

# Guidelines on design and operation of wave energy converters

A guide to assessment and application of engineering standards and recommended practices for wave energy conversion devices

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# 1 FOREWORD FROM THE CARBON TRUST

The Marine Energy Challenge (MEC) was established in response to the Carbon Trust's strategic work highlighting the potential for wave and tidal stream development in the UK. The main driver was to establish in the medium term if these technologies can become cost competitive. Through partnering large engineering design organisations with existing wave and tidal stream technology developers, the Challenge aims to accelerate the development of marine energy in the UK.

Much of the technology or application of existing technology in marine energy devices is considered relatively new and unproven. As such there are no specific codes of practice, standards or guides that can be drawn on to facilitate their design and development. With this in mind the Carbon Trust commissioned Det Norske Veritas BV (DNV) to develop this Guideline to provide interpretation and guidance on the application of the various existing standards and guides, such as offshore engineering, to wave energy conversion (WEC) devices. The guideline focuses on WEC devices due to the predominance of WEC developers participating in the MEC, however we would recommend that a similar guidelines be developed for tidal stream developers in the near future.

Whilst the Guideline is very useful to much of the industry, it should be noted that the document is not a standard in itself and should be seen as a starting point for further standards work. The Guideline has been developed solely to provide guidance, act as reference to principal relevant standards and highlight some major issues that developers or other stakeholders may wish to consider during development of WECs. Persons using this document are responsible for checking the current status of reference guides and standards and the Carbon Trust takes no responsibility for any errors or omissions in this guidance document or any document referenced from it.

The Marine Energy Industry offers a path to a more sustainable future and we hope the 'Guidelines on design and operation of wave energy converters' provides assistance to the industry and represents one clear marker along that path.

## 2 INTRODUCTION

The objective of this Guideline is to provide interpretation and guidance on the application of existing Codes and Standards (mainly from industries such as Offshore and Maritime) to wave energy conversion (WEC) devices and should be read in conjunction with the Standards, Recommended Practices and other documents referred to in the text. The standards referenced generally guide the user to choose the relevant safety level. Thus they can be used for critical and less critical applications as far as they are relevant for wave energy devices. This document provides guidance on concept development, design, construction and life cycle processes to contribute to the reliability of the wave devices throughout their in-service life.

The environmental loads and technical challenges faced by offshore WEC devices are very similar to those experienced by offshore oil and gas installations. The solutions found for the oil and gas industry and the associated technology development have been calibrated to an internationally acceptable safety level and have an adequate track record. The adaptation of this technology to wave devices is not only useful from the point of view of the target safety level, but also incorporates cost-effective solutions and practices already available to the industry. It also takes advantage of existing infrastructure available for the industry in terms of fabrication practices and yards and “off the shelf” components.

The qualification process described here can be applied to different stages of development or to devices with novel design aspects and where codes and standards may not be adequate. The qualification process can also be used as an improvement tool to achieve adequate functional requirements and as a systematic demonstration of reliability and levels of risk.

The guidance and recommendations given here are based on an investigation of the design process applied to different types of devices, with due consideration of critical aspects and items where deviations from existing codes were identified during the design process and tests.

The DNV Offshore Standards and Recommended Practices referred to in this Guideline adopt a consistent approach regarding defined safety levels and in-service philosophies. Additional requirements or advice is given regarding specific subjects or uncertainties in the wave energy converter device design considering the safety and in-service philosophies adopted. Summaries and highlights of important aspects in the design codes are also provided.

This guideline may also be used as contractual reference document and as the basis for common understanding of the safety philosophy, risks and reliability targets defined for the project between all parties involved in a wave farm development. These parties include the designers, manufacturers, suppliers, operators, utility companies, regulators, third parties, other authorities, financiers, insurers and society in general.

Steel, concrete and composite materials, (fibre reinforced plastic laminates and sandwich structures) are also addressed in the Guideline.

Whenever possible the Guideline highlights the differences between system design philosophies reflected in offshore codes and wave device design. It must be recognised

that failure mechanisms that govern the normal design in an offshore installation may change in the case of WEC devices for the following reasons:

1. Although the probability of failure may be the same in both offshore and wave device applications, the consequence of failure is much smaller for a wave device that is normally unmanned, since different and less hazardous conditions may exist and further escalation of failure is less likely. This may happen without affecting the reliability of the equipment.
2. Standard equipment in a WEC device may be subject to different loads and thus consideration of other dominant failure modes should be made. For example, design for resonance with wave conditions makes fatigue a governing failure mechanism which in turn affects reliability.

Given the understanding of the intent of the Guideline above, the following section explains the use of the Guideline.

### 3 WORKING WITH THE GUIDELINE

As the Guideline is a multi-discipline document it is important to describe how the Guideline is structured.

#### 3.1 Qualification Process and Building Blocks

The first issue discussed is the Qualification of new unproven technology. The reason for this is that the process described in this section is extremely useful to address new technology systematically or even existing technology applied in a different way. As it is a generic process, developers may apply this approach to the whole device or parts of it. The Qualification process was especially adapted by DNV to cover typical marine renewable devices.

The Guideline has used a systems approach to encompass the different types of WEC concepts that have been proposed. The information provided constitutes the basic building blocks that can be combined in different ways in different concepts. The basic blocks addressed in this Guideline are normally located within Technology Class 1 and 2 groups (see Section 4). In short, systems or components with proven technology and known application are Class 1 new fields of application are Class 2.

There are design aspects that are not covered in this document. These are normally systems or components in Technology Classes 3 or 4 where the Qualification process should be applied to capture new failure modes and to achieve “fit for purpose” status at the end of the process.

Frequently, the Guideline refers to several standards and recommended practices. The objective is to minimise repetition of requirements and recommendations that are perfectly acceptable as they are currently reflected in the standards. In some cases a summary of the subject and approach is provided. This is done in order to allow the reader some appreciation of the issues under discussion in the section and also to introduce some complementary information from different standards.

#### 3.2 Standards

The Guideline uses a consistent set of standards across different disciplines and subjects. This is important to keep a consistent approach and avoid the possibility of dangerous “standard hopping” that may lead to areas of design not covered or covered in an inconsistent way. The standards referred to in the main text of the Guideline also refer to other international standards that specify an equivalent level of safety and reliability. The developer may be more familiar or feel more comfortable in using these other standards. All the standards referred to are widely used by industry. A list of the relevant standards referred to in the DNV Offshore Standards (OSs) and Recommended Practices (RPs) are given in Section 28 REFERENCES. In the same section, alternative standards covering same or similar subjects as those covered by DNV are listed.

The reader needs to bear in mind that the Guideline and its recommendations and requirements were devised from the investigation of several different concepts of wave devices and consultations with different stakeholders. Despite the huge effort and collaboration with all involved it is still a limited part of the wave renewable sector. Developers and other stakeholders reading this document may need to take the recommendations given from similar approaches or systems and adapt the design

philosophy to their particular application. It is expected that this situation will improve with the development of the sector and the gathering of experience.

Another important aspect that needs to be highlighted is the *Principle of Equivalence*. The recommendations and requirements given here are not necessarily the only way to achieve an equivalent level of safety or reliability. They are considered to be the best approach and hopefully it is also the most suitable for all concerned. However, it may be that other more effective and simpler ways are more suitable to the needs of developers. The developer should investigate and document the approach used and in order to demonstrate that it satisfies the overall goals.

### 3.3 Safety and Reliability Targets

Section 8 discusses the safety and reliability targets that the device should be designed for. The definition of the targets is a decision that needs to bring different levels of expectation from different stakeholders and bring a balance between survivability, reputation, maintenance, repairs and production costs.

The decisions on the safety and reliability levels are applied to the Qualification Process, forming important part of the first step (Qualification Basis), and to the implementation of the recommendations given across the Guideline. In line with the proposed consequence levels to be considered during a risk assessment, safety and reliability levels may also have different objectives in different areas such as life, asset, environment and operation.

As normally unmanned structures, the safety levels of WEC devices must be balanced by consideration of the need of the device to survive extreme conditions, the protection required while personnel are on board, and the protection to third parties. Survival requirements could be directed to protect reputation at certain phase of the device development and / or to protect the investment made in the asset. However, it is also important to define the safety level considering any possible impact on fatigue aspects (in most cases the likely governing factor in the design) and other deterioration mechanisms.

As the Guideline has a modular approach reliability issues are discussed in several sections in the light of the different section headings.

### 3.4 Glossary and Verbal Forms

Glossaries can be found in the standards referred to in the Guideline.

Although this is a Guideline and not a mandatory document, some verbal forms have been used to highlight the importance of the recommendations given here:

*Shall / must*: Indicates a mandatory or important requirement to be followed. The statement is associated with an important step / action / requirement to be observed or complied with. Deviations require rigorous assessment and evaluation of suitability to be accepted by all relevant contracting parties if applicable).

*Should*: Indicates a recommendation that a certain course of action is preferred or particularly suitable. Alternative courses of action are possible where agreed between contracting parties but shall be justified and documented.

*May*: Indicates a permission, or an option, which is allowed.

*Can*: Requirements and recommendations containing ‘can’ indicate a possibility to the user of the Guideline and may have conditions attached.

### 3.5 Production in Series

It is envisaged that devices will eventually be manufactured in a series. In this case the advice given in this Guideline can be explored even further with the objective to obtaining the best design and manufacturing process. This means refining the fatigue and reliability aspects to the specific characteristics of the device. An example can be seen in A14 Qualification of New S-N Curves where the process described may not be appropriate for the construction of one device,, may be relevant for the production of a series.

## 4 QUALIFICATION OF NEW AND UNPROVEN TECHNOLOGY

### 4.1 General Considerations

Wave devices are developed using new or unproven technology or using well-established technology in a non-conventional way. In order to speed up the development process and improve the reliability of devices a qualification process should be applied. Reference is made to RP-A203: Qualification Procedures for New Technology.

Qualification may be defined as "the process of providing the evidence that the technology will function reliably within specific limits". In particular two parts of the definition need to be emphasised:

- "Providing the evidence" implies that technology qualification confirms all work has been done to create the necessary documentation. This differs from third party services (verification / certification / classification) which aim to confirm that available documentation complies with given specifications, codes and standards.
- "Function reliably" indicates that technology qualification should focus on functionality, not on compliance. For new technology in particular, where the lack of relevant codes and standards is common, Qualification according to functional reliability targets provides a rational approach in this case. Further, many codes and standards do not address the functionality of the technology, but are primarily concerned with safety aspects.

Qualification is achieved by means of technical analysis and studies, technical risk and reliability assessments, laboratory testing, review of prototype results, etc. The risk and cost of introducing unproven technology can be high and in the context of this industry, the use of qualification will allow:

- The level of maturity of the new technology to be defined (by benchmarking its risk with the risk of well-proven technology for which statistics are available).
- The level of reliability of the device and its impact on in-service costs to be defined.
- Component criticality and priority areas for improvement to be based on a balance between cost vs. risk/criticality.

The assessment is based on defined functional requirements of the WEC, rather than technical specifications. Depending on which stage of development the energy conversion device is in, the required qualification process will have different levels of assessment.

In the concept stage, when the knowledge of the technology is limited, the uncertainty regarding failures during the in-service life is large. The aim of the qualification process is to reduce the uncertainty to an acceptable level in order to determine the service life performance and cost (Figure 4.1).

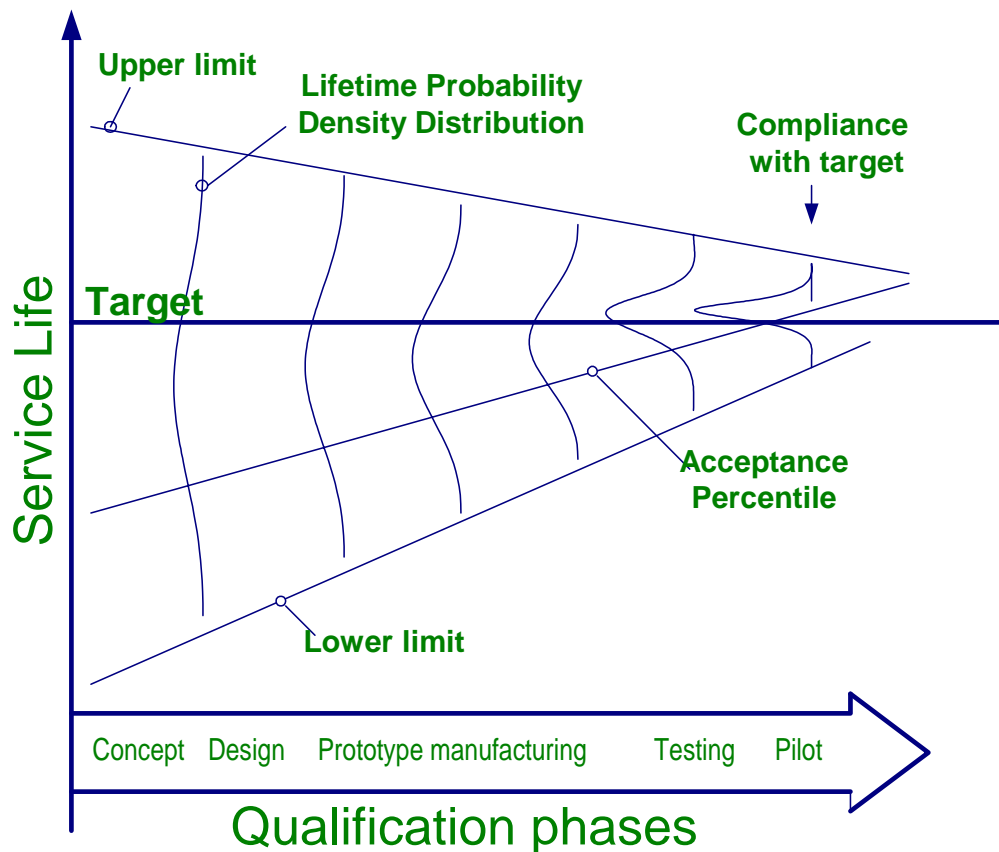


Figure 4.1 : Reduction of Uncertainty during the Qualification Process

The extent of qualification will depend on the level of uncertainty or novelty of the technology under assessment, the level of uncertainty from the qualification methods used and the specified targets (qualification basis) and associated tolerances.

If the results of the qualification process carried out at the design stage are considered satisfactory and uncertainties at the end of this stage have been qualified within the acceptable tolerances, the qualification process may proceed further to prototype testing and a pilot scheme in order to reduce the level of uncertainty to an even narrower distribution and to allow for improvements and evaluation of modifications on the production model, based on the results from prototype, to be part of the final qualification statement.

However, there will be cases that the formal qualification process should be extended to prototype and pilot phases as the existing uncertainties at the stage before the prototype phase are still beyond the tolerances specified. It may also be the case that the Tests and Analysis stage (see Section 4.2 ) will only be complete at the prototype stage due to complex interaction between different systems within the unit or of the systems and the unit with the environment or any other limitation.

For new technology in particular, there will be little or no generic reliability data available at the concept stage. The reliability therefore has to be documented by identifying all failure modes of concern and deriving the technical data and knowledge necessary to determine the service life.

A systematic approach to qualification is expected to have a major impact on costs:

- Necessary analyses and tests are identified at an early stage, which reduce the need for re-work and delays in the development phase.
- Identification of improvements in technology is necessary to avoid unplanned interventions and long mitigation periods, thus improving the expected return on investment in the concept.
- Tests that do not address the failure modes of concern can be omitted.

## 4.2 Qualification Process

The process described here is an adaptation from the process presented in DNV RP-A203. The adaptation considers the use of the Qualification process with the context of this Guideline. Reference is also made to an on-going project for updating RP-A203 with a specific Appendix on Marine Renewables. The various steps in the qualification work process are:

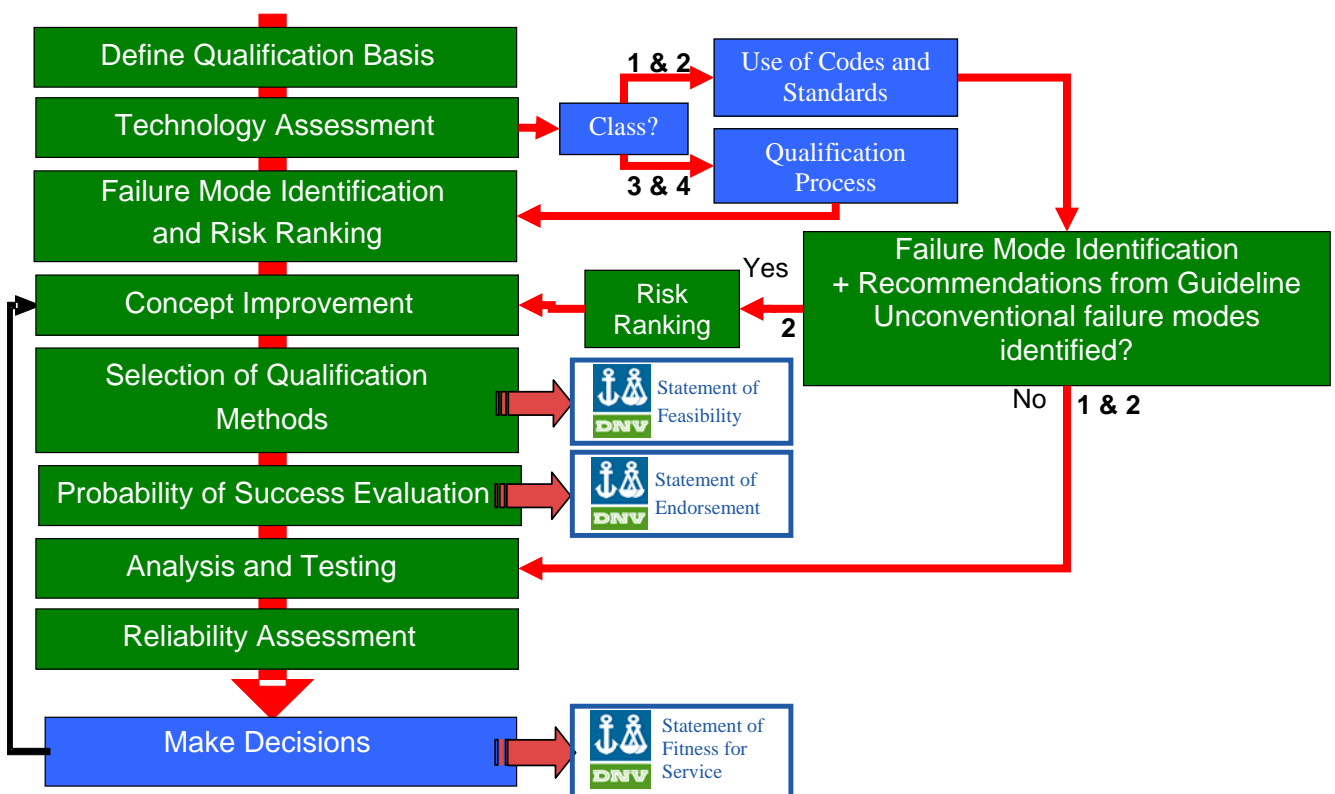


Figure 4.2 : The Qualification Process

The Qualification Basis will describe the technology and state the system functional requirements, preferably in terms of reliability and cost targets.

The input for the Technology Assessment is the Qualification Basis with supporting documents such as detailed drawings of items subject to qualification, drawings and descriptions of control and safety systems, material specifications, outline fabrication procedures, outline installation procedures and outline inspection and maintenance procedures.

The purpose of Technology Assessment is to divide the technology into manageable elements in order to assess which elements involve aspects of new technology and to identify the key challenges and uncertainties. Normally, the Technology Assessment includes the following issues:

- Division of the technology into manageable elements.
- Assessment of the technology elements with respect to novelty.
- Identification of the main challenges and uncertainties related to new technology aspects.

The technology division shall be done by dividing the technology into one or more of the following types of elements as relevant:

- Sub-systems and components with functions.
- Process sequences or operations.
- Project execution phases based on procedures for manufacturing, installation and operation.

The degree of novelty of the technology is determined by classifying the technology elements with respect to application area and technology maturity. Elements classified as New Technology need further assessment.

The main challenges and uncertainties related to the new technology aspects shall be identified. For complex systems it is recommended that the main challenges and uncertainties are identified by carrying out a high level “HAZID” (HAZard IDentification). According to the DNV RP-A203, the technology can be classified as:

<i>Application area</i>	<i>Technology</i>		
	<i>Proven</i>	<i>Limited field history</i>	<i>New or unproven</i>
Known	1	2	3
New	2	3	4

This classification implies the following:

- 1) No new technical uncertainties.
- 2) New technical uncertainties.
- 3) New technical challenges.
- 4) Demanding new technical challenges.

This classification applies to the totality of the applied technology as well as each separate part, function and subsystem.

The Failure Mode Identification and Risk Ranking (see Section 4 below) is a key step which ensures that all failure modes of concern are addressed. Especially for new technology, generic reliability data is generally not available. It is therefore necessary to determine the reliability based on understanding of the mechanisms leading to the potential failure modes. The technology is therefore broken down to such a detailed level that each *failure mechanism* is understood.

This work is preferably carried out with qualified engineers representing the relevant technical disciplines and fields of experience (design / fabrication / installation / operation).

At this stage Concept Improvements may be evident and appropriate to implement.

Selection of Qualification Methods is a planning activity where it is decided *how* all failure modes of concern, which can include technical analyses, laboratory testing, collection of data and knowledge or simply to state procedural precautions to avoid a potential problem, will be addressed.

This is important as *it is impossible to plan an adequate qualification process unless the potential failure modes have been identified and are understood*. Today, many expensive tests are carried out without adequately addressing the failure modes of concern.

A main issue in the early stages of a development project is the probability of a successful completion of the overall qualification program within a given deadline and cost frame. This probability is commonly referred to as Probability of Success (PoS). After having identified the necessary qualification activities one will have a good basis for evaluating the technical challenges, duration and costs of the activities and identifying possible “show stoppers”. The PoS gives a basis for making the right decisions regarding funding of further qualification work which usually represents a major part of the overall costs.

Evaluation of the PoS may be carried out at various levels of sophistication depending on the developer’s needs for information on their own decision process and accessibility to input parameters. As a minimum, each individual qualification activity shall be assessed on a qualitative basis with respect to technical challenges and available time to qualification. A more sophisticated and informative assessment of the total PoS for the whole qualification process may be carried out in order to give the PoS as function of time. The assessment requires that a qualification execution plan that includes all qualification activities is prepared and that both the probability of a successful outcome for each activity and the uncertainty in the duration are estimated.

A financial assessment of the qualification activities may be carried out following the same principles as above, where the time parameter is replaced by costs. This requires that cost estimates with uncertainties are carried out for each qualification activity.

In the Data Collection (Analysis and Testing) phase the above qualification activities are carried out. These activities usually represent the major costs of the qualification process. It is therefore essential to ensure the areas to be covered are the relevant ones in terms of reliability and cost. Qualification projects in the past have typically led directly to this step with a minimum of effort spent on the preceding steps, to ensure that the right things are done the first time.

A Reliability Analysis is finally carried out to quantify the overall reliability of the technology, i.e. to confirm that the functional requirements laid down in the Qualification Basis are met. Although a technology may be convincingly proven fit for service without using reliability measures, a quantitative reliability analysis ensures that the technology is competitive. This is important in a market that needs to achieve medium-to long-term costs comparable to conventional and other renewable sources of energy in more advanced stages of development and implementation.

The items discussed below should be addressed in the qualification process and risk assessment.

## 5 FAILURE MODE IDENTIFICATION AND RISK RANKING

### Failure Mode

Central to the success of a failure mode identification study is the composition of the study team. Ideally the team should consist of;

- design engineers,
- the main equipment fabricators,
- the suppliers of main components such as generators,
- operation and maintenance members.

Other contributing factors to the success of the study team include;

- the experience of the personnel,
- previous knowledge base,
- the technique to be used in conducting the study.

A commonly used technique to carry out such a study for new technology is the What-If technique. A typical example is the SWIFT (Structured What-If checklist Technique) method. Other techniques as HAZOP, FMECA and FTA may also be applied depending on the project stage.

The SWIFT is based around a list of guidewords which guide the users to look at what can go wrong and why. For convenience of conducting the exercise, the guidewords are usually grouped into a number of categories. For an offshore development, the typical categories are:

- Material Failure - corrosion/erosion/brittle fracture/degradation of synthetic material, etc.
- Equipment Malfunction - mechanical failures such as out-of-alignment, fatigue, etc.
- Utility Failure - electrical/hydraulic/air/communication/software, etc.
- Environmental events - as seismic events, sediment movement, current, wave loading, marine growth, etc.

The kinds of failure may vary depending on the lifetime of the equipment. This is why it maybe necessary to look at the different stages of the production lifetime;

- specification stage,
- design stage,
- manufacturing stage,
- installation and commissioning stage, and the
- operation and maintenance stage.

A more detailed listing of some well-known failure modes is available in the RP A-203 (Qualification Procedures for New Technology).

Coupled very closely with the failure mode identification process is risk ranking of the failure modes. The ranking process is simply to rate the frequency of a specific failure

against the severity of the consequence of the failure. The importance of risk ranking is two-fold:

- It allows the study team to prioritise the issues at hand; and
- It can feed into the overall risk assessment plan.

It is very important to use the information generated from failure mode identification to feed into the overall risk assessment. This is because the overall risk assessment normally aims at very high-level failure events and other external influences. The failure mode identification process is specific to the device and it is ideal to fill any gaps in the overall risk assessment.

### Risk Ranking

The risk is the combination of probability and consequence. A semi-qualitative method to determine the risk level is illustrated in Figure 4.1. This has to be adjusted to fit the purpose. The adjusted matrix shall govern the qualification plans with respect to priority, with focus on the highest risk. The probability level can be estimated on a 5 level scale as suggested below in Table 4.1, or based on test results, field tests, numerical analyses, etc. Similarly, consequences of failure can be estimated on a 5 point scale, as shown in Table 4.2. For more detail, see European Trends - Appendix 3 - Marine Renewables modification of DNV-RP-A203 (under development).

Class	Estimate of frequency of occurrence
1	Very infrequent, e.g. once in a lifetime
2	Infrequent, several times in a lifetime
3	Typical occurrence once in 5 years
4	Occasional occurrences e.g. once per annum
5	Several occurrences per annum

Table 5.1 : Levels of Probability Assessment

The risk category for each failure mode shall be identified. Failure modes with medium and high- risk shall be investigated further, and are defined as *failure modes of concern*. Failure modes with low risk can be dealt with based on a qualitative assessment made by qualified personnel. Failure modes with low risk shall not be deleted from the list of possible failures.

Class	Description of consequences (impact on)				
	Function	Safety	Environment	Operation	Assets
1	Minimal effect, easily repairable or redundant system	No injury, effect on health	No pollution	Minimal effect on production	Negligible
2	Loss of redundant function, reduced capacity	Minor injuries, health effects	Minor pollution	Some small loss of production	Significant, but repairable
3	Loss of parts of main function, with significant repairs required	Significant injuries and/or health effects	Limited levels of pollution, manageable	Light intervention required to replace equipment	Localised damage, repairable
4	Shutdown of system	A fatality, moderate injuries	Moderate pollution, with some clean-up costs	Significant loss of production, major repair needed	Loss of main function, major repair needed
5	Complete failure	Several fatalities, serious injuries	Major pollution event, with significant clean-up costs	Total loss of production, major repairs / replacement required	Loss of device (or major component), with potential consequences

Table 5.2 : Levels of Consequence

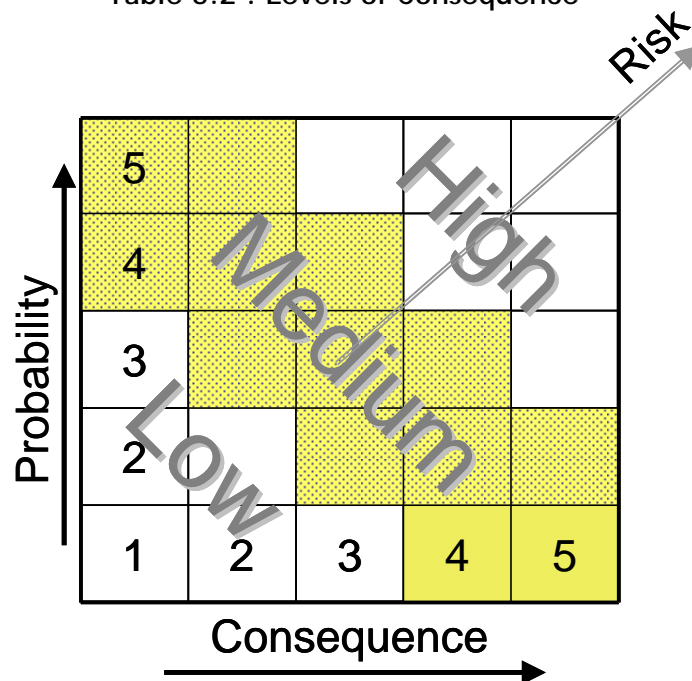


Figure 5.1 : Risk Matrix

## 6 VALUE MANAGEMENT AND LIFE CYCLE ANALYSIS

Value Management (reference is made to BS EN 12973:2000) is a management tool used to ensure that value objectives are met through the application of various value management methods. Value management can be applied to products, business models, organisations, etc. For example, when selecting an alternative energy solution, many different economic factors will be considered to justify a certain development. In this guideline, only value management of a particular type product development is considered.

Once a particular product or concept is selected, there are many ways to evaluate the design, manufacturing, operation and maintenance of the equipment to meet the value objectives. Typical techniques include:

- Value Engineering/Analysis - this technique is particularly useful to look at the design and manufacturing processes. It concentrates on getting the best value against a set of functions. The most well-known technique is FAST (Function Analysis System Technique). This technique is very useful during product development. The analysis focuses on breaking down the device into component level and looks at the function of each component and questions whether there is a cheaper way to achieve the same function.
- Life Cycle Analysis (see also Section 7) - this technique takes into account the costs of operation, maintenance and decommissioning in order to evaluate the overall lifecycle cost of the equipment. Whilst FAST is used to drive the capital expenditure (CAPEX) down, it is not always possible to analyse the effect on operational expenditure (OPEX). Only a lifecycle analysis can accurately address the balance of CAPEX and OPEX and therefore give a more accurate picture on the overall value of the device. The implications of unplanned events and business interruptions should be incorporated into business decision analyses that seek to evaluate the viability of new technology. These analyses introduce a third component to the economic balance, namely reliability expenditures. This is defined as the potential costs due to component failures. It is derived by multiplying the estimated cost of a failure by the estimated likelihood of occurrence. Summing the cost of all events yields the total reliability expenditure, referred to as RISKEX. A life cycle cost approach including the RISKEX element gives the following relation:

$$\text{Profit} = \text{Revenue} - \text{CAPEX} - \text{OPEX} - \text{RISKEX}$$

Again, when carrying out these studies, it is essential that the relevant personnel are involved in the evaluation, as discussed above.

A good value management approach will ensure the right balance of benefits versus costs thus making the product more competitive in the market place.

## 7 RELIABILITY AND COST

Wave energy device manufacturers wish to optimise their machines so that they deliver electricity at the lowest possible cost per unit of energy. In this context, it is not necessarily optimal to maximise the annual energy production, if that would require a very expensive device. Since the energy input is a free natural resource, the optimal design is one with the lowest production costs per produced kWh taking into account CAPEX, OPEX and RISKEX as referred to above. Any optimising control software used should take account of this in its logic algorithms and be capable of operational adjustment to take economic issues into account as well as technical performance. For example, a lower overall cost per kWh may be achieved by operating the unit at a slightly lower average output in order to increase the maintenance interval.

### 7.1 Reliability issues

Reliability is a key aspect to be considered in the development of any wave energy device. There are ways to incorporate implicit reliability into the design: redundancy, streamlined design (by reducing connection points and areas that are known of frequent maintenance requirements), design for robustness, low utilisation of mechanical strength (a higher resulting reserve or safety factor), environmental simulation testing of components subject to various environmental loads, use of well-proven components, FMEA study tightening up of manufacturing, fabrication and commissioning procedures in such a way to reduce the incidence of failures induced by poor workmanship or human induced problems, etc.

Figure 7.1 shows the variation of failure rates during the lifetime of equipment or component and the typical aspects contributing to the failures, thus affecting reliability.

The failure rates follow what is commonly known as the “bath-tub” shape. At the early stage of service life, most of the root causes of failure are introduced from the design and manufacturing phases. Towards the end of life of the equipment, the failures are strongly related to wear and degradation caused by the use of the equipment.

Managing the design aspects and quality during the manufacturing stage has a considerable impact on controlling the early failures. An adequate maintenance and inspection regime would contribute to control and avoid or reduce failures later during the service life.

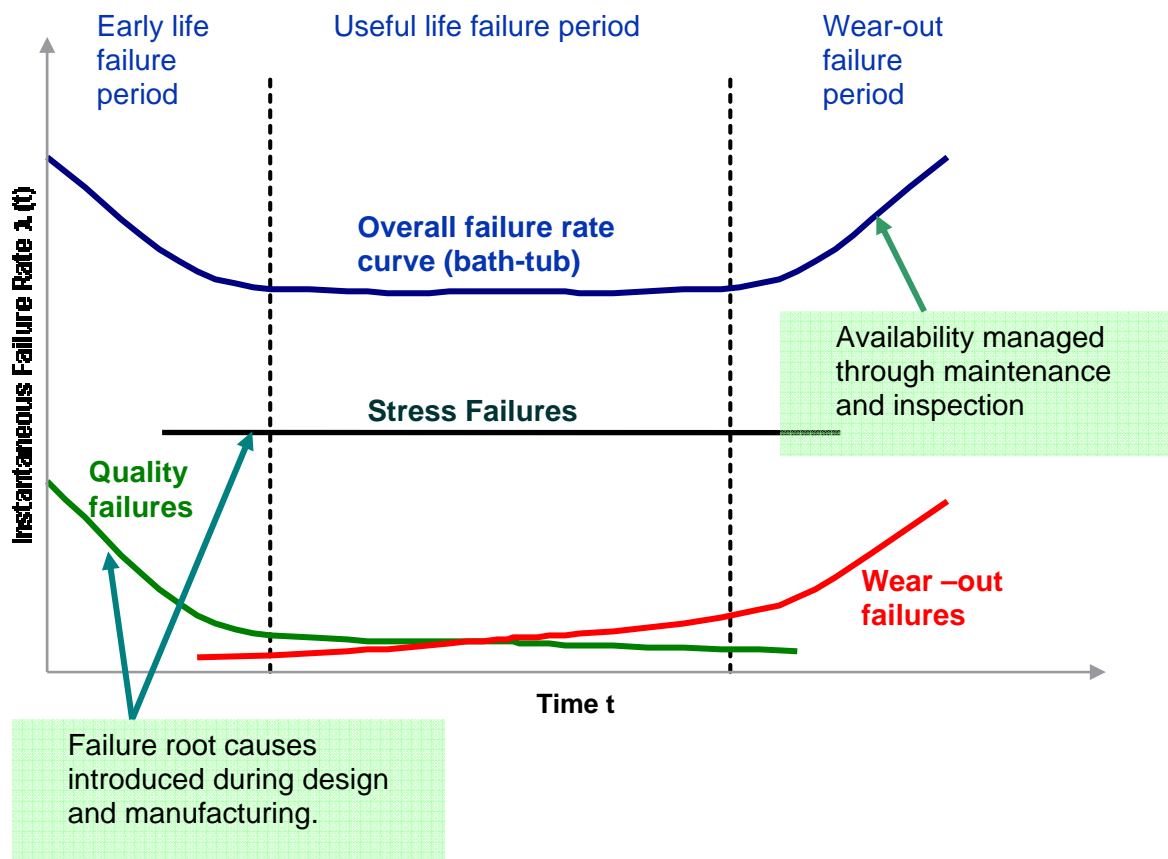


Figure 7.1 Common types of failure rates vs. time dependency

However, depending on the development stage and the target reliability, this can be approached in a more comprehensive way, going towards a more complex evaluation of the reliability. The reliability for wave devices is directly connected to cost. The balance between cost and reliability also depends on proper identification of the aspects demanding more attention; this contributes significantly to the overall performance of the devices. Reliability is also connected to the maintenance requirements and inspection regimes defined for the device.

## 7.2 Life Cycle Cost (LCC)

The aim of conducting LCC analyses is to estimate the economic performance of a project over its entire lifecycle. Such analyses are normally applied in the early phase of capital intensive projects within the petroleum, defence and aerospace industries, as well as some infrastructure development projects to compare alternative system designs, operational requirements, performance and effectiveness factors, maintenance concepts, production capacity, utilisation factors, and so on. LCC analyses are commonly used to select the system/ project alternative with the lowest total cost over its lifecycle.

From the point of view of WECs, the LCC is well suited especially to define feasibility of devices and the best option in terms of alternative designs, the use of different components and other design decisions to be taken earlier in the project. As the project develops, the LCC can be updated and the new life cycle cost derived.

One particular feature of complex projects is the significant risk of unforeseen or unscheduled events, during the feasibility phase, project development phase, the construction phase and during subsequent operational phases (RISKEX). The risks associated with these events may be difficult to quantify, but as they represent significant statistical costs they should be included in the LCC analysis.

The estimation of the net present value (NPV) of an investment project predicts the expected increase in profit, measured in today's money and is therefore an important method for evaluating alternatives. Other commonly applied measures are the internal rate of return (IRR) and the pay back time (PB).

### 7.3 Fault Tree Analysis (FTA)

A fault tree is a visual logic model that is used to describe how a specific unwanted event in a system may be caused by the effects of a single failure or combination of failures. The specific unwanted event is known as the "top event". The analysis considers ways in which this top event can occur, and with the inclusion of the correct data, it can calculate with what frequency or probability that event will occur. FTA is particularly suited to the analysis of complex system that may have a number of sub systems.

FTA can be used qualitatively to indicate combinations of events or single events that need to occur in order for the top event to occur. The FTA can also be quantified and the frequency or probability of the top event can be calculated. Sensitivity studies can then be completed which will indicate which events make the greatest contribution to the top event result.

The fault tree analysis technique has the ability to identify the combinations of basic equipment failures, and human errors that can lead to an accident or undesired event. This allows the analyst to focus on the significant basic causes of the accident / event and identify preventative or mitigative measures to reduce the likelihood of the event.

### 7.4 Reliability Block Diagram

A reliability block diagram (RBD) analysis is a deductive (top-down) method. A RBD is the graphical representation of a system's logical structure in terms of sub-systems and components. The RBD allows the system success paths to be represented by the way in which the sub-systems and components are logically connected. A RBD is appropriate to model one system function only. If the system has more than one function, each function is considered individually, and a separate RBD is necessary. Non-repairable series systems, non-repairable parallel systems and repairable systems are addressed.

### 7.5 Failure Modes and Effects and Criticality Analysis (FMECA)

The Failure Mode and Effects Analysis (FMEA) is a qualitative reliability technique for systematically analysing each possible failure mode within a hardware system, and identifying the resulting effect on that system, the mission and personnel. The criticality analysis (CA) is a quantitative procedure which ranks failure modes according to their probability and consequences (i.e. the resulting effect of the failure mode on system, mission or personnel).

The FMEA and CA (FMECA together), were originally developed by NASA as a means of assuring that hardware built for space applications had the desired reliability characteristics. In the offshore industry FMEA and FMECA have been increasingly utilised.

For Reliability, Availability and Maintainability (RAM) the FMECA is a powerful means to get insight in the system and to identify relevant subsystems/failure modes to be accounted for. This activity is also part of the Qualification process (Section 4).

There are several standards addressing issues related to reliability covering data collection, techniques for FMEA, fault tree analysis and life cycle costs:

- IEC 60300-1 (2003) Dependability management - Part 1: Dependability management systems
- IEC 60300-3-2 (2004) Dependability management - Part 3: Application guide - Section 2: Collection of dependability data from the field
- IEC 60300-3-3 (1996) Dependability management - Part 3: Application guide - Section 3: Life cycle costing
- IEC 60300-3-9 (1995) Dependability management - Part 3: Application guide - Section 9: Risk analysis of technological systems
- IEC 60812 (1985) Analysis techniques for system reliability - Procedures for failure mode and effect analysis (FMEA)
- IEC 61025 (1990) Fault tree analysis
- IEC 61078 (1991) Analysis techniques for dependability - Reliability block diagram method
- IEC 61165 (1995) Application of Markov techniques
- IEC 61882 (2001) Hazard and operability studies (HAZOP studies) - Application guide
  
- ISO 14121:1999 Safety of machinery - Principles for risk assessment
- ISO 14224 (1999) Petroleum and natural gas industries - Collection and exchange of reliability and maintenance data for equipment
- ISO 15663-1 (2000) Petroleum and natural gas industries - Life cycle costing - Part 1: Methodology
- ISO 15663-2 (2001) Petroleum and natural gas industries - Life-cycle costing - Part 2: Guidance on application of methodology and calculation methods
- ISO 15663-3 (2001) Petroleum and natural gas industries - Life-cycle costing - Part 3: Implementation guidelines
  
- MIL-STD 1629A (1980) Procedures for performing a failure mode, effects and criticality analysis
  
- NORSOK O-CR-001 (1996) Life cycle cost for systems and equipment
- NORSOK O-CR-002 (1996) Life cycle cost for production facility
- NORSOK Z-013 (2001) Risk and Emergency Preparedness Analysis
- NORSOK Z-016 Regularity management, reliability technology
  
- NUREG-0492 (1981) Fault Tree Handbook
  
- SAE ARP 4293 (1992) Life Cycle Cost - Techniques and Applications
- SAE ARP 4294 (1992) Data Formats and Practices for Life Cycle Cost Information
- SAE J1739 (2002) Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)
- AS/NZS 4360 (1999) Risk management
- IEC 62198 (2001) Project risk management - Application guidelines

## 7.6 Reliability Centred Maintenance (RCM)

The methodology developed to optimise the preventive maintenance activities are based on the theories of Reliability Centred Maintenance (RCM). This is discussed further in Section 25.2.2.

## 8 RISK ASSESSMENT

Any significant offshore development will have to bear in mind the risk involved with the lifecycle risk of the development. A typical offshore development risk assessment would include the follow category of events (consideration should be given to all phases during the device's life: fabrication, installation, in-service and decommissioning):

- Anchor/foundation failure
- Mooring failure
- Breach of water integrity of compartments or equipment
- Stability failure
- Collision risks
- Interference with commercial and recreational marine activities
- Structural failure
- Fishing gear impact
- Personnel risks to operators and to the general public
- Pressure containment failure from hydraulic or pneumatic systems
- Electrical failures and shore connector failures
- Seismic events
- Fires
- Interference floating debris with device

By analysing the above failures coupled with the engineering limits of the device, the consequences can be predicted. The frequency of failure can be evaluated through the use of reasonable estimates and historical failure data.

