution of metocean parameters.

7.3.7.9 Parked with an idling fault (DLC 7.1 to 7.2)

This design condition considers deviations from normal behaviour of a parked MEC resulting from the occurrence of a fault in the PTO unit. If any fault produces deviations from the normal behaviour of the MEC in parked conditions, the possible consequences shall be considered. The designer shall consider parking failure, which may include the inability to park during severe conditions.

The fault condition shall be combined with extreme environmental conditions and a return period of 1 year.

If a grid failure may occur and no backup energy system or redundant electricity supply is provided, the behaviour of mechanical brakes and the safety system shall be considered in the load assumptions. The probability and the possible duration of such failures shall be investigated and considered. The safety of the MEC shall be independent of the grid.

Either a steady or turbulent current model shall be used for design conditions. If the turbulent current model is used, the response shall be estimated using a full dynamic simulation. If the steady current model is used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

Additionally, either regular waves or irregular sea state shall be considered. If irregular sea state is considered, the response shall be estimated using a full dynamic simulation. If the regular waves are used, the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response.

The 1-year return period of the significant wave height for WECs and the 1-year return period of the mean current speed for TECs shall be considered.

7.3.7.10 Transport, installation and maintenance (DLC 8.1 to 8.2)

Long periods where the MEC is not fully installed or is without grid connection shall be considered. Although the period to be considered shall be case-specific, a period of 3 months may be used as a guide.

The maximum permissible significant wave height and/or current speed for vessel operations near the MEC installation shall be stated in the Operation and Maintenance (O and M) manual. Any areas where vessels are not permitted to operate in close proximity shall also be specified in the O and M manual.

See Clause 12 for additional information on transportation, installation and maintenance.

7.3.7.11 Loss of stability, watertight integrity, leakage

Refer to DNV-OS-C301, Stability and watertight integrity or other suitable standards that cover stability and watertight integrity as far as applicable to a MEC. When the device is manned these considerations are particularly important.

Temporary phases such as transportation to site, cofferdams used for access, installation or removal may require a marine operations assessment (see ISO 19901-6). Additional guidance is provided in Clause 12.

7.3.7.12 Loss of station keeping

For MECs that are held in position by mooring systems, the condition after loss of station keeping shall be considered. IEC 62600-10 provides guidance on the design of mooring systems.

7.3.7.13 Earthquake, tsunami

The loading caused by sub-sea earthquakes shall be taken into account in regions at risk of seismic activities. The investigation of earthquake-generated loads is based on the combination of the current and wave loads and earthquake acceleration with a return period of 500 years.

The loading caused by earthquakes shall be combined with normal environmental conditions. All relevant load cases shall be taken into account.

Tsunami-type waves resulting from sub-sea earthquakes may have to be considered in particular cases. It will be decided from case to case, depending on the probability of occurrence, whether a tsunami and the resulting loading have to be considered in connection with the design earthquake, or as an accidental load.

8 Materials

8.1 General

This clause provides general principles, engineering guidance and requirements for material selection for all parts of MEC installations. There are many factors that influence material selection for MECs. Consideration shall be given to:

- component shape;
- dimensional tolerances required;
- mechanical properties (static, dynamic and fatigue strength and stiffness, tensile and compressional characteristics);
- corrosion properties (coating selection, temperature, seawater properties, surfaced and submerged, depth);

- effect of combining material systems (possible electrolytic reactions); and
- life-cycle cost (e.g. cost of material, cost of manufacture, cost of maintenance and cost of installation and removal).

Primary consideration shall address the manufacturing process proposed for candidate material systems.

8.2 Material selection criteria

Only suitable materials with documented mechanical properties shall be used for the force- and moment-transmitting components of a MEC. Materials chosen shall be matched to the demands to be made on the device, particularly the type of load (i.e. static, shock, or oscillating), environmental conditions and component geometry. Clause 9 addresses partial safety factors for material that take into account uncertainties of material physical properties.

Required design analyses and material tests shall be determined by the risk-based assessment outlined in Clause 5 and guidance provided in Clause 9. The type and extent of material testing depends on the importance of and stress on a component and on the variability associated with the manufacturing process.

A material with suitable fracture toughness for the actual design temperature and thickness shall be selected. Fracture toughness is dependent on temperature and material thickness. For metals, fracture toughness in the weld and the heat-affected zone is also very dependent on the welding procedure. For composite structures, special attention needs to be paid to secondary bonding.

Cyclic wave or machinery loads can induce mechanical vibrations that can lead to early failure. The ability of structural material systems to passively mitigate structural vibration (damping characteristics) shall be considered.

The corrosion and biofouling resistance, density, coefficient of thermal expansion, thermal conductivity, electrical resistivity, and magnetic properties and resistance to UV exposure of candidate materials systems shall be considered based on their importance to the device design and operation. When combining dissimilar materials within a structure, special attention shall be paid to the compatibility of physical properties (especially thermal expansion and galvanic potential).

The fatigue strength, crack initiation and growth, effects of loading rate, frequency (e.g., low cycle, high cycle), mean stress, notch effects, and biaxial effects of materials considered for MEC construction shall be considered.

Material selection shall take into account the fact that permanent static loads may cause creep (plastic deformation with time), stress rupture, static strength reduction, or stress relaxation (accompanied by a reduction of the elastic modulus).

8.3 Environmental considerations

The environmental impact of long-term deployment shall be considered when selecting MEC material systems. These include hydrolytic resistance and ultra violet radiation susceptibility. Empirical data or accelerated test methods shall be used to characterize materials.

Structural materials above the lowest waterline shall be selected based on service temperatures equal to the lowest daily mean temperature for the area where the unit is to operate. External structures below the lowest waterline need not be designed for service temperatures lower than 0 °C (32 °F). A higher service temperature may be accepted if adequate supporting data can be presented relative to the lowest average temperature applicable to the relevant actual water depths. The effects of solar gain on structures above the water shall also be considered.

In general, materials that have shown to be benign in a marine environment shall be selected for deployed devices. When hazardous materials shall be used, a hazard risk assessment and mitigation plan shall be developed. Substances that biomagnify up the aquatic food chain shall be avoided. These include heavy metals, such as cadmium, mercury, lead and polychlorinated biphenyls (PCBs).

Specific substances that are deemed detrimental to the marine environment are listed in the Annexes of the *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter*, 1972 known as the *London Convention*.

Consideration shall be given to the possible detrimental environmental consequences should the device experience catastrophic failure at sea. This includes both material components that sink and those that remain at the ocean's surface.

Any component permanently exposed to seawater where efficient cathodic protection (see Annex A) cannot be ensured shall be fabricated in materials immune to corrosion in seawater. Exceptions are components where corrosion can be tolerated. Material selection should take into account the probability and consequence of component failure.

8.4 Structural materials

8.4.1 General

Structural materials are defined as the materials used to fabricate the device's primary structure and foundation. Materials used for secondary structure, such as equipment foundations and mechanical elements are also covered by this subclause.

8.4.2 Metals

8.4.2.1 General

The primary metal used for offshore structures is carbon steel, although stainless steel may be used in oxygenated environments and aluminum for weight-critical applications. Other non-ferrous metals may be suitable for device components.

8.4.2.2 Carbon steel

Selection of steel shall be based on design temperature (normally based on lowest daily mean temperature), structural categories (floating units or bottom fixed units) and plate thickness. ISO 19902 specifies methodologies for classification of steel properties and requirements for inspection and testing during fabrication.

The essential requirements for carbon (structural) steel are strength, toughness and weldability. Strength shall be determined by tensile testing of specimens and the toughness shall be determined by fracture toughness testing.

Fabrication and welding of steel members shall be carefully qualified through non-destructive testing (NDT), mechanical tests and welder qualification procedures. Test specimens shall reflect the production weld procedure, including weld orientation.

8.4.2.3 Stainless steel

Stainless steels generally exhibit outstanding corrosion resistance but can be subject to corrosion under certain environmental conditions. Strength and corrosion performance varies for different types of stainless steel and heat treatments. Consideration shall also be given to the risk of galvanic corrosion of adjacent materials, particularly carbon steel and aluminum.

NOTE 1 Corrosion resistance can be adversely affected if the component is used in a non-oxygenated environment.

NOTE 2 According to the International Stainless Steel Forum (ISSF), Austenitic stainless steel grades 1.4401 (AISI 316) and its derivatives are suitable for coastal service environments, splash zone applications and intermittent submersion in seawater. Although 1.4401 and its derivatives were once known as "marine grade" stainless steel, they are no longer recommended for permanent contact with seawater. Superaustenitic stainless steels containing 6 % molybdenum are now recommended for permanent immersion in seawater. Duplex stainless steels (e.g. 1.4462/ASTM S31803) may be used in brackish waters (eg estuaries where the chloride content of the water is less than that of the open sea). Superduplex stainless steels (e.g. 1.4410/ASTM S32750) may also be used in direct and prolonged contact with seawater (e.g. in offshore oil platforms).

8.4.2.4 Aluminum

Only aluminum alloys that are suited to the marine environment shall be used. Proper processing and suitable corrosion protection shall be applied in order to prevent contact corrosion. Stress corrosion cracking shall be minimized by using plate with greater than 3 % manganese (except in high heat applications).

Hardened aluminium alloys suffer from a reduction in strength in the heat affected zone after welding. Special attention to joint details, filler materials, weld procedures and post-weld heat treatment is required when welding aluminum alloys.

Consideration shall be given to aluminum anodizing, an electrochemical process that provides a durable corrosion resistant, anodic oxide finish.

8.4.3 Concrete

In a hostile environment such as seawater, special attention shall be paid to ensure the long-term durability of concrete structures. Concrete durability is dependent on using appropriate materials and design considerations. In particular, designs shall consider the likelihood of crack propagation occurring when members are in service.

The composition and processing of concrete shall be in accordance with ISO 19903. The desired material compressive strength shall always be specified. In addition, tensile strength, modulus of elasticity and fracture energy shall also be specified if the structure is subject to these types of loads.

8.4.4 Composites

8.4.4.1 General

Composite materials are sometimes referred to as fibre-reinforced plastics, or FRP. These heterogeneous materials contain fibrous reinforcement materials that are encapsulated in either a thermoset (reaction cured) or thermoplastic (solidified upon cooling) resin system. The architecture and orientation of reinforcing materials shall be selected to resist anticipated loading. Process parameters influence material mechanical properties and shall be considered in conjunction with material selection.

The strength of composite materials can degrade with moisture absorption. The designer shall consider sealing laminates (especially edges) to avoid moisture intake and using an appropriate design margin to account for this effect. Epoxy barrier coatings have proven to be among the best sealing agents, but require additional UV protection.

The selection of composite materials shall be based on a thorough evaluation of the functional requirements for the specific application. Dependent upon the application, properties to be evaluated include:

- physical and mechanical properties;
- thermal stability and ageing resistance at specified service temperature and environment;
- thermal expansion;
- electrical conductivity;
- liquid diffusion; and

– control of manufacturing process.

When selecting composite materials, design for cyclic loads shall consider reduction of elastic properties as a result of matrix cracking. The design of composite components and development of device FMECA shall consider failure modes that may not be apparent using only visual inspection.

8.4.4.2 Laminates

Laminates shall be specified by designating each ply by type and orientation in the stack, as well as resin system and fibre volume. The mechanical material properties needed for design shall be obtained using the ISO test standards shown in Table 9. Test specimens shall reflect the as-built composite component.