Depending on the consequences, the risks can normally be considered in three categories:

- Risk of business interruption
- Risk to the environment
- Risk to personnel

Risk of business interruption depends on energy supply contracts, penalty levels and the business model. Therefore for different projects there may be a different approach to the business risk assessment.

The criteria for environmental risks are difficult to define. Different societies have a different acceptance level to the risk of environment impacts. Like many other offshore developments, an Environmental Impact Assessment would probably be required. Only selected aspects are covered in this guideline for example, use of antifouling compounds, pollution from leaks or foundering of devices.

Risk to personnel in the offshore industry has been a focus for many years with parts of this experience transferable to wave energy devices. A guidance on this topic has been published by the HSE in the UK for risk assessment and criteria selection (Guidance on ALARP for offshore division inspectors making an ALARP demonstration (SPC/Enf/38)).

Although the ALARP (As Low As Reasonably Practicable) principle is normally associated with safety for personnel, the principle is used here to highlight the process used to reduce risks in general to as low as reasonably practicable levels. The level of “reasonable” is dictated, in case of assets, environment or production, by the balance between the cost required to reduce the risk and the benefit obtained. “Reasonably practicable” is also a well-understood expression in the legal profession.

The results of the risk assessment fall into 3 basic categories:

- Acceptable level - at which the risk is considered to be acceptable without any further justification;
- Tolerable level - at which an ALARP approach is required to justify the development; and
- Intolerable level - at which the development is considered socially unacceptable.

In the offshore industry, the risks are usually expressed in terms of Individual Risk Per Annual/Potential Loss of Life. For a typical wave farm development, there would be two groups of people who could be affected and need to be considered in the risk assessment. The first group is the people whose work requires them to be present in the vicinity of the device. For example, a maintenance person could fall into the water and drown. The other group is the one that has nothing to do with the development. For example if a fishing boat is sunk as a result of getting caught in collision with a unit drifted off from a wave farm, the crew of the fishing boat has inherited this risk.

## 9 SAFETY PHILOSOPHY

### 9.1 General Considerations

In defining targets for the qualification process or preparing the design basis, an overall safety philosophy should be clearly established covering all phases from conceptual studies up to and including decommissioning.

A Safety Philosophy should be derived considering the following aspects and stakeholders:

- Risk to life (during installation and removal, access to device during in-service life, risk to navigation and others during in-service life).
- Environmental impact due to any fluid releases, anti-fouling coatings, bilge water, and location of site relative to sensitive environments (protected species or sensitive sites and visual impacts).
- Loss of production.
- Inspection and maintenance cost, risks during removal of equipment for inspection and maintenance.
- Reputation of developer, industry, concept (survivability of the device to extreme environment is very important in terms of reputation).
- Underwriter perception of risks and definition of premium value (during installation and removal, and in-service life).
- Financial or venture capital communities' perception of risk to the return on investment.
- Expected safety level by Authorities. This may include Authority requirements in other countries which are potential marketing target for the devices.

In general, when selecting Safety Level, Safety Classes can be defined as:

#### Safety Level Low

Where failure implies low risk of human injury and minor environmental and economic consequences.

#### Safety Level Normal

For temporary conditions where failure implies: risk of human injury, significant environmental pollution or very high economic or political consequences.

This level normally aims for a risk of less than  $10^{-4}$  per year of a major single accident. It corresponds to a major incident happening on average less than once every 10,000 installation years. This level equates to the experience level from major representative industries and activities.

#### Safety Level High

For operating conditions where failure implies: high risk of human injury, significant environmental pollution or very high economic or political consequences.

Note that it may be useful to specify separate target levels for Personnel, Asset, Production and Environmental Safety.

## 9.2 Structures

The requirements for wave energy devices can be covered in large parts by codes for offshore steel structures as in OS-C101 (OS-C501 for composite components and OS-C502 for concrete structures). These provide internationally acceptable level of safety by defining minimum requirements for structures and structural components.

OS-C501 is a comprehensive and generic design and fabrication code for structures and components using composite materials (laminated or sandwich).

OS-C502 is particularly adequate to WEC devices that considers the use of concrete as the ratio between wave responses and dead load response will generally be high. In this load situation, most other standards are not applicable. For offshore concrete structures this especially applies to fatigue calculations. OS-C502 is in fact very similar to NS3473 (that would be equally applicable to WEC devices) except for some areas. The most important difference is fatigue Wöhler curves for reinforcement.

In OS-C502 the results by a British research project "Concrete in the Ocean" is implemented and these Wöhler curves are stricter than the Wöhler Curves in NS3473 and in the Eurocode. NS3473 and Eurocode base their fatigue curves on reinforcement not exposed to a marine environment i.e. no corrosion fatigue.

Furthermore, the load response part of OS-C502 is very similar to the draft ISO code (ISO/DIS 19903) for offshore concrete structures. This code may also be an alternative once it is finally agreed.

For temporary phases (e.g. installation or removal), requirements are given in the DNV Rules for Planning and Execution of Marine Operations. This uses a somewhat higher probability of failure when compared to requirements for in-place survival condition, as these marine operations can be characterised by single event operation with implementation of special procedures and better control of environmental limits, etc. The RP-H101 provides guidance and recommendations on how to reach an acceptable and controlled exposure to risk during marine operations for personnel, environment, assets and reputation.

The consideration of selected safety class can be taken into account for some aspects of the structural design such as: the definition of the Design Fatigue Factor, derivation of characteristic loads, definition of load factors to be applied (see OS-C101 Section 2 D404), definition of accidental loading (see OS-A101 Section 2 D103 and Risk Assessment) and selection of structural category (OS-C101 Section 4 C200 - taking into account the significance of component in terms of consequence of failure).

## 9.3 Equipment and Systems

Safety classes may be considered while defining redundancy or safety features for the equipment and systems. Reliability is also an important aspect to be taken into account.

Because wave energy devices are usually unmanned, the overall risk level to personnel will be low. However, because of the difficulty in access for maintenance and the potential penalty of downtime to provide energy to the grid, it may require a higher level of reliability than otherwise would be required for the device. A good example of this is subsea equipment for the oil industry where access to subsea equipment for maintenance

or work-over is expensive. Thus, the equipment used in subsea oil and gas developments usually demand a maintenance-free regime for the design lifetime of the equipment.

To obtain such a level of reliability through the use of standard off-the-shelf equipment, where it is possible, requires careful management. Some examples from the offshore industry are given below:

- A low utilisation of mechanical strength, or a higher reserve, sometime referred to as the safety factor is employed.
- Redundancy of equipment - this is usually applicable to electronic and moving parts.
- Rigorous testing of moving parts subject to cyclic loads.
- Rigorous testing of components subject to various environmental loads.
- Use of well-proven components.
- A thorough FMEA study.

## 10 DOCUMENTATION

A systematic approach to documentation to be produced by designer and developer is presented in RP-A201. The level of documentation varies with the complexity of the design and stage of development of the project. However, the final documentation should:

- provide a basis to verify that safety and operation critical parts of the device comply with requirements of the standards or with the objectives set out in the qualification basis;
- allow traceability of conclusions and results to be obtained;
- confirm and document all assumptions and conditions used during design process;
- demonstrate how changes and deviations were monitored and satisfactorily dealt with;
- demonstrate and document the control of all interfaces during design, fabrication and installation;
- demonstrate control of documents issued (numbering, revisions, approval and review process, etc);
- provide information on the operation of the device, including maintenance.

The level of documentation is an important step in order to obtain the recognition from financiers and underwriters that the risks (including those affecting performance and production) were identified and were controlled to the defined risk levels.

Although the documentation system in the RP has been conceived to satisfy requirements related to Classification, the breakdown in different disciplines, the definition of the areas to be covered and the outline of the contents of documents is especially useful for the organisation, authorities, third parties, banker's engineers, etc.

OS-C502 Section 3 details the required documentation prior to construction and as-built for concrete offshore structures.

OC-C501 Section 2 details the requirements regarding the documentation content for composite structures (drawings and design report).

# 11 MATERIAL SELECTION

## 11.1 Steel

The offshore standard OS-B101 provides principles, technical requirements and guidance for metallic materials to be used in the fabrication of offshore structures and facilities, and is also relevant for wave energy devices.

Selection of steel is given in OS-C201 Section 4, based on design temperature (normally based on lowest daily mean temperature), structural categories and plate thickness.

Material designations for steel are given in terms of a strength group and a specified minimum yield stress according to steel grade definitions given in DNV-OS-B101 (Chapter 2, Section 1) The steel grades are referred to as NV grades. Structural steel designations for various strength groups are referred to as given in OS-C101 Table D1 reproduced below.

<i>Designation</i>	<i>Strength group</i>	<i>Specified minimum yield stress (<math>f_y</math> (N/mm<sup>2</sup>) <sup>1)</sup></i>
NV	Normal strength steel (NS)	235
NV-27	High strength steel (HS)	265
NV-32		315
NV-36		335
NV-40		390
NV-420		420
NV-460	Extra high strength steel (EHS)	460
NV-500		500
NV-550		550
NV-620		620
NV-690		690

<sup>1)</sup> For steels of improved weldability the required specified minimum yield stress is reduced for increasing material thickness, see DNV OS-B101.

Table 11.1 : Material Designation (from OS-C01)

Each strength group consists of two parallel series of steel grades:

- steels of normal weldability
- steels of improved weldability.

The two series are intended for the same applications. However, the improved weldability grades have, in addition to leaner chemistry and better weldability, extra margins to account for reduced toughness after welding. These grades are also limited to a specified minimum yield stress of 500 N/mm<sup>2</sup>.

Within each defined strength group, different steel grades are given, depending on the required impact toughness properties. The grades are referred to as A, B, D, E, and F for normal weldability grades and AW, BW, DW, and EW for improved weldability grades as defined in Table D2 of OS-C101. Additional symbol: Z = steel grade of proven through-

thickness properties. This symbol is omitted for steels of improved weldability although improved through-thickness properties are required.

Conversions between NV grades and steel grades used in the EN10025 and EN10113 standards are given in Table A4 and A5 in OS-J101 Design of Offshore Wind Turbines (as reproduced below). The number of one-to-one conversions between NV grades and EN10025 grades given in Table G.1 is limited, because the E-qualities of the NV grades are not defined in EN10025 and because no qualities with specified minimum yield stress  $f_y$  greater than 355 MPa are given in EN10025.

For tables and guidance notes on steel grade conversion see APPENDIX G - STEEL GRADE CONVERSION

## 11.2 Concrete

Requirements to material properties, composition, extent of testing, inspection, etc. are given in Section 3 of OS-C502. Ferro-cement is not covered in this guideline. Concrete grades are defined in OS-C502 Sec.6 C100 Table C1 and are summarised in Table 11.4.

Strength	Concrete Grade <sup>1)</sup>									
	- LC15	C25 LC25	C35 LC35	C45 LC45	C55 LC55	C65 LC65	C75 LC75	C85 LC85	C95	C105
Characteristic compressive cube strength, $f_{ck}$	15	25	35	45	55	65	75	85		
Characteristic compressive cylinder strength, $f_{cck}$	12	20	28	36	44	54	64	74	84	94
Nominal structural compressive strength, $f_{cn}$	11.2	16.8	22.4	28.0	33.6	39.2	44.8	50.4	56.0	61.6
Characteristic tensile strength, $f_{tk}$ <sup>2)</sup>	1.55	2.10	2.55	2.95	3.30	3.65	4.00	4.30	4.60	4.90
Nominal structural tensile strength, $f_{tn}$	1.00	1.40	1.70	2.00	2.25	2.50	2.60	2.70	2.70	2.70
<sup>1)</sup>	Concrete grades are related to the characteristic compressive cube strength (100 mm cubes) and is denoted by C for normal dense aggregate concrete and LC for lightweight aggregate concrete.									
<sup>2)</sup>	The given tensile strength applies to concrete subjected to uniaxial tension.									

Table 11.4 : Concrete Grades and Structural Strength (from OS-C502)

Prestressed reinforced concrete structures shall not be designed using concrete of grade less than C35. For concrete exposed to sea water, the minimum concrete Grade is C45. The material coefficients  $\gamma_m$  for concrete and reinforcement are given in Table 11.5.

Limit State		ULS	ALS and FLS	SLS
Reinforced concrete	Concrete, $\gamma_c$	1.25 <sup>1</sup> (1.40) <sup>2</sup>	1.10 <sup>1</sup> (1.20) <sup>2</sup>	1.0
	Reinforcement, $\gamma_s$	1.15 <sup>1</sup> (1.25) <sup>2</sup>	1.00 <sup>1</sup> (1.10) <sup>2</sup>	1.0
Plain concrete	$\gamma_c$	1.50 <sup>1</sup> (1.75) <sup>2</sup>	1.25 <sup>1</sup> (1.50) <sup>2</sup>	1.0
<p><sup>1</sup> When the design is to be based on dimensional data that include specified tolerances at their most unfavourable limits, structural imperfections, placement tolerances as to positioning of reinforcement, then these material coefficients can be used. When these coefficient are used then any geometric deviations from the “approved for construction” drawings must be evaluated and considered in relation to the tolerances used in the design calculations.</p> <p><sup>2</sup> Design with these coefficients allows for tolerances in accordance with C400 or alternatively on cross sectional dimensions and placing of reinforcements that do not reduce calculated resistance by more than 10%. If specified tolerances are in excess of those given in C400 or the specified tolerances lead to greater reductions in calculated resistance, the excess tolerances or the reduction in excess of 10% is to be accounted for in resistance calculations. Alternatively, material coefficients may be taken according to given under <sup>1</sup></p>				

Table 11.5 : Material Coefficients for Concrete and Reinforcement (from OS-C502)

### 10.3 Composites

The sandwich structures are normally selected considering weight saving under mechanical bending conditions as sandwich structures are very stiff at low weight. Also, due to its properties the use of sandwich structure is advantageous to avoid the use of stiffeners for buckling capacity.

For in-plane tensile loads sandwich and laminate structures are equally good. Production of a sandwich structure can be more complex and the foams are expensive. However, the case for selecting sandwich structures can be very much improved in this aspect when the foam can be used as a mould.

Laminated materials are covered in Section 4 of OS-C501 and Sandwich structures in Section 5.

## 12 CORROSION PROTECTION

Reference is made to OS-C101, Section 10.

### 12.1 Steel Structures

The decision on the most adequate method of protection against corrosion should be evaluated considering inspection regime, position of the structure (or part of) related to the splash zone, criticality of fatigue and definition of corrosion allowances.

For areas in the splash zone, cathodic protection is not efficient and for fatigue sensitive areas, coating is recommended. However, the efficiency of coating should be considered together with inspection and maintenance regime. Also for areas subject to impact or wear special consideration should be provided regarding coating. Information on coating is given in OS-C101 Section 10 D.

For areas not protected against corrosion (or with ordinary paint coating only), an additional corrosion allowance shall be considered (see Section 10 B 400). BS6349 also provides advice on free corrosion for steel in maritime structures.

Classification Note 30.7 (Fatigue Assessment of Ship Structures, Item 2.4) gives information on effective life times for a common corrosion protection system using coating (Table 2.4). S-N curves for air may be used for the period of design life that the coating is considered effective. For the rest of the design life S-N curves for free corrosion should be used for details in the splash zone. Alternatively S-N curves for seawater with cathodic protection should be used if relevant.

### 12.2 Concrete Structures

For concrete structures, corrosion control is discussed in OS-C502, Section 6. Minimum concrete cover regarding corrosion protection is a function of environmental class and sensitivity of reinforcement to corrosion. For wave devices, environmental class MA (severely aggressive environment) should be considered. In this case, the minimum concrete cover for corrosion protection purposes should be between 40 and 50mm (see Q200).

Concrete rebars and pre-stressing tendons are adequately protected by the concrete itself, (assuming adequate coverage and type/quality of the aggregate is provided). However, rebar portions freely exposed to seawater in case of concrete defects, embedment plates, penetration sleeves and various supports which are freely exposed to seawater or the marine atmosphere will normally require corrosion protection.

As wave device structures are likely to be located in the splash zone corrosion rates can reach 0.3mm per year for uncoated C-steel in high ambient temperatures, while for internal heated surfaces the corrosion rate can amount to 3mm per year.

### 12.3 Composite Structures

Galvanic corrosion should 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 composites should be electrically isolated from metal components.

Material may degrade due to chemical composition. OS-C501 deals with this by time-dependence of strength and stiffness values (see Section, 6 Q).

## 12.4 Chains, Steel Wire and Fibre Rope

Corrosion of chains and steel wire ropes used for mooring of floating wave energy devices are covered in OS-E301 and Classification Note No. 2.5.

Fibre rope segments in mooring lines are normally protected by an outer jacket, which is to have adequate resistance to hydrolysis, chemicals, UV, fish bite, friction and shear while retaining adequate flexibility at minimum exposure temperatures in order to meet the requirement to protect the rope core (for more information see Classification Note No. 2.13).

## 13 STRUCTURAL DESIGN CRITERIA

### 13.1 Structural Classification

Steel components are classified into structural categories according to their significance in terms of consequence of failure (see also Safety Philosophy above) and stress conditions together with possible weld defects or fatigue cracks. Definitions are given in OS-C101 Section 4. The classification of the component will determine the requirement regarding the grade of steel and inspection during fabrication and during the lifetime of the structure.

### 13.2 Hull Structure and Mechanical Connections

Reference is made to Section 2 of OS-C101 for definition of limit states and design principles.

Coastal structures, i.e. structures located near-shore or at the shore line, should consider the application of coastal engineering standards such as:

BS 6349 - Maritime Structures, or  
US Army Corps of Engineer - Coastal Engineering Manual (EM 1110-2-1100)

### 13.3 Ultimate Limit State Load Factors, Steel

Reference is made to Section 3 of OS-C101 for definition of loads to be considered for design for the Ultimate Limit State (ULS) for steel structures.

Load factors and load combination is defined in Section 2 D400. Table 13.1 summarises the load factors for ULS and the combinations that need to be considered for operating and temporary conditions.

<i>Combination of design loads</i>	<i>Load categories</i>			
	G	Q	E	D
a)	1.3 (1.2) <sup>1</sup>	1.3 (1.2) <sup>1</sup>	0.7	1.0
b)	1.0	1.0	1.3 (1.15) <sup>1</sup>	1.0

Load categories are:  
G - permanent load                      Q - variable load  
E - environmental load                D - Deformation load  
For description of load categories see Section 3 - OS-C101

<sup>1</sup> See text below

Table 13.1 : Load Factors for ULS (from OS-C101)

When permanent loads (G) and variable functional loads (Q) are well defined, (as for hydrostatic pressure) a load factor of 1.2 may be used in combination with these load

categories (combination a). If a load factor  $\gamma_f = 1.0$  on G and Q loads in this combination results in higher design load effect, the load factor of 1.0 shall be used.

Based on a safety assessment (see Section 9 SAFETY PHILOSOPHY ) considering the risk for both human life and the environment, the load factor for environmental loads may be reduced to 1.15 (combination b) if the structure is unmanned during extreme environmental conditions.

Material factors are given in OS-C101 Section 5. The material factor  $\gamma_M$  for plated and tubular structures is 1.15. Table C1 gives material factors for buckling for shell structures.

Where structural response is affected by active mechanisms, additional variable functional loads shall be considered. These additional loads can be defined as system loads generated primarily from the operation of such mechanisms located within the machine.

The maximum forces which can be acting on the structure under normal operation should be specified. If the maximum forces are determined from weak link considerations (like failure of a pin / weak link) the 95<sup>th</sup> percentile value of the breaking strength shall be used as characteristic load.

The forces in the active mechanisms are significantly correlated with the environmental loads. Thus these loads could also be defined as environmental loads in Section 2 of OS-C101. If it is defined as a variable load, it is recommended to use a load factor for this force equal to 1.3 for load combination b (reference Section 2 of OS-C101). Otherwise it is recommended to use the load and resistance factors in OS-C101.

#### 13.4 Ultimate Limit State Load Factors, Concrete

The design should be performed according to limit state design principles as detailed in OS-C101, Section 2. The design shall provide adequate strength and tightness in all design situations.

The representative values of loads are to be selected according to OS-C101 Section 3 and OS-C502. The partial safety factors for loads are chosen with respect to the limit states and the combination of loads. They are, in general, given in OS-C101 Section 2 and specifically for reinforced concrete in OS-C502 Section 5 C100. Characteristic values for material strength are given in Section 6 B300 with material coefficients given in Section 6 B607.

The load and load effects are given in OS-C101 Section 3 and OS-C502 Section 5B. Load combinations and Partial Safety Factors are discussed in OS-C502 Section 5C.

The defined safety philosophy for the device can be matched with the aspects regarding exposure levels, relating life safety category of structure and its consequence of failure. For WEC devices, an exposure level at least consistent with an unmanned structure is expected to be considered (assuming that consequence of failure is taken as medium for the concrete structure following risk assessment and FMEA).

The requirements for the design of structures with such exposure level are similar to unmanned structure and with high consequence of failure (designed in accordance with

the requirements of OS-C502 for environmental and functional loads including accidental loads), except that inspection of execution may be based on Inspection Class 2 (see OS-C502 Section 7 D200).

Material coefficients for concrete and reinforcement are given in Section 6 B607. It is important to highlight that the selection of material coefficient is dependent on whether construction tolerances (dimension and placement of reinforcement) are included in the design calculation, at their most unfavourable limits, or if the design allows for tolerances in accordance with the geometrical dimensions defined in OS-C502 Section 6 C400 (or that the cross sectional dimensions and placing of reinforcements do not reduce calculated resistance by more than 10%).

Effects of temperature, shrinkage, creep and relaxation are discussed in Section 5 D300.

### 13.5 Ultimate Limit State Load Factors, Composite Structures

OS-C501 makes a specific distinction between loads and environment. Loads refer to direct and indirect loads (e.g. wave load on a structure, functional load, accidental loads). The term environment means the surroundings that impose no direct load (e.g. ambient temperature or moisture) or may impose indirect loads on the structure (e.g. thermal stresses or swelling due to moisture uptake) and it is generally considered for its effect on the degradation of material strength.

OS-C501 does not give specific load conditions and characteristic load effects as a wide range of applications may be constructed using this material. Thus, only general guidance is given on the definition of load values. This information is provided in Section 3I (Loads). Environment is discussed in Section 3J and the combination of load effects and environment is given in Section 3K.

### 13.6 Accidental Limit State Loads

An assessment should be able to indicate the main parameters for definition of accidental loads. Vessels attending a wave farm and vessels passing in shipping lanes nearby should be considered for collision studies with due attention to visibility of the wave device to vessels and information on charts, etc. Potential impact of fishing gear on mooring lines, subsea cables, etc should be assessed considering the mooring characteristics (compliant system) and the extent of the exclusion zone.

Debris may be considered within Accidental Limit State (ALS), depending on specific risk assessment for the device and location. It may be that, for some debris under certain dimension, physical characteristics, characteristics of protection structure and probability of occurrence, this case may be considered, combined with functional and environmental loading, as part of operating conditions under ULS.

Extreme waves should be defined based on safety philosophy, device characteristics and metocean data. Accidental flooding should be considered for stability and structural survival of the device.

It is also recommended that an FMEA is performed in order to assess probability of a malfunction that might introduce abnormal forces in the system other than those considered in ULS.

DNV Guideline No. 13 (Interference between Trawl Gear and Pipelines) provides information on trawl equipment for derivation of impact forces.

### 13.7 Fatigue Limit State Analysis

A detailed treatment of the methodology for Fatigue Limit State (FLS) is presented in APPENDIX A - FATIGUE ANALYSIS METHODOLOGY.

### 13.8 Serviceability Limit State

The serviceability limit state may not be considered provided the design complies with the other limit states. Attention should be paid to accelerations, displacements and distortions that may affect the operational performance of equipment and systems or may result in damage to coating and painting.

For concrete, the serviceability limit state shall be considered. The requirement is given in OS-C502 Section 6 O. The criteria are related to;

- Durability,
- limitation of cracking,
- tightness, and
- limitation of deflections and vibrations.

The properties of the materials under short- and long-term actions and the effect of shrinkage, temperature and imposed displacements, if any, shall be taken into account. Cracking of concrete is to be limited so that it will not impair the function or durability of the structure. The crack size should be controlled by ensuring that the predicted crack width by calculations is within the nominal characteristic crack width limits in OS-C502 O Table O1, depending on the environmental class and the sensitivity of reinforcement to corrosion.

For wave devices environmental class MA (severely aggressive environment) is to be considered.

Concrete structures are to have at least a minimum amount of reinforcement to provide adequate ability for crack distribution and resistance against minor load effects not accounted for in design. For further details, see OS-C502, Section 6R.

In the analysis and structural design it shall be ensured that displacements and cracks, spalling of concrete and other local failures are not of such a nature that they make the structure unfit for its purpose in the serviceability limit state, nor alter the assumptions made when designing in the other limit states.

In order to protect the reinforcement against corrosion and to ensure the structural performance, the reinforcement shall have a minimum concrete cover as given in OS-C502 Section 6 Q200 and the nominal crack widths calculated in accordance with OS-C502 Section 6 O200 shall be limited as given in Table O1.

For wave devices requirements to tightness should be considered in accordance with OS-C502 Section 6 O200 , O500 and O600. The following should be applied;

- concrete with low permeability and suitable material composition shall be selected,

- the acting tensile stresses and nominal crack widths shall be limited, and the
- geometrical form and dimensions shall be chosen which permit a proper placing of the concrete.

Members subjected to an external/internal hydrostatic pressure difference (O502) are to be designed with a permanent boundary compression zone.

For composite structures, see Section 2 C200, C503 (for service class) and Section 8 C603 (for SLS partial resistance factor).

### 13.9 Structural Response Methodology

The environmental loading and structural response depends strongly on the location and the kind of wave energy converter. WECs may be categorised in terms of location and the method is used for energy extraction. The environmental conditions and corresponding loads may change strongly with location of the device, while the specific design for optimal wave energy extraction determines the structural response.

The first wave energy converters were installed at the shoreline with low installation costs. These devices can be categorised as *shoreline devices*. Since the wave energy density is higher away from the shore, devices were later installed out in the open sea, resting directly on the seabed. These can be categorised as *nearshore devices*. Recently new ways of extracting energy from waves have made it possible to deploy floating moored devices in deeper water where wave energy density are even higher. Such devices can be categorised as *offshore devices* and benefits from the long experience in offshore technology when it comes to station keeping methodology.

Shoreline device : Located on shore  
 Nearshore device : Located on seabed in shallow water  
 Offshore device : Moored floating structure in deeper water

The structural response methodology is different for different devices from floating devices in deep water to fixed devices at the shoreline.

The design of a wave energy converter shall be based on the most severe environmental loads that the structure may experience during its design life. Environmental loads on a wave energy device are mainly due to:

- waves
- currents
- wind

For most wave energy devices wave and current loads are the dominating environmental loads. In addition loads due to tidal effects, marine growth, snow and ice shall be considered. Detailed information regarding environmental loads and load effects are given in Classification Notes No. 30.5. The parameters describing the environmental conditions shall be based on observations from or in the vicinity of the site of the wave energy device and on available knowledge about the environmental conditions in the area. The proper combinations and joint occurrences of waves and current conditions as given in OS-C101 should be applied.

For offshore wave energy devices in deep water, the environmental loads shall be determined with stipulated probabilities of exceedance while in shallow water the wave height is limited by the maximum wave height due to breaking, expressed as a fraction of the water depth.

### 13.9.1 Wave Environment

The wave environment is represented by the significant wave height  $H_s$  and the spectral peak period  $T_p$ . Stationary wave conditions with constant  $H_s$  and  $T_p$  are assumed to prevail over a 3- hour or 6-hour period. In moderately deep to deep water the significant wave height is defined as four times the standard deviation of the sea elevation process. However, this may not hold for shallow water waves. The short term 3- or 6-hour sea state may be represented by a wave spectrum  $S(\omega)$ , i.e. the power spectral density function of the sea elevation process. The wave spectrum is a function of  $H_s$  and  $T_p$ . Wave statistics shall be used as a basis for representation of the long-term and short-term wave conditions. Empirical statistical data used as a basis for design must cover a sufficiently long period of time. Ref. OS-J101.

A detailed review of wave modelling, wave kinematics and wave loading is presented in APPENDIX B - WAVE MODELLING AND LOADS.

### 13.9.2 Current environment

The current consists of a wind-generated current and a tidal current. Current statistics are used as a basis for representation of the long-term and short-term current conditions. Empirical statistical data used as a basis for design must cover a sufficiently long period of time. Variation of the current with the water depth shall be considered when relevant. The variation of current velocity with depth is given in DNV CN-30.5 in the case where there are no detailed field measurements available.

## 13.10 Structural Capacity Verification - Steel

Requirements for checking ultimate strength capacity and accidental limit state for steel structure elements are given in OS-C101 Section 5 and 7 respectively.

It is a fundamental requirement that all failure modes are sufficiently ductile such that the structural behaviour will be in accordance with the anticipated model used for determination of the responses. In general all design procedures, regardless of analysis method, will not capture the true structural behaviour. Ductile failure modes will allow the structure to redistribute forces in accordance with the presupposed static model. Brittle failure modes shall therefore be avoided or shall be verified to have excess resistance compared to ductile modes, and in this way protect the structure from brittle failure (except for parts designed to work as a weak link).

The following sources for brittle structural behaviour may need to be considered for a steel structure:

- unstable fracture caused by a combination of brittle material, low temperature in the steel, a design resulting in high local stresses and the possibilities for weld defects
- structural details where ultimate resistance is reached with plastic deformations only in limited areas, making the global behaviour brittle
- shell buckling
- buckling where interaction between local and global buckling modes occurs.

Checks of the structural capacity of all structural components shall be performed. The capacity check shall consider both excessive yielding and buckling (RP-C201 may be used for verification of buckling capacity). Simplified assumptions regarding stress distributions may be used provided that the assumptions are made in accordance with generally accepted practice, or in accordance with sufficiently comprehensive experience or tests. Any corrosion allowance shall not be accounted for in the determination of design resistance for the Ultimate Limit State. Half the corrosion allowance may be included for the Fatigue Limit State.

Provision for capacity check according to other codes (i.e. AISC LRFD or Eurocode 3 for stiffeners and girders) is given in Section 5 B400. The buckling stability of shell structures may be checked according to RP-C202. Slip resistant bolt connections is discussed in Section 5 H.

Structures shall be checked in ALS in two steps:

- Resistance of the structure against design accidental loads.
- Post accident resistance of the structure against environmental loads should only be checked when the resistance is reduced by structural damage caused by the design accidental loads.

The overall objective of design against accidental loads is to achieve a system where the main safety functions are not lost by the design accidental loads, though limited damage is acceptable.

The design against accidental loads may be done by direct calculation of the effects imposed by the loads on the structure, or indirectly, by designing the structure to tolerate accidents. Examples of the latter are compartmentation of floating units which provides sufficient integrity to survive certain collision scenarios without further calculations.

The inherent uncertainty of the frequency and magnitude of the accidental loads, as well as the approximate nature of the methods for determination of these effects, shall be recognised. It is therefore essential to apply sound engineering judgement and pragmatic evaluations in the design.

Typical accidental loads are:

- impact from ship collisions
- impact from dropped objects (temporary phases or during maintenance)
- fire
- explosions
- abnormal environmental conditions
- accidental flooding.

For wave devices, failure criteria may be defined by deformation leading to leakage of compartments, damage to equipment and systems or impairment of safety features (shear pins, collapsible panels, relief valves etc).

More information on the design against accidental actions can be found in NORSOK N-004 Annex A and in NORSOK N-003 Action and Action Effects. Accidental actions are further

discussed in Section 9. Reference may also be given to RP-C204 Design Against Accidental Loads.

If non-linear, dynamic finite element analysis is applied for design, it shall be verified that all local failure modes, e.g. strain rate, local buckling, joint overloading, joint fracture, are accounted for implicitly by the modelling adopted, or else subjected to explicit evaluation.

Although related to non-linear frame analyses, the ULTIGUIDE (Best practices for use of non-linear analysis methods in documentation of ultimate limit states for jacket type offshore structures) provides recommendations that are also valid, to some extent, for other types of structures.

### 13.11 Structural Capacity Verification - Concrete

Concrete structures are to be designed to behave in a ductile fashion in order to ensure that the structure can withstand abnormal or accidental loads to some extent, and that a redistribution of the loads can take place. More details are given in OS-C502 Section 6C.

For members subjected to moment loading, it is to be ensured that the steel on the tension side of the member will achieve twice the yield strain before the concrete on the compressive side reaches its ultimate compressive strain. Where this requirement cannot be fulfilled due to high axial loads, ductility is to be ensured by use of stirrups.

Capacity for bending moments and axial forces (including slender structural members), shear forces in beams and slabs, slabs subjected to concentrated actions, torsional moments in beams, shear force in construction joints, bond strength and anchorage are given in OS-C502 Section 6D.

### 13.12 Structural Capacity Verification - Composite Structures

Failure mechanisms for laminates and sandwich structures and design criteria for the failure mechanisms (fibre failure, matrix cracking, delamination, yielding, buckling, impact, wear, resistance to explosive decompression, etc) are presented in OS-C501 Section 6.

A mechanism of failure is the underlying phenomenon at the material level that determines the mode of failure. Depending on its level of severity a mechanism of failure can lead to various failure modes. For example, matrix cracking can lead to seepage of a fluid through the laminate or lead to fracture depending on the severity of the cracks. Failure mechanism can be regarded as the cause of failure and failure mode as the effect.

Local and global failure shall be identified. On a material level, failure tends to be local, i.e. over an area of a few square centimetres, or even less. This local failure may have global consequences immediately, or after some growth with time. In some cases, the local failure does not grow and does not have any global consequences therefore it does not affect any of the design requirements of the structure. In such a case local failure may be acceptable. Only failures that are related to critical failure modes should be considered.

OS-C501 Section 6 describes the different failure mechanisms (fibre failure, matrix cracking, delamination, yielding, elastic buckling, stress rupture, fatigue, etc) for

different materials and the relationship between the failure mechanisms and failure type (brittle, plastic, ductile) and the design criteria for each of relevant failure mechanism.

Special attention is to be taken to joints and interfaces (see OS-C501 Section 7). Joints are defined as load bearing connections between structures, components or parts. Interfaces are defined as the area or region where different structures, components or parts meet each other. A typical interface is the area where the surface of a load bearing structure and a liner meet. Three basic types of joints are considered:

- Laminated joints, i.e. joints fabricated from the same constituent materials as the laminates that are joined, such as over-laminations, lap joints, scarf joints, etc.
- Adhesive joints, i.e. joints between laminates, cores or between laminates and other materials e.g. metals.
- Mechanical joints, i.e. joints including fasteners, such as bolted connections.

The safety provision (based on consequences of failure) and service classes (frequency of service interruptions or restrictions caused by SLS modes of failure) can be defined based on the safety philosophy defined for the device and types of failure. The selection of partial safety (model and system) factors are defined based on selected safety class (see Section 2 C600, Section 8, Section 9 L and APPENDIX E - INSPECTION). Information regarding model and system factors are provided in Section 8.

### 13.13 Other Issues

The following aspects should also be highlighted with reference to OS-C501:

- Modification of material static properties modification upon exposure to long term loads and environments (reduction of modulus of elasticity and static strength due to cyclic loading, for example) (Section 4C).
- Check of static strength considering reduction due to cyclic loads (Section 4 C900 for laminates and Section 5 C800 for sandwich materials).
- Requirements of material property qualification against representative data are defined in Section 4H for laminate and Section 5H for sandwich materials. Table H2 defines the qualification required for each mechanical parameter as a function of safety class.
- Structural analysis (Section 9): While the FE method is applicable for a wide range of problems, analytical solutions and the finite series approach often put too many restrictions on laminate lay-up, geometry, etc, and are thus insufficient in the design of most real world composite structures.
- The local response of the structure can, in principle, be analysed at the following different material levels:
  - the “*constituent* level” corresponding to the fibre, matrix and core, separately,
  - the “*ply* level” corresponding to the individual layers in a laminate or the faces of a sandwich structure, and
  - the “*laminate* level” corresponding to the whole laminate or sandwich structure.

- Due to the lack of theoretical knowledge or for practical reasons, it is not always possible to check a given failure mechanism at all material levels. The local response of the structure shall be analysed at a material level consistent with the failure criteria used in the failure analysis. All failure criteria (except for buckling) require the stresses or strains to be accurately represented on the level of each ply. Buckling is generally checked on larger parts of the structure and based on average stresses over large areas. Under such conditions a coarser analysis may be sufficient. However, if the FE method is used to calculate buckling stresses, a very local analysis of the structure may be needed.
- Non-linearities: Most composite structures possess linear material properties when intact. However, composites can develop various failure mechanisms, e.g. matrix cracking at very low strains leading to reduced stiffness parameters. This non-linear behaviour of the material shall be taken into account when failure analysis of composite components is performed.
- A decision to use a progressive, non-linear failure analysis or a simplified (linear) failure analysis should be based on the failure modes of the structure and component and the failure mechanisms investigated. The decision of whether to use 2-D or 3-D analysis methods should generally be made depending on the level of significance of the through-thickness stresses. Additionally, the analysis of certain laminate and sandwich structures may be simplified by a through-thickness (cross section) 2-D approach, in which the plane strain condition is assumed to prevail. A relation between analysis methods (progressive, linear non-degraded, linear degraded, two-step non-linear) and failure criteria is given in Section 9C.
- A structure or part of a structure can in some cases be qualified by testing only, i.e. no structural analysis as presented in Section 9 is performed. Testing can in some cases be carried out to document the design or increase confidence in design calculations. It is an alternative or complement to analysis based on basic material properties. Section 10 describes the qualification process based on tests, important aspects regarding testing of components with multiple failure mechanisms and updating material parameters for analysis based on component testing.

## 14 FOUNDATION DESIGN

Foundations relevant for wave energy converters can be pile foundations, gravity type foundations and anchor foundations. Reference is made to OS-C101 Section 11. The partial coefficient method is the preferred method in foundation design. The design of foundations shall consider both the strength and deformations of the foundation structure and of the foundation soils.

Failure due to the effect of cyclic loading is treated as an ULS limit state, alternatively as an ALS limit state, using load and material coefficients as defined for these limit state categories. The load coefficients are in this case to be applied to all cyclic loads in the design history.

Material coefficients shall be applied to soil shear strength. For soil resistance to axial pile load, material coefficients shall be applied to the characteristic resistance. For anchor foundations, material coefficients shall be applied to the characteristic anchor resistance.

Design of foundations for wave energy converters shall be based on site specific information. The extent of site investigations and the choice of investigation methods shall take into account the type and size of the wave energy device, the uniformity of soil and seabed conditions. For application of anchors the soil stratigraphy and range of soil strength properties shall be assessed. Site investigations should provide information about the soil to a depth required to check effect of possible weak formations.

The design of foundations shall consider both the strength and the deformations of the foundation structure and of the foundation soils. OS-E301 distinguishes between two failure consequence classes (CC), depending on whether failure of a mooring line or an anchor can lead to serious consequences or not. The values of the partial safety factors for the respective limit states are differentiated with respect to the consequence class that applies, which gives more flexibility than the total safety factor format without consequence classes. As an example, fluke anchors may according to RP-E301 be designed for zero anchor drag (CC2) or for a situation where drag is acceptable (CC1), in the latter case with lower safety factors.

Anchors for taut (fibre rope) mooring systems must be capable to resist both vertical and horizontal load components. Applicable anchors in this category are e.g. plate anchors, see RP-E302, or suction anchors. A design code for suction anchors is under development through a Joint Industry Project and will be published as RP-E303, tentatively in 2005.

## 15 MOORING SYSTEM ANALYSIS

### 15.1 Acceptance Criteria

Reference is made to Section 2 of OS-E301 for mooring system analyses. The design can be performed with the mooring system considered under Consequence Class 1.

#### 15.1.1 Ultimate Limit State

Reference is made to Section 2 of OS-E301 for mooring system analyses for the Ultimate Limit State.

#### 15.1.2 Accidental Limit State

Reference is made to Section 2 of OS-E301 for mooring system analyses for the Accidental Limit State.

#### 15.1.3 Fatigue Limit State

Reference is made to Section 2 of OS-E301 for mooring system analyses for the Fatigue Limit State. According to OS-E301 Chapter 2 Section 2 G 400 the safety factor will vary between 5 and 8 depending on the grouping of the mooring lines, and has to be calculated based on the fatigue damage in two adjacent lines.

Requirements and recommendations for stationkeeping systems for wave energy devices are also found in API-RP-2SK and ISO/DIS 19901-7.

### 15.2 Anchor Design

General design aspects of anchor foundations are given in OS-C101 Section 11 E. Analysis of anchor resistance shall be carried out for ULS and ALS provisions. The ULS is intended to ensure that the anchor can withstand the loads arising in an intact mooring system under extreme environmental conditions. The ALS is intended to ensure that the mooring system retains adequate capacity if one mooring line or anchor should fail for reasons outside the designer's control.

Two consequence classes are considered, both for the ULS and for the ALS, defined as follows:

- *Consequence Class 1 (CC1)*: Failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking.
- *Consequence Class 2 (CC2)*: Failure may well lead to unacceptable consequences of these types.

Load coefficients ( $\gamma$ ) for the two alternative methods to calculate line tension are given in Table 15.1 and Table 15.2 for ULS and ALS, respectively. For mooring in deep water (i.e. water depth exceeding 200m, see OS-E301 Chapter 2 Section 2 B100) a dynamic analysis is required.

Consequence class	Type of analysis	$\gamma_{\text{mean}}$	$\gamma_{\text{dyn}}$
1	Dynamic	1.10	1.50
2	Dynamic	1.40	2.10
1	Quasi-static	1.70	
2	Quasi-static	2.50	

Table 15.1 : Load Coefficients for ULS (from OS-C101)

Consequence class	Type of analysis	$\gamma_{\text{mean}}$	$\gamma_{\text{dyn}}$
1	Dynamic	1.00	1.10
2	Dynamic	1.00	1.25
1	Quasi-static	1.10	
2	Quasi-static	1.35	

Table 15.2 : Load Coefficients for ALS (from OS-C101)

For wave energy devices with a dynamic response to wave loading and/or novel mooring configuration, a complete time domain simulation combined with tank testing may be necessary. For cases when the mean of the tension time series can be identified as the static component and the remaining part as the dynamic component, the relevant safety factors as given in OS-E301 should be applied. The mooring system can also be designed by direct application of structural reliability analysis, as an alternative to the simplified design calculations based on partial safety factors for quasi-static and dynamic tension. Such an analysis should be at least as refined as the reliability analysis used to calibrate the design procedure as given in OS-E301, and must be checked against the results of the calibration, for at least one relevant test case. (See OS-E301 Chapter 2, Section 2J, References). Guidelines for design based on structural reliability analysis are given in DNV CN No. 30.6 -Structural Reliability Analysis of Marine Structures.

Due consideration shall be given to the specific aspects of the different anchor types and the current state of knowledge and development.

When clump weight anchors are designed to be lifted off the seabed during extreme loads, due consideration shall be paid to the suction effects that may develop during rapid lift-off. The effect of possible burial during the subsequent set-down shall be considered.

Pile anchors can be designed in accordance with general requirements given in OS-C101 Section 11 E.

Fluke anchors are applicable for horizontal and unidirectional load application. Some uplift may be allowed under certain conditions both during anchor installation and during operation design conditions. Recommended design procedures for fluke anchors is given in RP-E301.

Drag-in-plate anchors are applicable for taut mooring systems since they can resist both vertical and horizontal loads transferred to the anchors. Recommended design procedures for drag-in-plate anchors are given in RP-E302.

## 16 STABILITY AND WATERTIGHT INTEGRITY

### 16.1 General Considerations

The OS-C301 Standard “Stability and Watertight Integrity” can be used as a guide by applying it as far as applicable to a wave energy device. When the device is manned (e.g. during towing, installation or maintenance during operation) these considerations are particularly important.

For normally unmanned installations, the overall target safety level may be reduced, as long as safety for personnel interaction during the transportation, installation and retrieval phases are considered and covered through by operational measures or provision of special facilities through the type of support vessel or equipment being provided. These aspects should be covered by a risk assessment.

Temporary phases like transportation to site, installation or removal may require a marine operations type of assessment and Warranty Survey for insurance purposes (see Rules for Planning and Execution of Marine Operations). Minimum design requirements for watertight integrity, strength of the device, closing devices for access hatches or openings, bilge and ballast systems, ventilation arrangements should be considered. Note that for more substantial devices, it may be relevant to check against Class requirements for ships as this is often used as a basis for the system requirements for objects to be covered by a marine operations assessment.

### 16.2 Stability Considerations

This should include consideration of flooded or partly flooded compartments in case of loss of watertight integrity, inadvertent shift of permanent ballast, and safe limits for access to the device. Note that permanent ballast in the form of loose material must to be provided with adequate restraints against shifting due to device movements. Loose material may also become fluidised should water be inadvertently added from leaks or other mechanisms.

Further more, it is necessary to consider how to restore adequate stability through connecting or alternatively starting onboard bilge and/or ballast pumps. Provision of emergency supply to pumps, or provisions for piping for external connection of such pumps should be considered.

For those devices that are designed to achieve resonance conditions rather than best possible damping, the dynamic behaviour of the device may require special considerations beyond the normal margins provided by the stability curves and requirements for ships or floating offshore installations. Also, non-standard arrangements compared with ships or offshore codes may require special considerations of stability and stability testing.

## 17 ELECTRICAL AND MECHANICAL EQUIPMENT

### 17.1 General Considerations

Guidance on the design, selection and installation of commercially available components, together with appropriate references to ISO or IEC standards is given in the DNV Offshore Standards (OS's) and Recommended Practice (RP's) as seen in the references below. The following standards referring to Mobile Offshore Units may be referred to as relevant for certain aspects of mechanical, electrical and instrumentation systems and components in WECs:

OS-D101: Marine and Machinery Systems and Equipment  
OS-D201: Electrical Systems and Equipment  
OS-D202: Instrumentation and Telecommunication Systems  
OS-A101: Safety Principles and Arrangements

These documents have been written for manned offshore installations and therefore items which are directly related to the safety of operating staff may be modified for a device which is normally unmanned. Due account needs to be taken of manned periods for installation, commissioning, testing, maintenance or removal periods, however. Correct functioning of the device as a power producing unit may require the same aspects to be considered.

During the design phase, consideration should be given to the required design life, criticality of the system / component (production or safety), the level of reliability / performance required from the system / components, the maintenance needed to keep the reliability / performance and the associated level of protection necessary to achieve controlled degradation. This should be reflected when defining equipment specification for suppliers and contractors.

It is important to define the internal environment that the systems will be exposed to. These comprise:

- accelerations and inclinations from device movements,
- temperature,
- humidity,
- salinity,
- vibration levels,
- slamming/shock loads,
- presence of (salt) water,
- electromagnetic interference,
- ionising effects (e.g. upon short circuits/tripping of circuit breakers), and
- presence of explosive atmosphere (e.g. from trickle charging of batteries).

The following sections provide guidance on the main aspects to consider together with some references and requirements in the standards referred to above for the practical handling of such aspects.

However, due to the unmanned nature of devices for WEC, significant deviations may exist for the internal ambient conditions due for example, to minimal ventilation and reduced capability for removal of waste heat produced. Internal ambient conditions to the unit should thus be assessed at an early stage for input to design basis and selection of equipment.

## 17.2 Electrical Equipment

In the design of electrical systems for WEC devices consideration should be given to the number of devices to be interconnected as well as the onboard system of the individual device. The design of the system should take account of the legislation, codes and regulations applicable to the network to which the device is to be connected. It should take into consideration operation and maintenance as well as construction.

The designer of the electrical system, in choosing equipment, should remember that the WEC device may be subject to shock loads as well as movements not normally encountered in land or fixed offshore installations. The design of the system, choice of equipment, must be appropriate to the purpose and the circumstances in which it is to be used. Definition of construction, installation, protection (both electrically and mechanically), use and maintenance must be such as to prevent danger, interference with or interruption of supply, so far as is reasonably practicable.

For the general installation of electrical equipment and systems in a WEC device, the reference in Appendix F provides a scope of aspects that should be considered. OS-D201 applies to mobile offshore units. The standard provides guidance that may be used as far as applicable. Selected items from the OS-D201 contents list that may provide relevant guidance is presented in Appendix F (F1 Electrical Systems). This will in many cases have to be modified or adapted to the WEC design being considered.

Although OS-D201 applies to mobile offshore units and relevant parts only must be used, it references all the ISO and IEC standards and may be adopted as a general approach in the design philosophy. The WEC grid connection must also comply with the appropriate Grid Codes and Connection Agreements applicable to the point of connection.

The following onshore-related standards will apply to the onshore-related parts of the project.

- Electricity at Work Regulations
- Electricity Supply Regulations
- IEE Wiring Regulations 16<sup>th</sup> Edition
- Electrical Equipment (Safety) Regulations

Modular electrical equipment may be advantageous to facilitate offshore maintenance by simple replacement of a module. Early consideration of the extent of this is necessary in the design philosophy.

The system should be designed to meet EMC (Electro Magnetic Compatibility) requirements as laid down in IEC 61000. It should be remembered that during operation and maintenance periods VHF, UHF and mobile phones may be used in close proximity to the WEC device and may affect system operation.

The choice of standards should be based on the applicability of the standards to the WEC installation. The rating and application of equipment in the system should take account of potential enclosed spaces, hazardous environment and environmental impact considerations. The use of oils for insulation should be avoided (See Section 1.2.4).

Where variable frequency or dc generation systems are adopted ratings of equipment, cables and auxiliary supply systems should take account of all possible operational conditions. Where a 50Hz supply is required for auxiliaries, consideration must be given to the need for this supply to be derived from shore either in a separate cable or additional power cores included in the shore connection cable.

Onboard environmental conditions on WEC devices should be specially considered, particularly when equipment is put in non-ventilated enclosed spaces when heat, humidity, salt content, etc, may be high. Also floating WEC devices with shallow draft (say less than 7.5 m) may be prone to bottom wave slamming. Bottom slamming may cause shock loading to the structure and equipment mounted inside. Such shock loading may cause faulty operation of relays or other equipment.

The design basis document for the device should reflect the internal environment and conditions which equipment needs to be designed for. The guidance under Section 19 of OS-D201 should also be referred to.

### 17.2.1 Generator Types

The choice of generator type, speed and rating must be made in consideration of the prime mover and its control system. The designer could select from:

- Rotating Synchronous 50Hz
- Rotating Asynchronous (Induction) 50Hz
- Dual Fed Induction Generators (DFIGs)
- Linear Synchronous
- Linear Variable Frequency

Other arrangements are possible but will be of a more specialist nature. Generally, any machine of novel design will require to go through a qualification procedure similar to that described in DNV-RP203 (See Section 4 of this guideline).

Conventional synchronous and induction generators may be used in most devices using some form of mechanical or hydraulic conversion, usually involving a storage accumulator of some form. However, a more direct form of wave energy conversion is possible and has the potential to simplify and thus improve the reliability and efficiency of the overall energy conversion facility.

Rotating Electrical machines should be designed in accordance with IEC 60034 which covers both general requirements and specification of these machines.

#### Synchronous Generators

The most common type will be rotating machines running at 50Hz driven either directly or through a step up gearbox. For rotating fixed speed synchronous generators the prime mover must be capable of full speed governor control. This type of machine can be operated in power factor or KVAR mode offering advantages to the grid system. The use

of synchronous generators will require the addition of synchronising equipment in the control scheme adding to the overall complexity.

### Induction Generators

The unit cost of conventional induction generators is lower, but the designer must take into account of:

#### *Power Factor and Speed Range*

As power factor correction capacitors can cause induction generators to self-excite, it may be necessary include some additional form of protection which recognises this e.g. by a sudden vector shift. Hence DFIGs with their wider speed range capability may need to be considered.

Conventional induction generators have a very limited speed range over which they can generate without excessive reactive power requirements, even with some power factor correction facility.

#### *Starting characteristics*

The starting characteristics of the asynchronous generator will have to be considered in the overall system design and the protection system designed to allow for the initial inrush currents.

### DFIGs and Power Electronics

If variable frequency (power electronics) systems are employed as is necessary with DFIGs for example, care must be taken to ensure that the impact of harmonics is taken into account. The ability to provide some power factor control in these schemes may assist in the grid connection design requirement for power factor. The converter equipment should be designed in accordance with IEC 60146 Semiconductor Converters. The transformers and reactors associated with such devices require special design to take account of the harmonic content of the waveform IEC 61378 applies.

### Linear Generators

Wave energy devices usually extract power in the form of a reciprocating motion at low speed (typically less than 0.5m/s). Direct extraction of this low speed, high torque energy is possible using linear generators, but the electrical output will need some electronic processing of the waveform to enable grid connection.

Based on conventional machine topologies, a 100kW linear machine responding to wave velocities of around 1m/s and having to react to a wave forces of around 100kN, would require an air gap area of approximately 5m<sup>2</sup>. More novel machine topologies using permanent magnets, which allow much higher air gap shear stresses, will be required if the size and cost of the machine is to be viable. A low speed permanent magnet linear synchronous machine has already been utilised in a WEC device.

### Control Systems

The control systems of the energy conversion device shall ensure that the generator is operated within its rating, particularly the reactive current rating. Alarm and trip facilities are to be provided to protect the system should the generator be driven beyond its normal operating speed.

Protection devices are also required to ensure that the generator power input is short-term diverted, dumped or disconnected should connection or delivery to the shore supply system be lost or prohibited, depending on how quickly the connection can be restored.

Guidance on the connection to the shore supply system and national requirements for “embedded generation” are covered under the section on Grid Connection.

### 17.2.2 Grid Connection

The connection arrangements shall be in accordance with national standards for embedded generation. In the UK, these are as follows:

- Electricity Safety, Quality and Continuity Regulations (2002) (Section J - Generation). Publication reference URN 02/1544. The Guidance notes for this are available to download from the DTI website <http://www2.dti.gov.uk/electricity-regulations/index.htm>
- G59/1 : Recommendations For The Connection Of Private Generating Plant To The Regional Electricity Companies (RECs)
- G75: Recommendations for the Connection of Embedded Generating Plant to Public Electricity Suppliers Distribution Systems (above 20kV or with outputs over 5MW).

There will be voltage limitations in respect of connecting a generator to the nearest onshore distribution circuit. Provided a suitable transmission voltage is selected so as to balance losses against cost, subsea AC transmission is feasible up to around 50km. At distances beyond 50km, voltage control becomes progressively more difficult, and transmission via a high voltage DC link will eventually need to be considered. Compact mini DC link technology is already available “off the shelf”.

Adequate instrumentation and remote reading and control must be provided to enable commissioning, monitoring and control of the electrical power generation equipment and delivery to shore. Remote access links should have security features.

### 17.2.3 Earthing and Protection

The configuration choice, voltage level, security of supply and safety must all be considered on the design of the earthing and protection scheme. Fault level considerations at the point of grid connection as well as generator fault contributions must be taken into account. The designer must ensure that the choice of equipment and installation methods takes full account of the conditions applying in an offshore environment.

Protection system design and settings must ensure adequate discrimination at each level and with the grid connection. The configuration of an existing distribution system into which the device connects (usually via a step-up transformer and subsea cable) must be considered to ensure compatibility with protection grading and existing distribution transformers and their tap changing systems. Automatic tap changers on grid transformers may only be designed for unidirectional power flow.

The generator protection scheme must include out of balance protection as required by the local distribution or transmission Company. In the UK this will require fitting relays of the type required by G59/1 or G75. The application of these relays must be agreed with the grid connection operator. It is assumed that loss-of-mains protection will be fitted to the device generator. Particularly in a “farm” situation, this protection should be

designed to ride out transient faults and only trip the generator on loss of mains. Reference is made to Technical Guide to the Connection of Generation to the Distribution Network - Appendix C3.

The designer should ensure that the method of resetting relays after operation takes account of the remote nature of the generator installation.

#### 17.2.4 Transformers / Reactors

The IEE recommendations for electrical and electronic equipment for mobile and fixed offshore installations forbid the use of oil filled transformers. In any case, bund arrangements for control of leaks would not be practicable in a device subject to violent wave motion. IEC60076 Power Transformers should be used for this type of equipment.

Care must be taken in the design and specification of this type of equipment to allow for inrush currents, harmonics and fault level.

#### 17.2.5 Umbilical Cables

See Section 20 UMBILICAL CONNECTIONS

#### 17.2.6 Switchboards

Switchboards and control gear should be designed to IEC 62271-200 for HV and IEC 60439-1 and IEC 60092-302 for LV equipment. The general principles of OS - D201 Section 4 are relevant.

#### 17.2.7 Lighting and Small Power

The provisions of SOLAS Reg II -1 Section 41 may apply and should be considered where applicable, noting that the WEC Device is not-normally-manned

#### 17.2.8 Ancillary Systems

##### *Batteries*

Consideration should be given to eliminating the use of batteries wherever possible. The designer must ensure that allowance for ventilation may be required.

Placing of batteries with chargers should be carefully considered if installed in areas without or with very low ventilation. If batteries are claimed to be a "sealed type" (which do not give off hydrogen), this still depends on a charger avoiding overcharge voltage once the battery is fully charged. It may be possible in principle to show that the integrity and monitoring of the charging device is adequate to prevent over-voltage to a fully charged battery.

Even if a "sealed" type, hydrogen gas will be produced in the case of over-voltage against a fully charged battery. The charger monitoring and voltage control should cater for the case of a short circuit of one of the cells of the battery and also ambient temperature effects on the definition of "overcharging" when hydrogen generation may take place. The limiting charger voltage normally goes down with rising temperature and can greatly affect the reliability of the equipment and the WEC.

### *Navigation Lights*

The designer should consult the relevant bodies (in UK - Trinity House or the Northern Lighthouse Board in Scotland) for guidance on what navigation aids will be required. International guidance is available from the IALA Codes.

It must be remembered that in the event of an electrical failure occurring during the winter, prolonged periods of loss of supply may be encountered.

### *UPS Systems*

Design of these should be compatible with NORSOK E-001, Rev 4, 2001 and meet the requirements of BS EN 50091- Parts 1 and 2. Routine tests shall be performed according to IEC 60146-4, clause 7.

### *Emergency Power*

In the event of failure of all generation, provision may be required for import of emergency power. Consideration of this requirement should normally be made during the design of the cable connection to shore and provision to provide power for initial start be included if required. Load shedding for emergency power may need to be considered to remain within the capacity of the supply.

## **17.3 Mechanical Equipment and Marine Systems**

Different wave power converters may use a wide range of systems and components to convert the energy of the wave to electrical power. This section brings together a brief guide to the main components and systems that may be employed in the broad range of devices.

### **17.3.1 General**

For the general installation of mechanical equipment and systems in a WEC device, the reference below provides a scope of aspects that should be considered. OS-D101 applies to mobile offshore units. The standard provides guidance that may be used as far as applicable. Special consideration needs to be given to aspects related to required reliability considering the expected level of maintenance and associated costs.

OS-D101 applies to marine equipment and machinery systems which are defined as marine systems on a floating offshore unit or installation.

For mechanical and marine systems, reference is made to SOLAS Chapter II-1 for Maritime Authority requirements to such systems for seagoing vessels. These form the basis for Maritime Authority requirements and Class Society Rules, and requirements for WECs should be considered from these as relevant.

Other applicable DNV publications that may be relevant are (potentially relevant topics in parentheses) are;

- OS-A101 Safety Principles and Arrangement (layout, hazardous area classification, shutdown and protection),
- OS-B101 Metallic Materials (mostly for: steel tubes, pipes, forged items and castings ),
- OS-C301 Stability and Watertight Integrity (primarily for: vents, discharges, doors and hatches),
- RP-A201 Standard Documentation Types (document formats),
- RP-A202 Documentation of Offshore Projects,

- Rules for Classification of Ships Classification Note 41.2 Calculation of Gear Rating for Marine Transmissions (gearboxes).

Selected items from the OS-D101 contents list that may provide relevant guidance is presented in Appendix F (F2 Mechanical and Marine Systems). This will in many cases have to be modified or adapted to the WEC design being considered.

### 17.3.2 Design and Layout

The arrangement of machinery and piping systems should be such that maintenance access may readily be facilitated. Although WEC devices are normally unmanned, it is possible that some limited access may be required under controlled circumstances for first line short-duration maintenance such as changing an integrated circuit card. It is unlikely that a prudent operator would carry out significant work in situ, but when a device is removed to a safe haven, safe and cost effective maintenance requires a physical layout that gives access to maintainable items. Consideration should be given to modular designs that mean maintenance becomes the simple change-out of a unit.

Vulnerability of any component to damage from leaking fluid from piping or seals is another layout consideration. Valve operation is also relevant in this context, easy visibility of valve position and minimisation of risk of inadvertent operation during maintenance must be considered.

The impact of the continuous movement of a WEC device on component operability and reliability must be borne in mind as this may be very different from the degree of movement encountered in a ship or other floating installation for which the component has been designed. The exposure to salt and damp atmosphere may also be increased over ship or other floating installations.

Redundancy is an important concept when considering reliability. It refers to the ability to maintain or restore a function when one failure has occurred. Redundancy can be achieved for instance by installation of more than one unit (component redundancy) or by having two or more separate systems capable of performing the same function (system redundancy).

Redundancy types may be defined in terms of the time lag accepted upon restoring a lost function, due to failure in a component or system, designed with redundancy.

Redundancy type and time lag in re-establishment of function used in the DNV standards are:

0	None (continuously available)
1	Up to 30 s
2	Up to 10 minutes
3	Up to 3 hours
Not defined:	More than 3 hours

See also Section 7 on RELIABILITY AND COST.

### 17.3.3 General Mechanical Components and Sub-systems

#### 17.3.3.1 Pipework and Valves

Some specialist piping systems such as those for hydraulic service are given specific mention below, but certain WEC devices may use seawater systems that are part of the power take-off arrangement that will require unusually stringent performance from stop valves or non-return valves. Consideration should be given in the design process, to selection of valves for unusual duties such as rapidly repeated operation. A modified design of valve body, seat or actuator may be necessary and functional testing may need to be arranged with potential vendors. It is also possible that tried and tested components, designed and built to established codes will need a qualification exercise (see Section 4) carried out due to a combination of configuration, duty and environment in a WEC device.

Pipe support methods to deal with cyclic loading and vibration may also need particular attention. Addition of flexible elements or shock absorbing materials should be considered for relevant systems

#### 17.3.3.2 Equipment and Machinery

Pressure vessels, pumps, compressors and heat exchangers that may be part of a WEC device should be specified to the normal international codes. However the same considerations of atmospheric environment, movement and vibration and unusual operational duties must be considered alongside the usual design code requirements. Where a duty or condition is outside the code, a judgement must be made as to whether any further qualification or testing is required to ensure proper safety and performance.

#### 17.3.4 Hydraulic Systems

Some offshore buoyancy type devices use a hydraulic power system to capture the power from the wave and store this energy under pressure in order to drive a turbine driven generator. A typical hydraulic power system may consist of the following;

- hydraulic cylinder and piston,
- hydraulic piping,
- hydraulic valve block,
- accumulators and tanks, and
- hydraulic pumps.

##### 17.3.4.1 Cylinders

The hydraulic cylinders and rams are fundamental to certain types of wave energy devices. The forces from the waves push and pull a piston in a cylinder, thus producing work. The resulting energy can be stored in an accumulator and in turn drive a power converter, e.g. a hydraulic motor driving a generator. Sophisticated schemes are used in some devices. The cylinders may be configured as a set in order to harness the multiple motion input from relative motion of the buoyancy modules making up the device. The integrity of this configuration and correct functioning of power conversion and control systems are very important to the power producing ability of the design. Refer to comments on fatigue loading and relation with other structural elements mentioned under structural Fatigue Limit State 13.7 and APPENDIX A - FATIGUE ANALYSIS METHODOLOGY.

The primary consideration for the hydraulic cylinder is pressure containment. If standard hydraulic cylinders are used, they will be made to one of many applicable codes which can be used for the design, for example PD 5500, BS EN 13445, ASME VIII, etc. For a wave energy device, there are some very important additional considerations:

- Fatigue of pressure containment and piston rod;
- Buckling of the piston rod;
- Wear properties of the seals, pins and bearing surfaces involved;
- Degradation rate of hydraulic fluids through oxidation, accumulation of debris, bacterial growth, and resulting increase in viscosity of the fluid;
- Filter arrangements and filter quality mesh size and cleaning arrangements;
- Heat generation and limiting temperatures, including power cut-off arrangements in case of. loss of onshore electrical connection or excessive sea and power input conditions.

If the hydraulic cylinder is subjected to heavy cyclic loading, the fatigue aspect of the cylinder is very important. In addition, the sealing system for the piston needs to be of a suitable type to withstand the same level of cyclic loading.

Buckling strength is an important factor in a standard cylinder design. Obviously the more slender the cylinder, the lower the limiting axial load before buckling starts. In general, this axial load is inversely proportional to the square of the slenderness of the rod. A simplified equation to determine the axial strength of the piston rod can be found in OS-D101 Chapter 2 Section 4 H300, which recommends a safety factor of 4. Depending on the safety principle of the project, this safety factor may vary.

In addition to the normal pressure and temperature loading, the hydraulic piping system will also undergo many cycles of pressurization. Therefore the fatigue life of the hydraulic piping need to be considered. BS EN 13480 is a comprehensive standard for the design of industrial piping. Alternatively, ASME codes are also used in the hydraulic industry.

#### 17.3.4.2 Piping

Bending of tubing should follow the relevant recommended practices to avoid kinks. Piping and tubing should be securely fastened to prevent excessive vibration.

Use of flexible hoses should be minimised and kept as short as practicable and should be suitably type tested to a recognised standard. Couplings are a source of leakage and particular attention should be paid to couplings and use of correct connector parts relative to the approved versions.

#### 17.3.4.3 Valve block

The valve block is an assembly to house a series of hydraulic valves that control the hydraulic fluids in the system thus regulating the pressure. The valve block can be treated as piping component and follow the relevant piping codes as listed above. The valve block itself may need proof testing as the shape of the block is a non-standard item. The valves themselves will undergo many operating cycles; therefore the long-term reliability of the valves is important in the component selection process.

#### 17.3.4.4 Accumulator

The accumulator is likely to be of a standard design and therefore should be covered by the relevant pressure vessel codes such as those listed for the cylinder. It is recommended to avoid using piston type accumulators with air as the compressible

medium, as the increase in oxygen partial pressure with compression combined with potential catalytic action from debris accumulating over time can lead to auto-ignition and explosion of the accumulator.

#### 17.3.4.5 Pump and Motors

Some systems may utilise hydraulic pumps. These pumps or motors are likely to be standard off-the-shelf items and would normally conform to recognised industrial standards such as API, ISO, or BS. For variable demand applications swash-plate type pumps may be used. These are routinely used e.g. in cranes. They are fairly complicated devices with a substantial range of potential failure modes, and it is important that they are operated within the manufacturer's specifications.

#### 17.3.4.6 Overpressure

One of the most important design aspects of the hydraulic system for wave energy device is the control of the hydraulic pressure. Guidance on control systems is covered under a separate section. In this section we will concentrate on mechanical aspects of the control.

The system needs to be protected from the possibility of overpressure. Suitably sized relief valves should be installed to protect the system from overpressure. If the pump can generate overpressure, it should be shut-off on detection of high pressure. In the case where hydraulic cylinders provide the pumping and are not easily disconnected a thorough assessment on pressure build-up is required.

Non-return valves should be placed in the correct places in order to avoid undesired back flow. Because the objective of the hydraulic system involves manipulating pressure on either side of the cylinder, the design of the systematic needs to be methodically established to avoid undesired back flow.

Filters should to be installed at suitable points to protect the system from unwanted blockage or wear and to limit any damage occurring from e.g. the failure of a component in the system. Consideration needs to be given to how to clean and maintain filters.

Pressure setting of any pressure regulating valves should be established and documented. Any changes in the system control/modelling/demands may require the setting to be altered. If relief valves are to be used as means of regulating, the long term reliability of the valves need to be assessed.

The efficiency of hydraulic systems are such that considerable heat may be produced. As high temperature is detrimental to hydraulic oil oxidation rates, and the rate of ageing of electrical and electronic components, the temperature and need for cooling devices need to be considered.

#### 17.3.4.7 Cylinder Ram Movements

Movements of the cylinder rams should be evaluated for extreme conditions and checked regarding end of ram excursion points (overextension and retracted position). Cylinder rams should not move beyond these points as seals may be damaged and forces that may be transferred through the cylinders may not have been considered in the design of the cylinders, their supports and structure in the vicinity or the hydraulic system itself.

#### 17.3.5 Pneumatic System

Pneumatic system used in wave energy devices are likely to be of two types.

The first is a low pressure large volume system (usually part of the energy conversion system).

This type of pneumatic system uses wave energy to create pressure differential and in turn this energy drives a turbine.

The second is high pressure low volume system (mainly for monitoring and control systems. Depending on the pressure level, all the relevant pressure system design protocols as described in the hydraulic system are applicable. However, high pressure pneumatic systems have other issues to be addressed:

- Due to the high energy stored in the system, the operation and maintenance of the system must be controlled to prevent risks to personnel in case of undesired failure. This may include having an overpressure relief system to the outside in case of high temperature or fire situations.
- Any debris in the system could create erosion or malfunction problems. The system needs to be maintained to a high level of cleanliness.
- Flexible hoses need to be secured in case of connector failure resulting in mechanical damage to other parts.
- Suitable control to avoid pressure shock in the system.
- Suitable filter system should be provided to prevent contamination of hydraulic and pneumatic systems.
- To avoid accumulation of liquid, the dryness of the air should be controlled.

#### 17.3.6 Turbines in Wave Energy Devices

The use of turbines in WEC devices consist mainly of turbines moved by water or air. The turbines moved by seawater may for example be hydro-turbines of the Kaplan or Pelton types, while turbines suitable for use with air flow include but are not limited to the Wells or Denniss-Auld turbines.

The main aspect to be taken into account in the context of WEC applications is that the turbines will be operating in an environment and regime different from their original design and, in some cases, its normal application. The marine environment, motions and accelerations, corrosion, working pattern, maintenance and remote monitoring of key parameters are aspects that are essential to consider. The Qualification process described in this Guideline is recommended to address the issues highlighted. From the environmental point of view the impact on fish and other animals should be considered.

The Kaplan turbine is normally most suitable when the head is low and consequently there is a high flow rate through the turbine. The turbine is submerged in the water passage. Its design combines radial and axial features. The motion of the WEC and its reservoir and interaction with the sea surface and outlet needs to be considered in the evaluation of the pressure head and any possible cavitation. Protection against debris and cleaning of the gates should be considered.

At intermediate ranges of head and speed, turbine types such as Francis or Turgo may be used depending on head and flow required for the WEC. A diagram showing the operating range of the turbine types may be found at:

<http://www.answers.com/topic/water-turbine>.

At the opposite end of the specific speed scale, the Pelton turbine (impulse type turbine) is most suitable when the head is high and consequently the flow rate through the turbine needs not to be high to create power. For WEC devices subject to different wave heights this impulse turbine may, depending on the generation and transformer arrangement, use an accumulator to smooth the pressure variation in the turbine. With the water flow going through the turbine, issues related to corrosion and marine growth are now inside the turbine and are more difficult to inspect and maintain.

The Wells Turbine was invented by Professor Alan Wells in the late 1980's and is often used in fixed seabed and shore-mounted devices. This air turbine differs from other air turbines due to the design of its blades that are symmetrical about the horizontal axis, allowing it to accept airflow in either axial direction while always rotating the same way. The Wells turbine can rotate at high speeds (1500 - 3000 rpm), and so the electrical generator can be attached directly to the shaft of the turbine, obviating the need for a gearbox to raise the generator speed.

Another air turbine, the Denniss-Auld turbine has very different operating characteristics to the Wells turbine. It is designed to run at lower speed (500rpm) and high torque. It has low shaft losses. The turbine has variable pitch blades and a variable speed control capability that can make it effective over a broad range of operating conditions. (Ref: Previsic et al, "System Level design Performance & Costs - San Francisco California Energetech Offshore Wave Power Plant", Report No. E21 -EPRI - 006B - SF, Dec 2004.)

A literature search shows that there currently are no standards or guidelines developed to cover these designs.

As air turbines will be working with air saturated with sea water droplets, the corrosive environment needs to be considered in the design.

#### 17.3.6.1 Hydraulic Turbines

The IEC (International Electrotechnical Commission), prepares international standards and also issues publications in the form of technical reports. The IEC Technical Committee (TC 4) deals with hydraulic turbines.

It is considered that the IEC standards could be used for turbines in wave energy devices, providing due consideration is given to the environment and device operating mode, as well as the functional and reliability requirements.

There is a series of Technical Reports (IEC 61366 series) which deals with tendering documents for hydraulic turbines, storage pumps and pump turbines. The series consist of seven parts of which the following are relevant here:

Part 1: General and annexes (IEC 61366-1)

Part 2: Guidelines for technical specification for Francis turbines (IEC 61366-2)

Part 3: Guidelines for technical specification for Pelton turbines (IEC 61366-3)

Part 4: Guidelines for technical specifications for Kaplan and propeller turbines (IEC 61366-4)

Reference is also made to:

IEC 60545 (1976-01)	Guide for commissioning, operation and maintenance of hydraulic turbines
IEC 60609 (1978-01)	Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines
IEC 60609-2 (1997-11)	Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines - Part 2: Evaluation in Pelton turbines
IEC 60308 (work in progress)	Hydraulic turbines - testing of control systems

For preparation of Kaplan and propeller turbine specifications the following factors should be considered:

- Design conditions - project arrangement, hydraulic conditions, mode of operations, generator characteristics, synchronous condenser characteristics, transient behaviour data, system stability, noise, vibration, pressure fluctuation and safety requirements.
- Technical performance and other guarantees;
  - power,
  - discharge,
  - efficiency,
  - maximum and minimum momentary pressure,
  - maximum momentary over-speed,
  - maximum steady-state runaway speed,
  - cavitation pitting,
  - hydraulic thrust, and
  - maximum weights and dimensions for transportation, installation and maintenance.
- Mechanical design criteria - design standards, stresses and deflections and special design considerations.
- Materials and construction - material selection and standards, corrosion protection and painting.
- Regulating apparatus for guide vanes - servomotor, connecting rods, regulating ring, guide vane linkage system, guide vane overload protection and locking devices.
- Rotating parts, bearings and seals - runner, main shaft, intermediate shaft, guide bearing with oil supply, oil/water cooler, instrumentation.
- Runner blade regulation - servo motor assembly with oil supply. Linkage system, crosshead and oilhead.
- Instrumentation - controls, indication and protection.
- Protection of the WEC device from excessive energy input and divert or dump this energy if required. The vertical axis of the rotating turbine means that particular design consideration must be given for acceptable thrust bearing life. Surge tanks must be provided to provide a by-pass when water is not required for driving the turbine.

### 17.3.6.2 Air Flow Turbines

#### Component Design

Design of turbines consists of both analysis and testing. For some components, a combination of testing and design calculations may be necessary, while either testing or calculations may document other components.

In general instrumented test runs shall support and calibrate analyses of high cycle fatigue, low cycle fatigue and creep. Components subjected to high cycle fatigue shall be tested at all speeds in the operational speed interval with small separation steps ensuring more than  $10^7$  cycles at a possible resonance condition. In the case of shrouded blades the Campbell diagram shall show the frequencies above and below the lock-up speed of the blade, together with the blade lock-up speed. The lock-up speed in a shrouded turbine disc is the speed where the blades become coupled to each other through the outer shroud. This implies a change of blade dynamic characteristic and the natural blade modes and frequencies will become different when passing the lock-up speed.

In general, the main aspects regarding turbine components design to be considered are outlined below considering the turbine is installed in a floating structure.

#### Failure Mode and Effect Analysis

A FMEA of the turbine shall identify critical components and systems together with failure modes and consequences. The analysis shall, as a minimum, cover the following as applicable;

- bearings,
- seals,
- lubricating oil/grease system,
- control system,
- control system power supply,
- instrumentation system (e.g. vibration, temperature, pressure),
- mechanical control system (e.g. variable guide vanes),
- anti-icing system,
- noise reduction system, and
- inlet air / fluid systems (e.g. filtration).

Coupling shaft failure and its consequences shall be identified and documented.

#### Maintenance

As a minimum, the following aspects should be considered;

- assembly and disassembly process with tools and procedures, such as clearances, pre-tightening procedures, torque limits, etc,
- time between inspection, overhaul and change out of major components, e.g. blades, disks, etc,
- methods used to identify the remaining lifetime on the component, and
- acceptance and rejection criteria of major components, e.g. maximum blade crack length, for acceptance without repair, with repair, and reject.

Overhaul is normally to be accomplished at the engine manufacturer's plant or at an OEM's approved plant. It should include disassembly, examination, cleaning and repair of the turbine engine and accessories.

See also Section 25.

### Functional Tests

Functional tests and collection of operating values shall be carried out. The relevant results shall be presented. Component inspections after completion of the test program shall be conducted.

Testing of operation at the limits of the protection system should be carried out. Operation at the turbine overspeed limit is one such test that is normally required.

Lubricating oil pressure and temperature shall be monitored and recorded during the test. The parameters shall be within the manufacturer's recommended values. The recommended values shall be stated in the operating instructions.

Lateral vibration and vibration levels should be measured. A leak check shall be performed prior to all runs. In general, no cracks or major wear shall be seen in rotating parts after testing of a turbine. Minor cracks, indents or tear in uncritical stationary parts may be accepted based on documented acceptance criteria.

Boroscope inspection of the turbine blades shall be conducted to the extent allowed by engine design (e.g. boroscope ports placement).

### Mounting System

The loads given in Table 17.3.6.2 shall be considered in the design of the mounting system. Preferably, the turbine casing shall not absorb deflections in a floating structure. This might, however, be acceptable if it can be shown by calculations that casing deflections are within acceptable limits.

<i>Operational loads</i>		<i>Extreme loads</i>	
a.	Maximum environmental conditions such as list and trim shall be considered for determination of mass reaction forces.	a.	Forces derived from blade loss or, in the case of a centrifugal impeller, parts from one blade root failure.
b.	Maximum operational acceleration loads.	b.	Any other extreme loads that may be relevant for the individual application.
c.	Reaction forces due to generator torque (including short circuit torque in case of electrical generators).		
d.	Forces transferred to foundation members due to deflection of floating structure.		
e.	Forces derived from interfacing components.		
f.	Pressure loads plus centrifugal loads		
g.	Any other operational loads that may be significant for the individual application		
<i>A combination of the above loads shall be considered</i>			
The following prevails for the worst expected operational loads (left column):			
a.	Turbine supports (struts) shall have documented an adequate safety factor (see Safety philosophy) against buckling.		
b.	Stresses on foundation members shall be well below the fatigue curve for the material, and maximum deflections shall be within limitations set by the turbine and adjacent components (e.g. flexible coupling). In case of extreme loads (right column), the foundation integrity shall be maintained.		

Table 17.3.6.2 : Operational and Extreme Loads

### Inlet and Outlet Passages

The air intake shall be arranged and located such that the risk of ingesting foreign objects is minimised. Depending on the arrangement it may require that a grid be fitted on the air intake.

The inlet ducting and components in way of inlet airflow, such as filters, silencers and anti-icing devices shall be constructed and mounted to minimise the risk of loose parts entering the turbine. Icing at the air intake shall be prevented by suitable means, if applicable.

When considered necessary, according to turbine maker's requirements for inlet air and fluid quality, the air/fluid intake system shall incorporate an effective filtration system preventing harmful particles from entering the inlet. Pressure drop across filters should be monitored. Corrosion and marine growth formation due to sea salt and other substances should be considered for turbines using seawater. Water washing systems may be required to remove salt encrustation.

Any active measures fitted in the ducts shall have a fail-safe action as to the integrity of the turbine. Welds in inlet and exhaust ducts are not to be located in areas with stress concentration such as corners and dimension changes.

### Turbine Enclosures

In case personnel are allowed to enter the enclosure when the turbine is in operation, at least two exits should be arranged in the opposite ends of the enclosure, or in a manner providing easy escape routes from all relevant positions inside the enclosure. Signboard to be displayed on all the enclosure doors to restrict or prohibit the entrance to the enclosure during operation.

## 17.3.7 Power Transmission Using Gearboxes

### 17.3.7.1 Introduction

A complete reference to design, fabrication and testing of power transmission based on gears can be found in DNV Ship Rules for Ships Pt.4 Ch.4. Information is also available in the Guidelines for Design of Wind Turbines (DNV/Risø) and in the Recommendation to Comply with the Requirements in the Technical Criteria for the Danish Approval Scheme for Wind Turbines - Gearboxes Energistyrelsen - The Danish Energy Agency - Oct 2002. The American national standard "AGMA 6006-A03 (2004) Standard for Design and Specification of Gearboxes for Wind Turbines" is the most recent gearbox standard for wind turbines.

As the gearbox is likely to be manufactured by sub suppliers some additional aspects may need consideration. Requirements for reliability, robustness, flexibility of couplings and protection against seawater ingress are issues that need consideration depending on the regime for maintenance, access, monitoring and loading of different devices. Target design life should be defined in order to give the required level of reliability.

When considering requirements defined in the DNV Ship Rules, depending on actual operating and maintenance regime of the WEC, allowance should be given to the level of maintenance possible in a ship as well as the level of monitoring and intervention available in the ship. The implicit reliability of the gearbox as per requirements on the

Ship Rules, is based on the importance of the component (related normally to propulsion) and the level of intervention and monitoring available on board of the ship.

When considering the recommendations used for wind turbine, the target reliability of the gearbox is in most cases based on the balance of manufacturing cost and maintenance cost. However, the migration of the wind turbines from onshore to offshore has added requirements on the gearbox reliability as well as maintainability and condition monitoring as the access to wind turbines is not as easy offshore as onshore. Furthermore, full load testing of gearboxes in the workshop as well as in the field have more or less been standard procedure for the development of larger wind turbines. WEC developers applying the requirements and experience for wind turbine should carefully consider the differences on the environment where the gearboxes would be operating, possible additional motions imposed to the gearbox as well as load input characteristics.

This Guideline presents some of the main issues and general guidance is providing considering the requirements for vessels adapted to WEC, combined with experience from the wind sector.

#### 17.3.7.2 General aspects

The gearbox is to be designed for conditions relevant for the specific WEC design. Conditions can be for example:

- load conditions
- power and speed
- temperature
- humidity
- elastic coupling characteristics
- damper characteristics.

The reliability and safety of components and complete units should additionally be documented by means of approved tests or service experience. The use of service experience will be very valuable especially if a relevant load history can be documented. Relevant load history means a suitable operation period under running conditions similar to the expected running conditions for the product to be accepted.

The main components for power transmission based on gears are:

- Shafts, couplings (rigid couplings as flange couplings, shrink-fit couplings, keyed connections, clamp couplings, splines, and/or compliant elements as tooth couplings, universal shafts, rubber couplings, etc), shaft bearings and shaft seals
- Gear transmissions (pinion and wheels, gear casing, shafts, bearings, clutches and couplings, gearbox support)
- Lubrication system (filtering, cooling, sealing)
- Instrumentation (control and monitoring)

The power transmission should be checked for vibrations. Fatigue and extreme loads should be considered in the design of the power transmission components such as shafts and couplings. The loads acting on the shaft should be derived based on all relevant conditions that the device is subjected. Requirements for materials and hardening treatments for components in power transmission can be found in DNV Rules for Ships Pt.4 Ch.2.

For design of roller bearings reference is made to ISO 281/1 and ISO 76 (static capacity of rollers). Requirements for materials and hardening treatments for gear transmission can be found in DNV Rules for Ships Pt.4 Ch.2.

For gears the load levels are the focus rather than the load ranges. Surface durability, tooth strength, and scuffing load capacity are key elements for the gear capacity. Damage such as wear, grey staining (micropitting) and fractures starting from flanks may also limit the gear capacity. It needs to be mentioned that limited or no calculation procedure are given for the associated capacities.

Surface durability and tooth root strength is discussed in Guideline for Design of Wind Turbines, Classification Note 41.2 - Calculation of Gear Rating for Marine Transmissions (CN 41.2), ISO 6336. Scuffing load capacity may be calculated using the method described in DNV CN 41.2.

The gear rating procedures given in CN 41.2 are mainly based on the ISO-6336 Part 1-5 (cylindrical gears), and partly on ISO 10300 Part 1-3 (bevel gears) and ISO Technical Reports on Scuffing and Fatigue Damage Accumulation.

For design of roller bearings reference is made to ISO 281/1 and ISO 76 (static capacity of rollers).

### 17.3.7.3 Lubrication

Gears are characterised by relative motion of surfaces in contact under load. Separation of surfaces by a thin film of oil is a key factor for smooth operation and reliable functioning. Oils for gear lubrication have to meet different performance requirements including: stability, resistance to foaming, separation from water and corrosion prevention as well as the protection of the rubbing surfaces of the gear teeth.