Table 9 – ISO test standards for composite laminates

ISO Standard	Description
ISO 527	Plastics – Determination of tensile properties
ISO 13003	Fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions
ISO 14126	Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction
ISO 14125	Fibre-reinforced plastic composites – Determination of flexural properties
ISO 14129	Fibre-reinforced plastic composites – Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the ±45° tension test method
ISO 14130	Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method
ISO 15024	Fibre-reinforced plastic composites – Determination of mode I interlaminar fracture toughness, G_{IC}, for unidirectionally reinforced materials

Due consideration shall be given to take into account the effect of environment on properties. The combination of water and high temperature may be more critical than the individual effects of temperature and water. For complex parts, destructive testing of representative structure is strongly recommended.

8.4.4.3 Sandwich structures

A sandwich structure is made up of a lightweight core embedded between two FRP laminate faces (or skins). Sandwich laminates are very efficient for resisting out-of-plane loads, such as hydrostatic and hydrodynamic forces. However, sandwich laminates have more failure modes than solid laminates and these failures may be more difficult to detect with visual inspection. Good skin-to-core bonds and maintenance of watertight integrity shall be verified with manufacturing quality assurance documentation. Special attention needs to be paid to the thickness of the outside skin of sandwich structures assuring that they have sufficient thickness to resist impact, abrasion and puncturing.

8.4.4.4 Mechanical and physical properties

a) Static properties – The static properties after exposure to long term loads and environmental conditions may be more representative of the design strength than the static properties of a new material. Static properties are generally assumed to be identical to quasi-static properties, measured at a testing strain rate of about 1 % per minute. If loading rates in the component differ from this rate, tests shall be made at the relevant rates or corrections of the data shall be considered.

b) Properties under long term static and cyclic and high rate loads – Creep behaviour of the composite sandwich structure, stress rupture under permanent static loads, static strength reduction due to permanent static loads, stress relaxation, change of modulus of elasticity under cyclic loads, cycles to failure under fatigue loads, static strength reduction due to cyclic loading, and effect of high loading rates due to shock loads/impact shall be documented if relevant to the application.

c) Other properties including thermal expansion coefficient, swelling coefficient for water or other liquids, diffusion coefficient, thermal conductivity, friction coefficient, wear resistance and the associated effects shall be considered as applicable.

d) Influence of the environment on properties – Due consideration shall be given to take into account the effect of the environment on laminates and core materials. The fibre/matrix interface can have an important influence on the environmental resistance. The interface properties are influenced primarily by the type of fibre, the sizing, the matrix, and the processing conditions.

e) Influence of process parameters – Changes to the process parameters in the production of composite laminates may influence some or all material parameters. A re-qualification of the materials data shall be done if the production process is not similar to the original process.

8.5 Compatibility of materials

When different structural materials are used in combination, attention shall be given to isolate materials that may create electrolytic corrosion (see Annex A), such as dissimilar metals (even of the same alloy) or metal – carbon fibre laminate combinations. Particular care shall be taken when small components can act as anodes in conjunction with surrounding dissimilar materials. Careful attention shall also be paid to matching material strain characteristics and thermal expansion coefficients.

9 Structural integrity

9.1 General

When determining the structural integrity of elements of a MEC, national or international design codes for the relevant material may be employed. Special care shall be taken when partial safety factors from national or international design codes are used together with partial safety factors from this technical specification. It shall be ensured that the resulting safety level is not less than the intended safety level in this technical specification.

Material models consisting of relations between forces or stresses and deformations (i.e. constitutive relationships) shall be formulated. The variables in such relations, including modulus of elasticity, yield limit, and ultimate strength shall be considered as uncertain quantities. They may be time dependent or space dependent

A material property can be represented by a characteristic value f_k, which corresponds to a fractile of a statistical distribution of the particular property of the material, specified by relevant standards and tested under specified conditions.

9.2 Material models

Structural materials shall be modelled by functions and parameters (f_k, material properties) describing stress-strain relationships. Corresponding model uncertainties shall be taken into account.

The characteristic material property generally corresponds to a specified fractile of the statistical distribution. If higher values govern the design, the characteristic value can be defined as the value below which 95 % of the values are expected to fall.

9.3 Partial safety factors for materials

Material partial safety factors, γ_m, account for uncertainties associated with the variability of the structural strength. The partial factors for materials shall be properly determined in consideration of adverse variations in strength from characteristic values, variations between properties in specimens and actual structures, the influence of properties on limit states, changes in properties with time, and differences between real characteristic values and published values.

The partial safety factors for materials used in this specification take account of:

- possible unfavourable deviations/uncertainties of the strength of material from the characteristic value;
- possible inaccurate assessment of the resistance of sections or load-carrying capacity of parts of the structure;
- uncertainties in the geometrical parameters; and
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens.

These different uncertainties are sometimes accounted for by means of individual partial safety factors but in this specification the material related factors into one factor γ_m.

Partial safety factors for materials shall be determined in relation to the adequacy of the available material properties test data.

9.4 Design of steel structures

9.4.1 General

The ultimate strength capacity of steel structural elements in yielding and buckling shall be assessed using methodologies outlined in ISO 19902. Sufficient global analyses of the structural system shall be performed to allow subsequent assessment of structural components. The strength capacity of structural components shall be checked considering both excessive yielding and buckling. All structural analyses performed shall simulate, with sufficient accuracy, the action effects for the limit state being considered.

9.4.2 Steel partial safety factors

The partial safety factor for steel accounts for uncertainty with material properties (e.g. Young’s modulus, yield strength, ultimate tensile strength) used and component geometry.

The following ULS partial safety factors shall apply to specific steel structural geometries:

- plate member axial tensile strength, 1,05;
- tubular member axial tensile strength, 1,05;
- tubular member axial compressive strength, 1,18;
- tubular member bending strength, 1,05;
- tubular member shear strength, 1,05;
- hoop buckling strength, 1,25; and
- joints for all primary structural members, 1,05.

Table 10 gives γ_m values for buckling of shell structures.

Table 10 – Material partial safety factors γ_m for buckling

Type of structure	$\lambda \leq 0{,}5$	$0{,}5 < \lambda < 1{,}0$	$\lambda \geq 1{,}0$
Girder, beams stiffeners on shells	1,10	1,10	1,10
Shells of single curvature (cylindrical shells, conical shells)	1,10	$0{,}80 + 0{,}60\lambda$	1,40

where:

$$\lambda = \sqrt{\frac{f_y}{f_E}} \tag{12}$$

f_y is the specified minimum yield stress;

f_E is the elastic buckling stress for the buckling mode under consideration.

The material FLS partial safety factor γ_m for welded and structural steel where the 97,7 % survival probability is used as basis for SN curves is 1,10. This factor may be reduced when warranted by consequence of failure and inspectability issues.

9.5 Design of concrete structures

9.5.1 General

The design of concrete structures shall be performed in accordance with ISO 19903. The design of MEC concrete structures shall be performed according to limit state design and the design shall provide adequate strength in all design conditions.

Design principles shall ensure a durable design in a marine environment. Important in this context are the following:

- the selection and combination of appropriate materials;
- adequate concrete cover of reinforcement, typically a minimum of 50 mm in the splash zone and a minimum of 40 mm elsewhere; for prestressing tendons, a minimum of 90 mm; and
- limitation of crack widths under SLS conditions.

The characteristic resistance of concrete structural elements shall be derived from characteristic values of material properties and nominal geometrical dimensions. Design material properties are obtained by amending the characteristic values by the use of material partial safety factors contained in this subclause.

The strength of concrete is typically characterized as the 28-day compressive strength, defined as a 95 % fractile value found from statistical analysis of tested 150 mm × 300 mm cylindrical specimens.

9.5.2 Concrete material partial safety factors

The partial factors for the materials in reinforced concrete shall be chosen for the limit state considered.

Ultimate limit state values for γ_m shall be 1,5 for persistent and transient loads and 1,2 for accidental loads, unless test data and quality control procedures justify a lesser value.

For components that show a large coefficient of variation for fatigue strength during testing, i.e. 15 % to 20 %, the FLS partial safety factor γ_m shall be increased to at least 1,7.

9.5.3 Reinforcing steel

In general, hot-rolled, ribbed bars of weldable quality and with high ductility shall be used. Galvanized reinforcement may be used where requirements are made to ensure that there will be no reactions with the cement that have a detrimental effect on the bond to the galvanized reinforcement. Stainless steel may be used provided the requirements for mechanical properties of ordinary reinforcement steel are met. A partial safety factor of 1,05 shall be used for steel reinforcement.

9.6 Design of composite structures

9.6.1 General

The structural design of composite structures shall follow the principles prescribed in the EUROCOMP Design Code and Handbook for the Structural Design of Polymer Composites, where ULS partial safety factors shown in 9.6.2 and 9.6.3 are derived. Serviceability limit states for composite structures shall also consider:

- deformations or deflections that affect the performance of the MEC;
- vibration that causes damage to the MEC or that limits its functional effectiveness;
- cracking or delamination of the composite that compromises structural integrity or water-tightness; and
- local composite damage that is likely to lead to loss of durability.

9.6.2 Composite material partial safety factors

The partial safety factor γ_m for material properties, at the ultimate limit state, is given by the formula:

$$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}\gamma_{m4} \tag{13}$$

where:

γ_{m1} reflects the level of uncertainty associated with test values;

γ_{m2} represents the variation in manufacturing process;

γ_{m3} accounts for environmental factors, such as temperature and duration of loading;

γ_{m4} addresses fatigue strength.

Values for value uncertainty, γ_{m1} shall be taken from Table 11, unless more detailed information or test data justifies a lesser value.

Table 11 – Values for test value uncertainty, γ_{m1}

Derivation of properties	γ_{m1}
Properties of constituent materials (i.e. fibre and matrix) are derived from test specimen data	2,25
Properties of individual laminae are derived from theory	2,25
Properties of the laminate, panel or pultrusion are derived from theory	2,25
Properties of individual plies are derived from test specimen data	1,5

Derivation of properties	γ_{m1}
Properties of the laminate, panel or pultrusion are derived from theory	1,5
Properties of the laminate, panel or pultrusion are derived from test specimen data	1,15

Values for manufacturing variation, γ_{m2} shall be taken from Table 12, unless more detailed information or test data justifies a lesser value.

Table 12 – Values for manufacturing variation γ_{m2}

Method of fabrication	γ_{m2}	
	Postcured	Not postcured
Manual chopper gun (spray-up)	2,2	3,2
Automated chopper gun (spray-up)	1,4	2,0
Hand layup	1,4	2,0
Resin infusion	1,2	1,7
Prepreg	1,1	1,7
Pultrusion	1,1	1,7
Filament winding	1,1	1,7

Values for environmental factors, γ_{m3} shall be taken from Table 13, unless more detailed information or test data justifies a lesser value.

Table 13 – Values for environmental factors, γ_{m3}

Operating design temperature °C	Resin heat distortion temperature °C	γ_{m3}	
		Short-term loading	Long-term loading
25 – 50	55 – 80	1,2	3,0
	80 – 90	1,1	2,8
	> 90	1,0	2,5
0 – 25	55 – 70	1,1	2,7
	70 – 80	1,0	2,6
	> 80	1,0	2,2

Values for fatigue, γ_{m4} shall be taken from Table 14, unless more detailed information or test data justifies a lesser value.

Table 14 – Values for fatigue, γ_{m4}

Inspection and access	γ_{m4}	
	Fail-safe components	**Non fail-safe components**
Component subject to periodic inspection and maintenance. Detail accessible.	1,5	2,0
Component subject to periodic inspection and maintenance. Poor accessibility.	2,0	2,5
Component not subject to periodic inspection and maintenance.	2,5	3,0

NOTE Composite structural components are considered fail-safe if their failure does not result in failure of the entire structure or large sections of it.

9.6.3 Joints and interfaces

Structural requirements for composite material joints and interfaces are based on achieving the same level of reliability as the structure. If metal components are part of a joint or interface, the metal components shall be designed to be compatible with the composite structure.

Joints are load-bearing connections between structures, components or parts. The following three basic types of joints shall be considered:

- laminated joints are joints fabricated from the same constituent materials as the laminates that are joined, such as over-laminations, lap joints, and scarf joints – these joints can use either primary or secondary bonds;
- adhesive joints are joints between laminates, cores or between laminates and other materials for example metals that utilize a specialty adhesive matrix; and
- mechanical joints use fasteners and bolted connections.

Material selection and fabrication environment critically affect the durability of structural joints. The effects of time, thermal stresses, fatigue and long-term creep shall be considered for all joints and interfaces.

The ULS partial safety factor γ_{mj} for adhesive joints is given by the formula:

$$\gamma_{mj} = \gamma_{mj1}\gamma_{mj2}\gamma_{mj3}\gamma_{mj5} \quad (14)$$

where:

γ_{mj1} reflects the source of adhesive properties;

γ_{mj2} represents the method of application;

γ_{mj3} accounts for type of loading;

γ_{mj4} addresses fatigue strength.

Values for adhesive joints, γ_{mj} shall be taken from Table 15, unless more detailed information or test data justifies a lesser value.

Table 15 – Values for adhesive joints, γ_{mj}

Adhesive variable	γ_{mj}
Source of the adhesive properties	γ_{mj1}
Manufacturer or textbook values	1,5
Values obtained by testing	1,25
Method of adhesive application	γ_{mj2}
Manual application, no adhesive thickness control	1,5
Manual application, adhesive thickness controlled	1,25
Established application procedure with repeatable and controlled process parameters	1,0
Type of loading	γ_{mj3}
Long-term loading	1,5
Short-term loading	1,0
Environmental conditions	γ_{mj4}
Service conditions outside the adhesive test conditions	2,0
Adhesive properties determined for the service conditions	1,0

10 Electrical, mechanical, instrumentation and control systems

10.1 Overview

MEC electrical, mechanical, instrumentation, protection and control systems include all equipment up to and including the interface at the MEC point of common connection with the grid or other boundary system. The designer shall consider all failures in the electrical, mechanical, instrumentation and control systems that can have critical impacts on the operability and integrity of the MEC using environmental conditions given in Clause 6.

10.2 General requirements

All machinery, electrical, instrumentation and control systems subject to inspection shall be installed and arranged for easy access. All components in a system shall be satisfactorily matched with regard to function, capacity and strength. Relative motions between parts of the machinery shall be allowed for without inducing detrimental stresses. All machinery shall be equipped with control and protection mechanisms necessary for safe operation of the machinery.

Normal operating modes or faults can cause a resonant response from various MEC elements. Therefore, the designer shall carry out a FMECA on electrical, mechanical, instrumentation and control systems to ensure that normal operation or any fault cannot critically increase the resonant response of the element.

10.3 Electrical

10.3.1 General

The MEC electrical system shall comply with the applicable portions of Clauses 4 to 15 of IEC 60204-1:2016 for LV electrical systems and of Clauses 4 to 16 of IEC 60204-11:2018 for MV electrical systems, as well as relevant national standards and local codes.

The design of the electrical system shall ensure minimal hazards to humans as well as minimal potential damage to the MEC and external electrical system during operation and maintenance under all normal and extreme external conditions.

The manufacturer shall state the design standard(s) used. The design of the electrical system shall take into account the fluctuating nature of power generation from MECs.

10.3.2 Electrical system design

The design of the electrical system shall take into account the effects of the marine environment. As a minimum, the following operating conditions shall be considered:

- accelerations and inclinations from device movements;
- temperature;
- humidity;
- salinity;
- vibration levels;
- slamming/shock loads (e.g. wave slamming, sloshing of tank contents, local structural vibration, impact, excitation from hydraulic, pneumatic and mechanical stresses, etc.);
- presence of (salt) water;
- electromagnetic interference and compatibility;
- electrical contingencies (e.g. upon short circuits/tripping of circuit breakers);
- presence of explosive atmosphere (e.g. from trickle charging of batteries); and
- atmospheric pressure (may fluctuate in sealed compartments).

10.3.3 Protective devices

The over-voltage protection shall be designed in accordance with the requirements of IEC 62305-4. MEC electrical systems shall include suitable devices that ensure protection against malfunctioning of both the MEC and the external electrical system. This shall be done in accordance with IEC 60204-1:2018,11.1.2 safety systems, and 7.4 through 7.10. Examples of such devices are fuses and circuit breakers for over-current protection, and thermistors for temperature. The functional safety of electrical, electronic and programmable electronic safety-related systems shall be in accordance with IEC 61508.

10.3.4 Disconnect devices

It shall be possible to disconnect a MEC electrical system from all electrical sources of energy, including induced currents from subsea cabling, as required for maintenance or testing. Circuit breakers at the shore facility shall include a rack-out position for assurance of full isolation. Semiconductor devices shall not be used alone as disconnect devices.

Where lighting or other electrical systems are necessary for safety during maintenance, auxiliary circuits shall be provided with their own disconnect devices, such that these circuits may remain energised while all other circuits are de-energised.

Any part of the electrical system that can excite the MEC generator shall automatically be disconnected from the grid and remain safely disconnected in the event of loss of power at the MEC, subject to local grid requirements.

Isolation from all sources of supply will be particularly important when using a permanent magnet or other types of generator capable of self-excitation where work or testing on the device, subsea cable system or connectors is likely to require electrical isolation from the generator as well as from the shore supply. Isolation requirements shall be considered at the design stage. If remotely operated equipment is selected for isolation purposes, it will require careful design to ensure firstly that it can be confirmed that the remote equipment has operated correctly to provide isolation and secondly that the equipment can be secured in the isolated position.

10.3.5 Earth system

The design of a MEC shall include a local earth electrode system to meet the requirements of IEC 60364-5-54 and local electrical code authorities. The installation, arrangement, and choice of earthing equipment (earth electrodes, conductors, bars, and main terminals) shall match the application of the MEC for lightning protection. Provisions shall be made in any electrical system operating above 1 000 VAC or 1 500 VDC for earthing during maintenance.

10.3.6 Lightning protection

The lightning protection of a MEC shall be designed in accordance with IEC 62305-3. All MEC protection system circuits and surge protection devices that could possibly be affected by lightning and other transient overvoltage conditions shall be protected according to IEC 61643-11.

It is not necessary for protective measures to extend to all parts of the MEC, provided safety is not compromised.

10.3.7 Electrical cables

All conductors shall consist of plain or metal-coated annealed copper according to IEC 60092-350 and shall be stranded according to IEC 60228 class 2 or class 5.

NOTE The use of other conductor metals may be considered in applications where copper cannot be used for chemical reasons.

The conductors of a MEC shall be rated for the particular application with respect to the temperature, voltage, current, environmental conditions and exposure to degraders (oil, UV exposure) in accordance with IEC 60204-1:2016, Clause 13 and Clauses 13 – 14 of IEC60204-11:2018.

Mechanical stresses, including those arising from twisting and bending that the conductors may be subjected to during installation and operation shall be considered. Conductors shall be installed in accordance with IEC 60204-1:2016, Clause 14 and Clauses 13 – 14 of IEC60204-11:2018.

Where there is a probability of cables being damaged, armoured cables or conduits shall be used.

Offshore cabling shall be protected by suitable means to avoid damage by mechanical overstrain from the weight of the suspended cable, fatigue from repeated bending and twisting caused by tidal or wave movements, elasmobranch attack (sharks, rays, etc.) and marine growth.

The mechanical integrity of the offshore cabling and its connections (including other subsea cables used for control, services or instrumentation) should be given specific consideration if any of the following circumstances apply to any part of the installation:

- any part of the installation floats;
- any part of the cable in the water column is self-supporting;
- the installation requires repeated bending and/or twisting of the cable;
- any part of the cable is subjected to cyclic mechanical loading;
- any part of the cable has the potential to rub against the seabed or other hard surface;

- the design is such that under normal or fault conditions any part of the cable is required to transmit a force comparable to or greater than its self-weight; or
- any part of the cable is exposed to tidal or wave induced currents.

The limits of the protection shall be designed so that any over-voltage transferred to the electrical component will not exceed the limits established by the component insulation levels.

10.4 Mechanical

10.4.1 General

The design and function of rotating machines shall generally comply with the requirements of IEC 60092-301. For basic machine design, the relevant parts of IEC 60364 apply.

The operating environment will require some different considerations from normal mechanical systems. For example, pollution from leakage shall be minimized or designed out if possible. Also, given the difficulty of access for maintenance, consideration should be given to designing for higher levels of availability. The MEC mechanical system shall be capable of operating at all inclinations both static and dynamic that the device could experience. If there are any mechanical systems that are part of a safety system, these shall remain operating at all inclinations both static and dynamic that could occur if the device is damaged.

10.4.2 Bearings

Plain bearings may be used and may operate with various fluids on the contact surfaces. Due to the low speeds of many systems, care should be taken to establish if a hydrodynamic wedge is present under operating conditions.

10.4.3 Gearing

Gear loading shall consider all design load cases (as defined in Clause 7) that provide static or dynamic loading to the gearing. It is noted that some gearboxes may be subject to additional loads in the form of forces and bending moments. These can be considered at the gearbox input shaft and the gearbox output shaft for the gearbox strength calculations. These loads are in addition to normal torque transmission loads.

10.5 Piping systems

10.5.1 General

The materials used for components within MEC piping systems shall be suitable for the fluid and the service for which the components are intended. The component material, sizing and construction details shall follow the design concepts laid out by a recognized international standard.

The risk assessment of the piping systems shall consider, as a minimum, the following:

- pollution arising from leakages;
- what level of redundancy is necessary;
- routing of piping and compartment penetration; and
- possible failures of control or alarm systems.

10.5.2 Bilge systems

The risk assessment of the bilge system shall consider, as a minimum, the following:

- clogging of bilge suctions;
- failure of valves leading to leakage or flooding; and
- leakage rates.

10.5.3 Ballast systems

Buoyancy tanks and ballast systems can be used to expedite the submerging and lifting of MECs or to reduce structural loads during operation of the MEC.

The risk assessment of the ballast system shall include the failure of valves leading to leakage or flooding.

10.5.4 Hydraulic or pneumatic systems

Where MECs use hydraulic or pneumatic energy systems, these shall be so designed, constructed and equipped as to avoid all potential hazards associated with pressurized working fluids or gases.

The risk assessment of the hydraulic or pneumatic systems shall consider the consequence of rupture and the probability of leak detection.