Application of gearbox, characteristics of loading, maintenance and monitoring regime, and consequence of failure are major factors to consider on the lubrication system. The selection of lubricant depends on requirements for minimum operating temperature, viscosity, viscosity index, pour point, additives, capacity to resist micropitting, costs, gear tooth loads and pitchline velocity. Oil heaters may be needed depending on minimum operating temperature, especially during start-up operation at low temperatures.

Recommended criteria for acceptance of gear lubricants are given in Recommendation to Comply with the Requirements in the Technical Criteria for the Danish Approval Scheme for Wind Turbines - Gearboxes - Section 5 Lubrication as well as in AGMA 6006-A03 and the Guidelines for Design of Wind Turbines - DNV/Risø Table 6-5 and are presented below.

Parameter	Methodology	Requirement
Viscosity (mm <sup>2</sup> /s)	ISO 3104	± 10%
Viscosity indices	ISO 2909	Min. 90
Oxidation stability	ASTM D 2893	Increase in viscosity of a test sample oxidised at 121° C should not exceed 6% of reference value.
Corrosion properties, Iron	ISO 7120 (DIN51 355)	No rust after 24 hours with synthetic sea water.
Corrosion properties, Copper	ISO 2160 (DIN 51759)	#1b strip after 3 hours at 100° C
Foaming properties	ASTM 892	Sequence 1: max. 75/10 10:00 Sequence 2: max. 75/10 10:00 Sequence 3 max. 75/10 10:00
Load carrying property (scuffing)	ISO 14 635-1	Load stage min. 12
Micropitting resistance test	FVA, No 54	Stage 10
Filterability	ISO/DIS 13 357-1, 2	As stated in standard
Cleanliness	ISO 4406	-/14/11

Table 17.3.7-1 - Recommended criteria for acceptance of gear lubricants

For gears with forced lubrication system the oil flow and pressure should be monitored. If the pressure drops below the minimum specified the equipment should be shut down, except if the forced system is used for oil cooling and the gear can work properly with splash lubrication. However it is important that any drop in the oil pressure is indicated in the monitoring system and identification of problem and rectification is provided within a timeframe that will not affect the reliability of the gearbox. For non-pressurised lubrication systems, oil level indication should be provided in way such that, during maintenance, the level can be verified. Oil temperature should be monitored and any temperature in excess of the approved maximum should result in automatic shutdown of the system. In case of malfunction of monitoring system the equipment should automatically shutdown.

The oil should be sampled during maintenance and its quality and cleanliness should be checked against prescribed oil parameters. The tables with recommended cleanliness of lubricants and properties of lubricants in operation, from the Recommendation to Comply with the Requirements in the Technical Criteria for the Danish Approval Scheme for Wind Turbines - Gearboxes - Section 5 Lubrication. They are presented below:

Description	Cleanliness <sup>2)</sup>	Conditions
Min. cleanliness of new lubricant whenever poured into the gearbox	-/14/11	Workshop conditions
Min. cleanliness before applying load	-/14/11	
Min. cleanliness during run in and tests (at stabilised conditions)	-/15/12	
Min. cleanliness at scheduled maintenance but not longer than 3 months for the first sample and the following at fixed intervals typical 6 months	-/16/13	Field conditions <sup>1)</sup>
Min. cleanliness immediate after commissioning or repair of gearbox/lubrication system	-/16/13	
Action programme 1. See table 17.3.7-3	-/17/14	
Action programme 2. See table 17.3.7-3	-/18/15	

1) Field condition means that an oil sample is taken and subsequent analysed.

2) XX/YY/ZZ corresponds to number of particles per 100ml sample greater than 2µm, 5µm and 10µm respectively

Table 17.3.7-2 Recommended cleanliness of lubricants

Analyse parameter	Normal	Action programme 1. Intensified monitoring. New analyse	Action programme 2. Lubricant has to be cleaned or changed
Changes in viscosity from point of reference	Within ±10%	Interval between ±10% and ± 15%	Outside ± 15%
Contaminants			
- Water contents 1) (mg/kg)	< 200	< 500	> 500
- Changes in TAN (mgKOH/g)	0,5	< 1,0	> 1,0
- Cleanliness (ISO 4406)	-/15/12	-/17/14	-/18/15
- Wear particles/contaminants			
- Iron (mg/kg)	< 30	< 50	> 50
- Copper (mg/kg)	< 10	< 20	> 20
- Silicon 3) (mg/kg)	< 10	< 20	> 20
Additives 2)			
- Contents of EP/AW-additives	> 50 %	> 40 %	< 30 %
Oxidation stability 2)			
- Changes in TAN (mgKOH/g)	< 0,5	< 1,0	> 1,0

1): Borderline only valid for mineral lubricants and synthetic lubricants type PAO.

2): It is recommended to use the IR-spectrum to measure oxidation products in the lubricant and consumption of additives.

3): If Si compounds are used as anti foam additive, the figures may not apply.

Table 17.3.7-3 Recommended properties of lubricants in operation

Information on Shaft, Gear Transmission, Clutch, and Couplings is presented in APPENDIX D - TECHNICAL CONSIDERATIONS FOR GEARBOXES

### 17.3.8 Flexible Hoses

Short lengths of flexible hoses can be used when necessary to admit relative movements between machinery and fixed piping systems. The hoses with couplings needs to be of independently certified and with adequate track record for the proposed application.

Hoses of non-metallic materials used in systems containing flammable fluids or seawater should have at least one ply internal wire braid.

In fresh cooling water lines the requirements above may be dispensed with provided that an arrangement with an independent cooling system is provided. Rubber hoses with internal textile reinforcement fitted by means of hose clamps may be accepted provided the hose is a short and reasonably straight length fitted between two metallic pipes.

New types of non-metallic hoses with couplings should be subjected to a prototype test. The bursting pressure should be from 2.5 to 4 times the maximum working pressure depending on the standard applied. Reference can be made to API RP 17B - Flexible piping for design and fabrication of flexible hoses.

Fire tests may be required for hoses intended for systems conveying flammable liquids or for use in seawater cooling systems.

Every hose should be hydrostatically tested at a hydrostatic pressure of 1.5 times the working pressure.

Flexible hoses should be accessible for inspection. Means should be provided to isolate flexible hoses used in systems for fuel oil, lubricating oil, seawater cooling and compressed air. When used in systems conveying flammable fluids flexible hoses should be shielded from hot surfaces and other sources of ignition.

## 18 FIRE PROTECTION

Fire protection should be considered for protection of personnel during maintenance and inspection activities and protection of the device during in-service and maintenance. The evaluation of fire protection system requirements should be carried out during the risk assessment. Due consideration should be given to health and safety requirements. Temporary portable fire detection, portable extinguishers and ventilation facilities should be installed prior to undertaking maintenance work within the device hull. Escape routes identified with battery-backed illuminated markers should also be considered depending on the size of the compartment and device size. If the device is fitted with permanent firefighting facilities, manual initiation of firefighting should be available at access points. In considering active fire fighting systems, due consideration must be given to the effect on personnel, electrical systems, buoyancy and stability (if deluge systems), etc.

OS-D301 provides the requirements for fire protection for offshore installations. In the context of the wave device (unmanned installation, confined space and absence of hydrocarbons) some of the combined requirements in Section 8 D200 and D300 should be considered. Information on extinguishers is given in Chapter 2 Section 3 C. Fire detection system requirements are given in Section 4. If the detection system is activated and due to oxygen starvation (in a closed compartment) the fire is extinguished or made dormant, special procedures for entry in the affected compartment should be considered.

Even a small fire involving synthetic materials (e.g. from electrical cables) cause hydrochloric deposits on surfaces and equipment which will very seriously increase corrosion rates, reduce tracking resistance of electrical insulating materials, and thus reduce future reliability of equipment. Proper cleaning procedures using specialist firms familiar with these aspects should be considered if required.

The requirements of the Confined Spaces Regulations 1997 (SI 1713) should be met (refer to Section 27.7 under Confined Spaces Regulations item).

Operational implementation of fire precautions and procedures should be in accordance with the guidance in 25.1.6.1 H&S Management System.

## 19 INSTRUMENTATION AND CONTROL SYSTEMS

### 19.1 System Monitoring and Control

The requirements of instrumentation and control systems are addressed in OS-D202 and Safety shutdown systems in OS-A101. These documents have been written chiefly to cover manned installations and should be read in that light, particularly with respect to operator interface and maintenance issues.

The control and monitoring requirements for the WEC device should be summarised in a Functional System Design (FSD) which describes the objectives and attributes of the control system in terms of functional capability at locations (on-board, electrical substation, control centre etc). The FSD may be prepared using Sections 2 and 3 of OS-D202 as a check list.

For the general installation of instrumentation equipment and systems in a WEC device, the reference in Appendix F contains aspects that should be considered. OS-D202 applies to mobile offshore units. The standard provides guidance that may be used as far as applicable. Selected items from the OS-D202 contents list that may provide relevant guidance is presented in Appendix F (F3 Instrumentation and Control Systems). This will in many cases have to be modified or adapted to the WEC design being considered.

### 19.2 Control Hierarchy and Channel Separation

The central controller which communicates with the remote control location should be at least a dual processor system designed to continue operation on the loss of one processor or control link.

The control of each component should be independent and implemented separately in such a way that:

- Control logic failure for one component (end element) does not directly effect any other system component.
- Recovery mechanisms must be available should a software crash occur.
- When the remote control link is lost, local control is maintained.
- Start ups and restarts shall be possible without specialised system knowledge. On power-up and restoration after loss of power, the system shall be restored and resume operation automatically.
- If electrical power is lost, a mechanical mode of control must be available which will prevent damage in normal conditions and allow survival of the device.
- Special arrangements should be made for vital control loops and data links

### 19.3 Internal Environment

Special attention should be given to effects on monitoring and control systems from the following:

- vibration (wave slamming, sloshing of tank contents, local structural vibration, impact, excitation from hydraulic, pneumatic and mechanical systems etc);
- temperature,
- humidity,

- salinity,
- explosive gases (e.g. from trickle charging of batteries),
- electromagnetic interference,
- atmospheric pressure (may fluctuate in sealed compartments), and
- assumptions on quality and variability of electric, hydraulic, pneumatic, light (fibre optic devices) and power supplies.

The design basis for the device should consider the prevailing environmental conditions, and categorise compartments and locations in terms of the environmental requirements to be placed on the equipment and systems to be installed.

In the marine and offshore industry a wide range of equipment is available that has already been Type Approved including Type Testing when relevant to specified criteria. Such Type Approvals are available through a number of Classification Societies and Notified Bodies under the EC directives.

The Type Approved instrumentation and certificates listed on the DNV website have been subjected to environmental simulation testing according to the approval scheme in DNV Certification Note 2.4 "Environmental Test Specification for Instrumentation and Automation Equipment" and the conditions referenced in the relevant certificate issued to the Manufacturer.

In specifying the internal environment that equipment should withstand, the following extract from the DNV approach to ships and mobile offshore units may be relevant:

<i>Parameter</i>	<i>Class</i>	<i>Location</i>
Temperature	A	Machinery spaces, control rooms
	B	Inside cabinets, desks. etc. with temperature rise of 5 °C or more installed in location A
	C	Pump rooms, void spaces, rooms with no heating
	D	Open deck, masts and inside cabinets, desks etc. with a temperature rise of 5 °C or more installed in location C
Humidity	A	Locations where special precautions are taken to avoid condensation
	B	All locations except as specified for location A
Vibration	A	On bulkheads, beams, deck
	B	On machinery such as internal combustion engines, compressors, pumps, including piping on such machinery
	C	Masts (or other external appurtenances)
Electro-magnetic compatibility (EMC)	A	All locations except as specified for open deck
	B	All locations including open deck

Table 19.1 : Parameter Class for Different Shipboard Locations

The environmental conditions are classified as follows:

#### Temperature

Class A: Ambient temperatures +5 °C to +55 °C

Class B: Ambient temperatures +5 °C to +70 °C

Class C: Ambient temperatures -25°C to +55°C

Class D: Ambient temperatures -25°C to +70°C

### Humidity

Class A: Relative humidity up to 96% at all relevant temperatures, no condensation

Class B: Relative humidity up to 100% at all relevant temperatures.

### Salt Contamination

Salt-contaminated atmosphere up to 1 mg salt per m<sup>3</sup> of air, at all relevant temperatures and humidity conditions.

### Oil Contamination

Mist and droplets of fuel and lubricating oil.

### Vibrations

- Class A: Frequency range 3 to 100 Hz  
Amplitude 1 mm (peak value) below 13.2 Hz  
Acceleration amplitude 0.7 g above 13.2 Hz
- Class B: Frequency range 3 to 100 Hz  
Amplitude 1.6 mm (peak value) below 25 Hz  
Acceleration amplitude 4.0 g above 25 Hz
- Class C: Frequency range 3 to 50 Hz  
Amplitude 3 mm (peak value) below 13.2 Hz  
Acceleration amplitude 2.1 g above 13.2 Hz

### Electromagnetic Compatibility

Electrical and electronic equipment should be designed to function without degradation or malfunction in their intended electromagnetic environment. The equipment should not adversely affect the operation of, or be adversely affected by any other equipment or systems used on board or in the vicinity of the device. Upon installation, it may be required to take measures to reduce electromagnetic noise signals. See e.g. the DNV Classification Note No. 45.1 “Electromagnetic Compatibility”. Such measures may be in form of a list of electromagnetic noise generating and sensitive equipment, and an estimate on required noise reduction, i.e. an EMC management plan. If using power control equipment with thyristors, then non-harmonic content should be checked. Testing may also be required to demonstrate electromagnetic compatibility, based on the EMC Directive, which should be observed.

### Inclination and Accelerations

Equipment designed for installation in ships will typically be designed for roll +/- 22.5 degrees, static heel +/- 15 degrees, pitch and trim +/- 10 degrees. If ship shaped units, peak acceleration +/-1.0 g for length less than 90 m, and +/-0.6 g for greater length should be considered. Roll period 5 to 10 s. For other configurations the specific values should be calculated or derived from model tests.

### Miscellaneous

Other environmental parameters may influence the equipment, e.g.;

- fire,
- explosive atmosphere,
- temperature shock,
- wind, rain, snow, ice and dust,

- audible noise,
- mechanical shock or bump forces,
- splash and drops of liquid, and
- corrosive atmospheres of various compositions.

## 19.4 Software Development

Software should meet FDS requirements and be developed in accordance with the following:

- A software lifecycle plan shall be developed which identifies all deliverables and specifications in accordance with IEE 1228 and IEC 12207.
- The competence of the software development team should be established using IEE/BCS/HSE Guidelines.
- A qualification approach according to RP-A203 should be considered, but as a minimum a failure mode and effect analysis (FMEA) and/or HAZOP shall be undertaken to systematically review the consequences of failure or anomalous software behaviour for each software module and for the system as a whole.

The software shall be tested under all normal and reasonably likely abnormal conditions (as identified in the HAZOP) to ensure that the expected behaviour is achieved.

## 19.5 Primary Data Link

The primary data link that provides the normal means of controlling the device should be designed with appropriate redundancy and with a protocol which can deal with errors and is able to maintain control on the loss of one link.

## 19.6 UHF Link

At least one of the telemetry and control links should be a radio link that should include a safety shutdown loop that will shut down the device to a safe condition if the link is lost for more than a pre-determined period. UHF telemetry link requirements for ESD and similar safety related systems should be based on:

- OFCOM Performance Specification MPT 1411 and where systems are considered safety critical, using the Safety Integrity Levels (SIL) arrived at in a formal assessment based on IEC 61508.

The principal requirements of such a system are:

- Duplication of components, including power supplies with automatic changeover during failure events.
- Power supplies to have battery backup.
- The telemetry link shall be duplicated throughout its length using two separate and independent frequencies.
- Failure of one channel or a forced switch from one channel to the other should not cause loss of the link.

## 19.7 SCADA System

The SCADA should meet the requirements of the FDS in terms of safety, reliability and operational objectives.

A number of options for the communication system associated with SCADA or data collection systems are available including:

- Fibre optical
- Copper twisted pair (RS485)
- Radio telemetry

The choice will be influenced by the quantity of data, distance over which the data is to be transferred and robustness required. One of the main advantages of optical and radio systems is the inherent isolation provided. While optical solutions provide high bandwidth over long distances they require more sophisticated jointing and testing is not straightforward through sub-sea, umbilical and on-device cabling systems.

The design should consider the reliability required in the system and the use of the system to alert operators to faults even if immediate shut down is not required. Additional provision in the system may be justifiable if it enables the operator to restore conditions in the device without costly intervention at sea.

Consideration should be given in the design of the SCADA and its communication system to its use for voice and CCTV communications.

Adequate instrumentation and remote reading and control must be provided to enable commissioning, monitoring and control of the electrical power generation and delivery to shore. Remote access links should have appropriate security features to minimise inadvertent operation.

#### Use of PLC's

Many WEC devices may not require full SCADA systems so in those cases a suitably proven PLC system should be specified. This should meet the requirements of the FSD and those specific requirements described in Sections 19.2 to 19.6 and 19.8 that are relevant, plus any specific needs from sections 19.9 and 19.10 that may be necessary.

## 19.8 Reliability Issues

If the device is normally unmanned and risks to personnel are low, the need for IEC 61508 type SIL assessment will be restricted to all but the most critical components such as the emergency shutdown facilities. However, for commercial viability the reliability of the electrical and electronic equipment within the device must be kept high, not only due to the need to ensure continuity of output power, but also to keep intervention costs to a minimum by extending maintenance intervals.

A high level FMEA or similar type of review should be undertaken after prototype testing and before the device goes into production, in order to ensure all areas of poor reliability have been identified during the test process. The identified areas can then be focused on for more detailed analysis. For software, the lifecycle plan should also take this into account. Where practicable, all equipment should be type-tested to a recognised standard and be commercial off-the-shelf with a proven track record for reliability.

#### Electrical

As a minimum, single mode failures should be avoided through the test/analysis process, and where this process has identified vulnerability, steps should be taken to prevent such

failures occurring. Where this has been achieved by duplication and redundancy, checks should be made that each element is totally independent of the other by separation of equipment, cabling, auxiliaries and energy sources (batteries, fuel tanks and accumulators). CO<sub>2</sub> or other similar fire fighting systems should be considered if the internal compartment volumes are small enough. (See also Section 18).

Power factor correction capacitors for induction generators are considered to be components requiring particular reliability focus. It is recommended that fast protection be provided to remove them from the generator circuit should a capacitor fault occur.

#### Instrumentation

MTBFs for electronic and control components such as relays are usually quoted by manufacturers and therefore it is not difficult to select only high reliability components, provided the internal environment has been specified.

Separation and redundancy in instrumentation and control systems is equally important. Even if a fault within a device not equipped with fire fighting facilities results in a fire, some physical separation of duplicated systems may give vital additional time to transmit data about the cause of the failure before the device is lost.

Software issues are covered in Section 19.4 .

## 19.9 Hydraulic Systems and Controls

One of the most critical aspects for power conversion based on hydraulic systems is the control of hydraulic pressure. As with many control system, the reliability of the system is essential and it needs to be established to all basic components as follows:

- The control valves and the associate solenoids - these will be the valves in the valve block. The wave device will require these to be operating at a high number of cycles. Therefore suitable valves will need to be selected for reliability. Cleanliness in the system is also very important to avoid potential blockages.
- The logic of the power circuits needs to be designed taking all start-up scenarios, including black start (no power available) shut down and emergency cut-out or stop conditions into account, along with the various fault conditions that may develop.
- The front end controller - this is the control card which manipulates the valves in the system. Fail-safe states need to be defined to ensure that any communication failure with higher level devices will not cause undesired effects on the system. Limited states in the system should also be taken into account when entering into survival modes. The monitoring of these states and the reliability of the monitoring are also important considerations.
- Sensing devices such as pressure/temperature transducers. Due consideration should be given to what configuration or redundancy is required in order to achieve the desired reliability target.
- Distributed systems with associated computer and network equipment. This is where all the complex analysis can be performed and the control algorithm in the front-end controller can be updated. At the same time the systems can communicate via links with onshore stations. The key aspect for this layer of equipment concerns reliability and availability. Consideration should be given to the level of redundancy required in order to achieve the reliability target and how data should be managed in order to achieve the optimum performance.

- A computer management system onshore which communicates with the computer hub at the device. This is the data management centre where new software can be tested and downloaded to the computer at the device. It can also communicate with the outside world. Because it is onshore and readily accessible, maintenance of the system is easier.

#### Testing during qualification

The key aspect about testing a complex control system is preparation. A robust testing programme should be established in order to address all performance and reliability issues. These should include:

- Response to communication failure.
- Response to power failure.
- Performance of the response - is the time from command to action taking too long?
- Redundancy testing.
- System stress testing (by introducing overload data onto the system to see how it performs).
- Communication protocol testing if it is a proprietary protocol.
- Software testing and validation.

### 19.10 Air Flow Turbine Control

The documentation of the control system shall, as a minimum, encompass the following;

- transfer functions for control of turbine parameters,
- results of open and closed loop simulation of turbine control parameters,
- interface specification to control system superior to turbine control system,
- listing of all turbine control parameters such as vibration, temperature, speed, etc,
- alarms, step to idle and shutdowns (with set points as applicable),
- normal and abnormal stop and start sequence,
- load control,
- automatic purge cycle,
- other systems such as fire detection and prevention,
- compressor surge control,
- override functions (when applicable), and
- minimum monitoring requirements are given in Table 19.10 .1.

<i>Control parameter</i>	<i>Parameter value</i>	<i>Action</i> <sup>1)</sup>
Clogged air intake filter, differential pressure	High	Alarm
Anti-icing system failure, pressure		Alarm
Lubricating oil, pressure	LowLow-LowHigh	Alarm Shutdown Alarm
Lubricating oil, temperature	HighHigh-High	Alarm Step to idle
Lubricating oil level	Low	Alarm
Clogged lubricating oil filter, differential pressure	High	Alarm
Turbine rotor overspeed	HighHigh-High	Alarm Shutdown
Anti-surge system, if applicable	Indicated surge	Alarm
Vibration	HighHigh-High	Alarm Shutdown
Inlet guide vanes, bleed valves, variable stator vanes actual position not in synchronisation with command value, as applicable		Alarm if anti surge system, otherwise step to idle
Bearing temperature (material or oil outlet)	HighHigh-High	Alarm Step to idle
Thrust bearings temperature (material or oil outlet)	HighHigh-High	Alarm Step to idle
Power loss of control and monitoring system		Shutdown
Failure to reach idle speed		Shutdown
<sup>1)</sup> All "Step to Idle" to result in a "Shutdown" if the fault is still critical after a defined operation time at Idle. Provided it can be documented that safety is maintained "Step to Idle" might be replaced with "unloading to a safe power level",		

Table 19.10 .1 : Monitoring Requirements

The control system shall be equipped with an uninterruptible power supply. Total loss of control system power shall lead to a controlled turbine shutdown. Control systems shall be arranged so as to allow local control and operation of the turbine, irrespective of the state of the overall control system.

Turbine control systems shall be provided with hardwired (or equivalently fast) overspeed protection preventing the turbine speed from exceeding the maximum permissible speed.

## 20 UMBILICAL CONNECTIONS

### 20.1 Design

The umbilical design, fabrication and operation shall generally be based on ISO 13628-5, Part 5 'Subsea Umbilicals'.

Dynamic umbilical connections from the wave device to the seabed will be exposed to environmental loading due to currents and direct wave loading as well as forced motions of the floating wave device. The static and dynamic response characteristic of the umbilical is similar to other compliant slender structures applied in the offshore in industry (e.g. flexible risers, hoses and control umbilicals). Such structures may have a pronounced nonlinear global response characteristic. It should be expected that possible non-linearities are strongly system and excitation dependent.

The global load effect analysis should be conducted by means of Finite Element (FE) computer software tailor-made for offshore riser applications. A Time Domain (TD) solution scheme should be applied for dynamic load response analyses.

The global analyses shall cover all relevant static and dynamic load cases for the system. Due regard shall be given to operational aspects of the floating wave device (e.g. operational modification of the motion characteristics of the floating wave device to optimise wave energy absorption). The load cases shall cover relevant extremes as well as fatigue loading cases. Critical load cases during the installation phase shall also be covered.

The guidelines given in OS-F201 'Dynamic Risers' on global load effect analysis should be adopted (especially those involving system modelling, non-linearities, analysis methodology and model verification). Dedicated local analyses shall be performed to establish load sharing between the internal components of the umbilical (i.e. to determine internal stress/strain due to applied global load effect). Sufficient capacity shall be documented for all internal umbilical components. Extreme load cases as well as fatigue shall be addressed. Acceptance criteria shall be based on ISO 13628-5, Part 5 'Subsea Umbilicals'.

### 20.2 Quick Disconnect Options

Commercial off-the-shelf underwater mateable connectors are commonly available.

It is important to note that these connectors are expensive high performance devices normally specified for the defence and oil related industries, and therefore other solutions should be considered where practicable. Some solutions may involve radio-activated guillotines for which operational procedures require careful consideration.

## 21 CABLE CONNECTION TO SHORE

### 21.1 General Considerations

Marine environment and underwater connections shall preferably be commercial off-the-shelf type approved products with known quality, reliability and performance. The use of plugs and sockets is acceptable provided:

- They are suitable for their working environment.
- They are keyed to prevent connection to the wrong circuit.
- They are positively locked in position and not just a “push fit”.
- Where large numbers and/or sizes of plugs and sockets are used (i.e. where mating and disconnection forces exceed 10kg), they should be located in hydraulically operated frames.

### 21.2 Terminal Boxes

Terminal boxes shall be commercial off-the-shelf type approved to the appropriate IEC Standard and of suitable material and ingress protection for their location.

### 21.3 Cable Installation

The route of the cable must be planned to avoid hazards such as shipping lanes, fishing grounds, rocks, wrecks and areas of high currents or shifting sands. Burying the cable may reduce the hazard but will increase costs.

### 21.4 Installation, In-Service and Extreme Loading

Medium voltage cables are not designed to take significant tension or flexing loads and therefore the site mooring facilities should ensure that cables experience loads well within the maximum figures quoted by the manufacturer. Recommendations on stability design of cables can be found in RP-E305.

### 21.5 Design and Strength

As stated in Section 20.1, the ISO 13628-5 Standard is to be employed. The standard gives recommendations for the design, material selection, manufacture, design verification, and testing of umbilicals (including a power cable from a floating WEC device). Normative references/standards regarding electrical cables are included in this standard.

From a functional point of view the power cable shall be capable of withstanding all design loads and load combinations, and to perform its function for the specified service life. Furthermore, the cable shall have to operate at the specified temperatures, and the materials must be compatible with the environment to which they are exposed. The electrical cables shall be capable of transmitting power and signals with the required characteristics. End termination interfaces with the umbilical components are a critical area and should be addressed during the design review stage. End terminations and ancillary equipment shall, as a minimum, meet the same functional requirements as the umbilical/power cable.

## 21.6 Fatigue Design

Fatigue design of cables can be performed following the same principles as used in RP-C203. Where S-N data are not available fatigue test data should be derived and assessed to achieve the same safety level as implied by use of RP-C203 for fatigue design.

## 21.7 Fabrication and Testing

EPR or XLPE (IEC 502) type technology is highly field-proven in submarine applications for medium/high voltages (46-69 kV). Their advantages are that they can operate at high temperatures (90°C) and at high electrical stresses. When cables are operated in a wet environment, particular attention has to be paid to the reliability and long-term ageing performance of the insulation under electrical stress. For XLPE, this generally requires that an impervious metallic sheath (e.g. a lead sheath) is applied over each core to avoid direct contact with water. EPR compounds (blended from different materials) can be formulated in such a way as to give an excellent performance from both electrical reliability and ageing points of view, thus removing the need for an impervious metallic sheath. This is the so called "Wet Design" that could give significant advantages for cable handling and installation, due to the reduced cable weight and dimensions.

## 21.8 Slip-rings and Other Critical Components

Electrical slip-rings normally require regular servicing and may not prove very suitable for this service. However 11kV, IP66/7/8 devices are available.

## 21.9 Penetrations

There are a number of proprietary devices available and the choice will depend to some extent on the application as follows:

Between bulkheads, Lycab and Hawke Transits are suitable up to water pressures of 5 barg.

- Hull penetrations. Junction boxes should be used where the interior is filled with a suitable setting compound which will have been type-tested to the required degree of watertightness. Hermetically sealed underwater mateable connectors may be used, but may prove expensive for this application.
- Refer to OS-D201 Chapter 2 Section 10 C 300 (Penetrations of Bulkhead and Decks).

See also Section 20.2 Quick Disconnect Options.

## 21.10 Cables and Umbilicals

Refer to IEC 60502 for cables and API 17E for umbilicals.

## 21.11 Protection Requirements

Protection relays should meet the requirements of BS EN 60255. As a minimum, overcurrent and differential protection should be provided, with inter-tripping. Generator protection will depend on the type of generator utilised, but statutory requirements for connection of embedded generation is described under Section 17.2.2 Grid Connection above.

## 22 MANUFACTURING

### 22.1 General Requirements

The requirements for fabrication and testing are, in general, in line with the requirements for offshore installations. However, special considerations should be implemented considering the access to structure and equipment / system during the in-service life, the planned maintenance regime and required reliability of the device.

The particular expertise required of manufacturers of WEC devices will vary according to the make-up of the device and power take-off system employed. However, suitable manufacturers will be able to demonstrate and incorporate similar experience and track record to enable successful manufacture of the WEC device.

Device manufacture may be by the owner or by an owner selected manufacturing entity. It will probably consist of structural / equipment fabrications and sub-assemblies combined to form the wave energy conversion system. Some sub-assemblies may be well proven items and should be purchased or fabricated against existing codes. However, most marine primary energy converters have only parts of their technology proven e.g. a tethered buoy with untried technology in the internals. Hence the manufacturer should participate as necessary in the Qualification process (see Section 4).

A Manufacturing Plan should be developed by the manufacturer of the device. This should include all sub-assemblies and discrete parts which together make up the WEC device. Where possible, the added value of the manufacturer's production engineering expertise should be incorporated to assist in driving down the device cost.

Particular efforts should be made to avoid any misunderstanding between purchaser and manufacturer. This includes the interpretation of specifications and any other design requirements. Meetings between the purchaser and manufacturer should be held prior to the commitment of the order to facilitate these aspects.

A procedure to obtain purchaser permission for a repair in manufacture (e.g. to a casting) should be agreed where appropriate.

Material Selection for the WEC device is dealt with in sections 10.1 Steel, 10.2 Concrete and 10.3 Composites. These material selections impose levels of inspection and certification which are reflected in this section.

Movement of partially completed structures should consider provisions from DNV Rules for Planning and Execution of Marine Operations (load out, lifting, transportation - dry tow or wet tow).

Testing of the WEC device, or part thereof, may be by the manufacturer or qualified test house as appropriate. Procedures for factory/yard testing should be developed in a timely manner and included in the manufacturing plan.

The quality and inspection of materials used in manufacture is covered in the appendices.

The testing and certification referenced in this section is required to establish documented traceability of the material and fabrications used in the WEC device.

## 22.2 Manufacturing Surveys

### 22.2.1 Audit and Survey

The manufacturing facilities should be surveyed as part of the manufacturing selection process. It is highly desirable, to improve effectiveness of audit activity, if the manufacturer is accredited to work to the ISO 9000 series of standards or an acceptable equivalent.

After manufacture has commenced, interim audits of manufacturing should be carried out to give assurance of manufacturing quality. This may be done by one or more of the following means:

- Use of experienced third party auditor
- Internal developers audit team (subject to competence)
- Manufacturer or fabricator internal QA/QC system

Tests and inspections should be also adjusted to the required level of reliability. Depending on the results of tests and inspections the level of inspection may need to be increased. Fabrication procedures may need modification and personnel may need re-qualification.

Supplier quality systems should also be confirmed by unscheduled inspections during the manufacturing period.

### 22.2.2 Inspection

Inspection requirements for fabrication of steel, concrete and composites are covered in OS-C401 Chapter 2, OS-C502 Section 7. and OS-C501 Section 11 respectively.

Inspection of steel fabrication should cover the following aspects:

- correct identification and documentation and use of materials,
- qualification and acceptance of fabrication procedures and personnel,
- inspection of preparatory work (assembly, fit-up form work, reinforcement, etc.),
- welding inspection (which must match the highest structural category of the items being welded),
- inspection of fabrication work for compliance with specifications and procedures,
- witnessing NDT, control and other testing e.g. material coupon and weld stress tests (again reflecting the structural category of the item being inspected),
- inspection of repairs,
- inspection of corrosion protection systems, and
- functionality of examination or test equipment and of recording and/or measuring devices vital for correct operation of equipment and machinery used in fabrication.

More inspection details are given in Appendix E for steel, concrete and composites as well as equipment and systems.

Inspections during manufacturing have the objective of verifying compliance between accepted / verified / certified designs and actual as-built structures and/or systems.

Inspections can also be used to ascertain that the manufacturing process will contribute to the required level of confidence on the performance (survivability and reliability) of structure and/or systems.

In addition, the requirements defined below should be considered.

## 22.3 Steel Structures

When applicable, structural steel should be manufactured at works which are internationally recognised (see OS-B101 Chapter 3). Steel manufacturers are normally approved by Classification Societies for steel to be used in ships or offshore structures. For wave energy devices the same level of steel manufacturing approval should be applied.

Steel should be certified and the certification scheme to be applied will depend on the approval / verification / certification regime selected for the wave energy device. As a minimum, it is suggested that steel materials shall be delivered with inspection documents as defined in BS EN 10204 (or equivalent standard). The following level of certification (listed in descending order of criticality) should be applied:

<i>Certification process</i>	<i>Material certificate (EN 10204)</i>	<i>Structural category</i>
<i>Test certificate</i> As work certificate, inspection and tests witnessed and signed by an independent third party body	3.2 (old 3.1.C)	Special
<i>Work certificate</i> Test results of all specified tests from samples taken from the products supplied. Inspection and tests witnessed and signed by QA department	3.1 (old 3.1.B)	Primary
<i>Test report</i> Confirmation by the manufacturer that the supplied products fulfil the purchase specification, and test data from regular production, not necessarily from products supplied	2.2	Secondary

Table 22.1 : Certification Process for Steel Structure

Inspection requirements for steel are given in APPENDIX E - INSPECTION.

### 22.3.3 Concrete Structures

Where appropriate, material certification requirements for concrete constituents and reinforcements are given in OS-C502 Section 4. A summary is provided here.

Cement is to be delivered with a mill certificate containing, at least, the following information:

- Physical properties, i.e. fineness, setting times, strength in mortar, volumetric stability, normal consistency and soundness.
- Chemical composition, including mineralogic composition, loss on ignition, insoluble residue, sulphate content, chloride content and pozzolanicity.

The certificate should, in addition to confirming compliance with the specified requirements, also to state the type and grade with reference to the approved standard and specification, batch identification and the tonnage represented by the document.

Aggregates are to be delivered with a test report containing, at least, the following information:

- Description of the source.
- Description of the production system.
- Particle size distribution (grading) including silt content.
- Particle shape, flakiness, etc.
- Porosity and water absorption,
- Content of organic matter.
- Density and specific gravity.
- Strength in concrete and mortar.
- Potential reactivity with alkalis in cement.
- Petrographical composition and properties that may affect the durability of the concrete.

Additions shall conform to requirements of recognised standards, and only additions with established suitability shall be used.

Relevant test report(s) from a recognised laboratory are to be submitted before use of an admixture.

Reinforcement and pre-stressing steel shall be delivered with a Works Certificate. The requirement for a Works Certificate may be waived if the reinforcement is produced and tested under a national or international certification scheme, and all the required test data are documented based on statistical data from the producer. All steel shall be clearly identifiable. Components for the pre-stressing system are to be delivered with Works Certificate, as are mechanical splices and anchorages.

#### 22.3.4 Materials and Components

Requirements for certification of materials and components is given in OS-D101 Chapter 3 Section 1 C. Three levels of documentation, depending on the importance of equipment and experience gained in service, are defined (in ascending order of importance):

*Test Report (TR)* is a document signed by the manufacturer which states;

- conformity with the rule requirements,
- tests were is carried out on samples from the current production of equal products.

The manufacturer is to have a quality system that is suitable for the kind of certified product. The surveyor is to check that the most important elements of this quality system are implemented and may carry out random inspection at any time. The products shall be marked to be traceable to the test report.

*Work Certificate (W)* is a document signed by the manufacturer which states;

- conformity with the rule or standard requirements,
- that the tests are carried out on the certified product itself,

- that the tests are made on samples taken from the certified product, and
- that the tests are witnessed and signed by a qualified department.

The manufacturer is to have a quality system that is suitable for the kind of certified product. The surveyor is to check that the most important elements of this quality system are implemented and may carry out random inspections at any time. The component shall be marked to be traceable to the work certificate.

*DNV Certificate (NV)/ Independent Third Party Certificate* is a document signed by a surveyor which states;

- conformity with the rule requirements,
- that the tests are carried out on the certified product,
- that the tests are made on samples taken from the certified product,
- that the tests are made in the presence of a DNV surveyor, a third party surveyor or in accordance with special agreements.

Inspection requirements for materials and components are given in Appendix E.

## 22.4 Minimum Structural Requirements

Information regarding minimum requirements for the fabrication and testing of steel structures is given in OS-C401.

For composite structures information is provided in OS-C501. For concrete see OS-C502.

## 23 INSTALLATION AND RETRIEVAL, TEMPORARY PHASES

Requirements and guidance for temporary phases are given in DNV Rules for Planning and Execution of Marine Operations. Recommendations and requirements in the rules shall be considered in relation to structural and operational complexity, sensitivity and type of marine operation to be performed.

Marine operations shall be planned and prepared to bring the device from one defined safe condition to another according to safe and sound practice. The handled object shall remain in a stable and controlled condition if a failure should occur.

The rules requirements are tailor-made to take into account special procedures, environmental limits and weather forecasts. Risk assessments or HAZOP studies are recommended for complex operations to reveal all possible hazards and their potential consequences.

All possible contingency situations shall be identified and contingency plans or actions shall be prepared for these situations.

A design basis, describing the basic input, parameters, characteristic environmental conditions, characteristics load / load effects, load combinations and load cases, and / or a design brief, describing the planned verification activities, analysis methods, software tools, input specifications, acceptance criteria, etc, should be developed to obtain a common basis and understanding all parts involved during design, engineering and verification.

Most wave devices are expected to be wet-towed to and from location. Design and procedure requirements are given in Part 1 and Part 2 Chapter 2 (for towing) or Part 2 Chapter 3 (self-floating towing). Tug capacity, towline design and attachments to devices, operating reference period (planned operation period plus estimated contingency time) should be defined as well as if the operation is weather restricted or not (resulting in definition of environmental limits and design loads). Marine Operation Manuals should be prepared. Considering that the operation may be repeated several times, the manuals should be developed and maintained, incorporating lessons learned and modifications for specific modification considering the different locations where devices are to be installed. In cases where the device is lifted, requirements for lifting are given in Part 2 Chapter 5. For activities requiring subsea operations (with objects lowered, pulled down or ballasted from the sea surface to its final position at the seabed), guidelines are provided in Part 2 Chapter 6.

Offshore installation (by launching or upending) is described in Part 2 Chapter 4. Sensitivity studies should be carried out to evaluate the influence of variation of main parameters in the outcome of the operation.

Requirements for structural design are given in Part 1 Chapter 4. Structures shall be able to resist local damage without a total collapse, with structural components and details designed to behave in a ductile manner as far as possible.

For stability and watertight integrity requirements during temporary phases, see item above and Rules for Planning and Execution of Marine Operations. Special consideration

should be given to aspects regarding preservation of equipment during installation of device (not only survivability). For ULS and PLS load factors see Part 1 Chapter 4 Section 3.2.5. Resistance and material factors are given in Part 1 Chapter 4 Section 4.

Materials and fabrication requirements for marine operations are given in Part 1 Chapter 4 Section 4.2.

System and equipment used for installation shall be selected based on a thorough consideration of functional and operational requirements for the complete operation. Emphasis shall be placed on reliability and contingency. All essential systems, parts of systems or equipment shall have back-up or back-up alternatives. Necessary time for change over operations shall be assessed.

## 24 COMMISSIONING AND HANDOVER

By definition, commissioning is the process that starts at mechanical completion, which must be verified by a comprehensive check and inspection of all systems. It involves testing and recording the functioning of the components and systems on a planned basis and the full integration of them into the overall working device. In the case of WECs, the moorings, foundations and installation or deployment process should be included as an important part of the commissioning activity. The collation of full documentation on all systems and the preparation of this documentation for handover to the operator with the device, both form key aspects of the handover process. This includes a comprehensive dossier of completed signed test records for operational, diagnostic and maintenance purposes at the end of the commissioning phase.

A comprehensive dossier of completed signed test records should be available for operational diagnostic and maintenance purposes at the end of the commissioning phase.

This section provides an overview of commissioning methodology and it is advised that a dedicated commissioning manager be required to act as focal point for the activities. These activities are broken down into a series of logical steps recommended on the basis of experience gathered mainly in the energy sector industries and described below.

NORSOK Z-007 (Mechanical Completion and Commissioning) provides information and typical lists regarding commissioning philosophy and methodology as well as typical check lists.

As much commissioning as practicable should be undertaken onshore or at quayside prior to deploying the device.

### 24.1 Commissioning Plan

An overall plan (in linked bar chart form) for the commissioning process is essential due to the detailed nature and complexity of the task. Preparation should be carried out and progressed against this plan. Commissioning activity requires an early input at design stage of the device(s) to do three activities (see 24.1.1):

- defining the systems and sub-systems;
- ensuring that a feasible logical sequence for commissioning is practicable; and
- defining the documents required for handover.

Due to the potentially restricted space available in the device, a detailed commissioning plan should be drawn up, which should include pre-commissioning of individual pipe-runs and circuits, and take account of commissioning sequence and workspace requirements.

The next stage of the commissioning process, beginning at a suitable time before mechanical completion, is the detailed definition of the commissioning workscope and indexing of the system manuals (see 24.1.2).

#### 24.1.1 Activity Early in Design Phase

##### a) Systems Definition

A system, in this context is a part of the whole device that has three attributes viz.:

- It may be identifiable clearly and unambiguously on the schematic diagram(s) of the device. The diagrams may involve wiring, fibre-optic, piping, mechanical or radio links or other types of interfaces. The whole of the device schematics should be broken down into these identified systems
- Next, the system should be commissionable in a stand-alone sense. That is, such that system connectivity may be proven, the functioning of the components or subsystems proven to the extent that, when the system is joined in context with its neighbouring systems, the combination may reasonably be expected to operate.
- Lastly the system should be isolatable from pressure, fluid flow, electrical power so that the system can be considered as an entity.