Means of isolating or discharging stored potential energy shall be included in such systems. All pipes and/or hoses carrying hydraulic oil or compressed air and their attachments shall be designed to withstand or be protected from potential internal and external stresses.

Leakage from hydraulic or pneumatic systems shall be detected by e.g. level sensors in the fluid tank and should not impede the ability to bring the MEC to a safe condition.

10.6 Instrumentation and control system

10.6.1 General

The designer shall consider casualties that can be induced by the control system.

MEC systems that are intended to operate near resonance shall have a control means to reduce motions during access for inspection and maintenance.

The control system can influence resonant response of both structural and mechanical elements (both passively and actively), therefore the designer shall carry out an FMECA for the control system to ensure that there are no failure modes which can increase the resonant response of either the structural or mechanical elements.

10.6.2 Locking devices

Some MECs may have locking mechanisms to prevent unintended movement of parts (such as a rotor during maintenance). The strength analysis of the locking system shall consider the maximum rotor lock torque resulting from the relevant design loads as outlined in Clause 7. The strength analysis shall include all load-transmitting parts of the locking mechanisms.

10.6.3 Protection against unsafe operating conditions

The designer shall demonstrate that all necessary precautions have been taken to prevent the MEC transitioning into an unsafe condition or state due to conditions such as, but not limited to:

- loss of the control system;
- electrical and mechanical component failure;
- loss of onshore communication with the device; and
- loss of load.

If an unsafe condition or state occurs, the marine converter control system or redundant control system shall implement a safe and controlled stop of the device to a safe condition.

10.7 Abnormal operating conditions safeguard

The designer shall demonstrate that all necessary precautions have been taken to prevent the MEC transitioning into an abnormal condition or state due to conditions such as, but not limited to:

- loss of the control system;
- electrical and/or mechanical component failure;
- loss of telemetry communications;
- loss of load;
- overspeed;
- loss of station keeping;
- allision;
- sinking; and
- vandalism.

If an abnormal condition or state occurs, the MEC electrical, mechanical and control system shall transition to an offline safe condition or state. The MEC shall be designed for loads arising from such abnormal condition.

The machinery shall be so arranged that a single inadvertent operational error won't lead to reduced safety of the device or personnel.

11 Mooring and foundation considerations

11.1 General

This clause includes additional requirements for the consideration of MEC station keeping, including the design of the geotechnical interface. The adequacy of the station-keeping systems for moored floating structures shall be demonstrated by adhering to the requirements of IEC TS 62600-10. For moored MECs, the mooring attachment point shall be designed not to fail before mooring system elements. Refer to ISO 19901-4 for further guidance on geoscience and foundation engineering for MECs with fixed foundations.

11.2 Unique challenges for wave energy converters

a) Wave-induced response

Wave energy converters may have structures designed to react to wave loads and induce a motion response to absorb energy from the prevailing wave climate. This structural loading and motion response shall be resisted by the foundation and moorings systems in extreme wave conditions.

b) Shallow deployment sites exposed to ocean wave climates

In shallow water, there is significant wave-induced hydrodynamic shear at the seabed with the consequent effect of:

- loading on seabed foundation structures; this is especially the case for low-density gravity base structures (e.g. self-installing gravity base structures), where such large volume structures can attract significant wave loading on the foundation itself;
- lack of stable sediment accumulations for drag embedded anchors owing to seabed scour; and
- severe scouring of the seabed and undermining of foundations.

11.3 Unique challenges for tidal energy converters

Where TECs are deployed in tidal streams exposed to ocean waves, similar issues to those described above for wave energy converters apply, especially for floating installations. The issues of lack of seabed sediment due to strong currents exist, as sediments can be mobilized and transported away from the site and rocky seabeds, where large boulders are common geotechnical issues. Wave-induced loading on foundation structures may also be significant.

11.4 Fixed structures

In general, the foundation design and analysis shall comply with ISO 19900. Geotechnical and foundation specific requirements that are applicable to a broad range of offshore structures are provided in ISO 19901-4. The design of piled foundations that have a traditional association with fixed steel structures is detailed in ISO 19902. Particular requirements for the design of shallow gravity foundations that have a traditional association with fixed concrete structures are detailed in ISO 19903. Where appropriate, the principles for concrete gravity bases can also be applied to steel gravity base solutions.

The foundation shall be designed to carry static and dynamic (repetitive as well as transient) actions without excessive deformation or vibrations in the MEC. Special attention shall be given to the effects of repetitive and transient actions on the structural response, as well as on the strength of the supporting soils. The possibility of movement of the sea floor against foundation members shall be investigated. The loads caused by such movements, if anticipated, shall be considered in the design.

Loads acting on the foundation during transport and installation shall be taken into account (see Clause 12). For piled structures, an analysis shall be undertaken to calculate the fatigue damage sustained by the pile as it is driven into the seabed. The fatigue analysis shall consider the loads associated with pile driving impact, taking account of the structural dynamics of the pile and stress increases due to the details of the pile design and the pile driving process.

11.5 Compound MEC structures

Compound MEC structures combine the function of stationkeeping with other MEC functions, such as:

- the provision of a reaction to PTO forces that permits energy conversion from wave induced or current induced loads;
- where controllable power conversion machinery (e.g. hydraulic cylinders, linear generators, hose-pump elements) transfers the environmental loads from the primary wave-activated structure to the anchor reference point, forming an essential part of station-keeping for a large portion of the MEC structure; and
- attitude control – a controllable actuator delivers loads between the foundation and the MEC to affect optimal orientation of the structure to enhance energy conversion.

12 Life cycle considerations

12.1 General

This clause covers MEC design conditions that may be experienced over the life of the device exclusive of normal operations, which are covered in Clause 7.

The designer shall consider the entire life cycle of the MEC and the effects of both frequent and infrequent operation. Fabrication, transportation, installation, inspection and maintenance, and decommissioning phases for MECs are significantly different than the operational phase. Each of these phases can impose loads that can affect the engineering integrity of the MEC. Careful planning is required to provide an appropriate level of protection against damage from all hazards that may lead to failure of the MEC, injury to personnel or damage to the environment. National and international regulations on personnel safety and protection of the environment shall govern marine operations. Refer to ISO 19901-6 for guidance on marine operations.

12.2 Planning

The assembly, transportation and installation of MECs and associated equipment shall be planned in order for the work to be carried out safely. As appropriate, the planning shall include:

- detailed drawings and specifications of the work and a quality assurance plan;
- procedures for safe execution of activities that have to do with foundation and underwater construction (for example pile driving, laying of scour protection and cable laying) especially taking into consideration local weather conditions, time of year, ocean and tidal currents, wind condition and seasonal storm situations;
- procedures for installation of anchors and moorings lines;
- health, safety and environmental rules for offshore work, including safety rules for diving and work in enclosed spaces; and
- evacuation procedures, including procedures for monitoring of wind conditions and sea states to determine when evacuation is in order.

12.3 Stability and watertight integrity

12.3.1 General

During the life of a MEC, the device may be floating, submerged or semi-submerged. It is critical that the stability and watertight integrity of the device be maintained during all these conditions. Refer to DNV-OS-C301 for guidance on stability and watertight integrity.

12.3.2 Stability calculations

An allowance shall be included in the stability calculations to account for uncertainty in mass, buoyancy, location of centre of gravity, density of ballast and ballast water, and density of seawater. Allowance for ice accumulation on exposed structures should also be taken into account if there is a potential for air temperature to be below 0 °C.

If motion responses in various floating stages (such as construction afloat, towing and installation) can cause loss of freeboard, stability or station-keeping, model tests and CFD simulations may be warranted in combination with dynamic analyses.

12.3.3 Watertight integrity and temporary closures

The number of openings in watertight boundaries shall be kept to a minimum. Weathertight hatches, which can be submerged or exposed to slamming or sloshing, should be designed for such actions and suitably verified as fit for purpose. Type and securing of seals and gaskets should be carefully considered. The placement and positioning of watertight hatches shall be done in such manner that during opening and accessing there is no risk of down flooding.

12.4 Assembly

12.4.1 General

A MEC shall be assembled in accordance with the manufacturer's instructions. Inspection shall be carried out to confirm proper lubrication and pre-service conditioning of all components. The adequacy of corrosion prevention measures shall be verified after final assembly.

12.4.2 Fasteners and attachments

The corrosive environment where MECs are deployed shall guide material selection for fasteners and attachments. Threaded fasteners identified as critical shall be checked to ensure proper installation torque. Suitable locking mechanisms shall be used on threaded fasteners subject to vibration.

Post-construction inspection shall be carried out to confirm the adequacy of handling attachment points.

12.4.3 Cranes, hoists and lifting equipment

Cranes, hoists, slings, cables, hooks and other lifting apparatus shall be adequate for safe lifting and handling. Manufacturer's instructions and documentation with respect to installation and handling shall provide information on expected loads and safe lifting points for components and assemblies. All hoisting equipment shall be periodically tested and certified for the rated safe load. Special attention shall be paid to ensure that cranes are not exercised beyond their rated radius for a given load.

12.5 Transportation

A plan to minimize the risk of damage to the MEC, personnel or the environment during transportation shall include:

- weather windows for transportation and installation (see 12.7);
- damage control contingencies and monitoring systems;
- lashing and sea fastening for inertial loads;
- modularity and assembly at sea;
- freeboard of hatches, maintenance openings and risk of down-flooding;
- role of independent surveyors, harbour and coastal pilots;
- launch considerations, including dynamics and irreversible/unstoppable launching procedures;
- clearance of submerged and overhead hazards; and
- transitions in centre of gravity and centre of buoyancy and associated risks of capsizing:
  - physics of floating device;
  - physics of submerged device;
  - physics of bottomed device;
  - transitions between states;
  - limbering of tanks;
  - abnormal hydrostatic pressures;
  - lifts at sea:
    i) snap loads; and
    ii) entrained mass of water;
  - tensioning the mooring; and
  - power cable connections.

12.6 Commissioning

The site of a marine energy facility shall be prepared, maintained, operated and managed so that work can be performed in a safe and efficient manner in accordance with appropriate regulations and permitted requirements. This shall include:

- marking of individual structures, or fields of structures;
- installation of power cables between individual MECs, transformer stations, and shore;
- monitoring of the facility by the operator;
- procedures to prevent unauthorized access, where appropriate; and
- contingency plans to address:

- the possibility of individual MEC units breaking loose and becoming floating or submerged hazards;
- retrieval of lost or loose components;
- loss of vessel or barge control;
- loss of electrical power;
- fire;
- collision;
- pollution;
- leakage;
- structural failure;
- mooring line failure;
- man overboard;
- personnel accidents or medical emergencies, including medical evacuation from remote locations;
- grounding; and
- unexpected water depth limitations or sea floor hazards.

Installation procedures shall provide that at any point, if necessary, work can be curtailed and all assets expeditiously secured without causing danger to personnel or unacceptable loads on the MEC. In the case of a MEC that changes state from floating to submerged or bottomed, appropriate measures shall be taken to control buoyancy and stability and prevent dramatic change of centre of gravity/buoyancy. Critical ballasting and stability control precaution measures shall be included in the installation manual.