When these three attributes are met, a system is defined. For example a “hydraulic” system may be defined as the flange limits of the accumulators, pumps and valves up to the hydraulic inlet to a generator hydraulic motor, plus the interconnecting piping and valves with the directly coupled controls. The hydraulic motor is likely to be considered as part of the generator system, as once the motor is live to hydraulic pressure, the generator starts to function, and is, most properly, part of another system called “generation”. In this way a logical split of systems which together make up the whole device can be defined. These systems are then given a number as well as a title and the numbers are used for all documentation created that concerns that system or elements of it. Documentation here means procedures, plans, job cards, component manuals, test certificates etc.

It should be borne in mind that moorings, substructures or fabricated items may constitute systems - there will be documentation, drawings and test certification and perhaps verification reports associated with structural items. It is most convenient to hand these over as a system.

#### b) Commissioning logic sequence

Once the systems are defined, a sequence for their commissioning is required which is logical against a variety of rules. Examples of rules may be - system A is needed to be activated to power, drive or permit system B to be activated or System X is a safety-critical system that must be commissioned prior to any other.

The rule base is wholly dependent upon the nature of the device and the types of components and systems that are part of it.

The system break down should be agreed with all disciplines involved in assembly, commissioning and operations and maintenance.

#### c) Documentation Requirements

Each system should be fully documented for handover to the operator. This requires as a minimum that the following generic types of documents are collated within a system file:

- Technical Specifications - for main equipment and materials raised to “For Purchase” status.
- Design Drawings raised to “As built” status for piping, instrumentation, electrical systems, equipment layouts, general arrangements, fabrication details, schematics and connection diagrams.
- Purchase Orders - full copies are necessary to enable easy re-order in future or if required to facilitate future licensing of manufacture of the device.

- Warranties for all equipment - care should be taken at the PO stage to ensure that warranties actually cover operation rather than be wasted away in storage at the fabrication yard.
- Manufacturer's manuals - these should include, at least, Health and Safety instructions and procedures, Operating instructions and Maintenance manuals that fully describe the equipment and the maintenance procedures and schedules recommended by the manufacturer. (NB the latter may be incorporated into an overall schedule - see Maintenance section 26.2)
- Manufacturer Recommended Spares - lists of commissioning and insurance spares should be provided.
- Test sheets and Test certificates - whether from factory acceptance tests or site/field testing should be signed and witnessed by a competent independent person as the tests are done and collated into the system files. It is a matter for designer and operator to agree the nature and percentage of tests that should be witnessed.
- Instrument calibration data and traceability - some instrumentation may require specific calibration to a particular standard in order to fulfil its function. Such requirements should be addressed early as they can seriously impact delivery periods and should therefore be planned carefully to align with installation and commissioning.
- Handover Exception Lists by System - inevitably there will be some shortcomings in the test data and/or missing items of documentation. Typical exception lists should have no more than four or five items outstanding, or it means the system is not ready for acceptance. Lists of such exceptions that may be expedited and signed off by the recipient as exceptions are cleared.

If all systems have the above documents complete, they are ready for acceptance (See 24.2 c) below).

#### 24.1.2 Activity Ahead of Mechanical Completion

Some three months (depending on the device detail) prior to the date of mechanical completion, a small multi-disciplinary team must address the following tasks:

##### a) Procedures

It is usual to develop a general commissioning and handover procedure that describes the overall commissioning activity. In addition, each system of any complexity may well require a sequenced method statement giving the detailed steps to commission the system. This should be in a form that can be "ticked off" as each step is completed and any exceptions noted. These procedures should be prepared in advance during this detailed planning period.

##### b) Job Cards

Depending on the scale/number of the device(s) being commissioned; a commissioning contractor will need to evaluate the resources needed to execute the task. This requires each smaller activity that needs technician or fitter support to be defined and the man-hours evaluated on a "Job Card". Some of these will be bespoke; others may be repeats of standard tasks, which must be counted for the complete device(s). The aggregate of job card labour calculations will give the resource to be supplied by the contractor and allow work to be scheduled.

c) Handover forms

This is a form that is usually prepared for each system. It gives system number and name, references any specific procedure and the exceptions list and contains “offered by” and “accepted by” signature boxes. All system handover forms must be accepted prior to offering the whole device for handover. Generally the operator will wish to operate the device for a short proving period to iron out any early faults.

d) System manuals

The documentation as listed in 24.1 .c) should be collected as received and collated into files designated for each system. It is preferable to expedite missing documentation from Vendors from as early as possible to avoid a backlog at handover.

### 24.1.3 Mechanical Completion

At the mechanical completion stage, a number of checks should be performed to ensure the integrity and completeness of the final assembly. These include:

- Mechanical - e.g. dimension check, alignment check, cleanness of equipment, correct orientation, correct labelling, secured fastening, etc;
- Electrical - continuity check, earthing check, insulation of cables/generator/transformer/motor, static check of switches and control devices, battery preparation, lighting and socket outlet check, etc;
- Instrumentation/Communication - calibration of instruments, correct setting of instruments, loop testing, etc;
- General - suitable access and work area; cleanness of areas, adequate painting and preservation, correct provision of emergency and safety equipment, etc.

## 24.2 Commissioning Implementation

Once the documentation described in 24.1 is prepared the focus of commissioning shifts to physical implementation. The definition of roles and responsibilities is vital even if the handover is an internal one where the technology developer is also the operator of the devices. The formal steps of handover should be executed and recorded so that the subsequent audit trail is available. This is a basic requirement of an ISO 9000 series QA system. The tasks below should now be executed.

### 24.2.1 Organisation

The commissioning organisation should be led by a Commissioning Manager (CM) who should be responsible to the Operator, as ultimate client. There should also be an opposite number from the Constructor of the device who may be a fabricator or construction contractor and who is responsible for making the offer of the device, on a systems basis, to the CM.

Under the organisational arrangements, the CM will normally require access to discipline engineers from the designer and fabricator/manufacturer to query any technical discrepancies or missing data. Again, depending on the scale of the task, one or more field engineers will be needed to assist the CM in the checking of physical plant and the collation of documents. Access to technician and fitter resources from the fabricator will also need to be available to the CM to assist with tests and rectify faults. A person responsible for maintenance of the Health & Safety regime should also be available to the CM as well as reporting to the Operator directly.

### 24.2.2 Punch-Listing

This is the activity involved in detailed checking of the physical plant and equipment as well as the documentation. It should be reported on following the structure of the defined systems of the device(s). The activity commences close to mechanical completion in conjunction with the fabricator and under a permit-to-work regime to control health and safety aspects. It is intended to ensure an agreed definition of “Mechanical Completion”, from this point on responsibility for the device should be in the charge of the CM who will commission and prepare it to offer to the operator.

Lists of faults by system should be prepared and worked through as part of the commissioning process.

### 24.2.3 Exception listing by system

As each system is commissioned by the CM and his team, following the pre-prepared and agreed procedures, any outstanding minor faults and documentary errors or omissions should be developed for each system. The CM and the Operator must make judgements about what is acceptable, but a list of five items per system is a practical guide.

### 24.2.4 Preparation of handover documents

As each system’s exception lists are completed they should be attached to a system Handover Form which has the “Offer” Portion filled out and signed by the CM. Accompanying this form should be the completed documentation in a manual. It is usual to collect these together for the whole device rather than try to transfer them piecemeal. The Operations Manager will accept the system by signing off the forms and the individual items of the exception lists as they are cleared. A weekly meeting is the usual vehicle for this activity at which any areas of dispute can normally be resolved. Also included with handover are the remaining commissioning spares and insurance spares for all systems. Operators will need to ensure they have storage facilities available for spares.

### 24.2.5 Document Checks and Audits

Clearly the Operator cannot be expected to read and confirm every page of every document on a real-time basis at handover and contractual arrangements should recognise this practicality. However, the Operator does need to make some checks on documents received and the following suggestions are relevant:

- a high level scan for completeness against the document index
- take a sample of a selected system or a number of selected documents and review them in-depth for completeness. If unacceptably high levels of error or omission are found a further larger, sample should be taken and if that also shows unacceptable levels of error, consideration should be given to a full re-work by the Commissioning team.

Large and mature Operators often engage an independent consultant to carry out a post-commissioning audit, which would include physical plant and documentation. This is a matter for the Operator’s decision.

Once all the above procedures and activities have been completed, the device is commissioned and accepted for handover. One important aspect of WECs is that full and final proving of control systems and generators may not be possible until the device is on

station. The transportation and installation of WECs are covered in separate section of this Guideline (see Section 23).

Note that handover in the sense implied in this section is not the same as the legal transfer of the device as an asset. Companies have their own rules and procedures for this and they are outside the scope of this Guideline.

#### 24.2.6 Security of Logging Facilities

Recording facilities require back-up arrangements wherever they are located. Some logging facilities may need to be located on the device itself in the form of damage/water resistant black boxes, depending on the degree of risk that all links with the device may be lost.

## 25 IN-SERVICE PHASE - OPERATIONS AND MAINTENANCE

### 25.1 Operations

Developers of WECS technology may opt to license the manufacture of devices and may intend to sell machines to project developers rather than operate themselves. However, almost every developer will, in the testing and proving phases, need to operate one or an array of devices themselves to fully understand the operating modes of the machine. This section is intended to remind developers of operational issues and approaches that they need to prepare for to execute that part of the development process. A major focus of operations is health and safety and this is dealt with in more detail in Section 25.1.6- Management Systems (below). New operators and project developers will need to make arrangements along the lines set out below.

The main objectives of the operational phase should be borne in mind through the design process. An early draft of an “operational philosophy” is a valuable design document to ensure that design intent is directed to meet operational needs.

#### 25.1.1 Organisation

An organisation should clearly reflect operational responsibilities. An Operations Manager would normally be the focal point responsible to the Board for the daily running of the operation. The Board should ideally include a director responsible for health, safety and environmental issues and a director with a technical background (the nature of this should reflect the company’s philosophy for deploying or manufacturing its devices).

Where manufacturing is a significant activity of the company, as distinct from licensing technology to other manufacturers, a Quality Manager is essential. Production engineering is another skill worth adding to the organisation in that case.

Where the company chooses to operate a number of devices, a maintenance manager function would be required, depending on the scale of operations this may be combined with other responsibilities.

The remainder of this section assumes that the Company will operate a number of devices as a key part of its activity as well as be closely involved in manufacture.

#### 25.1.2 Routine Operations

##### *24 Hours per day Supervision*

A system for continuous supervision of the devices must be provided. This does not necessarily mean a fully manned control centre, unless that can be justified by the scale of the operation. It should be possible to utilise communications technology to provide a secure supervision and monitoring service by the use of a SCADA system.

Secure means of collecting and storage of data is assumed (see Section 25.2.6). A competent responsible person must also be available around the clock to investigate and respond to any external reports that may come into the company. This includes initiating appropriate emergency responses (see 25.1.7 below).

### *Data and Event Logging*

Logging of operational data is essential, particularly during prototype testing, and care must be taken to ensure that all essential parameters (identified throughout the design process) are recorded. Some of the key parameters to be considered include:

- reservoir oil pressure and temperature,
- ram oil pressures and temperatures,
- generator output current, voltage and power factor,
- transformer temperature,
- UPS and battery voltages and currents,
- status of control and communications equipment,
- status of any critical valves
- fault and trip status of protection devices,
- hydraulic motors - rpm,
- turbine key parameters (speed, vibration, lubrication) ,
- structural response, and
- motions.

### *Written Log Book*

It is normal practice that in addition to event logging and data recording carried out by an automated data collection system, a logbook of key events and work carried out will be maintained. Logbooks should be stored for a number of years to assist with investigations and as part of quality system documentation (see 25.1.6.3)

### *Liaison with Authorities and Related Operators*

An important part of operational discipline is to maintain communications with, other offshore operators, national and local electricity network operators, the national industry regulator (eg Ofgem in UK). Facilities and organisational arrangements must be put in place to ensure these relationships can be maintained effectively.

### *Regular Inspection of Sites and Equipment*

It is important to ensure that sites are inspected and equipment observed at regular intervals. Appropriate technology such as CCTV or webcams should be utilised where this can be justified or is required for security reasons.

## 25.1.3 Control of Work

It is essential to control all work carried out on the WEC system and the control and data collection facilities using a permit-to-work system. This will normally be part of a health and safety management system (see 25.1.6.1). In general all work should be planned in advance and agreed with the Operations Manager who is responsible to ensure safe work systems and to co-ordinate separate tasks effectively. Appropriate documentation should be provided to maintain control of activity and record outcomes.

Routine repetitive tasks should be subjected to a standard task risk analysis (TRA) using the guidelines published by the UK Health and Safety Executive (HSE publication INDG218 revised January 2004) or equivalent.

Certain tasks and activities in WEC operations involve higher than normal risk levels and merit special attention. Examples include (but are not limited to): work over water; entry into the confined spaces often found in WEC devices; operatives working alone (in an onshore context - no-one must ever be allowed to work alone offshore); diving

operations and emergency conditions that are far more difficult to deal with offshore such as evacuation of a casualty (Casevac). Particular attention must be paid to such eventualities in planning for the tasks and preparation of the permit to work. Appropriate safety measures must be included and emergency plans must be in place (see Section 25.1.7).

#### 25.1.4 Offshore Operations

If the developer of technology is operating a device or array in a designated area of sea, then the developer has a degree of responsibility to co-ordinate ship movements and activity in the vicinity of the WECS devices. It should be borne in mind that the Master of every vessel is solely responsible for the safety of his vessel and crew. His judgement is final and cannot be over-ridden by a separate organisation onshore. The International Maritime Organisation (IMO) publishes the full contents list of the “Safety of Life at Sea” (SOLAS) protocol, 1974 and amendments, on its website [www.imo.org](http://www.imo.org) that should be referred to for guidance. The Maritime and Coastguard Agency (MCA [www.mcga.gov.uk](http://www.mcga.gov.uk)) is responsible for implementing the UK Government maritime safety policy, which includes navigation, ship operation and prevention of pollution by shipping. Marking and delineation of designated sea areas and navigation aids is a matter for Trinity House - the General Lighthouse Authority for England, Wales and the Channel Islands ([www.trinityhouse.co.uk](http://www.trinityhouse.co.uk)) and the Northern Lighthouse Board ([www.nlbcorp.com](http://www.nlbcorp.com)) for Scotland and the Isle of Man.

However, the two topics below are worth specific mention.

##### 25.1.4.1 Communications with Offshore

Communication must be maintained with a suitable marine band VHF radio transceiver so that all offshore operations can be conducted effectively and the emergency channel (Channel 16) can be monitored during offshore operations.

##### 25.1.4.2 Co-ordination and Simultaneous Operations (Simops)

All offshore activity should be subjected to a discipline of planning and co-ordination. This applies to regular and non-routine activity. Developers should ensure that proper ship/ship and ship/shore communication is established and the appropriate procedures followed for such work.

Specifically, where multiple vessels are involved in an operation, or in separate operations in close proximity (Simops), co-ordination must be established through planning and close adherence to agreed procedures. In ideal terms Simops should be avoided but this is not always possible therefore procedures must exist to deal with such eventualities..

#### 25.1.5 Non-Routine Operations

These operations are essentially “one-off” activities for which a unique, itemised method statement shall be prepared in advance for comment and agreement by all parties involved. It is normal to consider start-up, shutdown and other more major operations that are repeated in the “Non-Routine” category. This ensures the level of attention and focus that are appropriate to these operations.

Where necessary, a review of the work by face-to-face meeting should be carried out and time for this should be built into planning schedules for work of this nature. A permit

to work should describe the scope of the task(s) clearly and relevant procedural documents should be attached to the permit. Roles and responsibilities should be carefully defined and agreed by the involved parties.

The notes in Section 25.1.4 are also relevant to these operations.

### 25.1.6 Management Systems

Management systems are documentary statements of how key aspects of operations are managed that allow third parties to understand and audit activities and performance against them. They represent the best method by which to communicate externally how a company is managed. There are recognised standards (see below) for these systems which may be used for guidance or under which the operator may seek registration from a qualified accreditation body if they wish to do so. The Management Systems are structured in four discrete levels:

- Level 1 Policy Statement - outlines the commitment and intent of the company
- Level 2 Arrangements to implement the policy - often as a manual (similar to the Operations Manual used by offshore operators)
- Level 3 Procedures - covering the main activities (including O&M manuals for equipment and systems etc)
- Level 4 Records - maintaining an audit trail of implementation and activity (may be used for safety, technical or QA audits)

The sections below describe specific types of management systems that developers may wish to consider adopting.

#### 25.1.6.1 H&S Management System

A Health and Safety Management System (HSMS) is a key requirement for a company operating in the marine environment. It provides a framework for managing activity that carries significant human and business risk and a means of systematically identifying, ameliorating and monitoring that risk against a goal-setting approach to health and Safety. Most importantly, the HSMS is a method of ensuring that legislative requirements are met by the company, although regular update to keep abreast of changes is needed to make this effective. The Operations manual will normally be a key element of the HSMS, alternatively, the management systems for H&S, Environmental and Quality can be combined into an Integrated Management System (IMS).

The common standard specification used is OHSAS 18001 (see [www.bsi-global.com](http://www.bsi-global.com) for an introduction). BSI have also produced OHSAS 18002 which gives commentary on the requirements of the specification and guidance on how to develop and implement a compliant management system. More information is available on the BSI website.

Other relevant references include NORSOK Standard S-001 “Technical Safety” and DNV OS-A101 “Safety Principles and Arrangements”. These are oriented towards offshore installations for hydrocarbons drilling or production, but contain helpful guidance.

#### 25.1.6.2 Environmental Management System

An Environmental Management System is a helpful tool to focus a company on proper environmental performance and to show externally, commitment to concern for the environment. For a company involved in sustainable energy, it is highly advisable to

operate to an international specification. The specification in this case is BS EN ISO 14001:2004, which, together with the associated guideline documents, can be accessed via the BSI website.

### 25.1.6.3 Quality Management System

Whilst a Quality Management System (QMS) is not essential to a technology developer who is less involved in design or manufacture, it represents a means of establishing a management discipline that fits the processes of the business and does not encroach on other areas. The commonly used specification is BS EN ISO 9000:2000 which describes the fundamental aspects of a QMS and may be accessed via the BSI website. The companion documents are: BS EN ISO9001:2000 that describes the main quality management principles that influence company performance viz:

- Customer focus
- Leadership
- Involvement of people
- Process approach
- Systems approach to management
- Continual improvement
- Factual approach to decision making
- Mutually beneficial supplier relationships

Also BS EN ISO 9004:2000 that widens the objectives of the QMS to other interested parties (that is, other than customers) and organisational performance improvement. The latter two standards are complementary and may also be adopted separately.

BSI publish a useful document giving guidance on how to become registered under the ISO 9000 series (ISO 9000:2000 Achieving Registration, ISBN 0 580 40499 4) which is a suitable starting point for organisations deciding about registration and its potential value to the business.

### 25.1.7 Management of Emergencies

Provision for emergency situations is an essential part of managing a continuous offshore operation. A series of emergency response procedures are necessary which cover all the eventualities identified in a “Hazard & Risk Analysis” (HIRA) session. HIRA is conducted in a facilitated multi-disciplinary group using a formal risk template identifying hazards in response to a series of key words.

Each risk is quantified against a matrix of probability and consequence, ameliorative measures are identified and an assessment of the residual risk made. The risks and residual risks are classified into high/medium/low - the latter require no action, a number of medium risks may be acceptable, subject to appropriate management provisions. Any remaining high residual risk must be examined and specific management agreement sought to continue with it, together with measures to control it under particular circumstances. Such a risk should be regularly re-evaluated and considered in the light of any other event or activity that might affect the risk area.

Emergency Response Procedures should fulfil the following criteria:

- Cover the credible incident situations (eg collision, man overboard, mooring failure etc)
- Involve communication with all relevant external bodies (emergency services, hospital, diving medical support, local authorities etc)
- Provide clear guidelines to assist the person responsible for action to think rapidly and clearly (check-lists, pre-prepared forms for records etc)
- Recognise the responsibilities of statutory authorities eg MCA for mobilising search and rescue services.
- Contain all contact information to enable notification to be carried out rapidly.
- Be readily available to all the operational staff who may be called upon to deal with the emergency.
- Clearly define the levels of responsibility within the organisation for taking decisions related to emergencies.

One of the key requirements is rapid, effective communication - this should be tested in conjunction with the services and authorities involved in simulated exercises from time to time.

It may be most convenient to include the Emergency Response Procedures in the HSMS.

## 25.2 Maintenance

It is most important for personnel safety to be fully recognised in maintenance procedures and operations.

Assistance for safe (maintenance) workplace operations may be found in HSE publications at [www.hse.gov.uk](http://www.hse.gov.uk)

It is also necessary to recognise that difficulties may be imposed by the WEC device operating location. For example, there will be difficulty in approaching the WEC device in rough seas. Further there may be difficult or limited access to the device because of its necessary location to gain best advantage from available wave energy.

A Maintenance Plan should be written for the WEC devices which addresses planned and breakdown philosophies

Specific requirements, philosophy and guidance for in-service inspection, maintenance and conditional monitoring for concrete structures are described in OS-C502 Section 8. For composite structures see OS-C501 Section 12.

### 25.2.1 Procedures for Inspection, Repair and Maintenance (IRM)

Procedures for maintenance, inspection and repair should be developed at an early design stage. Consideration should be given to access to areas to be inspected and the extent, frequency and choice of inspection methods.

### 25.2.2 Reliability Centred Maintenance (RCM)

The methodology developed to optimise the preventive maintenance activities are based on the theories of Reliability Centred Maintenance (RCM). This means that the maintenance strategy is established on the basis of a systematic evaluation of failure modes and their effect for instance on safety, production loss and asset cost, or

environmental criteria. This activity connects very well with tasks carried out during the Qualification process (Section 4).

The actual risk evaluations and recommended strategies are based on the common experience of the members involved in the process. They also take into account generic information from reliability databases such as the offshore industry OREDA database. OREDA (Offshore Reliability Data Handbook) provides detailed reliability data for machinery, electric generators, mechanical equipment and control and safety equipment for application in reliability, availability, maintainability and safety (RAMS) plans.

The maintenance strategy is based on the following principles;

- time based (calendar or running hour),
- condition based,
- functional testing, and
- corrective strategies.

For wave devices, maintenance may strongly depend on access to the device and it is likely that weather window for access to the devices will not be easily available (and difficult to forecast) during certain seasons of the year. Thus, the maintenance strategy needs to consider this important issue.

The methodology is used to arrive at an optimum maintenance strategy based on a risk assessment of systems, equipment and components taking into account the probability of possible failures and all associated consequences such as risk. This process always demands participation of experienced operators. Their participation improves the quality of the RCM evaluations, and it enables the group to transform the results to practical activities in the maintenance program.

Considering the novelty aspects of the wave devices, there is a limited amount of operational experience in this sector. It will be necessary to apply amalgamation of experience from prototypes, due consideration of results from the Qualification process, in addition to experience transferred from other industries. The detailed approach in RCM analyses will change during the process in order to be tailored to the needs of the particular device.

There are several references that can be used for this approach:

- IEC 60300-3-11 (1999) Dependability management - Part 3-11: Application guide - reliability centred maintenance.
- SAE-JA1011 (1999) Evaluation criteria for reliability-centered maintenance (RCM) processes.
- SAE-JA1012 (2002) A guide to the reliability-centered maintenance (RCM) standard
- Reliability Centered Maintenance - Guidance Notes (2004) American Bureau of Shipping.

### 25.2.3 Task Risk Assessment

It is industry best practice to carry out risk assessments of all maintenance procedures. These procedures may be grouped into generic groups to streamline the risk assessment work.

A useful publication for assessing risks in the workplace is the HSE guidance document INDG163(rev1) first published 5/99, reprinted 7/03. This gives a 5 step guide to identifying and assessing the risks which may be involved in any workplace operation (including for maintenance).

Risk assessment is first addressed during the design phase; please refer to section 7 of this Guideline.

#### 25.2.4 In-service Inspection Plan

The objective of the IIP is to ensure that the wave device (structure and equipment / systems) is suitable for its intended purpose throughout its lifetime. A plan for in-service inspection should be developed as early as possible during the design stage. As the design evolves and design targets change, the in-service inspection plan should be updated. The IIP should be in-line with the safety philosophy and expected deterioration / failure of components.

Results from the fatigue assessment as well as the design considerations (Design Fatigue Factor for example) should indicate critical areas of the structure for inspection, the extent of inspection, its frequency and method to be used for inspection.

During fatigue assessment many assumptions are made due to some uncertainties on the loading, response, structural detailing, modelling, load effects, fabrication, etc. These uncertainties are in addition to the normal uncertainties associated with fatigue life calculations (see RP-C203 Section 6). The IIP should consider these aspects and should define a monitoring plan of the main parameters affecting the fatigue life.

The IIP should be modified during the in-service life to take into account the results of inspections and information obtained from the monitoring.

The IIP should also consider inspections to be performed in case of extreme or accidental loading to areas likely to be affected in this case.

The same principles described above are applicable to equipment and systems. In addition, a maintenance plan should be developed considering information and requirements from suppliers and requirements arising from the reliability of equipment and systems.

Personnel involved in the inspections and tests should be properly qualified for the tasks to be carried out. It is important that inspectors and surveyors are well familiarised with the design, operational aspects and criticality of the items to be inspected.

#### 25.2.5 Spare Parts

A spare parts philosophy should be defined taking into account the time from ordering from supplier to the availability of replacement part, criticality of the part (regarding survivability and functional requirements), maintenance requirements and costs of stock, preservation and storage of spare parts.

A list of spare parts should be produced and included in the maintenance plan.

### 25.2.6 Maintenance Records

It is necessary to keep records of all maintenance work carried out, also for the testing of reassembled equipment. These records should be readily available to the WEC device owner to aid future investigation into the effects and causes of failure.

A systematic process for recording and reporting should be implemented together with the IIP and Maintenance Plan. Logging of the in-service inspection results and control of inspections to be carried out or already carried out should be preformed. This information should be analysed and the following should be carried out:

- Update of IIP.
- Review of design assumptions and assessment of the impact on the design if deviation of assumption is found.
- Comparison between expected deterioration with found deterioration and any action to be implemented.
- Assessment of any damage found and action taken.
- Modification of design basis, design procedures and fabrication and level of inspection / surveillance / tests.
- Assessment of any modification or upgrade carried out in the structure or equipment / system.

### 25.2.7 Frequency of Inspection

The frequency for inspection will normally be governed by;

- maintenance philosophy,
- access restriction to device due to seastate limitations and seasonal variations on weather,
- energy demand,
- fatigue results,
- reliability results or mean-time between failures of components, and
- availability and cost of vessels.

The frequency should be defined considering the uncertainties associated with the parameters used. In terms of fatigue, it is normal practice to schedule inspections based on an interval between 20% and 25% of the calculated fatigue life.

The frequency should be adjusted based on the results of inspections and performance of equipment from the feedback process described in Section 25.2.6.

The sea state environmental and corrosive effects occurring at the installed location may not be fully known until after some time in operation. Hence it will be prudent to plan inspections (and maintenance operations) at conservative intervals which are not too long in the early months/years of operation

When satisfactory operation of the WEC device has been established the frequency of inspections may be able to be lengthened to reduce operating costs.

A range of computer based tools exist in the market place to assist operators plan, control optimise and execute maintenance. Their use and applicability should always be considered.

## 26 DECOMMISSIONING

Requirements for marine operations during decommissioning of wave devices can be found in OS-H102.

The device should be designed to allow for a safe and economic decommissioning. Recycling of materials and possible re-use of equipment should be considered at the design stage.

United Nations Convention on the Law of the Seas (UNCLOS) refers to removal of any installation or structures that are abandoned or disused shall be removed to ensure safety of navigation.

The IMO Convention on the Prevention of Marine Pollution by Dumping Wastes and Other Matters (London Convention) addresses the disposal of waste and material at sea and it also addresses the removal of offshore platforms while the IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone states: “Abandoned or disused offshore installations or structures on any continental shelf or in any exclusive economic zone are required to be removed, except where non-removal or partial removal is consistent with the following guidelines and standards”. This allow the decision to be made by coastal state with jurisdiction over the installation on a case-by-case basis.

Further development, for European waters, on the extent and the reasons for removal is the Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR) that requires the complete removal of any decommissioned installation at the sea. It is expected that, in Europe this will be extended to wave devices. In other parts of the world, the legislation may differ allowing, in some case, that clean structures and equipment may be sunk to form artificial reefs.

## 27 STATUTORY REGULATIONS

### 27.1 General Requirements

In the UK, depending on the location of the site, the relevant authorities may be DTI, the Crown Estate, the Maritime Coastguard Agency (MCA), local harbour authority, local council, Ministry of Defence (air and/or naval). The Health and Safety Executive will also have jurisdiction, but clarification of who is responsible for what is still ongoing. For delivery of wave devices for installation in other countries, a similar set of relevant legislation of national authorities will have to be complied with. The references provided in this guide are helpful to cover and obtain acceptance under such legislation, but must not be assumed to cover all relevant requirements.

The site may have to be vetted for environmental impact and if interfering with sites or migration routes of protected species (plants, animals, subsea features like coral accumulations or reefs). Contact with and possible review by the Joint Venture Nature Conservation Committee (JNCC) of choice of site should be checked. In any case, it is expected that an Environmental Impact Assessment (including all phases up to decommissioning) is to be carried out at an early stage of the project as part of the application process for the development of wave farm.

### 27.2 Navigation and Radar Requirements

Devices will normally be required to be provided with navigation lights having a secure power supply in line with normal coastal regulations for moored devices. Approval by the relevant authority is likely to be required.

Marking of the outer perimeters of a field of devices may be required by authorities.

Adequate radar reflection should be provided, addition of special radar reflecting device should be considered for ease of detection by ships and pleasure craft in line with General Lighthouse Authority (GLA) requirements. Clarification may be required by the Ministry of Defence for radar interference and military strategic consequences.

### 27.3 Identification Requirements

Clear marking of the device(s) to show the identity of the installation to shipping including recreational traffic will normally be required by the relevant authorities (GLA, MCA). Consideration should be given to obtain a restriction for commercial and recreational traffic to enter the general area of the installation by marking the area on Admiralty charts.

### 27.4 Environment and Safety Requirements

If anti-fouling paint is used, this needs to satisfy environmental requirements and restrictions. A guide for this may be the requirements for shipping as established under the International Maritime Organisation (IMO) conventions and codes, usually implemented in statutory regulations by maritime member states (International Convention on the Control of Harmful Anti-Fouling Systems on Ships (IAFS Convention)). E.g. lead based or tin (TBT) based compounds are not permitted. Any antifouling agents need to be considered. Countries such as the UK, Ireland, The Netherlands, USA and

Australia have a very restrictive legislation regarding sale and use of any TBT based paint.

An MCA guide for offshore wind turbines has been issued, and a Proposed UK Offshore Renewable Energy Installations (OREI) - Guidance on Navigational Safety Issues has been issued for consultation. Devices need to be considered for the event of recreational or commercial craft in trouble drifting in among the devices and how the device works as emergency occupation or shelter for stranded persons.

Proximity to busy shipping lanes should be considered in terms of setting an adequate target safety level. Devices breaking loose and drifting into shipping lanes can be a significant risk to shipping.

## 27.5 Safety Case or Risk Assessment Requirements

It is assumed that authorities will handle WEC devices in a similar manner to offshore wind installations, see Section 30.4 above and the MCA document referenced there. The MCA document requires a risk assessment to be carried out.

The authority issue is subject to a review by DTI and will be subject to consultation in the near future.

## 27.6 European Directives

Wave energy devices put on the market within the EEC (the wider economic area) will have to satisfy the requirements of relevant EC directives. The following directives need to be considered (the list may not be exhaustive):

- Pressure Equipment Directive (PED)
- Electromagnetic Compatibility (EMC)
- Low Voltage Directive (LVD)
- Machinery Directive (MD)
- Marine Equipment Directive (MED)
- ATEX Directive

The directives may apply to the device overall if put on the market in EU/EEA countries, unless exemptions should be granted or these devices are classed as marine vessels. Should the latter be the case, the legislation applying to ships and marine devices would need to be observed. Reference to Directives is to the original text issued under the EC banner. The Directives are implemented in the Statutory Regulations of the member countries, and the Directive reference changes to the legislative reference for the country in question.

A short outline of the scope of the Directives is given below.

### Pressure Equipment Directive

Pressure Equipment Directive applies in general to pressure equipment and assemblies with a maximum allowable pressure of more than 0.5 bar. Thus the whole hydraulic and pneumatic power system in wave energy devices would need to consider PED requirements.

### Hydraulic Cylinder and Accumulator

These usually have very high allowable pressure (in the range of 300 bar) and unless they are very small, it will have to meet the requirements of PED.

### Pneumatic Cylinder

If the allowable pressure and the volume meet the Simple Pressure Vessel requirement, then this could be exempted from PED. However, the system pressure is likely to be quite high, and it is almost certain to be included under PED.

### Piping Systems and Connecting Devices

In accordance with PED Guideline 1/19, pumps, control valves and actuators are exempted from PED.

### Electromagnetic Compatibility Requirements

These requirements cover electromagnetic interference of equipment both for emissions and for robustness against effects of exposure to electromagnetic noise levels.

EMC requirements for immunity, methods of testing, etc, are set out in IEC 61000. Specific EMC requirements for ships are given in IEC 60533 and IEC 60945, these are referenced below.

It is essential that the various systems controlling and monitoring the equipment within the wave energy device are immune to:

- Normal communications signals generated within the device by other systems.
- Abnormal electromagnetic emissions generated by faults in electrical and electronic equipment. This also includes those emissions generated by arcing and sparking, incorrect earthing and bonding, etc.

The European EMC Directive (83/189/EEC) requires that an electromagnetic compatibility assessment is carried out in order to determine the compliance of an apparatus with the protection requirements set out in the directive. The compliance with the directive is a UK statutory requirement as laid down in SI 1992 No. 2372 (see HM Stationery Office references below).

With reference to Flowchart 4 in Annex 8 of the Guide to Implementation of EU Directives, conformity assessment by the production of a Technical Construction File (TCF) is likely to be the best method, especially as a large proportion of the equipment is commercial off-the-shelf (COTS). The COTS equipment should have already been evaluated and therefore only evidence of conformity need be provided for this. The majority of the material in the TCF is likely to be related to evidence of the immunity of the bespoke electronic cards.

The electromagnetic compatibility assessment must take into account all normal intended operating conditions where the apparatus can take different configurations. The assessment must confirm that the apparatus meets the protection requirements in all possible configurations.

If using certain Marine radio equipment as required by the SOLAS regulations will be covered by the Marine Equipment Directive 96/98/EC.

### Low Voltage Directive

The low voltage directive covers electrical equipment and devices less than 1,000 Volts and includes most consumer and industrial electrical and electronic equipment, but not safety equipment on ships covered by the SOLAS Regulations. The topics covered include voltage and frequency limits and safe design, all of which are detailed in the associated harmonised standards listed in the following:

- Council Directive of 19 February 1973 on the harmonisation of the laws of Member States relating to Electrical Equipment designed for use within certain voltage limits OJ L 77/29 of 1973-03-26.
- Low Voltage Directive - LVD -Modification: Directive 93/68/EEC [CE Marking]

### Machinery Directive

This covers powered devices, with fairly extensive requirements to assessment of safety aspects, logic of devices, protection of personnel. A risk assessment is required as a basis for showing that instruction manuals cover all relevant safety issues.

The Machinery Directive applies to an assembly of linked parts or components, at least one of which moves. Since wave energy devices need to move, this directive is applicable.

For Hydraulic cylinders and accumulators the accumulator is covered by PED and is regarded as a pressure vessel - hence it is exempted from MD. Since the hydraulic cylinder is likely to be of high pressure and reasonable volume, it would be regarded as a pressure vessel by the definition of PED. However, the hydraulic cylinder and its piston act like a pump in reality. Therefore it is also reasonable to argue that MD applies. It may be considered prudent to ensure that the hydraulic cylinder should comply with both PED and MD requirements.

Piping systems and connecting devices such as pumps, control valves and actuators should be included in MD.

The provisions of the MD are applicable to the hydraulic motor.

### Control System

Since the control system of wave devices basic regulate the movement, relevant aspects of the control system need to be assessed against the requirements of MD.

### Protective Equipment

The MED applies to a range of personal protective equipment and devices for escape and rescue from maritime vessels and installations. Depending on the level of provision for the wave device, MED is applicable. The provisions are likely to include;

- lifebuoys,
- lifejackets,
- flares and rockets,
- embarkation ladders,
- portable fire extinguisher,
- penetrations,
- GPS systems,
- radio systems,

- electric Safety Lamp and lighting, and
- navigation lights.

#### ATEX Directive

This is not applicable to floating installations. [Note that in any case this Directive would only be applicable if flammable or explosive materials are present - for example if hydrogen is used in the energy conversion process].

## 27.7 UK Legislation

Other potentially relevant UK Legislation consist of the following:

#### PUWER

The Provision and Use of Work Equipment Regulations 1998 will apply when work is being undertaken in or on the device. PUWER can be regarded at as a “catch-all” for devices not covered by a specific EC Directive.

#### LOLER

Lifting Operations and Lifting Equipment Regulations 1998 will apply to any lifting operation, including device recovery as well as to installed lifting devices.

#### Confined Spaces Regulations

The interior of the device is a series of watertight compartments and must be treated in the same way as any confined space after it has been closed up for a an appreciable time, by for example;

- ensuring that the space has been well ventilated before entering, and
- always carrying a portable multi-gas tester when entering.

#### HSAWA

The Health and Safety at Work Act places a duty on “employers” apart from any liability under common law towards trespassers, to “conduct business in such a way as not to expose people to risks to health and safety”. This implies taking certain precautions to deter people from unlawfully entering the workplace. This would include general safety notices, permits to work systems, etc. It would also be advisable to warn people of the dangers of approaching the device (submerged moving parts or cables and mooring lines) or boarding it, or becoming trapped between sections of the device when wave motion is significant.

## 27.8 UK Electricity at Work Regulations

These regulations should be complied with as a whole. Specific comments on some of the regulations are given below.

#### Regulation 2

The scope of these regulations has been increased to include all offshore installations.

#### Regulation 3

Responsibility to ensure the safety of others would apply both when deployed unmanned due to possible hazard to other seafarers, etc, and when recovered for maintenance

#### Regulation 4

Regulation 4 (1) would apply when the device is deployed. Regulations 4 (2, 3, 4) would apply to recovery and maintenance operations.

### Regulation 5

Equipment should be adequately rated for both normal and fault conditions. As the device is unmanned in normal operation, a fault in this situation is unlikely to give rise to danger. However, unauthorised access is a possibility, and in a “farm” configuration, precautions must be taken to avoid danger when servicing one device with the farm operational (due to risk of unexpected live conductors).

### Regulation 6

There are obvious applications here, but the risk of danger would vary depending on the presence and location of personnel and the possibility of unauthorised access. Seawater ingress is likely to trip the electrical equipment, but there is still a risk that the device might remain live. The level of ingress and mechanical protection would need to be based on the worst operating conditions.

### Regulation 7

Commercial-of-the-shelf type approved electrical equipment should be used where possible. Where uninsulated conductors cannot be avoided, access to live conductors shall be prevented by door interlocks, shuttering mechanisms, etc. Creep and clearance distances must be allowed for particularly in medium voltage equipment.

### Regulation 8

Use of a combination of the following is recommended;

- a common reference point,
- equipotential bonding,
- safe voltages, and
- current limitations.

Earth-free or isolated systems require frequent maintenance in order to remove earth faults and avoid shock hazards to personnel. As the intention with these devices is to achieve long intervals between maintenance, unearthed systems are not recommended in this situation.

### Regulation 9

Continuity may be preserved by use of earth bars with bolted links or knife switches.

TN-C systems should be designed to prevent people coming into simultaneous contact with protective conductors and earth.

TN-S systems should be designed to prevent voltages appearing due to blown fuses, e.g., by use of double pole or TP&N switches.

### Regulation 10

This will apply generally to the electrical equipment in the device, but also particularly to the cable joints between the sections and to the medium voltage connections for any umbilical and shore supply cable.

### Regulation 11

This is the requirement for fuses, protection relays and other such overcurrent devices.

### Regulation 12

This is a design requirement as isolation facilities would need to be provided in design. However, personnel should only be exposed to danger on entry to the device. This certainly applies to the “recovered” situation, and would also apply to the deployed situation when operating in a farm configuration where external isolation devices would be required.

### Regulation 30

For the operational (unmanned) condition it may be possible to obtain exemption provided safe recovery and access can be assured by an approved procedure.

## 28 REFERENCES

The following is a list of the main references presented in the Guideline text. DNV references applicable to this Guideline and other main international standards are presented here.

### 28.1 Other international standards and papers referred to within the DNV Standards and Recommended Practices (selected list)

DNV Rules	
Rules for Planning and Execution of Marine Operations	
DNV Rules for Classification of Ships	
Offshore Standards	
OS-A101: Safety Principles and Arrangement	<p>Other references:</p> <p>DNV Rules for Classification of Ships</p> <p>Informative references: The codes and standards below are referenced in the text of this offshore standard, and may be used as a source of supplementary information.</p> <p>API RP 14C Analysis, Design, Installation and Testing of Basic Surface Safety Systems for Offshore Production Platforms</p> <p>API RP 14J Design and Hazard Analysis for Offshore Production Facilities</p> <p>API RP 521 Guide for Pressure-Relieving and Depressurising Systems</p> <p>COLREG Convention on the International Regulations for Preventing of Collisions at Sea, 1972</p> <p>IEC 61892-7 Mobile and fixed offshore units - Electrical installations - Part 7: Hazardous area</p> <p>IMO 1989 MODU Code - Code for the Construction and Equipment of Mobile Offshore Drilling Units, 1989, as amended</p> <p>IMO Res. A.830(19) Code on Alarms and Indicators, 1995</p> <p>ISO 10418 Petroleum and natural gas industries - Offshore production platforms - Analysis, design, installation and testing of basic surface safety systems</p> <p>SOLAS International Convention for the Safety of Life at Sea, 1974, as amended</p>

OS-B101: Metallic Materials	<p><b>Normative References</b></p> <p><b>General</b> The standards listed below include provisions which, through reference in this text, constitute provisions of this offshore standard. Latest issue of the standards shall be used unless otherwise agreed.</p> <p>Other recognised standards may be used provided it can be demonstrated that these meet or exceed the requirements of the standards in the table below.</p> <p>Any deviations, exceptions and modifications to the design codes and standards shall be documented and agreed between the supplier, purchaser and verifier, as applicable.</p> <p>ASTM A 275 Standard Test Method for Magnetic Particle Examination of Steel Forgings</p> <p>ASTM A 388 Standard Practice for Ultrasonic Examination of Heavy Steel Forgings</p> <p>ASTM E 165 Standard Test Method for Liquid Penetrant Examination</p> <p>ASTM E 709 Standard Guide for Magnetic Particle Examination</p> <p>ISO 3452 Non-destructive testing - Penetrant inspection/ testing</p> <p>ISO 9712 Non-destructive testing - Qualification and certification of personnel</p> <p>EN 10204 Metallic products - Types of inspection documents</p> <p>EN 473 Welding - Grooves for aluminium</p> <p>EN 10228-1/2/3/4 Non-destructive testing of steel forgings</p>
OS-C101: Design of Offshore Steel Structures, General (LRFD method)	<p><b>Other references</b></p> <p>AISC LRFD Manual of Steel Construction</p> <p>API RP 2A LRFD Planning, Designing, and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design</p> <p>BS 7910 Guide on methods for assessing the acceptability of flaws in fusion welded structures</p> <p>Eurocode 3 Design of Steel Structures</p> <p>ISO 13819-1 Petroleum and natural gas industries - Offshore structures - Part 1: General requirements</p> <p>NORSOK N-003 Actions and Action Effects</p> <p>NORSOK N-004 Design of Steel Structures</p>
OS-C102: Structural Design of Offshore Ships	
OS-C301: Stability and Watertight Integrity	<p><b>Informative references</b></p> <p>ISO 1751 Shipbuilding and marine structures - Ships' side Scuttles</p> <p>SOLAS 1974 The International Convention for the Safety of Life at Sea, 1974, as amended</p>

OS-C401: Fabrication and Testing of Offshore Structures	<p>Other references</p> <p>ANSI/AWS D1.1 Structural Welding Code - Steel</p> <p>ASME Section IX, Welding and Brazing Qualifications Non-Interfiled (Boiler and Pressure Vessel Codes)</p> <p>ASTM G48 Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution</p> <p>ASTM E562 Standard Test Method for Determining Volume Fraction by Systematic Manual Point Count</p> <p>BS 7448-2 Fracture mechanics toughness tests. Method for determination of K<sub>Ic</sub>, critical CTOD and critical J values of welds in metallic materials</p> <p>EN 287 Approval testing of welders - Fusion welding</p> <p>EN 1418 Welding personnel - Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanized and automatic welding of metallic materials</p> <p>IACS Shipbuilding and Repair Quality Standard, Part A - Shipbuilding and repair Quality Standard for New Construction and Part B - Repair Quality Standard for Existing Ships</p> <p>ISO 148 Steel - Charpy impact test (V-notch)</p> <p>ISO 898 Mechanical properties of fasteners made of carbon and alloy steel</p> <p>ISO 6507-1 Metallic materials - Vickers hardness test - Part 1: Test method</p> <p>ISO 8501-1 Preparation of steel substrates before application of paints and related products - Visual assessment of surface cleanliness - Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings</p> <p>ISO 9001:2000 Quality management systems - Requirements</p> <p>ISO 9606 Approval testing of welders - Fusion welding</p> <p>ISO 10042 Arc-welded joints in aluminium and its weldable alloys - Guidance on quality levels for imperfections</p>
OS-C501: Composite Components	<p>Other references</p> <p>API RP 2RD <i>Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)</i></p> <p>ISO/FDIS 2394 <i>General Principles on Reliability for Structures</i></p>
OS-C502: Offshore Concrete Structures	<p>Other references</p> <p>ISO 13819-1 Petroleum and natural gas industries - Offshore structures - Part 1: General requirements</p> <p>NORSOK N-003 Actions and Action Effects</p> <p>NORSOK N-004 Design of Steel Structures</p>
OS-D101: Marine and Machinery Systems and Equipment	<p>Other Normative references</p> <p>ICLL International Convention on Load Lines, 1966</p> <p>IMO MODU Code 1989 Code for the Construction and Equipment of Mobile</p>

	<p>Offshore Drilling Units, 1989</p> <p>ISO 281 Rolling bearings - Dynamic load ratings and rating life</p> <p>ISO 898 Mechanical Properties of Fasteners</p> <p>SOLAS 1974 SOLAS International Convention for the Safety of Life at Sea</p> <p>EN 288-3 Specification and Approval of Welding Procedures for Metallic Materials - Part 3: Welding Procedure Tests for the Arc Welding of Steels</p> <p>ISO 5817 Arc-welded joints in steel - Guidance on quality levels for imperfections</p> <p>Informative references Informative references are not considered mandatory in the application of the offshore standard, but may be applied or used for background information.</p> <p>ANSI/ASME B31.3 Chemical Plant and Petroleum Refinery Piping</p> <p>DNV-OS-E201 Hydrocarbon Production Plant Rules for Certification of Lifting Appliances</p> <p>EN 12239 Fire Protection Equipment - Self Contained Smoke Alarms</p> <p>ENV 12097 Ventilation for buildings - Ductwork - Requirements for ductwork components to facilitate maintenance of ductwork systems</p> <p>IMO Resolution A.753(18) Guidelines for the Application of Plastic Pipes on Ships</p> <p>ISO 75 Plastics - Determination of temperature of deflection under load</p> <p>ISO 1127 Stainless steel tubes - Dimensions, tolerances and conventional masses per unit length</p> <p>ISO 1461 Hot dip galvanized coatings on fabricated iron and steel articles - Specifications and test methods</p> <p>UKOOA Specification and Recommended Practice for use of GRP piping offshore</p> <p>Recognised codes for unfired pressure vessels ASME section VIII Boilers and Pressure Vessels Code</p> <p>BS 5500 Unfired Fusion Welded Pressure Vessels</p> <p>Rules for Classification of Ships Pt.4 Ch.7 Boilers, pressure vessels, thermal-oil installations and incinerators</p> <p>TEMA R Heat Exchanger Tubing</p> <p>Recognised codes for boilers API Std 675 Positive Displacement Pumps - Controlled Volume</p> <p>API Std 676 Positive Displacement Pumps - Rotary</p> <p>Rules for Classification of Ships Pt.4 Ch.1 Machinery System, General</p> <p>BS 5500 Unfired Fusion Welded Pressure Vessels</p> <p>Rules for Classification of Ships Pt.4 Ch.7 Boilers, pressure vessels, thermal-oil installations and incinerators</p>
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	<p>TBK-1-2 General Rules for Pressure Vessels</p> <p>Recognised codes for atmospheric vessels API Spec 12 F Shop Welded Tanks for Storage of Production Liquids.</p> <p>API Std 650 Welded Steel Tanks for Oil Storage.</p> <p>BS 2654 Vertical steel welded storage tanks</p> <p>DIN 4119 Tank installation of metallic materials</p> <p>Rules for Classification of Ships Pt.4 Ch.7 Boilers, pressure vessels, thermal-oil installations and incinerators</p> <p>Recognised codes for pumps API Std 674 Positive Displacement Pumps - Reciprocating</p> <p>API Std 675 Positive Displacement Pumps - Controlled Volume</p> <p>API Std 676 Positive Displacement Pumps - Rotary</p> <p>Rules for Classification of Ships Pt.4 Ch.1 Machinery System, General</p> <p>Recognised codes for compressors API Std 619 Rotary Type Positive Displacement Compressors for Petroleum, Chemical, and Gas Industry Services</p> <p>API Std 672 Packaged, Integrally Geared Centrifugal Air Compressors for Petroleum, Chemical, and Gas Industry Services</p> <p>Rules for Classification of Ships Pt.4 Ch.5 Rotating Machinery, Driven Units</p> <p>Recognised codes for gears AGMA 218/219 Gear Rating</p> <p>DNV Classification Note 41.2 Calculation of gear rating for marine transmissions</p> <p>Rules for Classification of Ships Pt.4 Ch.4 Rotating Machinery, Power Transmissions</p> <p>ISO 6336 Pt. 1-5 Gears</p> <p>Recognised codes for couplings Rules for Classification of Ships Pt.4 Ch.4 Rotating Machinery, Power Transmission</p> <p>API Std 671 Special Purpose Couplings for Petroleum, Chemical, and Gas Industry Services.</p> <p>Recognised codes for lubrication and sealing API Std 614 Lubrication, Shaft-Sealing and Control-Oil Systems and Auxiliaries for Petroleum, Chemical, and Gas Industry Services</p> <p>Piping ANSI/ASME B31.3 Chemical Plant and Petroleum Refinery Piping</p> <p>API RP 14E Design and Installation of Offshore Production Platform Piping Systems</p> <p>API RP 17B Flexible Pipe</p> <p>ISO 898-1 Mechanical properties of fasteners made of carbon steel and alloy</p>
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	steel - Part 1: Bolts, screws and studs.
OS-D201: Electrical Systems and Equipment	<p>Other Normative references</p> <p>IEC 60092 Electrical installations in ships</p> <p>IEC 61892 Mobile and fixed offshore units - Electrical installations</p> <p>IMO MODU Code 1989 International Maritime Organisation - Offshore; Code for Construction and Equipment of Mobile Offshore Drilling Units</p> <p>SOLAS 1974 International Convention for the Safety of Life at Sea</p>
OS-D202: Instrumentation and Telecommunication Systems	<p>Normative references</p> <p>EN 50082-2 Electromagnetic Compatibility - Generic emission standard</p> <p>IEC 60092-504 Electrical installations in ships - Part 504: Special features - Control and instrumentation</p> <p>IEC 60529 Degrees of protection provided by enclosures (IP Code)</p> <p>IEC 60945 Maritime navigation and radiocommunication equipment and systems - General requirements - Methods of testing and required test results</p> <p>IEC 61000-4-2 Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 2: Electrostatic discharge immunity test. Basic EMC Publication</p> <p>IEC 61000-4-3 Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 3: Radiated, radio-frequency, electromagnetic field immunity test</p> <p>IEC 61000-4-4 Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 4: Electrical fast transient/burst immunity test. Basic EMC Publication</p> <p>IEC 61000-4-5 Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 5: Surge immunity test</p> <p>IEC 61000-4-6 Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 6: Immunity to conducted disturbances, induced by radio-frequency fields</p> <p>IEC 61000-4-11 Electromagnetic compatibility (EMC) - Part 4: Testing and measuring techniques - Section 11: Voltage dips, short interruptions and voltage variations immunity tests</p> <p>IEC 61892 Mobile and fixed offshore units - Electrical installations</p> <p>Classification Note 45.1 Electromagnetic Compatibility</p> <p>Other Informative references</p> <p>Certification Note No. 1.2 Type Approval</p> <p>Certification Note No. 2.4 Environmental Test Specification for Instrumentation and Automation Equipment</p> <p>IEC 60533 Electrical and electronic installations in ships - Electromagnetic compatibility</p> <p>1989 MODU Code (IMO) Code for the Construction and Equipment of Mobile Offshore Drilling Units, 1989, as amended.</p>

<p>OS-D301: Fire Protection</p>	<p>The requirements of this standard are considered to meet the regulations of the International Maritime Organisation Code for Construction and Equipment of Mobile Offshore Drilling Units, 1989 (MODU Code) with regard to fire protection, detection and fire fighting systems and equipment.</p> <p>DNV Normative references</p> <p>EN 54-5 Components of Automatic Fire Detection Systems Part 5 Heat Sensitive Detectors - Point Detectors Containing a Static Element</p> <p>EN 54-7 Components of Automatic Fire Detection Systems - Part 7: Point-Type Smoke Detectors; Detectors Using Scattered Light, Transmitted Light or Ionization</p> <p>NFPA Codes National Fire Protection Association</p> <p>1989 MODU Code - Code for the Construction and Equipment of Mobile Offshore Drilling Units, 1989</p> <p>SOLAS International Convention for the Safety of Life at Sea, 1974, as amended (Including the 1996 Amendments of Ch. II-2, effective 1 July 1998)</p> <p>Fire Technical Requirements</p> <p>BS 6755-2 Testing of valves. Specification for fire type-testing requirements</p> <p>IEC 60331 Tests for electric cables under fire conditions - Circuit integrity Fire resisting cables</p> <p>IEC 60332-3 Tests on electric cables under fire conditions - Part 3 Flame retardant cables</p> <p>IMO res. A.653(16) Recommendation on Improved Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials.</p> <p>IMO res. A.754(18) Recommendation on fire resistance tests for "A", "B" and "F" class divisions (FTP Code Annex 1 Part 3)</p>
<p>OS-E301: Position Mooring</p>	<p>Other references</p> <p>ASTM A 487M Specification for Steel Castings Suitable for Pressure Service</p> <p>API RP 2A-LRFD Planning, Designing and Construction of Fixed Offshore Platforms - Load and Resistance Factor Design</p> <p>API RP 2A-WSD Planning, Designing and Construction of Fixed Offshore Platforms - Working Stress Design</p> <p>API Spec 2F Mooring Chain</p> <p>API RP 2SK Design and Analysis of Stationkeeping Systems for Floating Structures</p> <p>API RP 2SM Recommended Practice for Design, Analysis, and Testing of Synthetic Fiber Ropes in Offshore Applications</p> <p>BS 3226 Specification for thimbles for natural fibre ropes, 1960</p> <p>BS 7035 Code of practice for socketing of stranded steel wire ropes, 1989.</p> <p>CI 1505-98 Test Method for Yarn-on-Yarn Abrasion (draft)</p> <p>ISO 1704 Shipbuilding - Stud link anchor chains</p> <p>ISO 2232 Round drawn wire for general purpose non-alloy steel wire ropes</p>

	<p>and for large diameter steel wire ropes - Specifications</p> <p>ISO 3178 Steel wire ropes for general purposes - Term of Acceptance</p> <p>ISO/TR 13637 Petroleum and natural gas industries - Mooring of mobile offshore drilling units (MODUS) - Design and analysis</p> <p>ISO 13819-1: Offshore structures Part 1: General requirements</p> <p>NORSOK M-001 Material selection</p> <p>NORSOK N-003 Actions and Action Effects</p> <p>OCIMF Procedures for Quality Control and Inspection during the Production of Hawsers, 1987</p> <p>References</p> <p>Winterstein, S., Ude, T.C., Cornell, C.A., Bjerager, P. Haver, S.; (1994) <i>Environmental Parameters for Extreme Response: Inverse FORM with Omission Sensitivity</i>, Structural and Reliability, pp. 551-557, Balkema, Rotterdam.</p> <p>A M.K. Ochi, A Y.S. Shin, T.: Wind Turbulent Spectra for Design Consideration of Offshore Structures. 20<sup>th</sup> Offshore Technology Conference, OTC 5736, page 461-467, Houston 1988.</p> <p>Torsethaugen, K.: Model for a Double-peaked Spectrum, SINTEF, STF22A96204, SINTEF, Trondheim.</p> <p>Pinkster, J.A.: Low-frequency phenomena associated with vessels moored at sea, Soc. Petroleum Engineers Journal, Dec., pp. 487-94. (1975).</p> <p>Stansberg, C.T., (1992), <i>A Simple Method for Estimation of Extreme Values of Non-Gaussian Slow-Drift Responses</i>, Proc. 1st Int. Offshore and Polar Engineering Conf., Edinburgh.</p> <p>Stansberg, C.T., (1992), <i>Basic Statistical Uncertainties in Predicting Extreme Second Order Slow Drift Motion</i>, Proc. 2nd Int. Offshore and Polar Engineering Conf., San Francisco.</p> <p>Lie, H., Sødahl, N., (1993), <i>Simplified Dynamic Model for Estimation of Extreme Anchorline Tension</i>, Offshore Australia, Melbourne.</p> <p>Banfield, B., Versavel, T., Snell, R.O., Ahilan, R.V. (2000), <i>Fatigue Curves for Polyester Moorings - A State-of-the Art Review</i> OCT 12175.</p>
OS-J101: Design of Offshore Wind Turbine Structures	<p>Other references</p> <p>AISC LRFD Manual of Steel Construction</p> <p>API RP 2A LRFD Planning, Designing, and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design</p> <p>BS 7910 Guide on methods for assessing the acceptability of flaws in fusion welded structures</p> <p>EN10025 Hot rolled products of non-alloy structural steels</p> <p>EN10113 Hot rolled products in weldable fine grain structural steels</p> <p>EN 10204 Metallic structures - types of inspection documents</p> <p>EN10225 Weldable structural steels for fixed offshore structures - technical delivery conditions</p>

	<p>prEN50308 Wind Turbines - Labour Safety</p> <p>Eurocode 3 Design of Steel Structures</p> <p>IEC61400-1 Wind Turbine Generator Systems - Part 1: Safety Requirements</p> <p>ISO 12944 C5M Paints and varnishes - Corrosion protection of steel structures by protective paint systems; marine, offshore, estuaries, coastal areas with high salinity</p> <p>ISO 14688 Geotechnical investigations and testing - identification and classification of soil - Part 1: Identification and description.</p> <p>ISO/IEC 17020 General criteria for the operation of various types of bodies performing inspections</p> <p>ISO/IEC 17025 General requirements for the competence of calibration and testing laboratories</p> <p>ISO 19900:2002 Petroleum and natural gas industries - Offshore structures - General requirements for offshore structures</p> <p>ISO CD 19001-2 Seismic design procedures and criteria</p> <p>ISO 19902 Petroleum and Natural Gas Industries - Fixed Steel Offshore Structures</p> <p>NORSOK N-003 Actions and Action Effects</p> <p>NORSOK N-004 Design of Steel Structures</p> <p>NORSOK G-CR-001 Marine Soil Investigations</p>
OS-F201: Dynamic Risers	
<b>Recommended Practices</b>	
RP-A201: Standard Documentation Types	<p>Other References</p> <p>API RP14C American Petroleum Institute: Recommended Practise for Analysis, Design, Installation, and Testing of Basic Surface Safety Systems for Offshore Production Platforms</p> <p>IEC 60298 International Electrotechnical Commission: A.C. metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV</p> <p>ILLC 1966 International Maritime Organisation: International Convention on Load Lines, 1966</p> <p>IMO Resolution A.760(18) International Maritime Organisation: Symbols for Use in accordance with Regulation III/9.2.3 of the 1974 SOLAS Convention, as amended</p> <p>ISO 8501-1 International Standardisation Organisation: Preparation of Steel Substrates before Application of Paint and Related Products - Visual Assessment of Surface Cleanliness</p> <p>MODU Code 1989 International Maritime Organisation: Code for the Construction and Equipment of Mobile Offshore Units, 1989</p>

RP-A202: Documentation of Offshore Projects	n.a.
RP-A203: Qualification Procedures for New Technology	<p>Reference Standards IEC 60300-1 Dependability management.</p> <p>BS 5760 Reliability of systems, equipment and components Part. 5 Guide to failure modes, effect and criticality analysis (FMEA and FMECA) Part 8 Guide to assessment of reliability of systems containing software</p> <p>ISO Guide to the Expression of Uncertainty in Measurements (1995).</p> <p>IEC 61508 Functional safety of electrical/electronic/ programmable electronic safety related systems, part 1-7 (International Electrotechnical Commission)</p> <p>ISO/IEC 9126 Information technology - Software product evaluation - Quality characteristics and guidelines for their use.</p> <p>Z-016 NORSOK STANDARD, Regularity Management &amp; Reliability Technology</p> <p>ISO 14224 Petroleum and gas industries - Collection and exchange of reliability and maintenance data for equipment.</p> <p>BS 5760, Part 5, Guide to failure modes, effects and criticality analysis</p> <p>IEC-60300-9, Part 3: Application guide - Section 9: Risk analysis of technological systems.</p> <p>OREDA - Offshore Reliability Data</p> <p>PDS Handbook: 1999, Reliability Data for Control and Safety System Software.</p> <p>HRD4, BRITISH TELECOMMUNICATIONS PLC. Handbook of reliability, Ascot: London Information (Rowse Muir).</p>
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RP-C203: Fatigue Strength Analysis of Offshore Steel Structures	<p>References</p> <p>Classification Note No 30.7 Fatigue Assessment of Ship Structures. Det Norske Veritas 1998.</p> <p>Efthymiou, M.: Development of SCF Formulae and Generalised Influence Functions for use in Fatigue Analysis. Recent Developments in Tubular Joint Technology, OTJ.88, October 1988, London.</p> <p>Smedley, S. and Fischer, P.: Stress Concentration Factors for Ring-Stiffened Tubular Joints. : Proceedings of the First International Offshore and Polar Engineering Conference, Edinburgh, August 1991. pp. 239-250. Publ by Int Soc of Offshore and Polar Engineers (ISOPE), P.O.Box 1107,Golden, CO, USA.</p> <p>Lotsberg, I., Cramer, E., Holtsmark, G., Løseth, R., Olaisen, K. and Valsgård, S.: Fatigue Assessment of Floating Production Vessels. BOSS.97, July 1997.</p> <p>Eurocode : Design of steel structures. Part 1-1: General rules and rules for buildings. February 1993.</p> <p>Guidance on Design, Construction and Certification. HSE. February 1995.</p> <p>BS7910:1999. Guidance on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures. BSI. Draft 1999.</p> <p>Gurney, T. R.: The Basis for the Revised Fatigue Design Rules in the Department of Energy Offshore Guidance Notes. Paper No 55.</p> <p>Berge, S.: Effect of Plate Thickness in Fatigue Design of Welded Structures. OTC Paper no 4829. Houston, May 1984.</p> <p>Haagensen, P. J., Drågen, A., Slind, T. and Ørjasæter, O.: Prediction of the Improvement in Fatigue Life of welded Joints Due to Grinding, Tig Dressing, Weld Shape Control and Shot Peening. Steel in Marine Structures, edited by C. Noorhook and J. deBack Elsevier Science Publishers B.V., Amsterdam, 1987, pp. 689-698.</p> <p>Lotsberg, I., Fines, S. and Foss, G.: .Reliability of Calculated Fatigue Lives of Offshore Structures., Fatigue 84, 2nd Int. Conf. on Fatigue and Fatigue Thresholds, 3-7 September 1984. Birmingham.</p> <p>Haagensen, P. J.,Slind, T. and Ørjasæter, O.: Scale Effects in Fatigue Design Data for Welded and Unwelded Components. Proc. Ninth Int. Conf. On Offshore Mechanics and Arctic Engineering. Houston, February 1990.</p> <p>Berge, S., Eide, O., Astrup, O. C., Palm, S., Wästberg, S., Gunleiksrud, Å. and Lian, B.:Effect of Plate Thickness in Fatigue of Welded Joints in Air ans in Sea Water. Steel in Marine Structures, edited by C. Noorhook and J. deBack Elsevier Science Publishers B.V., Amsterdam, 1987, pp. 799-810.</p> <p>Razmjoo, G. R.: Design Guidance on Fatigue of Welded Stainless Steel Joints. OMAE 1995.</p>

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<p>CN-30.6: Structural Reliability of Marine Structures</p>	

<p>CN-30.7: Fatigue Assessment of Ship Structures</p>	<p>References</p> <p>Det Norske Veritas, Rules for Classification of Ships, Part 3, Chapter 1, <i>Hull Structural Design, Ships with Length 100 Meters and above</i>, Høvik, January 1993</p> <p>Hovem, L., Loads and Load Combinations for Fatigue Calculations - Background for the Wave Load Section for the DNVC Classification Note: Fatigue Assessment of Ships, DNVC Report No. 93-0314, Høvik, 1993</p> <p>Cramer, E.H., Løseth, R. and Bitner-Gregersen, E.,. <i>Fatigue in Side Shell Longitudinals due to External Wave Pressure</i>, Proceedings OMAE conference, Glasgow, June 1993</p> <p>British Maritime Technology, BMT, (Primary Contributors Hogben, H., Da Cunha, L.F. and Olliver, H.N), <i>Global Wave Statistics</i>, Unwin Brothers Limited, London, 1986</p> <p>Recommendations for the Fatigue Design of Steel Structures, ECCS - Technical Committee 6 - Fatigue, First Edition, 1985</p> <p>Maddox, S.J, <i>Fitness for purpose Assessment of Misalignment in Transverse Butt Welds Subject to Fatigue Loading</i>, Welding Institute Report 279, 1985</p> <p>Almar - Næss, A., Editor, <i>Fatigue Handbook</i>, Tapir, Trondheim 1985</p> <p>Det Norske Veritas, Classification Note no. 30.6, <i>Structural Reliability Analysis of Marine Structures</i>, Høvik, July 1991</p> <p>Gran, S, <i>A Course in Ocean Engineering</i>, Developments in Marine Technology, Vol. 8, Elsevier Science Publishers B.V., 1992</p> <p>Lotsberg, I. and Unnland, T. : Fatigue Assessment of Floating Production Vessels. Effects of Mean Stress. Stress at Cut-outs. DNV Report No 97-3403. November 1997.</p>
<p>CN-33.1: Corrosion Prevention of Tanks and Holds</p>	<p>References</p> <p>International Maritime Organization, (IMO). Resolution A.798(19), Guidelines for the Selection, Application and Maintenance of Corrosion Prevention Systems of Dedicated Seawater Ballast Tanks, adopted 1995.</p> <p>SOLAS June 1996 Amendments, Regulation II-1/3-2, Corrosion Prevention of Seawater Ballast Tanks, adopted by resolution MSC.47(66).</p> <p>International Association of Classification Societies (IACS). Guidelines for Acceptance, Application and Survey of Semi-hard Coatings in Ballast Tanks. IACS Recommendation No. 54, September 1998.</p> <p>Det Norske Veritas. Type Approval Programme for Protective Coating Systems. No. 1-602.1, 1998.</p> <p>IACS. Survey Guidelines for Tanks in which Soft Coatings have been applied. IACS Recommendation No. 44, 1996.</p> <p>Det Norske Veritas. Guidelines No. 8, for Corrosion Protection of Ships. (July 1996 or later edition).</p> <p>IACS Unified Requirement Z9 (1996).</p> <p>Det Norske Veritas. Rules for Classification of Ships. (July 1998 or later edition).</p>

<p>CN-41.2: Calculations of Gear Rating for Marine Transmissions</p>	<p>ISO-6336 Part 1-5 (cylindrical gears)</p> <p>ISO 10300 Part 1-3 (bevel gears)</p> <p>ISO Technical Reports on Scuffing and Fatigue Damage Accumulation</p> <p>ISO 701</p> <p>ISO/R31</p> <p>ISO 1328</p> <p>ISO 10300</p>
<p>CN-41.4: Calculations of Shafts in Marine Applications for Marine Transmissions</p>	<p>DIN 743 Part 1-3: 2000-04</p>
<p>CN-45.1: Electromagnetic Compatibility</p>	<p>References</p> <p>Paul R. Clayton; Introduction to Electromagnetic Compatibility; John Wiley &amp; Son, Inc. 1992</p> <p>Automation for Safety in Shipping and Offshore Petroleum Operations; A.B. Aune and J.Vlietstra, North-Holland Publishing Company 1980.</p> <p>IEEE Std. 519-1992 Recommended Practise and Requirements for Harmonic Control on Electrical Power Systems.</p> <p>Electromagnetic Interference Guidelines for Installations and Proposal for Test of Equipment; P.Gulbrandsen, K.Fotland, T.Heimly, H.Liland; DNV Paper Series No. 80 P008 1980.</p>
<p>Approval Scheme</p>	
<p>2.4 Environmental Test Specification for Instrumentation and Automation Equipment</p>	<p>These requirements are based on:</p> <p>IEC publication 60092-504, "Electrical installations in ships, part 504: Special features, control and instrumentation";</p> <p>IACS Unified Requirements E10, "Unified environmental test specification for testing procedure for electrical, control and instrumentation equipment, marine computers and peripherals covered by classification".</p> <p>DNV Rules for Classification, Part 4 Chapter 5, "Instrumentation and Automation".</p> <p><b>Note</b> Navigation and radio equipment is to comply with IEC Publication No. 60945, Marine navigational equipment - General requirements, given in Clauses 8, 9 and 10.</p>

Technical Report	
No. 97-0152	Proposal for Classification Note Fatigue Analysis of HSLC

## 28.2 Other International Standards and Codes

ABS	American Bureau of Shipping
	Rules for Building and Classing Mobile Offshore Drilling Units (2001)
	Rules for Building and Classing Single Point Moorings (1996)
	Rules for Building and Classing Offshore Installations (1997)
	Rules for Building and Classing Facilities on Offshore Installations (2000)
	Rules for Building and Classing Floating Production Installations (2004)
	Rules for Building and Classing Aluminum Vessels (1975)
	Guide for Buckling and Ultimate Strength Assessment of Offshore Structures (2004)
	Guide for Certification of Offshore Mooring Chain (1999)
	Guide for Fatigue Assessment of Offshore Structures (2003)
	Guide for Improvement for Structural Connections and Sample Structural Details - Service Experience and Modifications for Tankers (1995)
	Guide for Nondestructive Inspection of Hull Welds (2002)
	Guide for Shipbuilding and Repair Quality Standard for Hull Structures During Construction (1998)
	Guidance Notes on Alternative Design and Arrangements for Fire Safety (2004)
	Guidance Notes on Application of Synthetic Ropes for Offshore Mooring (1999)
	Guidance Notes on Application and Maintenance of Marine Coating Systems (1998)
	Guidance Notes on Risk Assessment Application for the Marine and Offshore Oil and Gas Industries (2000)
	Guidance Notes on SafeHull - Dynamic Loading Approach for Floating Production, Storage and Offloading (FPSO) Systems (2001)
	Guidance Notes on Spectral-Based Fatigue Analysis for Floating Production, Storage and Offloading (FPSO) Systems (2002)
	Guidance Notes (2004) - Reliability Centered Maintenance
API	American Petroleum Institute.
RP 2A - LFRD	Planning, design and constructing Fixed Offshore Platforms - Load and Resistance Factor Design.
RP 2FPS	Recommended Practice for Planning, Designing and Constructing Floating Production Systems
RP 2RD	Recommended Practice for Design of Risers for Floating Production Systems and Tension-Leg Platforms (TLPs)
RP 2T	Recommended Practice for Planning, Design and Constructing Tension Leg Platforms
RP 2SK	Recommended Practice for design and analysis of stationkeeping systems for floating structures.
Bull 2U	Stability Design of Cylindrical Shells
Bull 2V	Design of Flat Plate Structures
RP 9B	Application, Care, and Use of Wire Rope for Oil Field Service
RP 14C	Recommended Practice for Design, Installation and Testing of Basic Surface Safety Systems on Offshore Production Platforms
RP 14F	Recommended Practice for Design and Installation of Electrical Systems for Fixed and Floating Offshore Petroleum Facilities for Unclassified and Class I, Division 1, and Division 2 Locations

RP 14G	Recommended Practice for Fire Prevention and Control on Ope-type Offshore Production Platforms
RP 15TL4	Care and Use of Fiberglass Tubulars
RP 17B	Recommended Practice for Flexible Pipe
Spec 2B	Fabrication of Structural Steel Pipe
Spec 2F	Mooring Chain
Spec 9A/ISO 10425	Specification for Wire Rope Steel wire ropes for the petroleum and natural gas industries—Minimum requirements and terms for acceptance
Spec 17J	Specification for Unbonded Flexible Pipe
Spec 17K	Specification for Bonded Flexible Pipe
Spec 15HR	High Pressure Fiberglass Line Pipe
Spec 15LE	Polyethylene (PE) Line Pipe
Spec 15LR	Low Pressure Fiberglass Line Pipe
ASME	American Society of Mechanical Engineers
ASME 77-DE-39	Design Criteria to Prevent Core Crushing Failure in Large Diameter, Case Hardened, Ball and Roller Bearings
ASME section VIII	Boilers and Pressure Vessels Code
ASME section IX	Welding and Brazing Qualifications Non-Interfiled (Boiler and Pressure Vessel Codes)
ASME B31.3	Chemical Plant and Petroleum Refinery Piping
ASTM	
ASTM A892	Standard Guide for Defining and Rating the Microstructure of High Carbon Bearing Steels
ASTM D892	Standard Test Method for Foaming Characteristics of Lubricating Oils
ASTM D2893	Standard Test Method for Oxidation Characteristics of Extreme-Pressure Lubrication Oils
ASTM D3806	Standard Test Method of Small-Scale Evaluation of Fire-Retardant Paints (2-Foot tunnel Method)
BSI	British Standard Institute
BS 6349-1:2000	Maritime structures. Code of practice for general criteria
BS 6349-2:1988	Maritime structures. Design of quay walls, jetties and dolphins
BS 6349-4:1994	Maritime structures. Code of practice for design of fendering and mooring systems
BS 6349-5:1991	Maritime structures. Code of practice for dredging and land reclamation
BS 6349-6:1989	Maritime structures. Design of inshore moorings and floating structures
BS 6349-7:1991	Maritime structures. Guide to the design and construction of breakwaters
BS 7448-1	Fracture mechanics toughness testing. Part 1: Method for determination of KIC critical CTOD and critical J values of metallic materials
BS 7448-2	Fracture mechanics toughness testing. Part 2: Method for determination of KIC critical CTOD and critical J values of welds in metallic materials
BS 7910	Guidance on methods for assessing the acceptability of flaws in fusion welded structures
BS EN 12973:2000	Value management
BS EN 13445:2002	Unfired Pressure Vessels
BS EN 13480:2002	Metallic Industrial Piping
BS ISO 13628-	Petroleum and natural gas industries. Design and operation of subsea production

5:2002	systems. Subsea umbilicals
BS EN 60255	Electric Relays
BS ISO/IEC 12207:1995	Information technology. Software life cycle processes
CEN	European Committee for Standardization
	European Convention for Constructional Steelwork. European Recommendations for Aluminium Alloy Structures, ECCS-24, Committee T2
	European Convention for Constructional Steelwork. European Recommendations for Aluminium Alloy Structures, ECCS-212, Committee T2
	European Convention for Constructional Steelwork. European Recommendations for Aluminium Alloy Structures - Fatigue Design, ECCS-48
	European Structural Standards
EN 1991	Eurocode 1 : Actions on structures
EN 1993	Eurocode 2 : Design of Concrete Structures
EN 1993	Eurocode 3 : Design of Steel Structures
EN 10025	Hot rolled products of structural steels
EN 10113	Hot-rolled products in weldable fine grain structural steels
EN 10204	Metallic products. Types of inspection documents
EN 12238	Ventilation for Buildings - Air Terminal Devices - Aerodynamic Testing and Rating for Mixed Flow Application
EN 12239	Fire Protection Equipment - Self Contained Smoke Alarms
ENV 12097	Ventilation for buildings - Ductwork - Requirements for ductwork components to facilitate maintenance of ductwork systems
PD 5500	Specification for unfired fusion welded pressure vessels
EEMUA	
	158 Construction Specification for Fixed Offshore Structures in the North Sea
	176 Specification for Structural Castings for use Offshore
	194 Guidelines for Materials Selection and Corrosion Control for Subsea Oil and Gas Production Equipment (2nd Edition 2004)
	197 Specification for Fabrication of Non-Primary Structural Steelwork for Offshore Installation
IACS	International Association of Classification Societies
	IACS Unified Requirements for the Special Hull Surveys of Oil Tankers
	IACS Requirements concerning Mobile Offshore Drilling Units
	Shipbuilding and Repair Quality Standard
IEC	International Electrotechnical Commission
502	
60092	Electrical Installation in Ships
60300-1 (2003)	Dependability management - Part 1: Dependability management systems
60300-3-2 (2004)	Dependability management - Part 3: Application guide - Section 2: Collection of dependability data from the field
60300-3-3 (1996)	Dependability management - Part 3: Application guide - Section 3: Life cycle costing
60300-3-9 (1995)	Dependability management - Part 3: Application guide - Section 9: Risk analysis of

	technological systems
60300-3-11 (1999)	Dependability management - Part 3-11: Application guide - Reliability centred maintenance
60308 (work in progress)	Hydraulic turbines - Testing of control systems
60502-1 - Ed. 2.0	High Voltage cables
60533	Electrical and electronic installations in ships - Electromagnetic compatibility
60545 (1976-01)	Guide for commissioning, operation and maintenance of hydraulic turbines
60609 (1978-01)	Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines
60609-2 (1997-11)	Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines - Part 2: Evaluation in Pelton turbines
60812 (1985)	Analysis techniques for system reliability - Procedures for failure mode and effect analysis (FMEA)
60945	Maritime navigation and radiocommunication equipment and systems - General requirements - Methods of testing and required test results
61025 (1990)	Fault tree analysis
61078 (1991)	Analysis techniques for dependability - Reliability block diagram method
61165 (1995)	Application of Markov techniques
62198 (2001)	Project risk management - Application guidelines
61363	Electrical installations of ships and mobile and fixed offshore units
61366	Part 1: General and annexes (IEC 61366-1) Part 2: Guidelines for technical specification for Francis turbines (IEC 61366-2) Part 3: Guidelines for technical specification for Pelton turbines (IEC 61366-3) Part 4: Guidelines for technical specifications for Kaplan and propeller turbines (IEC 61366-4)
61508-SER - Ed. 1.0	Functional safety of electrical/electronic/programmable electronic safety-related systems
61882 (2001)	Hazard and operability studies (HAZOP studies)- Application guide
61892	Mobile and fixed offshore units - Electrical installations
IEEE	
IEEE 1228-1994	IEEE Standard for Software Safety Plans
IMO	International Maritime Organization
IMO MODU Code Consolidated Edition 2001	Code for the Construction and Equipment of Mobile Offshore Drilling Units
IMO Resolution A.653(16)	Recommendation on Improved Fire Test Procedures for Surface Flammability of Bulkhead, Ceiling and Deck Finish Materials
IMO Resolution A.753(18)	Guidelines for the Application of Plastic Pipes on Ships
ICLL	International Convention on Load Line, 1996
SOLAS 1974	SOLAS International Convention for the Safety of Life at Sea
ISO	International Organization for Standardization
ISO 75	Plastics - Determination of temperature of deflection under load
ISO 76:1987	Rolling bearings - Static Load Ratings

ISO 148	Steel - Charpy impact test (V-notch) Metallic materials - Charpy pendulum impact test - Part 2: Verification of test machines Metallic materials - Charpy pendulum impact test - Part 3: Preparation and characterization of Charpy V reference test pieces for verification of test machines
ISO 281:1990	Rolling bearings - Dynamic Load Ratings and Rating Life
ISO 898	Mechanical Properties of Fasteners
ISO 1127	Stainless steel tubes - Dimensions, tolerances and conventional masses per unit length
ISO 1328	Cylindrical gears - ISO system of accuracy
ISO 1461	Hot dip galvanized coatings on fabricated iron and steel articles - Specifications and test methods
ISO 2160	Petroleum Products - Corrosiveness to copper- copper strip test.
ISO 2394:1998	General principles on reliability for structures
ISO 2909	Petroleum Products - Calculation of viscosity index from kinematic viscosity
ISO 3016	Petroleum Products - Determination of pour point
ISO 3104	Petroleum products - Transparent and opaque liquids - Determination of kinematic viscosity and calculation of dynamic viscosity
ISO 3448	Industrial liquid lubricants - ISO viscosity classification
ISO 3722	Cleaning of oil sample bottles.
ISO 4021	Extraction of fluid samples from lines of an operating system.
ISO 4406	Hydraulic fluid power - Fluids - Method for coding the level of contamination by solid particles
ISO 4947	Steel and cast iron - Determination of vanadium content - Potentiometric titration method
ISO 4967	Steel - Determination of content of nonmetallic inclusions - Micrographic method using standard diagrams
ISO 5817	Arc-welded joints in steel - Guidance on quality levels for imperfections
ISO 6336-1:1996	Calculation of load capacity of spur and helical gears: Basic principles, introduction and general influence factors, incl. Cor. 1:1998 and Cor. 2:1999
ISO 6336-2:1996	Calculation of load capacity of spur and helical gears: Calculation of surface durability (pitting), incl. Cor1:1998 and Cor 2:1999
ISO 6336-3:1996	Calculation of load capacity of spur and helical gears: Calculation of tooth bending strength, incl. Cor1:1999
ISO 6336-5:2003	Calculation of load capacity of spur and helical gears: Strength and quality of materials
ISO/CD 6336-6:2003	Cylindrical gears - Calculation of service life under variable load-Conditions for cylindrical gears in accordance with ISO 6336 1997-09-01
ISO 6361-1:1986	Wrought Aluminium and Aluminium Alloy Sheets, Strips and Plates - Part 1: Technical Conditions for Inspection and Delivery
ISO 6361-2:1990	Wrought Aluminium and Aluminium Alloy Sheets, Strips and Plates - Part 2: Mechanical properties
ISO 6361-3:1985	Wrought Aluminium and Aluminium Alloy Sheets, Strips and Plates - Part 3: Strips - Tolerances on shape and dimensions
ISO 6361-4:1988	Wrought Aluminium and Aluminium Alloy Sheets, Strips and Plates - Part 4: Sheets and plates - Tolerances on form and dimensions
ISO 6507-1	Metallic materials - Vickers hardness test - Part 1: Test method
ISO 7120	Determination of rust-preventing characteristics in presence of water
ISO 8501	Preparation of steel substrates before application of paints and related products -

	<p>Visual assessment of surface cleanliness</p> <p>Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings</p> <p>Suppl:1994 Representative photographic examples of the change of appearance imparted to steel when blast-cleaned with different abrasives</p> <p>Part 2: Preparation grades of previously coated steel substrates after localized removal of previous coatings</p> <p>Part 3: Preparation grades of welds, cut edges and other areas with surface imperfections</p>
ISO 9089:1989	Marine structures - Mobile offshore units - Anchor Winches
ISO 9606	<p>Approval testing of welders - Fusion welding - Part 1: Steels</p> <p>Qualification test of welders - Fusion welding - Part 2: Aluminium and aluminium alloys</p> <p>Approval testing of welders - Fusion welding - Part 3: Copper and copper alloys</p> <p>Approval testing of welders - Fusion welding - Part 4: Nickel and nickel alloys</p> <p>Approval testing of welders - Fusion welding - Part 5: Titanium and titanium alloys, zirconium and zirconium alloys</p>
ISO 10042	Arc-welded joints in aluminium and its weldable alloys - Guidance on quality levels for imperfections
ISO 10300	Calculation of load capacity of bevel gears
ISO 10420:1994	Petroleum and Natural Gas Industries - Flexible Pipe Systems for Subsea and Marine Riser Applications
ISO 10825	Wear and damages on Gears
ISO 11171	Hydraulic fluid power - Calibration of automatic particle counters for liquids
ISO 13637:1997	Petroleum and Natural Gas Industries - Mooring of mobile offshore drilling units (MODUS) - Design
ISO 13628-1:1999	Petroleum and Natural Gas Industries - Design and Operation of Subsea Production Systems – Part 1: General requirements and recommendations
ISO 13628-2:2000	Petroleum and Natural Gas Industries - Design and Operation of Subsea Production systems - Part 2: Flexible pipe systems for subsea and marine applications
ISO 13628-5:20002	Petroleum and Natural Gas Industries - Design and Operation of Subsea Production systems - Part 5: Subsea Control Umbilicals
ISO/TR 13637:1997	Petroleum and natural gas industries - Mooring of mobile offshore drilling units (MODUS) - Design and analysis
ISO 13703:2000	Petroleum and natural gas industries - Design and installation of piping systems on offshore production platforms
ISO 13819-2:1995	Petroleum and natural gas industries - Offshore structures - Part 2: Fixed steel structures
ISO/TR 13989-1:2000	Calculation of scuffing load capacity of cylindrical, bevel and hypoid gear-Part 1: Flash temperature method
ISO 14104	Gears - Surface temper etch inspection after grinding
ISO 14121:1999	Safety of machinery - Principles for risk assessment ( = EN 1050:1996)
ISO 14224:1999	Petroleum and natural gas industries - Collection and exchange of reliability and maintenance data for equipment
ISO 14635-1	Zhnräder - FZG-Testverfahren - Teil 1: Testverfahren A/8,3/90 für relative Fresstragfähigkeit von Ölen.
ISO 15663-1 (2000)	Petroleum and natural gas industries - Life cycle costing - Part 1: Methodology
ISO 15663-2 (2001)	Petroleum and natural gas industries - Life-cycle costing - Part 2: Guidance on application of methodology and calculation methods
ISO 15663-3 (2001)	Petroleum and natural gas industries - Life-cycle costing - Part 3: Implementation

	guidelines
ISO 16889:1999	Hydraulic fluid power filters - Multi-pass method for evaluating filtration performance of a filter element
ISO 17776:2000	Petroleum and natural gas industries - Offshore production installations - Guidelines on tools and techniques for hazard identification and risk assessment
ISO/CD 18692	Fibre ropes for offshore station keeping - Polyester (under development)
ISO 19900:2002	Petroleum and natural gas industries. General requirements for offshore structures
ISO/DIS 13357-1,2	Petroleum Products - Determination of the filterability of Lubricating oils
ISO/DIS 19901-1	Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 1: Metocean Design and Operating Conditions (under development)
ISO 19901-2:2004	Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 2: Seismic Design Procedures and Criteria
ISO/CD 19901-3	Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 3: Topsides Structure (under development)
ISO 19901-4:2003	Petroleum and natural gas industries - Specific requirements for offshore structures - Part 4: Geotechnical and foundation design considerations
ISO/CD 19901-6	Petroleum and natural gas industries - Specific requirements for offshore structures - Part 6: Marine operations (under development)
ISO13357	Petroleum products - Determination of the filterability of lubricating oils - Part 1: Procedure for oils in the presence of water Petroleum products - Determination of the filterability of lubricating oils - Part 2: Procedure for dry oils
ISO/DIS 19901-7	Petroleum and natural gas industries - Specific requirements for offshore structures - Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units (under development)
ISO/DIS 19902	Petroleum and natural gas industries - Fixed steel offshore structures (under development)
ISO/DIS 19903	Petroleum and natural gas industries - Fixed concrete offshore structures (under development)
ISO/DIS 19904-1	Petroleum and natural gas industries - Floating offshore structures - Part 1: Monohulls, semi-submersibles and spars (under development)
ISO 20340:2003	Paints and varnishes - Performance requirements for protective paint systems for offshore and related structures
LRS	Lloyd's Register of Shipping
	Rules and Rules and Regulations for the Classification of a Floating Offshore Installation at a Fixed Location
	Rules and Regulations for the Classification of Mobile OffshoreUnits
NACE	
	Standard RP-01-76. Corrosion Control of Steel, Fixed Offshore Platforms Associated with Petroleum Production
	National Fire Protection Association
NFPA 10	Standard for Portable Fire Extinguishers

NORSOK	
J-003	Marine Operations
L-001	Piping and Valves
L-002	Piping design, layout and stress analysis
L-005	Compact flanged connections
M-001	Material selection
M-101	Structural steel fabrication
M-102	Structural aluminium fabrication
M-120	Material data sheets for structural steel
M-121	Aluminium structural material
M-122	Cast structural steel
M-123	Forged structural steel
M-501	Surface preparation and protective coating
M-503	Cathodic protection
M-601	Welding and inspection of piping
M-630	Material data sheets for piping
M-650	Qualification of manufacturers of special materials
M-CR-621	GRP piping materials
N-001	Structural design
N-003	Actions and Action Effects
N-004	Design of Steel Structures
R-001	Mechanical equipment
Z-006	Preservation
Z-007	Mechanical Completion and Commissioning
Z-008	Criticality Analysis for maintenance purposes
Z-013	Risk and emergency preparedness analysis
Z-016	Regularity management & reliability technology
NS	Norwegian Standards
NS-EN 1591-1	Flanges and their joints. Design rules for gasketed circular flange connections. Part 1: Calculation method. September 2001.
NS3473	Concrete structures - Design and detailing rules
NS 9415 (2003)	Marine fish farms. Requirements for design, dimensioning, production, installation and operation.
NPD	Norwegian Petroleum Directorate
	Regulations for risk analyses
OFCOM	
	Performance Specification MPT 1411
G59/1	Recommendations For The Connection Of Private Generating Plant To The Regional Electricity Companies (RECs)
G75	Recommendations for the Connection of Embedded Generating Plant to Public Electricity Suppliers Distribution Systems (above 20kV or with outputs over 5MW) [Only applies to "Farm" conditions]

UKOOA	
	Specification and Recommended Practice for use of GRP piping offshore

### 28.3 Further references

ULTIGUIDE (Best practices for use of non-linear analysis methods in documentation of ultimate limit states for jacket type offshore structures)

Electricity Safety, Quality and Continuity Regulations (2002) (Section J - Generation).