12.7 Metocean limits

It can be impractical and/or uneconomical to plan to transport or commission a MEC in extreme environmental conditions. Consequently, there is a need to establish weather windows of minimum duration with specified limits on the metocean parameters during which the marine operations can be performed. Setting the limits too high can lead to unacceptable risk, whereas setting the limits too low can lead to excessive waiting times.

A set of limiting metocean criteria based on the specific MEC transportation and commissioning requirements shall be established. Such criteria shall include, but not be limited to:

- wind magnitude and direction;
- wave height and period;
- current magnitude and direction; and
- swell magnitude and direction.

Other factors and combinations of factors that may need to be considered include:

- combinations of wind, wave and current;
- water level, including tide and surge;
- restricted visibility;
- sea ice, icebergs, snow and ice accretion on topsides and structure, exceptionally low temperatures; and
- tropical storms and local squalls.

12.8 Inspection

12.8.1 General

The requirements for a robust inspection strategy will vary according to the type of MEC and the offshore environment in which it is working. Given the harsh environmental conditions that MECs typically experience, access for inspection and in-situ working may be difficult to achieve in a safe manner, hence it may be necessary to transport the MEC back to shore or harbour for inspection.

The safety of personnel engaged in inspection is paramount. Appropriate risk assessments to eliminate or limit the need to expose personnel to dangerous working environments shall be considered during the design stage. However, since specific guidance on human safety is outside the scope of this document, designers should refer directly to local and national regulations.

Structural integrity monitoring and other diagnostic systems to provide a remote continuous assessment of MEC structural integrity and functionality are encouraged.

12.8.2 Coating inspection

Evaluation of coating condition is primarily performed by visual inspection to determine the need for recoating. A close visual examination will also disclose any areas where coating degradation has allowed corrosion to develop to a degree requiring repair or replacement of structural components.

12.8.3 Underwater inspection

The MEC design should anticipate the need for diver inspection and therefore not include features that may be hazardous to diving personnel. Designers should also anticipate the use of remotely operated vehicles (ROVs) for underwater inspection.

Inspection of cathodic protection systems may include visual examination of anodes and measurements of structure-to-seawater potentials and anode-to-sea water potentials. Safety regulations for diver activities when impressed current (IC) systems are in operation shall be developed.

12.9 Maintenance

12.9.1 General

The requirements for a robust maintenance strategy will vary according to the type of MEC and the offshore environment where it is deployed. The manner in which a MEC is operated and maintained will have a significant impact on its integrity and functionality throughout the intended design life. In order for any maintenance plan to be effective, it shall be considered in a holistic manner throughout the design, construction, commissioning and operation of the MEC.

12.9.2 Maintenance planning

The designer shall give due consideration to the individual subsystems and components that may have a much reduced design life compared to the MEC system. Maintenance strategies to consider include:

- time-based maintenance – where maintenance intervals are prescribed for the MEC system, subsystems, equipment and components. For example, some MECs may require periodical cleaning to control marine growth;
- condition-based maintenance – this involves monitoring the condition of the MEC system, subsystems, equipment and components and maintenance is scheduled when certain conditions are met; and

- risk/reliability based maintenance – where maintenance intervals are determined based on the risk to and reliability of the MEC system, subsystems, equipment or components.

MEC design shall take into consideration the need to remove components requiring maintenance, while ensuring that elements remaining on the seabed require little or no maintenance during their service life. Where electrical, hydraulic or other fixed connections exist between the device and shore, due consideration shall be given to how this connection will be made and broken safely and reliably during the operational life if it is intended to remove the device for maintenance. Electrical connections shall be isolated while maintenance is undertaken.

Maintenance activities can expose workers to a number of potential hazards. The planning stage of maintenance activities shall identify all potential hazards and identify means of reducing or eliminating exposure to these hazards. The maintenance strategy shall identify all local and national health, safety and environmental requirements that may apply to ensure the proposed activities comply.

12.9.3 Maintenance execution

All maintenance activities shall be carried out in accordance with the operations and maintenance (O & M) manual and shall be performed by personnel suitably trained or instructed in this activity. Access for maintenance of a MEC shall be a key consideration during the design stage. Because of the nature of MECs and the harsh environment, it might be necessary to recover the MEC to shore for periodic maintenance. Where on-site maintenance is considered, consideration shall be given to provision of refuge areas for personnel on the MEC. An appropriate risk assessment, or similar, shall be undertaken to determine safe methods of undertaking maintenance work.

An emergency procedure plan shall be defined as part of the O & M manual. The plan shall consider the risk to personnel when there is a fire or apparent risk of structural damage to the MEC or its components.

A strategy for inspection and possible removal of marine growth shall be planned as part of the MEC design. Inspection frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability and performance of the MEC and the extent of marine growth for the site-specific conditions.

Issues surrounding the growth type and any environmental impact of the removal of the growth, for example protected species, will require compliance with local regulations.

12.10 Decommissioning

Removal procedures shall be defined during the design of the MEC. Any removal aids that are integrated into the MEC should be installed at the time of construction, with a design service life exceeding the maximum foreseen operational life of the MEC itself.

Selection of a removal option depends on several environmental, technical and economical parameters, Including:

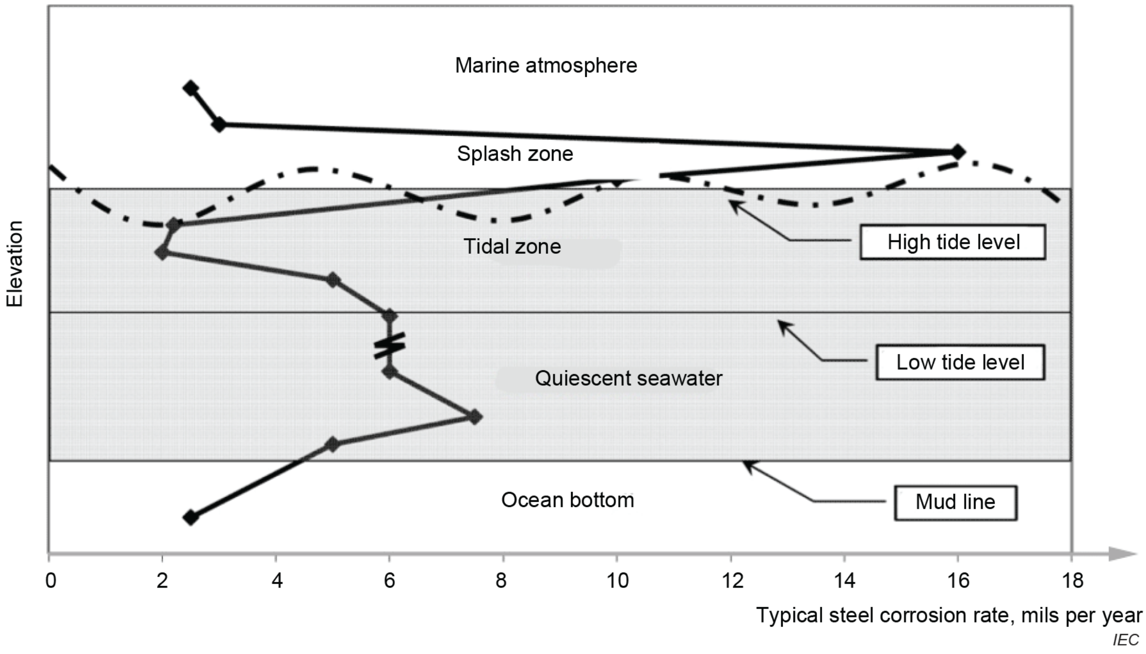
- effect of removal and/or disposal on marine life, navigation and fishing activities;
- regulatory requirements
- technical feasibility and risks; and
- risk to personnel.

Annex A
(normative)

Corrosion protection

A.1 General

As MECs will be working in a highly corrosive marine environment, structural materials shall be suitably protected or the impact of corrosion shall be offset by material thickness corrosion allowances. The designer shall identify which corrosion zones (see Figure A.1) each component of the device will exist within before considering forms of corrosion protection during design. Note that corrosion rates will be higher in tidal environments where scouring is possible. Cost, maintenance required and lifetime of the protection method against corrosion shall be considered.



SOURCE: AULT, J Peter, *The Use of Coatings for Corrosion Control on Offshore Oil Structures*, Journal of Protective Coatings and Linings, Volume: 23, Issue Number: 4, Technology Publishing Company, 2006

Figure A.1 – Profile of the thickness loss resulting from corrosion of an unprotected steel structure in seawater (1 mil = 0,025 4 mm)

A.2 Steel structures

A.2.1 General

Steel structures are subject to direct attack by chlorides in seawater or in the marine atmosphere. Unprotected carbon steelwork will suffer significant degradation within the service life of MEC structures and due consideration shall be given to ensuring adequate durability and performance. The decision on the most adequate method of protection against corrosion shall be evaluated considering inspection regime, position of the structure (or part of) relative to the splash zone, criticality of fatigue and corrosion allowances.

Protection of carbon steel structures is generally achieved by the provision of some combination of sacrificial thickness, an appropriate coating system and/or the application of cathodic protection. The use of appropriately specified stainless steel may also be considered in oxygenated environments.

A.2.2 Corrosion rates

The rate of corrosion of unprotected carbon steel is dependent on a range of environmental parameters including temperature, salinity and the material grade. ISO 11306 gives guidance as to likely corrosion rates in a range of environments. However conditions in the splash zone are likely to be more onerous. Very high corrosion rates may occur in tropical waters and subsea internal heated areas.

The corrosion rates shall be determined based on previous similar service experience in the deployment area. In the absence of accurate information, the basis for design shall define a corrosion rate. Consideration shall also be given to aggressive local corrosion (pitting and grooving). The inspection regime shall confirm the corrosion rates assumed in the design.

Calculations for ultimate and fatigue limit states shall be carried out with the minimum wall thickness expected at the end of the design life. Consideration shall also be given to scour of steel elements in contact with or embedded in the seabed (i.e. piled structures), as very high rates of steel loss can occur in some seabed conditions. Consideration shall be given to ice scoring in arctic waters.

A.2.3 Protective coatings

Reference may be made to ISO 12944 for general guidance as to the design and specification of coating systems. However the specification of specialized marine coatings is not covered in this document and reference shall also be made to coating manufacturers and classification society rules and guidelines. For areas that are not continuously submerged (such as the splash zone), suitable protection shall be provided through the application of protective coatings that have good hydrolytic, abrasion and ultraviolet (UV) resistance. Protective coatings shall be periodically monitored and maintained to ensure proper corrosion control. Consideration shall be given to the use of organic zinc-rich primers, higher build epoxies, and polysiloxane systems to enhance the longevity of applied coatings.

Where coatings are used, consideration shall be given to the rate and extent of deterioration of the coating and the provision of increased demand on the cathodic protection system as a result of this deterioration. If a marine coating is relied upon as the primary protection for a submerged structure, consideration shall be given to provision of a secondary protection system (i.e. cathodic protection) to limit the impact of scratches or other damage to the coating occurring during installation and operation. Also, the potential for the coating to become damaged due to particles in the flow and saltation shall be given adequate consideration.

Enhancement of corrosion processes by marine growth (e.g. through corrosive metabolites), commonly referred to as Microbiologically Influenced Corrosion (MIC), shall be considered. Marine growth may further interfere with systems for corrosion control, including coatings, linings and cathodic protection.

Anti-fouling paint containing the organotin tributylin (TBT) shall not be used in accordance with the International Convention on the Control of Harmful Anti-fouling Systems on Ships.

A.3 Cathodic protection

A.3.1 General

Cathodic protection shall be used for all submerged, metallic materials, except for materials that are immune to seawater corrosion. Submerged MECs can be effectively protected by cathodic protection using galvanic anodes or via impressed current systems. General considerations of cathodic protection are given in ISO 12473. Cathodic protection shall be designed in accordance with EN 12495, for fixed structures and EN 13173, for floating. Where an impressed current system is to be relied upon, sufficient secondary protection shall be provided for the period between maintenance opportunities in the event of system failure.

Cathodic protection is not effective in the splash zone and in these areas an allowance of a sacrificial thickness together with the use of an appropriate protective coating shall be considered. In areas subject to impact or wear, special consideration shall be given to the appropriate choice of coating.

Excessive levels of cathodic protection shall be avoided to minimize the possibility of cathodic disbonding of coatings and hydrogen embrittlement of welds and high strength steels.

For internal flooded steelwork, cathodic protection may be employed either with or without coatings, cladding or corrosion inhibitors.

A.3.2 Closed compartments

Closed compartments can be used to slow corrosion rates for un-protected steel exposed to seawater. The oxygen within the compartment is depleted and limits the amount of corrosion. Careful consideration shall be taken in evaluating the corrosion rates and overall structural integrity of these compartments including:

- volume of oxygen and water within the compartment, for calculation of corrosion rates and pressure effects due to loss of oxygen;
- expected number of openings of the compartment during design life (i.e. during maintenance);
- possible water and air leak paths;
- anaerobic corrosion; Microbial Induced Corrosion (MIC) is increased within oxygen-starved atmospheres;
- build-up of gases if cathodic protection is employed; and
- fatigue.

Closed structural compartments that are not filled with water need no internal corrosion protection if the compartments are completely sealed off by welding, or there is a proven gas tight gasket in any manhole or inspection covers.

A.3.3 Stainless steel

Where provision of cathodic protection or other protection cannot be achieved due to electrical isolation or other reasons, the use of marine grade stainless steel (see 8.4.2.3) may be considered in oxygenated environments.

Consideration shall be given to galvanic corrosion between stainless steel and carbon steel components. In general, small areas of stainless steel in contact with much larger areas of carbon steel (i.e. stainless steel fasteners) are acceptable. Where larger areas of stainless steel are required, appropriate measures of ensuring electrical isolation is required.

A.4 Concrete structures

A.4.1 General

Concrete structures containing reinforcing or pre-stressing steel are vulnerable to chloride-induced corrosion. Relatively small amounts of material loss can lead to significant damage due to the volume of corrosion products generated and protection of embedded steel against chlorides is important to ensure the durability of the structure. Plain concrete elements are not vulnerable to chloride-induced corrosion, although attention shall be paid to any cast-in steel elements.

A.4.2 Provision of adequate cover

The provision of sufficient concrete cover (50 mm) to steel elements is generally the primary means of protection against corrosion as it limits chloride ingress. Use of less porous concrete will reduce the rate at which chloride ions penetrate the concrete and thus extend the protection achieved with a given concrete thickness – this is generally achieved by specification of a higher strength grade.

Minimum concrete cover for corrosion protection is a function of environmental class and sensitivity of reinforcement to corrosion. Characterization of the corrosion environment shall be carried out with reference to ISO 19903.

For partially submerged concrete elements, consideration shall be given to the risk of enhanced corrosion of the reinforcement due to formation of corrosion cells with the exposed reinforcement. In this situation, the use of stainless steel or composite rebar reinforcement or adequate cathodic protection shall be considered.

Concrete exposed to wave borne sand, rocks and sediment in energetic marine environments may be subject to abrasion or scour. Appropriate allowance shall be made for any consequent reduction in the cover to reinforcement over the life of the structure. Careful consideration shall also be given to structural and other sources of cracking that will increase chloride ingress.

A.4.3 Use of stainless steel or composite reinforcement

Reinforcement exposed to seawater or marine atmosphere due to concrete defects, embedment plates, penetration sleeves or other cast in elements will normally require corrosion protection. Consideration shall be given to the use of a suitable marine grade stainless steel (see 8.4.2.3) or composite reinforcement for cast-in or exposed elements. Where the main reinforcement is to be carbon steel, stainless elements shall be electrically isolated from the main body of reinforcement.

In the case of concrete structures that are to be constructed in-situ, consideration shall be given to the likely ingress of air and waterborne chlorides into the concrete mix. The use of stainless steel reinforcement shall be considered in these situations in addition to the provision of adequate cover. The use of stainless reinforcement may also be considered in circumstances where inspection and repair of the concrete elements is likely to be disproportionately expensive or difficult.

A.4.4 Cathodic protection of reinforcement

Corrosion protection to carbon steel reinforcement and cast in elements may also be achieved by the use of an appropriate cathodic protection system. Reference shall be made to ISO 12473, for the design and specification of these systems. Particular care shall be taken when it is intended to protect pre-stressing steel using cathodic protection due to the risk of hydrogen embrittlement. This is a particular risk with impressed current systems.

Where attached or adjacent steelwork is provided with cathodic protection, allowance shall be made for interaction between this and the reinforcing or pre-stressing steel. In particular, attached or adjacent steelwork has in practice frequently been found to be electrically continuous with the reinforcing steel. Appropriate allowance shall then be made for the resulting drain on the cathodic protection system.

A.5 Non-ferrous metals

Non-ferrous metals commonly used in marine applications may be subject to a range of corrosion types. Specification of appropriate material grades and protection systems shall be undertaken with reference to appropriate recognized standards and specialist literature.

A.6 Composite structures

Galvanic corrosion shall be considered when carbon fibre composites are in contact with metal. Usually the metal degrades first, but in some cases, damage to the matrix and the fibres can also happen. Carbon fibre composites shall be electrically isolated from metal components.

A.7 Compatibility of materials

When different structural materials are used in combination, attention shall be given to isolate materials that may create electrolytic corrosion, such as dissimilar metals (even of the same alloy). Particular care shall be taken when small components can act as anodes in conjunction with surrounding dissimilar materials. Sacrificial anodes shall be included in a design when different materials are used.

Annex B
(normative)

Operational and structural resonance

B.1 General

The designer shall take into account the harmonic response both for structural and mechanical elements. Whilst structural damping can be expected to be quite low, hydrodynamic damping can be quite significant and should be estimated where practical.

It should be noted that avoiding natural frequencies will not eliminate all fatigue stresses.

B.2 Control systems

As the control system can influence resonant response of both structural and mechanical elements (both passively and actively), the designer shall carry out an FMEA for the control system to ensure that there are no failure modes which can increase the resonant response of either the structural or mechanical elements (e.g. loss of blade, out of balance rotor shaft or damaged gearbox bearings).

B.3 Exciting frequencies

The designer shall ascertain on which part of the device all forces or moments are acting and in which plane.

NOTE For any device there are forces or moments applied that are of a cyclical nature. The frequency at which these forces occur can be considered as exciting frequencies with respect to the harmonic response. These frequencies can be fixed, random or a function of another frequency. The most significant forces are fluid acting on the support structure, waves and the cyclic passing of turbine blades (or other moving components of the MEC). For TECs turbulence slicing can be significant as this can often generate periodic forces at the passing frequency of the blades somewhat larger than those caused by support structure shadow alone. Some of the excitation can be termed broadband excitation, containing a range of frequencies.

B.4 Natural frequencies

Both structural and mechanical elements will have primary and higher order natural frequencies. All natural frequencies that could be excited by exciting frequencies shall be identified. Vibration simulations can be used to identify possible effects. Due account shall be taken of added mass that submerged structural and mechanical elements can be influenced by. If a structural frequency is close (say within 10 %) to a hydrodynamic frequency, there is a tendency for them to move together. Vortex Induced Vibration is an example of this problem. The mode shapes of all natural frequencies shall be considered so that it is understood how such frequencies can be excited.

Where it is intended to avoid operating at a natural frequency the three most common approaches taken are to:

- ensure that the stiffness of the structural or mechanical elements is low such that the natural frequency will occur sufficiently below the exciting frequency;
- ensure that the stiffness of the structural or mechanical elements is relatively high such that the natural frequency will occur above the exciting frequency; and
- ensure that there is sufficient damping of the structural or mechanical elements such that the response to an exciting frequency will not result in the fatigue stresses induced being significant in comparison to the mean stresses.

Using the first approach requires the least amount of material in order to achieve a lower level of stiffness. However, the designer needs to be careful that whilst the first natural frequency is below any exciting frequency, the second (or third, etc.) mode of natural frequency is also not close to any exciting frequency. The second approach is the simplest method of avoiding a harmonic response. The third approach is difficult to achieve unless a separate damping component is added.

B.5 Analysis

Any analysis shall have three parts to it as follows:

- the natural frequencies shall be identified together with the mode shapes;
- the exciting frequencies shall be identified; and
- the relationship between the two shall be clarified.

The simplest way of identifying the relationship between the natural frequencies and the exciting frequencies is by means of a Campbell diagram (ISO 13373-2). The Campbell diagram shall indicate the exciting frequencies associated with various operating (or running) conditions of the device.

Any points where the natural frequencies and the exciting frequencies coincide shall be noted. For the design to be acceptable, the margin between natural frequency and operating speed range shall be at least ±20 %.

If a natural frequency is found to be within ±20 % of the expected structural excitation, then a forced response calculation that takes into account the damping of the system shall be carried out. Ideally, the model should reflect all six degrees of freedom. It is recommended that any natural frequencies that are found within ±20 % of operating speed range have a damping coefficient greater than 0,4, or an amplification factor less than 2,5.

NOTE When undertaking vibration analysis, software often considers only one degree of freedom. This approach has some limitations. For example non-resonant vibration in one degree of freedom can excite resonant frequencies in another degree of freedom. This can be a particular problem when a system has a mechanism for coupling vibration in one degree of freedom to another degree of freedom.

B.6 Balancing of the rotating components

When considering lateral (also known as whirling) vibration of rotating components, the designer shall take into account the effect of balancing.

Annex C
(informative)

Wave spectrum

C.1 Overview

Spectral models are used to obtain an estimate of the entire wave spectrum from known values of the significant wave height and wave period as obtained from hindcast calculations or by direct measurement. It is often useful to describe a sea state using a linear random wave model by specifying a wave spectrum. Two-parameter spectral formulations are generally preferred for offshore engineering applications. The parameters required for defining a wave spectrum are the significant wave height, H_{m0} and the peak period, T_P.

The most accurate wave spectrum is based on local geography, bathymetry and severity of the sea state. However, the most frequently used spectra for wind-generated seas are the Pierson-Moskowitz (PM) spectrum, for a fully developed sea, and the JONSWAP spectrum, for a developing sea. Both spectra describe wind conditions associated with the most severe sea states. For swell spectra, information can be found in ISO 19901-1.

The best results are obtained if these spectra are used with site-specific parameters that consider fetch and shallow water effects.