## APPENDICES

# APPENDIX A - FATIGUE ANALYSIS METHODOLOGY

## A1 General Methodology

### Methods of Analysis

The fatigue analysis should be based on S-N data, determined by fatigue testing of the considered detail, and the linear damage hypothesis. Reference is made to RP-C203. When appropriate, the fatigue analysis may alternatively be based on fracture mechanics. For calculations based on fracture mechanics, it should be documented that in-service inspection accommodates a sufficient interval between crack detection and the time of unstable fracture. Data for seawater environment should be used for calculations of crack growth based on fracture mechanics. Reference is made to BS 7910.

All significant stress ranges which contribute to fatigue damage in the structure, should be considered. The long term distribution of stresses may be found by deterministic or spectral analysis. Also a time domain simulation of each sea state contributing to fatigue damage may be used. Dynamic effects shall be duly accounted for when establishing the stress history.

Fatigue analysis should include all actions contributing to fatigue damage both in non-operational and operational design conditions. Local action effects due to wave slamming and vortex shedding are to be included when calculating fatigue damage if relevant.

### Deterministic Analysis

In a deterministic fatigue analysis a long term distribution of wave heights is established. For offshore devices moored on a fixed heading the analysis should include at least 8 different wave directions and at least 6 wave heights in each direction. Inshore and shoreline structures can take account of shallow water effects that cause larger amplitude waves to align themselves with the shoreline to consider a reduced range of wave headings. Then wave forces should be calculated in at least 10 positions in each wave. In performing a deterministic wave analysis, due attention should be paid to the choice of wave periods if such data are not explicitly specified, or can be determined based upon scatter diagrams relevant for the location. The calculated wave forces are imposed on the structure for analysis of stress at relevant hot spot stress areas. From this stress ranges are calculated and the fatigue damage can be derived. Bottom standing structures should take account of load variation due to variations in tide level when building up a load history.

### Wave Loading by Direct Computation

A linear modelling of the response is in general sufficient for fatigue assessment purposes. The response is then described by a superposition of the response of all regular wave components that make up the irregular sea, leading to a frequency domain analysis. The resulting stress may be established as a summation over all contributing dynamic loads/load effects.

The linear frequency domain results should normally be applied without any corrections for large wave effects as most of the fatigue damage is related to moderate wave

heights. For inshore devices, consideration should be given to filtering out large amplitude waves due to wave breaking. However, the consequence of this is that in the higher sea states the inshore device sees a much larger number of design waves than an offshore device, albeit that the design wave is of a lesser amplitude. For shoreline and near shore devices in very shallow water, the load process is non-Gaussian.

Transfer function values must be determined for a sufficient number of frequencies ( $\geq 20$ ) and headings ( $\geq 8$ ) (see note above on inshore and shoreline structures). It is important to select periods such that response amplifications and cancellations are included.

The length of the model should at least extend over the length of the structure. The mass model should reflect the weight distribution both in vertical, longitudinal and transverse directions.

The fatigue damage should be calculated so that the effects of all the main load conditions are accounted for.

In the evaluation of the structural response due to external wave induced loading, the effect of wave diffraction and radiation should be accounted for.

### The Long-Term Distribution

The long-term distribution of load responses for fatigue analyses may be estimated using the wave climate, represented by the distribution of  $H_s$  and  $T_z$ . For shallow water special wave spectra for developing sea should be applied. Otherwise, the environmental wave spectrum for the different sea states can be defined applying the Pierson Moskowitz wave spectrum,

$$S_{\eta}(\omega|H_s, T_z) = \frac{H_s^2}{4\pi} \left( \frac{2\pi}{T_z} \right)^4 \omega^{-5} \exp\left( -\frac{1}{\pi} \left( \frac{2\pi}{T_z} \right)^4 \omega^{-4} \right), \quad \omega > 0$$

The response spectrum of the structure based on the linear model is directly given by the wave spectrum, when the relation between unit wave height and stresses, the transfer function  $H_{\sigma}(\omega|\theta)$ , is established as

$$S_{\sigma}(\omega|H_s, T_z, \theta) = |H_{\sigma}(\omega|\theta)|^2 \cdot S_{\eta}(\omega|H_s, T_z)$$

The spectral moments of order n of the response process for a given heading may be described as

$$m_n = \int_{\theta-90^\circ}^{\theta+90^\circ} \sum_{\omega} f_s(\theta) \omega^n \cdot S_{\sigma}(\omega|H_s, T_z, \theta) d\omega$$

The spectral moments may include wave spreading as :

$$m_n = \int_{\theta-90^\circ}^{\theta+90^\circ} \sum_{\omega} f_s(\theta) \omega^n \cdot S_{\sigma}(\omega|H_s, T_z, \theta) d\omega$$

using a spreading function  $f(\theta) = k \cos^n(\theta)$ , where k is selected such that  $\sum_{\theta-90^\circ}^{\theta+90^\circ} f(\theta) = 1$ , and normally applying  $n = 2$ .

The stress range response for the structure can be assumed to be Rayleigh distributed within each short term condition. The stress range distribution for a given sea state  $i$  and heading direction  $j$  is then,

$$F_{\Delta\sigma_{ij}}(\sigma) = 1 - \exp\left(-\frac{\sigma^2}{8m_{0ij}}\right)$$

where  $m_0$  is the spectral moment of order zero.

### Transfer Function

The transfer function (frequency response function)  $H(\omega, \theta)$ , representing the response to a sinusoidal wave with unit amplitude for different frequencies  $\omega$  and wave heading directions  $\theta$ , can be obtained applying linear potential theory.

For free floating bodies the vertical bending moment may be estimated by making a hydrodynamic model of the structure including mass distribution data and by running a wave load program that determines the response for a set of wave frequencies and heading directions. The vertical bending moment transfer function is computed as the vertical bending moment  $M_v(\omega, \theta)$  per unit wave amplitude ( $H/2$ ). Care should be taken that linear transfer functions are appropriate for low freeboard devices in the higher sea states. Depending upon the device geometry the results may be conservative or optimistic and a non-linear analysis may be required.

The horizontal bending moment transfer function,  $M_h(\omega, \theta)$ , is to be determined similarly to the vertical bending moment transfer function with consistent phase relations.

The combined stress response may be determined by a linear complex summation of stress transfer functions.

For vertical buoy structures horizontal and vertical bending moments will be small but inertial loads on tail tubes due to whole body motions plus wave drag forces may be large.

### Local Finite Element Model

A local stress concentration model is used for the analysis. For analysis of details the mesh size is to be in the order of the plate thickness. Hence, all load effects, global and local, are taken care of in addition to the geometric stress concentration. Reference is also made to recommendations by Lotsberg (2004).

The global FE analysis is run for all wave load cases, i.e. 8-12 headings and 20-25 wave periods per heading. For each load case the deformations of the global FE model are automatically transferred to the local FE model as boundary displacements. In addition the local internal and external hydrodynamic pressures need to be automatically transferred to the local FE model by the wave load program. The part fatigue damage from each cell in the wave scatter diagram is then to be calculated based on the principal stresses from the local FE model extrapolated to the hotspot, the wave spectrum, wave spreading function, S/N data etc. Reference is also made to DNV-CN 30.7 (2003).

### References:

*Lotsberg, I. and Sigurdsson, G. (2004), "Hot Spot S-N Curve for Fatigue Analysis of Plated Structures". OMAE-FPSO'04-0014, Int. Conf. Houston.*

Lotsberg, I. (2004b), "Recommended Methodology for Analysis of Structural Stress for Fatigue Assessment of Plated Structures". OMAE-FPSO'04-0013, Int. Conf. Houston.

#### Time Domain Simulation

For structures showing responses with broad band spectra, one might improve the analysis results (likely reduce conservatism from frequency response analysis) by performing time domain simulation of each sea state and sum up the fatigue damage using a rain flow counting technique.

### A2 Long Term Stress Range Distribution

The long term stress range distribution for fatigue assessment can be based on expected values or values that are determined to be to the safe side. In case that the non-linearity in the response is significant it is recommended that the long term stress range distribution is derived from relevant time domain simulations using a Rainflow counting technique.

### A3 Fatigue Capacity

The fatigue capacity of the structure can be assessed based on OS-C101 (Section 6) and RP-C203.

### A4 Design Fatigue Factor

Design fatigue factors (DFF) shall be applied to increase the probability for avoiding fatigue failures. The DFFs are dependent on the significance of the structural components with respect to structural integrity and availability for inspection and repair.

DFFs are applied to the design fatigue life. The calculated fatigue life shall be longer than the design fatigue life times the DFF. The design requirement can alternatively be expressed as the cumulative damage ratio for the number of load cycles of the defined design fatigue life multiplied with the DFF shall be less or equal to 1.0.

The design fatigue factors in Table A4.1 are valid for steel devices with low consequence of failure and where it can be demonstrated that the structure satisfy the requirement to damaged condition according to the ALS with failure in the actual joint as the defined damage. The design fatigue factors shall be based on special considerations where fatigue failure will entail substantial consequences such as;

- danger of loss of human life, i.e. no compliance with ALS criteria,
- significant pollution,
- unacceptable economical consequences.

<i>DFF</i>	<i>Structural element</i>
1	Internal structure, accessible and not welded directly to the submerged part.
1	External structure, accessible for regular inspection and repair in dry and clean conditions
2	Internal structure, accessible and welded directly to the submerged part
2	External structure not accessible for inspection and repair in dry and clean conditions
3	Non-accessible areas, areas not planned to be accessible for inspection and repair during operation

Table A4.1 : Design Fatigue Factors (DFF)

## **A5 Hull Structure and Hydraulic Rams**

Reference is made to RP-C203 for the design of the hull structure and the hydraulic rams with respect to the Fatigue Limit State.

For discussion of recommended Design Fatigue Factor see separate section below. The proposed DFF will imply need for in-service inspection for fatigue cracks. An inspection plan for this should be developed as part of the design.

(The proposed design procedure and safety format for the Ultimate Limit States and the Accidental Limit States imply that the annual probability of failure for these limit states is less than  $10^{-4}$ . In order to achieve a similar safety level with respect to fatigue using a minimum DFF = 1.0 may imply in-service inspection at 1-3 year intervals depending on selected design strategy and details considered).

## **A6 Target Safety Level**

In the following it is assumed that the fatigue capacity is assessed based on RP-C203. It is further assumed that the long term stress range distribution for fatigue assessment is based on expected values or it is determined to be on the safe side [or conservative].

A graph for probability of a fatigue failure as function of DFF for a structure subjected to wave loading is shown in Figure A1. Here a design life equal 20 years is used. However, the graph for the accumulated failure probability will be the same if the design life is 15 years. The annual failure probability in the last year will be increased by a factor 20/15 if the design life was reduced to 15 years. It is recommended to use a Design Fatigue Factor (DFF) that is not less than 1.0.

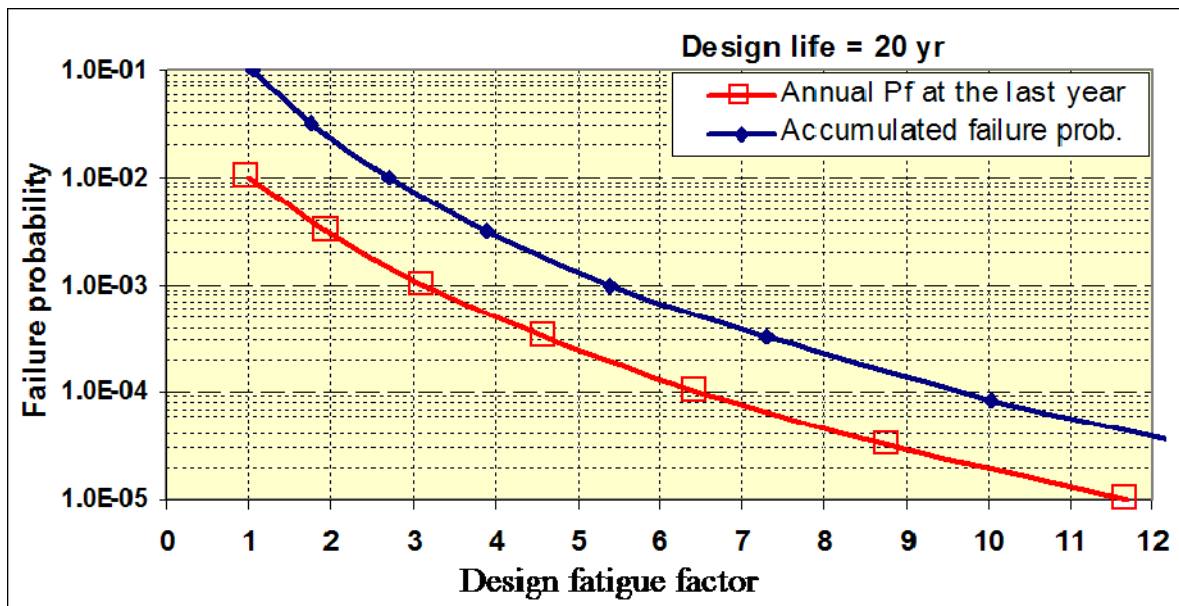


Figure A1: Fatigue Failure Probability as Function of Design Fatigue Factor

A higher design fatigue factor (DFF) may give a more cost optimal design taking the requirements to inspection and maintenance into account as well as consequence cost of a fatigue failure (cost of lost production). Knowing more of the costs involved it is possible to derive a recommended DFF based on economic considerations. Reference is made to Dalane et al. (1990) where DFFs were derived for a fixed steel offshore structure, a floating production ship and a tension leg platform based on such considerations.

A design life of 20 years has been assumed for derivation of annual probability of a fatigue failure the last year in Figure A1. The curve for accumulated failure probability is independent of design life. For shorter design lives than 20 years the curve for annual probability of fatigue failure will be shifted in the direction of the curve for the accumulated failure probability.

The cost of inspection will also be a function of scheduled maintenance of other systems of the wave device. The requirements to in-service inspection will be a function of the recommended DFF.

#### References:

*Dalane, J.I., Skjong R. and Lotsberg, I.: Optimal Fatigue Design of Offshore Structures. Int. Conf. Offshore Mechanics and Arctic Engineering. Houston, February 1990.*

*Lotsberg, I., Sigurdsson, G. and Wold, P. T. (1999), "Probabilistic Inspection Planning of the Åsgard A FPSO," OMAE'99 St. John's, Newfoundland, July 1999. Also Journal of Offshore Mechanics and Arctic Engineering, vol. 122, may 2000.*

*Sigurdsson, S., Landet, E. and Lotsberg, I. (2004), "Inspection Planning of a Critical Block Weld in an FPSO". OMAE-FPSO'04-0032, Int. Conf. Houston.*

## A7 High Strength Steel in Machined Components

For high strength steel in machined components a higher S-N curve than that of DNV-RP-C203 can be used, see Figure A2. The S-N curve can be applied to machined components with yield strength larger than 500 MPa and with a surface finish  $R = 3.2 \mu\text{m}$  or better. The design S-N curve reads

$$\text{Log}N = 17.446 - 4.70\text{Log}S$$

In air a constant amplitude limit at 2 Million cycles may be used. The corresponding stress range is 235 MPa. In seawater environment it is not recommended to use any constant amplitude limit.

In corrosive environments the S-N curves for seawater with free corrosion may be used (due to lack of relevant test data). Refer to Table 2.3-3 in DNV-RP-C203.

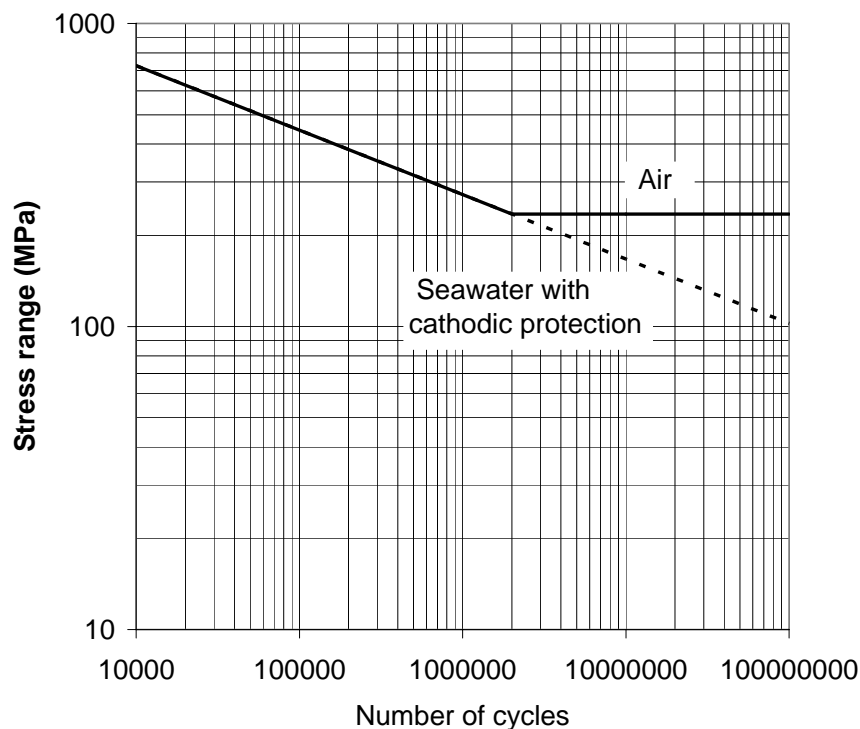


Figure A2 : S-N Curve for High Strength Steel

## A8 S-N Curves for Stainless Steels

Reference is made to RP-C203 Section 2.3.8 for S-N curves for stainless steels. However, for austenitic steel one may use the same classification as for C-Mn steels.

One might expect that for stainless steels the S-N curves in air also applies to components in seawater environment. This assumption can be made for smooth non-welded components with low stress concentrations where the fatigue life is mainly that of initiation.

However, some fatigue test results shows that the crack growth in seawater may be faster than in air and that similar crack growth parameters as for C-Mn steels in this environment should be considered used (Maura Branco et al. (2001)).

Reference:

Maura Branco, C., Maddox, S. J. and Sonsino, C. M.: *Fatigue Design of Welded Stainless Steels. Report EUR 19972 EN. 2001.*

## A9 S-N Curves for Aluminium

General

Reference is made to DNV Technical Report: Proposal for Classification Note Fatigue Analysis of HSLC Report no. 97-0152 and research carried out for definition of S-N curves applicable for all wrought standard aluminium alloys and temper conditions used for aluminium hull structures.

The S-N curves were obtained from fatigue test and are based on the mean-minus-two standard deviation curves for relevant experimental data, associated with a 97.6% probability of survival.

The basic design S-N curve is given as,

$$\log N = \log a - m \log S$$

S-N curve	Material		$N \leq 5 \times 10^6$		$N > 5 \times 10^6$	
			log a	m	log a	m
I	Base material	in air or in areas effectively protected from corrosion	21.10	7.00	21.10	7.00
II	Welded joint		13.82	4.32	17.12	6.32
III	Welded joint		11.87	3.37	14.94	5.37
IV	Welded joint	in corrosive environment	11.44	3.37	11.44	3.37

Table A9.1: Parameters for Standard S-N Curves for Aluminium

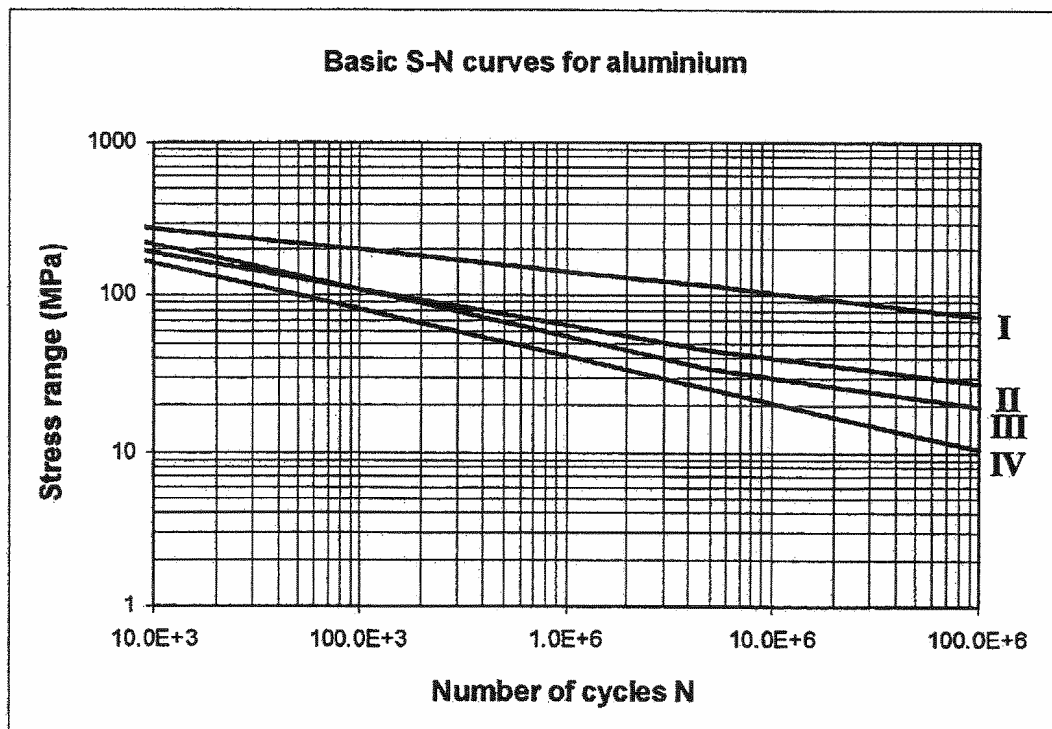


Figure A9.2 : Basic S-N Curves for Aluminium

The design S-N curves given here correspond to smooth specimens having a notch stress concentration factor  $K=1.0$ . For fatigue analysis of other details, the stress range  $S$  must incorporate notch stress concentration factor for weld geometry etc. For selection of S-N curve and K-factors to be considered in the different weld details, see below.

The fatigue strength of welded joints is to some extent dependent on plate thickness and on the stress gradient over the thickness. Thus for thickness larger than 25mm the thickness effect should be taken into consideration in cases where crack initiation or propagation may occur from the toe of the weld.

For fatigue analysis of regions in the base material not significantly affected by residual stress due to welding, the stress range may be reduced dependent on whether mean cyclic stress is in tension or compression.

#### Thickness Effect ( $K_t$ )

The thickness effect should not be taken into account for unwelded material. The stress concentration factor ( $K_t$ ) is to be taken as:

$$K_t = (t/25)^{0.25}$$

where  $t$  is the actual plate thickness.

#### K-factors

In order to correctly determine the stresses to be used in fatigue analysis, it is important to note the definitions of the different stress categories (see also RP-C203):

- Nominal Stresses are those derived from beam element models or from coarse mesh FE models. Stress concentrations resulting from the gross shape of structure are included.
- Geometric stresses includes nominal stresses and stresses due to discontinuities and presence of attachments, but excluding stresses due to presence of welds. Stresses derived from fine mesh FE models are geometric stresses. Effects caused by fabrication imperfections are normally not included in the FE model. The greatest value of the extrapolation to the weld toe of the geometric stress distribution immediately outside the region affected by the geometry of the weld is commonly denoted hot spot stress.
- Notch stress is the total stress at the weld toe (hot spot location) and includes the geometric stress and the stress due to the presence of the weld.

K-factors may be obtained from the discussion which follows. Alternatively, stress concentration factors or K-factors may be determined based on fine mesh finite element analysis or testing. The K-factors are to be used together with the applicable S-N curves shown in Table A1.

The fatigue life of a detail is governed by the notch stress range, where the notch is defined as a local stress concentrator in way of welds and/or changes in cross section shape or geometry. For components other than smooth specimens the notch stress is obtained by multiplication of the nominal stress by K-factors. The K-factors in this section are thus defined as:

$$K = \sigma_{\text{notch}} / \sigma_{\text{nominal}}$$

The relation between the notch stress range to be used together with S-N curve and the nominal stress range is

$$\Delta\sigma = K \cdot \Delta\sigma_{\text{nominal}}$$

All stress risers have to be considered when evaluating the notch stress. This can be done by multiplication of K-factors arising from different causes. The resulting K-factor to be used for calculation of notch stress is derived as:

$$K = K_g \cdot K_w \cdot K_{te} \cdot K_{t\alpha} \cdot K_t$$

where

- $K_g$  = SCF due to the gross geometry of the detail considered
- $K_w$  = SCF due to the weld geometry
- $K_{te}$  = SCF due to the eccentricity tolerance
- $K_{t\alpha}$  = SCF due to angular mismatch
- $K_t$  = SCF due to plate thickness exceeding 25mm

#### Grinding of Welds

For welding joints involving potential fatigue cracking from the weld toe an improvement in strength by a factor of approximate 2 on fatigue life may be obtained by controlled local machining or grinding of the weld toe. Grinding of welds in aluminium should be done with great care to avoid local thinning.

By additional grinding of the weld profile such that a circular transition between base material and weld surface is achieved, the stress concentration is further reduced (as the grinding radius is increased). This may lead to additional improvement of the joint connection (reduced K-factor).

The benefit of grinding may be claimed when properly documented and only for welded joints which are adequately protected from sea water corrosion.

In the case of partial penetration welds, when failure from the weld root is considered, the grinding of the weld toe will not give an increase in fatigue strength.

#### Construction Details and K-Factors

The tables below present the typical details, associated K-factors and applicable S-N curves.

**Table B.1 Workmanship related K-factors**

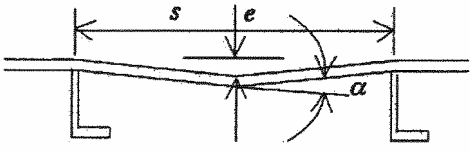

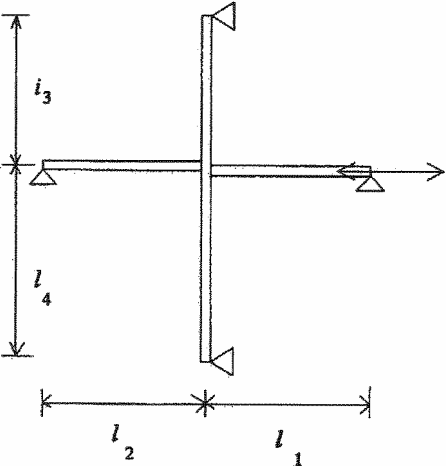

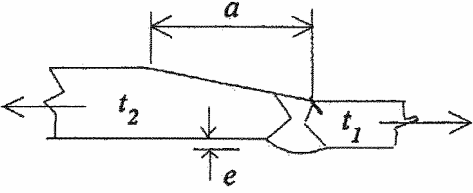
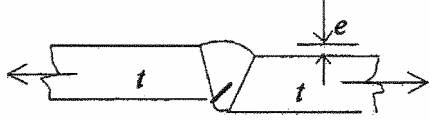
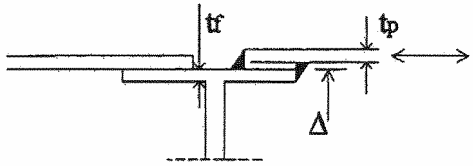
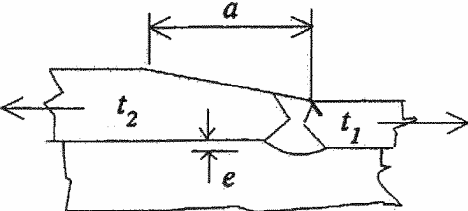
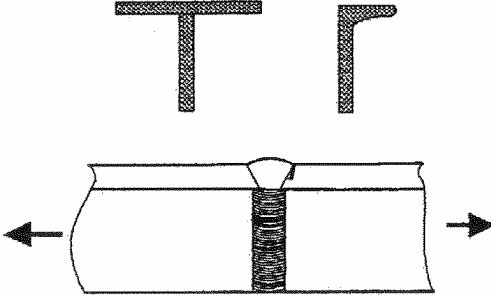
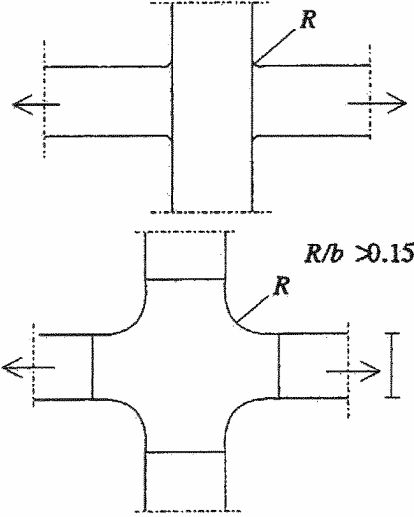
Geometry	SN-Curve	K-factor
<p><b>B.1.1 Angular mismatch</b></p>  <p><math>e = 0.015 s</math>. <math>e</math> may be defined as a value caused by a combination of angular mismatch and buckling caused by shrinkage</p>	<p>I, II, III, IV</p>	<p>Angular mismatch in joints between flat plates results in additional stresses at the butt weld and the stiffener</p> $K_{\alpha} = 1 + \frac{\lambda}{4} \alpha \frac{s}{t}$ <p>where:  <math>\lambda = 6</math> for pinned ends  <math>\lambda = 3</math> for fixed ends  <math>\alpha</math> = angular mismatch in radians  <math>s</math> = plate width  <math>t</math> = plate thickness</p>
<p><b>B.1.2 Eccentricity</b></p>  <p>Default :  <math>e = 0.15 t</math> or max. 4.0 mm</p>	<p>I, II, III, IV</p>	<p>Eccentricity in butt joints</p> $K_{te} = 1 + \frac{3e}{t}$
<p><b>B.1.3 Cruciform mismatch</b></p> 	<p>I, II, III, IV</p>	<p>Eccentricity in cruciform joints</p> $K_{te} = 1 + \frac{6t^2 \cdot e}{l_1 \left( \frac{t_1^3}{l_1} + \frac{t_2^3}{l_2} + \frac{t_3^3}{l_3} + \frac{t_4^3}{l_4} \right)}$

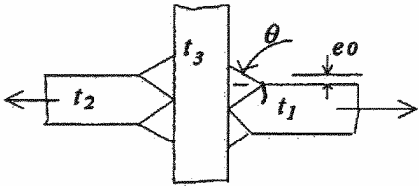
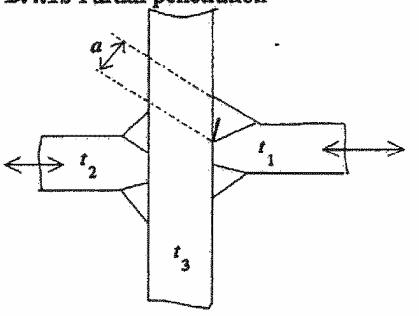
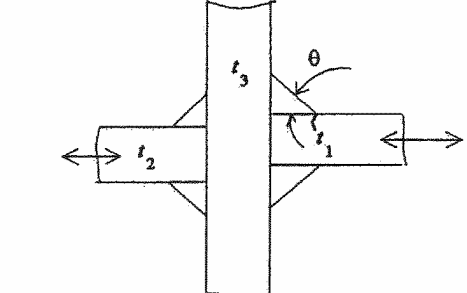
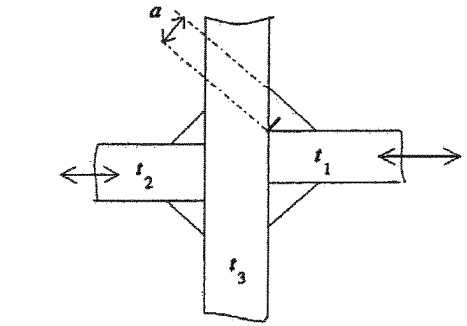
Table B.2 Butt welds

Geometry	SN-Curve	K-factor
<p><b>B.2.1 Welding from both sides</b></p> 	<p>II, IV</p>	<p><math>K_s = 1.0</math>                      Default value <math>K_w = 12</math>                      for <math>\theta = 50 \text{ deg}</math></p>
<p><b>B.2.2 Plate not restricted in out-of-plane movement</b></p> 	<p>II, IV</p>	<p><math>\Delta t = t_2 - t_1</math></p> $K_s = 1 + \frac{3 \frac{\Delta t}{t_1}}{1 + \left(1 + \frac{\Delta t}{t_1}\right)^3}$ $K_w = \left(1 + \frac{\Delta t + e}{2a}\right)$ $K_u = 1 + \frac{6 \frac{e}{t}}{1 + \left(1 + \frac{\Delta t}{t_1}\right)^3}$
<p><b>B.2.3 Welding from one side</b></p> 	<p>II, IV</p>	<p>Welding from one side against temporary or permanent backing. If the root side is ground flush the weld is to be regarded as welded from two sides.</p> <p><math>K_s = 1.0</math>                      Default value: <math>K_w = 14</math>  <math>K_u = 1 + \frac{3e}{t}</math></p>
<p><b>B.2.4 Overlap connection</b></p> 	<p>III, IV</p>	$K_s = \left(4 \frac{t_p}{t_f} + 3 \left(\frac{t_p}{t_f}\right)^2 + 6 \frac{\Delta t_p}{t_f^2}\right)$ <p><math>\Delta = \text{gap} = \text{tolerance}</math></p> <p>Default: <math>\Delta = 1.0 \text{ mm}</math></p> <p><math>K_w = 1.3</math></p>

**Table B.3 Built up sections**

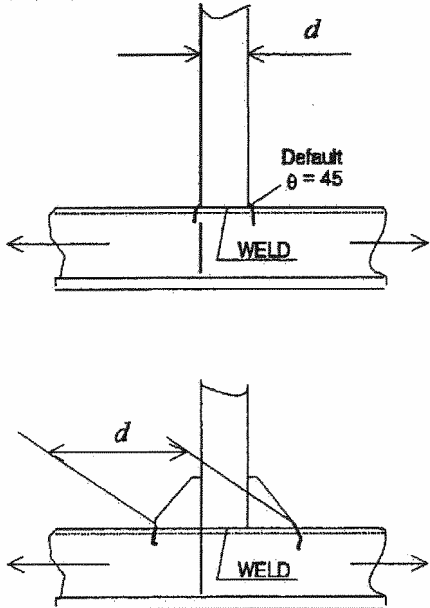
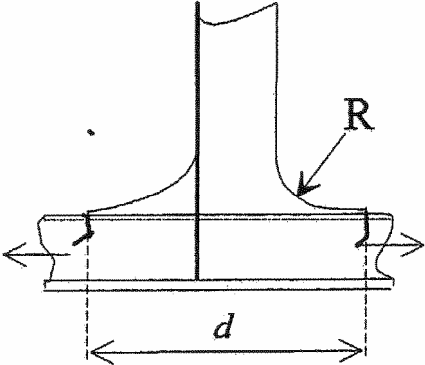
Geometry	SN-Curve	K-factor
<p><b>B.3.1 Plate restricted in out-of-plane movement (e.g. flanges)</b></p>  <p><math>e = 0.15 t_1</math> or max. 3.0 mm.</p>	<p>III, IV</p>	<p><math>\Delta t = t_2 - t_1</math>  <math>K_g = 10</math>  <math>K_w = 11 \left( 1 + \frac{\Delta t + e}{2a} \right)</math>  <math>K_{ts} = 10</math></p>
<p><b>B.3.2 Joining of extruded or built-up components</b></p> 	<p>III, IV</p>	<p><math>K_g = 10</math>  Welded from two sides  Default value <math>K_w = 1.3</math> for <math>\theta = 50</math> deg.  Welded from one side  Default value <math>K_w = 1.7</math></p>
<p><b>B.3.3 a/b Crossing of flanges</b></p> 	<p>III, IV</p>	<p><math>K_g \cdot K_w = 2.2</math>  <math>R \geq 125t</math>  Radius ground  welded from two sides  <math>t =</math> thickness of flange</p> <p>III, IV</p> <p><math>K = 1.9</math></p> <p>Note : To be used together with S-N curve I (for base material)</p>

**Table B.4 Cruciform joints**

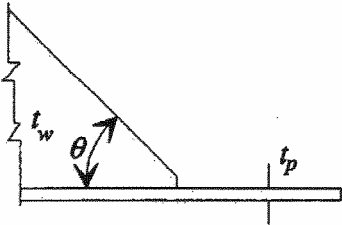
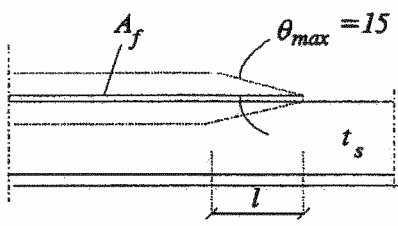
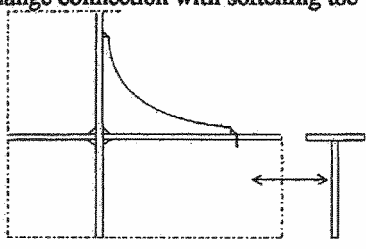
Geometry	SN-Curve	K-factor
<p><b>B.4.1a Full penetration</b></p> 	<p>II, IV</p>	$e = \frac{t_1}{2} + e_0 - \frac{t_2}{2}$ $t_1 \leq t_2; e_0 \leq 0.15t_1$ $K_g = 1.0; K_{ia} = 1.0$ $K_w = 1 + (\tan \theta)^{1/4}$ <p>Default value: <math>K_w = 2.0</math></p>
<p><b>B.4.1b Partial penetration</b></p> 	<p>II, IV</p>	$K_g \cdot K_w = 12 \frac{t_1}{a}$ $K_{ia} = 1.0$ <p><math>K_{ia}</math> is given in Table B.1</p>
<p><b>B.4.2a Fillet weld</b></p> 	<p>II, IV</p>	$K_g \cdot K_w = 1 + 1.4(\tan \theta)^{1/4}$ <p>Default value : <math>K_g \cdot K_w = 2.4</math></p> $K_{ia} = 1.0$
<p><b>B.4.2b Fillet weld</b></p>  <p><math>t_2 \geq t_1</math></p>	<p>II, IV</p>	<p>Based on nominal stress in member with thickness <math>t_1</math></p> $K_g \cdot K_w = 12 \frac{t_1}{a}$ $K_{ia} = 1.0$

K-factors for stiffener supports are given in Table B.5 The factors are applicable to stiffeners subject to axial- and lateral loads.