C.2 The Pierson-Moskowitz spectrum

The PM spectrum is applicable to a fully developed sea, i.e. when the growth of the waves is not limited by the fetch. For many areas, this will be the case most of the time and the PM spectrum is, therefore, often used for fatigue analysis. The spectral density of the surface elevation is given by:

$$S_{PM}(f) = 0{,}3125 \times H_{mb}{}^{2} \times f_{p}{}^{4} \times f^{-5} \times \exp\left(-1{,}25 \left(\frac{f_p}{f} \right)^{-4} \right) \tag{C.1}$$

where:

H_{m0} is the significant wave height (m);

f_P is the peak frequency (= 1/ T_P) (Hz);

f is the frequency (Hz).

Figure C.1 shows the PM spectrum for a sea state with H_{m0} equal to 2,25 m and T_P equal to 7,13 s.

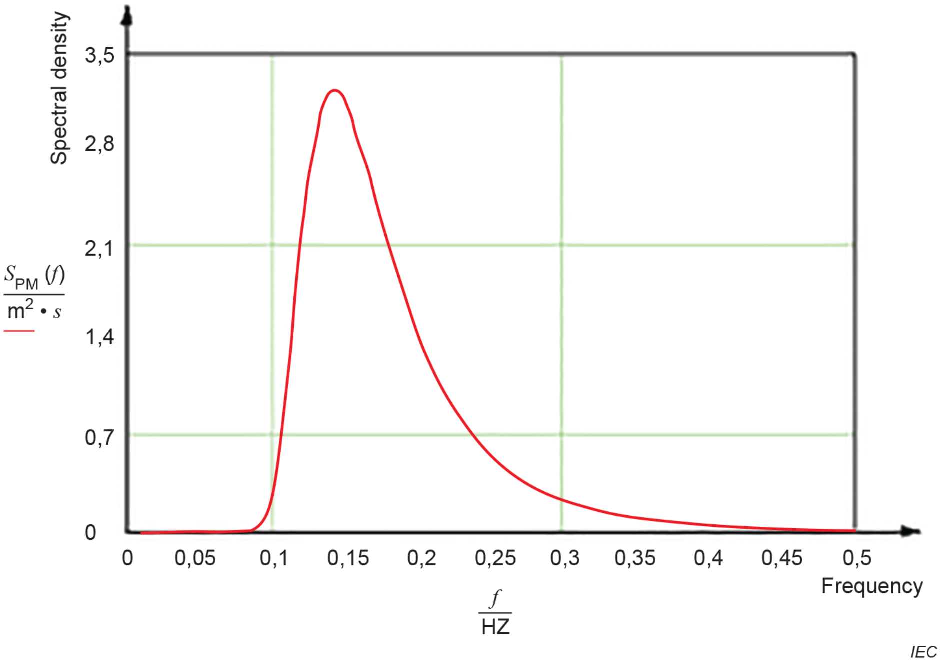


Figure C.1 – PM spectrum

The JONSWAP spectrum is formulated as a modification of the PM spectrum for a developing sea state in a fetch-limited situation. The spectrum was derived to account for a higher peak and a narrower spectrum in a storm situation for the same total energy as compared with the PM spectrum. Therefore, the JONSWAP spectrum is often used for extreme event analysis.

For the JONSWAP spectrum, two modification factors are introduced: a peak enhancement factor, γ^{α}, and a normalizing factor, $C(\gamma)$. The first factor increases the peak and narrows the spectrum; the second reduces the spectral density to ensure that both spectral forms have the same H_{m0} (energy). For γ = 1, the JONSWAP spectrum reduces to the PM spectrum.

The spectral density of the surface elevation is given by:

$$S_{JS}(f) = C(\gamma) \times S_{PM}(f) \times \gamma^{\infty} \tag{C.2}$$

where:

γ is the non-dimensional peak-shape parameter.

$C(\gamma)$ is the normalizing factor = $$\frac{\int_0^{\infty} S_{PM}(f)\,df}{\int_0^{\infty} S_{PM}(f) \times \gamma^{\infty}\,df} \tag{C.3}$$

Figure C.2 shows a comparison between the JONSWAP spectrum and the PM spectrum for a typical North Sea storm sea state (H_{m0} = 14,4 m, T_P = 15,4 s and γ = 3,3).

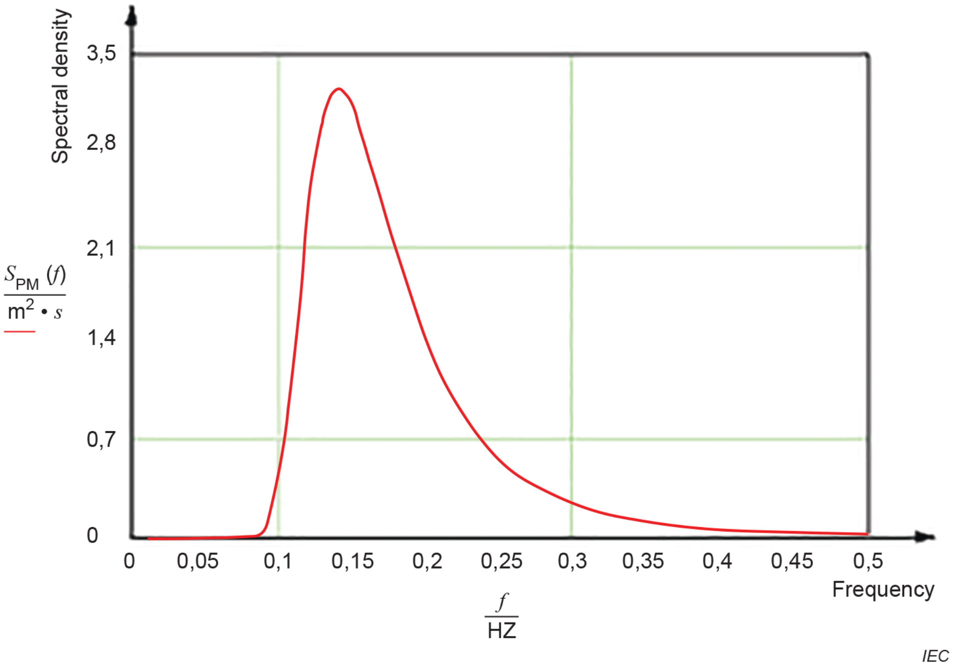


Figure C.2 – JONSWAP and PM spectrums for typical North Sea storm sea state

In lieu of more detailed information, the following values may be used:

$$\alpha = \exp\left(\frac{\left(f - f_p\right)^2}{2\sigma^2 f_p^{\ 2}} \right) \qquad \text{C.4)}$$

where:

σ = 0,07 for $f \le f_P$

σ = 0,09 for $f > f_P$

Peak-shape parameter:

$$\begin{aligned} &\gamma = 5 \text{ for } \frac{T_P}{\sqrt{H_s}} \le 3{,}6 \\ &\gamma = \exp\left(5{,}75 - 1{,}15 \frac{T_P}{\sqrt{H_s}} \right) \text{ for } 3{,}6 \le \frac{T_P}{H_s} \le 5 \\ &\gamma = 1 \text{ for } \frac{TP}{\sqrt{H_s}} \end{aligned} \qquad \text{(C.5)}$$

with H_{m0} in m and T_P in s.

Normalizing factor:

$$C(\gamma) = 1 - 0{,}287 \cdot \ln\gamma \qquad \text{(C.6)}$$

The normalizing factor shall be equal to unity for γ = 1.

The JONSWAP spectrum is expected to be a reasonable model for:

$$3{,}6 < T_p / \sqrt{H_s} < 5 \tag{C.7}$$

where the peak period T_P is in seconds and the significant wave height H_{m0} is in metres and shall be used with caution outside this interval.

C.3 Relationship between peak and zero crossing periods

The following approximate relationship exists between the peak period T_P and the zero-crossing period T_z. This relationship is valid for both the PM spectrum and the JONSWAP spectrum.

$$T_z = T_p \times \sqrt{\frac{5+\gamma}{11+\gamma}} \tag{C.8}$$

For γ = 1, the following relationship is found for the PM spectrum:

$$T_p = 1{,}41 \times T_z \tag{C.9}$$

C.4 Wave directional spreading

In the design of offshore structures, all waves are normally assumed to propagate in one direction, namely in the direction of the wind. All waves are thus assumed long-crested (2-dimensional). The one-dimensional wave spectra given above reflect this situation.

However, most real seas are composed of many large and small waves propagating in many directions, i.e. the wave energy at a point has both an angular distribution and a distribution over a range of frequencies. Such waves are called short-crested, as they do not have a long crest. Wave direction and spreading significantly influence the wave loads on offshore or coastal structures and the sediment transport in a surf zone. As compared to long-crested waves, they represent a reduction in the wave action, which may be expressed in a two-dimensional wave spectrum $S(f, \theta)$, where θ is a direction relative to the wind direction.

$$S(f,\theta) = S(f) \cdot D(f,\theta) \tag{C.10}$$

where:

$S(f)$ is the one-dimensional wave spectrum;

$D(f,\theta)$ is the directional spreading function.

The spreading function $D(f,\theta)$ is generally not known, and is, therefore, normally substituted by a symmetric, frequency independent function $D(\theta)$ over a sector on either side of the main direction. The directionality function fulfils the requirement:

$$\int_{-\pi}^{\pi} D(\theta) d\theta = 1 \tag{C.11}$$

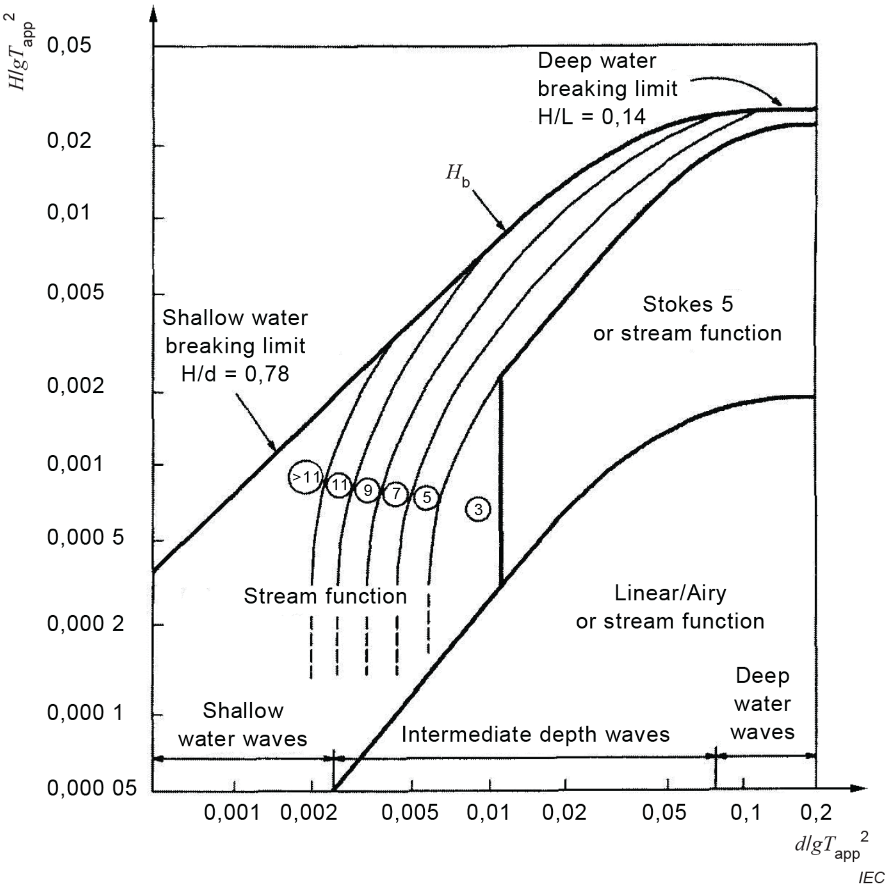
Normally, directional information is difficult to measure and validate. In practical design of fixed offshore structures, especially in shallow areas, unidirectional sea states are used.

Annex D
(informative)

Shallow water hydrodynamics and breaking waves

D.1 Selection of suitable wave theories

The kinematics of two-dimensional regular waves can be predicted using several periodic wave theories. Different theories provide approximate solutions to the same differential equations with appropriate boundary conditions. A waveform that is symmetric about the crest and propagates without changing shape is computed by all the theories. The theories differ in their functional formulation and the degree to which they satisfy the non-linear kinematic and dynamic boundary conditions at the wave surface. Figure D.1 provides guidance on the selection of suitable regular wave theories as a function of normalized wave height and water depth.



Key

$H/gT_{app}2$	is the dimensionless wave steepness
d	is the mean water depth
$d/gT_{app}2$	is the dimensionless relative depth
T_{app}	Is the apparent wave period
H	is the wave height
H_b	is the breaking wave height
g	is the acceleration of gravity

SOURCE: Atkins, 1990; Modified by API Task Group on Wave Force Commentary

Figure D.1 – Regions of applicability of stream functions, Stokes *V*, and linear wave theory

In deep water, waves of small height are approximately linear in nature. Regular waves in this region are sinusoidal in shape and may be modelled using linear Airy wave theory or a low-order stream function solution.

As the wave height is increased or the water depth reduced, wave steepness becomes greater and the height of the wave crest above the still water level becomes greater than the depth of the trough below the same datum. The wave profile and water particle kinematics can no longer be described accurately using linear wave theory. Stream function theory can be suitably applied over a wide range of depths. Stokes 5th order wave theory may be used to model steep waves in deep water.

As wave height is further increased or the water depth further reduced, the horizontal velocity of water particles in the wave crest will at some point exceed the wave celerity and the structure of the wave will break down. Water particles are ejected forward from the crest and the wave is said to break.

Further description of wave theories and their ranges of application may be found in ISO 19901-1.

D.2 Modelling of irregular wave trains

Irregular wave trains that represent random sea states may be modelled as a summation of sinusoidal wave components, each described by Airy theory. In intermediate or shallow water depths, the accuracy of Airy theory should be assessed.

Linear Airy wave theory defines water particle kinematics from the sea floor to the still water level. A wave stretching technique may be applied to take account of the varying height of the water surface. Wheeler-stretching and delta-stretching are two suitable methods and are described in ISO 19901-1:2015, A.8.4 and A.9.4.1.

The presence of a compact structure in the wave field may significantly influence the nature of the waves approaching the structure through scattering in many directions. Such cases require a diffraction analysis to be performed using the MacCamy-Fuchs [MacCamy 1954] correction to account for wave diffraction effects on applied structural loads.

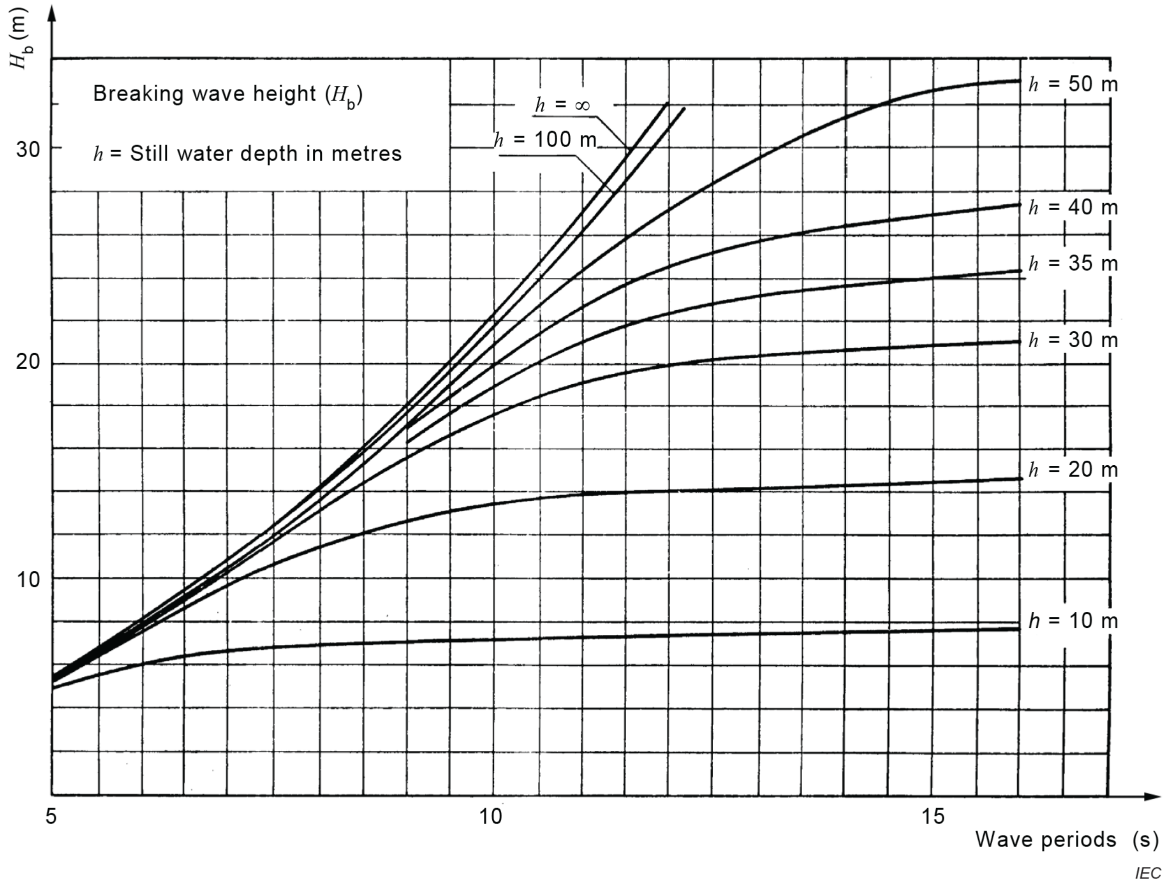
In shallow waters the surface elevation distribution will deviate from a Gaussian distribution and the distribution of individual wave heights will deviate from a Rayleigh distribution. In these cases, the wave height distribution developed for shallow water sites by Battjes and Groenendijk [Battjes and Groenendijk 2000] may be used.

D.3 Breaking waves

Waves may break in different ways, depending principally on the ratio of deep-water wave steepness to sea floor slope.

In shallow water, the empirical breaking limit of the wave height is approximately 78 % of the local water depth. The presence of a sloping sea floor (still water depth decreasing in the direction of wave propagation) can lead to breaking waves which are significantly higher than limiting height regular waves in the same local water depth. Guidance is provided by Barltrop and Adams [Barltrop and Adams 1991].

The breaking wave height as a function of wave period for different water depths is given in Figure D.2.



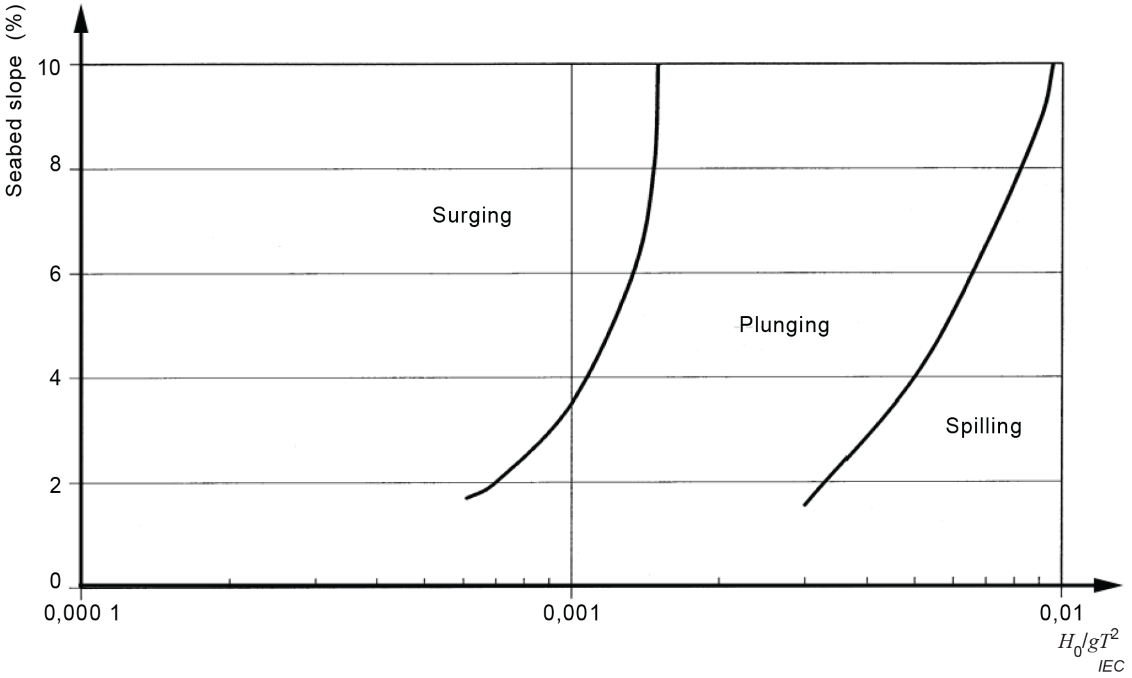
SOURCE: Recommended Practice DNV-RP-C205, Oct. 2010, pp.31

Figure D.2 – Breaking wave height dependent on still water depth

There are three types of breaking waves depending on the wave steepness and the slope of the seabed:

- surging breaker;
- plunging breaker; and
- spilling breaker.

Figure D.3 indicates which type of breaking wave can be expected as a function of the slope of the seabed, the wave period T and the wave height H_0 in deep waters.



SOURCE: DNV-OS-J101

Figure D.3 – Transitions between different types of breaking waves as a function of seabed slope, wave height in deep waters and wave period

Formation of a particular breaker type depends on the non-dimensional parameter:

$$\beta = H_b / (g \cdot T^2 \cdot m) \qquad \text{(D.1)}$$

where H_b is the wave height at breaking and m is the beach slope, assumed to be constant over several wavelengths.

Spilling breakers are characterized by foam spilling from the crest down on the forward face of the wave. They occur in deep water or on gentle beach slopes. Spilling breakers usually form when $\beta > 5$.

Plunging breakers occur on moderately steep beach slopes. They are characterized by a well-defined jet of water forming from the crest and falling onto the water surface ahead of the crest. Plunging breakers form when $0,1 < \beta < 5$.

Surging breakers occur on relatively steep beaches where there is considerable reflection with foam forming near the beach surface. Surging breakers form when $\beta < 0,1$.

The collapsing wave forms lower down the forward face of the wave and is a transition type between plunging and surging breakers, $\beta \sim 0,1$

The occurrence and type of breaking waves may also be influenced by the presence of the structure itself, especially for compact structures.

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