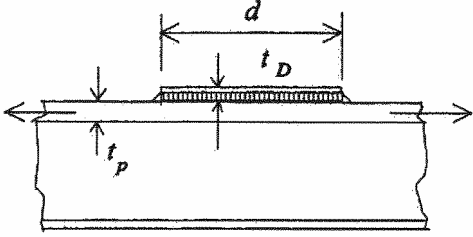
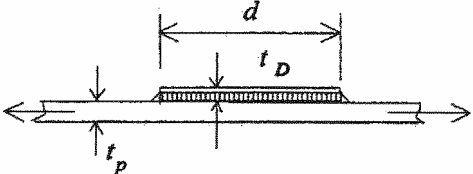
Table B.5 Stiffener supports

Geometry	SN-Curve	K-factor
<p><b>B.5.1a/b</b></p> 	<p>III, IV</p>	<p>Built-up stiffeners. For supporting members welded to stiffener flange:</p> $K_g \cdot K_w = 2.0 \quad d \leq 50$ $K_g \cdot K_w = 2.2 \quad 50 < d \leq 100$ $K_g \cdot K_w = 2.3 \quad 100 < d \leq 150$ $K_g \cdot K_w = 2.5 \quad d > 150$ <p>Extruded stiffeners. For supporting members welded to stiffener flange:</p> $K_g \cdot K_w = 1.8 \quad d \leq 50$ $K_g \cdot K_w = 1.8 \quad 50 < d \leq 100$ $K_g \cdot K_w = 1.8 \quad 100 < d \leq 150$ $K_g \cdot K_w = 2.0 \quad d > 150$
<p><b>B.5.2</b></p> 	<p>III, IV</p>	<p>Built-up stiffeners. For supporting members welded to stiffener flange:</p> $K_g \cdot K_w = 1.8 \left( \frac{60}{R} \right)^{0.05} \quad 100 < d \leq 150$ $K_g \cdot K_w = 2.0 \left( \frac{60}{R} \right)^{0.05} \quad d > 150$ <p>Extruded stiffeners. For supporting members welded to stiffener flange:</p> $K_g \cdot K_w = 1.7 \left( \frac{60}{R} \right)^{0.05} \quad 100 < d \leq 150$ $K_g \cdot K_w = 1.8 \left( \frac{60}{R} \right)^{0.05} \quad d > 150$

**Table B.6 K-factors for termination of stiffeners on plates**

Geometry	SN-Curve	K-factor
<p><b>B.6.1 Local elements and stiffeners welded to plates</b></p> 	<p>II, IV</p>	$K_g K_w = 2 \left( 1 + \frac{t_w \theta}{t_p 160} \right)$ <p><math>\theta</math> = angle in degrees of sloping termination</p>
<p><b>B.6.2 Sniping of top flanges:</b></p> 	<p>II, IV</p>	$K_g K_w = \frac{3A_f}{lt_s}$ <p>and <math>K_g K_w = \min 3.0</math></p>
<p><b>B.6.3 Flange connection with softening toe</b></p> 	<p>III, IV</p>	<p>Table B.5 may be applied</p> $K_g \cdot K_w = 2.0$

## B.7 Doubling plates

Geometry	SN-Curve	K-factor
<b>B.7.1 Cover plates on beams</b> 	II, IV	Welded at its end with throat thickness $a$ $K_g K_w = 3.0$
<b>B.7.2 Doubling plates welded to plates</b> 	II, IV	For $a \geq \frac{t_p \cdot t_D}{t_p + t_D}$ $K_g \cdot K_w = 19 \quad d \leq 50$ $K_g \cdot K_w = 21 \quad 50 < d \leq 100$ $K_g \cdot K_w = 2.4 \quad 100 < d \leq 150$

Note: If the welds of the doubling plates are placed closer to the member (flange, plate) edges than 10mm, The K-factors in Table B.7 should be increased by a factor of 1.3.

## A10 Welded Connections Between Hull Structure and Bulkheads

A reliable fatigue design of the fillet welded connections between the hull structure and bulkheads can be performed following the relevant sections in RP-C203.

For the bulkhead connection for a tubular shaped hull, the stress at the fillet weld on the inside of the hull will be less than the nominal axial stress in the shell. (The nominal stress in the shell is assumed to be due to the global bending moment over the hull structure). This reduced stress can be derived from Section 2.8.8 in RP-C203. The outside of the hull may be the most critical region with respect to fatigue crack initiation.

Therefore bulkheads should be placed a distance  $d = 2\sqrt{rt}$  away from circumferential butt welds, where  $R$  = radius of hull, and  $t$  = thickness of outer shell.

The longitudinal weld seams on the outside within a distance  $d$  on each side of the bulkhead may be the most critical regions with respect to fatigue. Here a flush grinding of the welds may be considered performed in order to improve the fatigue capacity if necessary.

## A11 Selection of S-N Curves

Reference is made to the S-N curves in RP-C203. A conservative design approach with respect to fatigue is to assume environment of seawater with free corrosion. However,

other alternatives may be considered depending on what corrosion protection is used and how often the structure is planned for the structure to be inspected:

Condition in air may be assumed for the inside.

Condition of free corrosion may have to be assumed for the outside if there is no coating.

A condition of air can be assumed as long as the fatigue cracks are small if there is a good coating at the hot spot areas. As the probability of presence of fatigue cracks is statistical in nature it is recommended that such an analysis assumption is combined with a planned inspection for fatigue cracks. Eddy Current (EC) is recommended for inspection of fatigue cracks of areas with coating. Then the coating need not be removed. In case of spurious indications it is recommended to remove the coating and perform inspection by Magnetic Particle Inspection (MPI).

The fatigue cracks are likely small as long as the calculated fatigue damage is less than 0.2. One design approach is to assume that S-N curves in air can be used for a period until the fatigue damage is equal to 0.2 and thereafter assume S-N curves in free corrosion. Or an alternative approach is to assume that inspection is carried out often and that fatigue cracks are repaired when they are detected and new coating is added. Then S-N curves in air can be assumed for the lifetime of the structure.

## **A12 Defects Associated With Different S-N Curves**

Reference is made to the S-N curves in RP-C203. Reference is made to OS-C401 for acceptance criteria for NDT. Reference is made to Table C3, C4 and C5. The given acceptance criteria are not directly linked to one S-N curve. In general planar (i.e. crack-like) defects are not accepted.

The highest S-N curves apply to rather smooth connections. This implies that the nominal stress over the thickness is large and rather uniform into the thickness. This means that if there is a defect at the surface it will grow at a faster rate than in connections classified as less good where the stress range is less and where the crack may grow from a highly stressed area into a less stressed area. This should be reflected in the in-service inspection plan for fatigue cracks. Thus in smooth connections with a high stress range level the need for inspection will be larger than in other connections. Requirements for inspection can be derived from fracture mechanics analysis that is recommended used for planning in-service inspection.

## **A13 Influence of Post Weld Heat Treatment**

If post weld heat treatment (PWHT) has been performed and provided that residual stresses at the hot spots are not introduced when welding the PWHT treated part into the main structure one might for these conditions use a factor 0.6 for reduction of the compressive amplitude similar to that of the base material.

## **A14 Qualification of New S-N Curves**

Some of the S-N data are based on a broad database considering geometry and fabrication. This means that it may be possible to arrive at better S-N data for a particular project where optimisation of the design and fabrication is performed. Items that may be optimised, for example at a butt weld, are fabrication tolerances, notch transition weld toe to base material depending on welding technique etc.

For qualification of new S-N data to be used in a particular project it is important that the test specimens are representative of the actual fabrication and construction used. This includes consideration of relevant production defects as well as fabrication tolerances. The sensitivity to defects may also be assessed by fracture mechanics.

It is recommended that fatigue testing of at least 15 specimens is performed in order to establish a new S-N curve. At least three different stress ranges should be selected in the relevant S-N region such that a representative slope of the S-N curve can be determined. Normally fatigue test data in the range  $10^5$  -  $10^7$  cycles are derived for high cycle fatigue S-N curves.

Reference is made to IIW document no. IIW-XIII-WG1-114-03 for statistical analysis of the fatigue test data. Normally fatigue test data are derived for number of cycles less than  $10^7$ . It should be noted that significant fatigue damage occurs for  $N \geq 10^7$  cycles for structures subjected to environmental loading. Thus extrapolation of the fatigue test data into this high cycle region is an important issue in order to achieve a reliable assessment procedure. In addition to statistical analysis one should use engineering judgement based on experience for derivation of the S-N data in this region. It is well known that good details where fatigue initiation contributes significantly to the fatigue life show a more horizontal S-N curve than for less good details where the fatigue life consists mainly of crack growth. Reference is also made to S-N curves with different slopes shown in the revised RP-C203 (2004).

It should also be remembered that there is additional uncertainty due to variable amplitude loading for  $N \geq 10^7$  cycles. This is an issue that should be kept in mind if less conservative S-N curves than given in DNV-RP-C203 are aimed for by qualification of a new S-N curve.

Also the probability of detecting defects during production should be kept in mind in this respect. The defects that normally can be detected by an acceptable probability are normally larger than those inherent in the test specimens that are produced to establish test data for a new S-N curve.

#### References

*Schneider, C. R. A. and Maddox, S. J. : "Best Practice Guide on Statistical Analysis of Fatigue Data". Doc. IIW-XIII-WG1-114-03.*

*DNV-RP-C203 "Fatigue Strength Analysis of Offshore Steel Structures", Revision planned November 2004.*

## **A15 Design Procedure for Cast Components**

Reference is made to the S-N curves in RP-C203.

The recommendation of design S-N curve for cast components in RP-C203 is based on the assumptions that it is likely that cast components will have to be weld repaired after the casting. If weld repair is not performed a higher S-N curve can be used. For example, if defects in the hot spot areas after casting can be ground away and that the internal defect sizes are acceptable, S-N curve B1 can be used.

In the case that the casting is not weld repaired during fabrication a compressive part of a stress cycle can be considered reduced as for other base material. Reference is made to Section 2.4 of RP-C203. If the casting is weld repaired at the hot spot region and that

Post Weld Heat treatment is performed afterwards, it should be documented by measurements that the residual stress is removed before the same Section in RP-C203 can be applied. Thus, it is recommended, that before a general design is considered using this alternative, a testing of the approach for such structures is carried out.

It is recommended that a fracture mechanics analysis is performed for assessment of crack growth from defects that may be present in the structure after the casting. This crack growth curve can be used for planning inspection and for determining requirements to material fracture toughness such as Charpy requirements and test temperature.

## **A16 Change of Direction of Principal Stress**

Reference is made to Section 2.2 in RP-C203. Where it is not clear what principal direction is most important the following design assessment may be recommended:

- Assume one main stress direction. Then calculate the fatigue damage for all principal stress within  $\pm 45^\circ$  to that of the main stress direction.
- Then try other main directions and follow the same procedure for derivation of fatigue damage.
- Finally select the largest fatigue damage that is assumed to be governing for the considered hot spot.

## **A17 Fatigue of a Hydraulic Ram System**

The S-N curves in RP-C203 can be used for the fatigue design of a hydraulic ram system. The following items should be assessed:

- The tubular that is subjected to varying internal pressure.
- Necks in bolted flanges.
- Bolts.
- Other regions with high stresses.

The effect of pretension can be included in the fatigue assessment of pretensioned bolts. (Pretension of the bolts reduce the stress cycle in bolts subjected to varying tension force but a fatigue analysis of the bolts is still recommended).

Reference:

*NS-EN 1591-1 Flanges and their joints. Design rules for gasketed circular flange connections. Part 1: Calculation method. September 2001.*

## **A18 Fatigue of Steel to Steel Bearings**

At contact surfaces the stress fluctuations will be compressive. These stresses may introduce fretting of the surfaces depending on magnitude of contact pressure. If the contact pressure is less than 10 MPa no special requirements are needed. It can simply be lubricated by the water. (The contact pressure is defined as total force divided by contact area). For increasing pressure up to 50-100 MPa special arrangements will be required to avoid fretting. Guidance on a reliable design can be achieved from other industries where similar supports are used.

## **A19 Fatigue of Bearings with PTFE**

The fretting problem can be removed by using bearings with polytetrafluoroethylene (PTFE) as sliding contact against machined surfaces. A relevant contact pressure should be selected based on manufacturer's specifications. Wear as function of sliding distance is a key parameter and have to be considered in design and when planning maintenance. Relevant test data with respect to contact pressure, sliding velocity, sliding distance, plus/minus sliding, temperature and environment should be provided as part of the documentation of the bearings.

## **A20 Local Design**

Using cast pieces the designer has a good possibility to develop a structure with a low stress concentration at the hot spot area.

It should be noted that a large radius is one way to reduce hot spot stress. However, alternative shapes of transition at notch areas may be more efficient such as ellipses. Refer to Peterson for initial design guidance. (*W. Pilkey: Petersons Stress Concentration Factors.*)

For welded connections similar to typical ship details stress concentration factors can be found in Classification Note 30.7, Appendix A.

## **A21 Finite Element Analysis of Hot Spot Areas**

Reference is made to RP-C203.

## **A22 Cast Steel Components**

### General

The designer should select materials and fabrication processes that lead to adequate levels of toughness and fatigue properties under service conditions.

### Toughness Testing

The materials and fabrication methods used should have sufficient toughness to avoid brittle failure. This can be achieved by specification of Charpy V-Notch toughness requirements at prescribed temperatures. Steel with increased thickness or increased strength may require alternate means for assessing toughness requirements.

CTOD (Crack Tip Opening Displacement) Testing together with rational target toughness values may be used. This approach involves testing of specimens with notches sharpened under cyclic loading to establish a sharp fatigue crack. Then the specimen is subjected to a static loading and the CTOD value at unstable fracture is measured

The target value of CTOD should ensure that detectable fabrication flaws will not propagate in an unstable manner due to quasistatic loading under service conditions. Effects of stress (or strain) concentration, residual stress, and loading rate should be incorporated into the selection of target values. Reference is also made to BS 7910 (1999).

## Fatigue Resistance

This practice recommends fatigue analysis based either on the Palmgren-Miner S-N approach or the fracture mechanics approach. DNV-RP-C203 provides recommended fatigue S-N curves that may be applied for cast components. Depending on combination of material and geometry higher S-N curves may be acceptable. However, it is recommended that a sound justification is established before accepting an S-N curve for design purpose. Such curves should be based on tests carried out on specimens of the appropriate material having micro-structures and weld profiles or notch effects (where appropriate) that model the general characteristics to be found in prototype components. Testing should be carried out under conditions consistent with the actual prototype operating environment with respect to loading frequency, area of application (in air, splash zone, submerged), level of cathodic protection, temperature, bioorganic environment, and stress level. Curves should cover the range of variables where they have significance to design.

The fracture mechanics approach to fatigue analysis should have reliable and pertinent fatigue crack growth data. As with S-N curves, the data should be gathered from tests on specimens having similar:

- Material chemistry and microstructure,
- Environment,
- Loading frequency,
- Cathodic protection,
- Temperature,
- Mean stress.

appropriate to the design situation. In particular, data should be collected at cyclic stress intensity levels pertinent to design. Testing should be carried out on specimens with known KI calibrations. Standard compact and three-point bend specimens should be considered used. Reference is also made to BS 7910 (1999).

## A23 Low Cycle Fatigue

It is assumed that low cycle fatigue due to environmental loading is covered by requirements to ULS design (or ALS for post-accident condition) for this type of structure.

## A24 Concrete Structures

FLS is covered in OS-C502 Section 6 M. Fatigue strength relationships (S-N curves) for concrete are to take into account all relevant parameters, such as;

- concrete quality,
- predominant load effect (axial, flexural, shear, bond or appropriate combinations of these),
- state of stress (cycling in pure compression or compression/tension), and
- surrounding environment (air, submerged).

The calculation of the fatigue strength is detailed in M200:

- Design fatigue life of concrete covering the cases for structure in air, in water with stress variation in the compression-compression range and in water with stress variation in the compression-tension range.

- Design fatigue life of reinforcement with due considerations given for straight and bent reinforcements.

Material coefficient for fatigue is given in Section 6 of B607.

## A25 Composite Structures

### Loading

For checking of fatigue stress (or strain) mean and amplitude of variations are to be used as load value.

### Cycles to Failure Under Cyclic Fatigue Loads

The number of cycles  $N$  to failure under a cyclic stress is described by an S-N curve for a specified R-ratio. The R-ratio is defined as the minimum stress divided by the maximum stress (tensile stresses are defined as positive, while compressive stresses are defined as negative). The material curve of fibre dominated properties for the lifetime strength analysis should be described as stress or strain representation.

All fatigue curves shall be obtained from load controlled tests, unless the structure is clearly only exposed to deformation controlled fatigue.

### S-N Curves

S-N curves may also be measured for specific load sequences if relevant. This may be beneficial, because Miner sum calculations would not be needed for that load sequence. The validity of the data for other load sequences would have to be demonstrated.

### Fatigue Factors

Factors for fatigue calculations is related to the selected safety class (based on the safety philosophy for the device) and it is given in Section 6 E100

### Fatigue Analysis Objective

Fatigue analysis considers two aspects (Section 6 K303): survivability of the structure to the expected load sequence and survivability of the structure to extreme load cases on the end of life.

### FE Modelling

Guidance on FE modelling for composite structures (for example, use of Gauss points rather than nodal points for evaluation of stress and strains due to better accuracy for layered composites) is given in Section 9 E. For laminate structures, layered shell elements with orthotropic material properties for each layer or solid elements with orthotropic material properties (at least two solid elements through the thickness of each ply or layered solid elements where the thickness of a single element includes two or more plies). Software requirements are given in E300 and E600 (validation and verification).

## APPENDIX B - WAVE MODELLING AND LOADS

### B1 Wave Modelling

The spectral density of the sea elevation process may be represented by the JONSWAP spectrum, see OS-J101. The JONSWAP spectrum describes wind sea conditions that are reasonable for the most severe seastates. Moderate and low sea states in open sea areas, not dominated by limited fetch, are often composed of both wind-sea and swell. A two-peak spectrum may be used to account for swell if this is of importance. The Ochi-Hubble spectrum is a general two peak spectrum applicable for most areas. The Torsethaugen spectrum is derived from specific North Sea data, see CN-30.5.

For near shore and shoreline wave energy devices, the evolution of the shape of the wave spectra as the waves propagate into waters of finite depth shall be taken into account. The Bretschneider and TMA wave spectrum can be used for shallow water. The TMA spectrum is developed to incorporate finite depth effects into the JONSWAP spectrum. A finite depth wave spectrum can also be obtained by multiplying an appropriate JONSWAP spectrum by a shape function.

In deep water, the short-term probability distribution of the wave height  $H$  can be assumed to follow a Rayleigh distribution. When predicting the probability of large waves in shallow water for near shore devices, the Rayleigh probability density function (PDF) will overestimate the probability of the expected wave. The reason for this is that the Rayleigh PDF has a finite probability for any wave height, however in shallow water the maximum height of any wave is limited by the water depth. In shallow waters the wave heights are limited by the water depth. The maximum wave height can be taken as 78 % of the water depth. Use of the unmodified Rayleigh distribution for representation of the distribution of wave heights in shallow waters is therefore on the conservative side.

Directionality of waves shall be considered for determination of wave height distributions when such directionality has an impact on the design of the wave energy device.

### B2 Wave Kinematics

#### **Non-Breaking Waves**

The kinematics of regular waves may be described by analytical or numerical wave theories. Wave theory and corresponding wave kinematics shall be selected according to recognised methods with due consideration to actual water depth. Wave kinematics can be described by linear wave theory for seastates with mild slopes, while Stokes wave theories apply for steeper waves. The Stream Function or Boussinesq wave theories can be used to represent the wave kinematics over a broad range of water depths. The ranges of validity of the various wave theories are given in OS-J101. For large volume floating structures where the wave kinematics is disturbed by the presence of the structure, radiation diffraction analyses shall be performed.

#### **Breaking Waves**

Special attention should be given to breaking waves, where wave kinematics deviate from those implied by the theories referred above. The kinematics of breaking waves depends on the type of breaking, surging, plunging or spilling breaker. The type of

breaking is influenced by the ratio of deepwater steepness to seabed slope, by wind-wave interaction, wave-wave interaction and current interaction.

*Spilling breakers* are waves with minor breaking and which retain a steep-sided profile. The kinematics of spilling breakers may be well described by the stream function wave theory. *Plunging breakers* occur when a wave is made to break suddenly by running up a seabed slope. The wave height of a plunging breaker can be high above the limiting regular wave height for the local water depth. The impinging of a plunging breaker on a near shore or at shore wave energy device can lead to high impulsive loads and high local pressures. An approximation of the horizontal water particle velocity between the still water level and the wave crest is  $u_{\max} = 1.25\sqrt{gh}$  where  $h$  is the water depth and  $g$  is the acceleration of gravity. Below the still water level the wave profile and kinematics can be described by the stream function wave theory. *Surging breakers* occur when a very long wave with relatively small amplitude encounters a beach with very gradual slope. These types of breaking waves are unlikely to be of importance for near shore wave energy converters. For certain near shore devices, the presence of the structure itself can cause the wave to break.

Details on different wave theories and wave spectra are given in CN 30.5 Environmental Conditions and Environmental Loads and ISO/DIS 19901-1: Metocean design and operating considerations.

### **B3 Hydrodynamic Loads and Response**

The hydrodynamic loads from waves and currents shall be determined by analysis. For some wave energy devices the geometry is simple enough that state-of-the-art computer tools can predict the response with good accuracy. These are geometries for which a linear wave-structure analysis is sufficient for prediction of structural response. For other geometries, theoretical predictions are subjected to significant uncertainties, for example when there are large variations in geometry close to the water surface. When the intersection angle between still water surface and surface of structure is small, non-linear local effects may be difficult to assess. In such cases calculations shall be supported by model tests or full-scale measurements of existing structures or by a combination of such tests and full-scale measurements.

#### **Model tests**

Hydrodynamic model tests should be carried out to:

- confirm that no important hydrodynamic feature has been overlooked by varying the wave parameters
- support theoretical calculations when available analytical methods are susceptible to large uncertainties
- verify theoretical methods on a general basis

Models shall be sufficient to represent the actual installation. The test set-up and registration system shall provide a basis for reliable, repeatable interpretation. In full-scale measurements it is important to ensure sufficient instrumentation and logging of environmental conditions and responses to ensure reliable interpretation.

Since numerical tools are not yet well suited for prediction of strong non-linear interactions between waves and structures, model tests of survival performance should

be carried out. Typically tests of structural response should be carried out in ULS sea-states with  $10^{-2}$  annual probability. If the wave energy converter is subjected to current loads, such ULS wave conditions should be combined with current conditions with  $10^{-1}$  annual probability.

### Combinations of environmental loads

Guidance on combinations of different environmental loads in order to obtain ULS combinations with  $10^{-2}$  annual probability is given in OS-C101 Chapter 1 Section 3 and it is given below:

Proposed Combinations of Different Environmental Loads (from OS-C101)					
<i>Limit State</i>	<i>Wind</i>	<i>Waves</i>	<i>Current</i>	<i>Ice</i>	<i>Sea Level</i>
ULS	$10^{-2}$	$10^{-2}$	$10^{-1}$		$10^{-2}$
	$10^{-1}$	$10^{-1}$	$10^{-2}$		$10^{-2}$
	$10^{-1}$	$10^{-1}$	$10^{-1}$	$10^{-2}$	Mean water level
ALS	Return period not less than 1 year	Return period not less than 1 year	Return period not less than 1 year		Return period not less than 1 year

Table B3.1

1 year, 10 years and 100 years return periods are common in offshore engineering and used throughout offshore standards. For a device service life considerably lower than 100 years lower return periods can be used as design criteria if this is acceptable for the safety and survivability of the structure.

### Model test specifications

General requirements and issues related to wave structure model testing can be found in “Review of model testing requirements for FPSO’s”, BMT Offshore Technology Report, 2000/123 (2001). Issues to be considered during a model test include;

- selection of test metocean conditions,
- selection of model scale,
- assessment of scale effects,
- wave generation techniques,
- generation of wind in wave basin,
- generation of current in wave basin,
- modelling of non-collinear environments,
- run duration,
- design of equivalent or hybrid mooring systems for deep water, and
- issues related to wave impact.

Full-scale measurements using a prototype device may be used to reduce uncertainties associated with loads and load effects that are difficult to simulate in model scale. In full-scale measurements it is important to ensure sufficient instrumentation and logging of environmental conditions and responses to ensure reliable interpretation.

## **B4 Analysis of Wave Loading**

Offshore wave energy devices are located in shallow to moderately deep water. For calculation of wave loads, a recognised wave theory for representation of the wave kinematics shall be applied. A calculation method for wave load prediction shall be selected that properly accounts for the size (in relation to characteristic wave length), shape and type of structure. For slender structures, Morison's load formula can be applied. For large volume structures, for which the wave kinematics are disturbed by the presence of the structure, a three-dimensional diffraction analysis shall be performed.

The loads exerted by the fluid on a body in waves may have different nature: diffraction or wave-making loads, inertia loads and viscous drag loads. Each of these loads may become dominant, according to the typical wavelength, structure size and wave height considered. A guidance to establish the limits of the different areas where each of these loads dominate is given in OS-J101.

### **Loads on Small, Slender Structures**

For small and slender structures, where the characteristic dimension is less than 1/5 of a typical wave length, Morison's load formula is applicable, using two-dimensional hydrodynamic coefficients for added mass, excitation forces, including viscous drag, in a strip theory formulation. The hydrodynamic force exerted on a strip of a cylinder of diameter  $D$  by a flow velocity  $u$  and acceleration  $a$  is

$$dF = \pi\rho \frac{D}{4} C_M a + \frac{\rho}{2} D C_D |u|u$$

where the first term proportional to the acceleration of the fluid is the inertia term and the second term is the viscous drag term representing flow separation, vortex shedding and shear forces. The hydrodynamic coefficients  $C_M$  and  $C_D$  are the mass and drag coefficients and depend on the cross-sectional shape of the structure. The hydrodynamic coefficients are in general functions of the Reynold's number, the Keulegan-Carpenter number and the relative roughness. They are determined by model tests or by Computational Fluid Dynamics simulations, solving Navier-Stokes equation for the fluid velocity vector and the fluid pressure.

Marine growth on submerged structures, caused by plants, animals and bacteria, may cause an increase in hydrodynamic drag and added mass. Similarly possible increase of cross-sectional area and changes of roughness caused by icing shall be considered, where relevant, when determining hydrodynamic loads.

Non-linear body dynamics effects can be modelled by using hydrodynamic coefficients evaluated at the instantaneous position of the structure in the vicinity of the free surface. Hydrodynamic coefficients for various 2D sections are given in CN-30.5.

### **Loads on Large Volume Structures**

When the structure is large enough to produce major disturbances to the incident wave field, and to radiate its own waves when it moves, viscous effects are generally small and potential flow theory can be used. The numerical modelling of the interaction between wave energy devices and water waves is usually done by solving Laplace's equation using the Boundary Element Method (BEM). Several commercial computer codes are available for prediction of wave induced response of fixed or floating large volume structures.

The numerical modelling of wave induced response of wave energy devices can follow two approaches: frequency domain and time domain and several levels of linearisation, from first order, second order, etc. to fully non-linear. At the lowest level, first order frequency domain it is assumed that the amplitudes of both wave steepness and body motions are vanishingly small, with all the flow and response quantities being harmonic in time at a single wave frequency  $\omega$ . This lowest level should always be the starting point for linking the dimensioning of the device to the dynamics of the body in waves. In the linear domain frequency and time domain are linked by reciprocal Fourier transform relationships.

For multi-body wave energy devices the diffraction computer code applied should be able to predict the response of N connected or independent floating bodies. For a structure consisting of N rigid bodies, there are in principle 6N degrees of freedom (dof). If the bodies are connected by joints with a limited number of dof's, the total number of dof's can be considerably reduced. In the case of joints with 2 degrees of freedom (i.e. pitch and yaw), the 6N equations of motion are reduced by eliminating the internal forces to a total number of 2N+4 degrees of freedom. In a time-domain analysis non-linear stiffness and damping can be modelled directly.

Linear Response Amplitude Operators for structural response in waves can be applied to annual wave spectra sets to provide predictions of annual power absorption. Hence, a linear frequency domain methodology can be used to perform large parametric studies or automated numerical optimisation of performance of marine energy devices.

A linear frequency domain methodology is well suited for large parameter and sensitivity studies. However, since some wave energy devices are designed and optimised to have large amplitude response to maximise power output, a non-linear analysis is often more necessary than other ocean structures. A time-domain analysis with linear body dynamics and non-linear stiffness and damping is applicable for prediction of response and power absorption in moderate seas, while a fully non-linear strip theory approach may be used to study ULS wave loading conditions and survivability in large seas.

Wave-structure interactions in large steep waves corresponding to a ULS loading condition, may include strong local nonlinearities like wave impact, slamming and exit from waves. Due consideration should be made to account for effects of pressure pulses of short time duration.

Characteristic values of individual environmental loads are defined by an annual probability of exceedance. The long-term variability of multiple loads is described by a scatter diagram of joint density function including information about direction. Environmental loads from waves and current shall be combined in such a way as to obtain ULS combinations with a specified annual probability of exceedance corresponding to the design life of the device. See DNV OS-C101.

Load effects in terms of motions, displacements and internal forces and stresses of the structure shall be determined with due regard for;

- spatial and temporal nature of load,
- relevant limit states for design check, and
- desired accuracy in the relevant design phase.

In general three frequency bands may need to be considered for a wave energy device:

- High frequency response: Flexural resonance periods below dominating wave period. Typical for monotower devices being exposed to impact loads from near breaking waves.
- Wave frequency response: Rigid body or flexural response at periods around peak period in wave spectrum
- Low frequency response: Slowly varying response with natural periods above dominating wave energy. Typical for moored wave energy devices.

It is often common procedure to predict the response of the floater and mooring (including mooring elements) using uncoupled analysis. For a moored floating wave energy device in relatively deep water, inertia and damping effects of mooring may require a coupled analysis, solving in the time domain for the floating device and mooring simultaneously. Recommendations on methods for coupled analyses are described in RP-F205.

## **B5 Analysis of Wave Loading on Near-Shore and Shoreline Wave Energy Devices**

### **Shallow Water Wave Data**

Shoreline WECs are located on land, while near shore WECs may be defined as being located in open water, but being visible from land A near shore WEC is fixed to the seabed. The environmental loading depends strongly on the location of the device.

The wave environment at the site of a near shore WEC is very much site specific, depending on the following variables: Coastline profile, water depth at device, bathymetry, incident wave spectra and directional spreading. The annual wave climate at the site of the device should be derived from measurements. If wave data for a waverider buoy further out to sea is to be used, the data should be transformed to the site using a derived transfer function.

### **Wave Loads from Breaking Waves**

When waves are likely to break on the site of the device, wave loads from breaking waves shall be considered in the design of the structure. Wave loads from breaking waves depend on the type of breaking waves due to differences in the wave kinematics. For plunging waves, an impact load model may be used to calculate the forces on the structure. The impact force from a plunging wave can be expressed as  $F = \frac{1}{2} \rho C_s A u^2$  where  $u$  denotes the water particle velocity at the plunging wave crest,  $A$  is the area of the structure which is assumed exposed to the slamming force, and  $C_s$  is the slamming coefficient. For a smooth cylinder, the slamming coefficient should not be taken less than 3.0. The upper limit for the slamming coefficient is  $2\pi$ . Careful selection of slamming coefficients can be made according to CN-30.5. For spilling breakers the total load can be calculated using a strip theory where the slamming coefficient for each strip is a function of the submergence of the strip, decaying from 5.15 when the wave hits the strip to 0.8 when the strip is fully submerged. (refer to OS-J101).

Dynamic effects shall be considered when predicting wave load effects on a structure. When breaking of waves takes place close to the structure, rather large dynamic amplification factors may develop in the structure. Depending on the frequency of the waves relative to the natural frequency of the structure, dynamic magnification may

arise, depending on the duration of the impact loading relative to the natural frequency of the structure.

### **Wave Loads Due to Run-Up and Green Water**

Loads due to run-up induced impact and green water over-topping the device should be considered.

## APPENDIX C - TECHNICAL CONSIDERATIONS FOR AIR FLOW TURBINES

### C1 Specifications, Features and Operational Modes

Key turbine parameters should be provided as given in Table C1-1 and the application constraints as given in Table C1-2, for instrumentation and automation, including computer-based control and monitoring, reference is made to Section 19 INSTRUMENTATION AND CONTROL SYSTEMS.

Mass (kg)				
Time between overhaul (hrs / cycles or equivalent hours)				
	RATING			
	IDLE	MCR ISO <sup>1)</sup>	MCR <sup>2)</sup>	PEAK <sup>3)</sup>
Maximum continuous ratings (kW)				
Maximum air mass flow rate (kg/s)				
Pressure at all main sections of the turbine(bar)				
Generator speed(s) (rpm)				
Turbine speed (rpm)				
	NORMAL			PEAK
Max. permissible rate of load increase and load decrease (kW/s)				
Max. permissible rate of acceleration and deceleration (rpm./s)				
1) MCR at standard ISO 2314 ambient conditions Temperature: 15 °C Humidity: 60% relative Barometric pressure: 1.013 bar (760 mm Hg). 2) Maximum parameter value for continuous running independent of ambient conditions 3) If applicable, maximum parameter value for time limited peak or emergency operation				

Table C1-1 : Documentation of General Technical Specifications

<i>Subject</i>	<i>Unit</i>
Max allowable list and trim	(degrees)
Max allowable pitch and roll	(degrees/s)
Max allowable shear force on output shaft	(N)
Max allowable axial force on output shaft	(N)
Max allowable bending moment at output shaft	(Nm)
Max allowable acceleration loads	(g)
Max allowable salt content in inlet air	(wppm)

Table C1-2 : Application Constraints

The design and construction should enable the turbine to meet the general requirements with regard to environmental conditions, functional capability and to reliability and availability. The turbine must be capable of withstanding environmentally induced acceleration loads during operations. A two-dimensional design envelope made up of

what may be sustained during normal operation and what may be experienced occasionally (e.g., storm conditions) should be carried out. The turbine must not suffer unreasonable distortion (or stress) if these loads are applied repeatedly.

## **C2 General Arrangement Drawings**

General arrangement drawings of the turbine should include the following;

- turbine rotor,
- bearings,
- seals,
- blades,
- disks, and
- shafts.

## **C3 Bladed Disks**

The documentation of the bladed disk should as a minimum contain the data required in this item. In addition drawings indicating main dimensions, materials and presence of coating should be submitted.

### **Static strength evaluation**

The following aspects should be considered;

- low cycle fatigue (LCF) and creep,
- centrifugal forces and aerodynamic pressure for steady state conditions and worst case transient conditions,
- geometric stress raisers e.g. blade neck, fir-tree blade, disk interface and typically disk stress raisers,
- finite element analysis (FEM) or equivalent methods should be used for the stress calculations,
- disk blade retention capacity, with special attention to the blade and root disk connections considering any foreseeable overspeeds, and
- disk burst speed capacity (higher than that achievable while the unit is governed by the control system).

Fatigue diagrams can be used in demonstrating life for LCF. For documentation of creep life, recognised methods, as e.g. Larson-Miller should be used.

A final analysis considering the actual material specification (including test specimen scatter) may be carried out to identify the final result in a margin of safety, at critical locations.

Blades fitted with interference shall have the local pressure documented, and analyses shall include combined stress. If rubbing of the blade tips can be expected during operation, the blades are to be designed so as to minimise the mechanical damage. In cases where the disk is connected to the shaft with interference fit, it is required to substantiate the disk's capability to transmit the required torque. Consideration should be given to the effect of centrifugal forces and interference tolerances.

## Dynamic strength evaluation

The following aspects should be considered:

- High cycle fatigue (HCF). When evaluating the HCF life of a bladed disc the dynamic loads shall be combined with the static loads in a total strength evaluation.
- Blade vibration modes. The excitation sources to be considered as a minimum are the following frequencies in the whole operating range: 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> order of rotating speed and 1<sup>st</sup> and 2<sup>nd</sup> order of nozzle passing frequency. The frequencies shall be presented in a Campbell diagram or equivalent for speeds from 0% to 110% full speed.
- Blade □ disc coupling influence on the blade natural modes (if applicable) with the nodal diameter of interest. In case resonance is excited by any source within 10% of the operating speed range, measurements and tests must document high cycle fatigue margin.

## C4 Casing

The following loads are applicable;

- tension,
- bending moment,
- shear, and
- torque.

Buckling is to be considered if applicable. The hoop-stress values shall not exceed the allowable values as required by international standards such as ASME codes (Section VIII Division 1, the revision which coincides with the validity of these rules) or equivalent aerospace standards.

## C5 Bolted Flange Design

Bolt pre-load calculations shall be performed, including fatigue considerations.

## C6 Containment and Rotor Failure

All sections of the casing exposed to rotating parts should be able to contain a projectile such as blades or parts thereof (minimum one blade for axial units, in the case of a radial units 1/3 disk disintegration) and not lead to failure in the mounting system. Exceptions to these requirements can be considered if the enclosure is designed for complete containment capability from the same rotor failure modes.

## C7 Inspection Openings

The design shall have features that permit boroscope inspection or equivalent.

## C8 Rolling Element Bearings

Design of rolling bearings should consider the following:

- Details of bearings, such as major dimensions, materials, grade of precision etc.
- Lifetime calculations based on normal loads (forces and gyroscopic moments in case of floating structure, vibration load, mass load, thrust load, misalignment load, pre-loading, etc. as applicable).
- Overload capability based on loss of a part, e.g. blade.

- Lubrication oil temperature and pressure.
- Blade-out loads based on worst case blade loss (in terms of resulting unbalance in the applicable time interval where these forces will act (shutdown, step to idle).
- Bearings are generally to be designed with the capability of withstanding forces resulting from any rotor failure modes.
- In case of a shaft coupling separation and consequent overspeed, the bearings should be capable of withstanding the increased unbalance forces (e.g. due to consequent blade loss). In this case the bearings only need to hold the rotor from complete destruction, bearings could themselves be damaged. Due consideration of historical failure data for the bearings.

## C9 Thrust bearings

The calculations should consider the following items;

- aerodynamic loading and the influence by design tolerances,
- allowable thrust load,
- the worst case vector sum of thrust forces,
- potential unloaded conditions (skidding for rolling bearing elements) must be carefully evaluated (e.g., change of direction for thrust in the speed range) and design should take into consideration the combination of clearances, loads, oil viscosity and operation so as to minimise the risk of this occurring.

## C10 Housing for Hydrodynamic Bearings

For the structure of the bearing housing and the casing the design should consider the following:

- Blade loss or other rotor damage will not cause the bearing housing or casing to fracture in the actual time interval when exposed to these abnormal forces.
- Bearing housing for pressure lubricated hydrodynamic bearings shall be adequate to maintain the oil and foam mixture level below the shaft seals at all times.
- Temperature rise in the bearings and bearing housing, together with lubrication oil temperature shall be within manufacturer's specifications when operating under the most severe conditions of ambient temperature and load.
- Bearings shall be equipped with replaceable labyrinth-type seals and deflectors where the shaft passes through the housing.

## C11 Rotors

The following should be considered for rotor design;

- calculations of natural frequencies, including support structures,
- maximum permissible residual unbalance,
- to be able to operate safely from zero to 110% of turbine trip speed,
- vibration calculations (lateral and torsional where applicable) (for data that cannot be given as constant parameters, the assumed parameter dependency and tolerance range are to be specified).

Rotors shall be able to withstand instantaneous coupling shaft failure at full load. Rotor disk or shaft failure or separation arising from the ensuing overspeed is not acceptable.

Blade loss will be acceptable provided it can be proven that the blade or blades loss can be contained.

## **C12 Shafts**

The following should be considered:

- surface finish
- strength analyses taking into consideration stress raisers, such as notches, holes, etc., and the effects due to interference fits
- normal running and abnormal conditions, such as shock-load conditions, where applicable.

The admissible run-out, electrical, and mechanical shall be documented. The admissible residual magnetism shall be stated.

## **C13 Starting Systems**

The following should be considered as a minimum:

Electric starting system;

- starting torque required,
- motor power and speed,
- starting logic and set points, and
- disengaging speed.

Alternatively, the grid energy can be used.

## **C14 Lubricating Oil System**

Turbine lubrication system should address the following;

- maximum and minimum pressure and temperature in the system,
- type of lubricating oil,
- maximum permissible amount by volume of water in the oil,
- oil filtration requirement, according to NAS 1638 or ISO 4406 (or equivalent),
- sufficient filtering, heat exchanger capacity, magnetic chip detectors located as necessary, and water separator arrangements (if necessary), and
- any shutdown of the turbine, either due to a normal shutdown or shutdown due to turbine trip is not to result in damage to any turbine bearings.

Normally, turbines with rolling element bearings shall have a separate lube oil system.

# APPENDIX D - TECHNICAL CONSIDERATIONS FOR GEARBOXES

## D1 Shafts

Consideration should be given to ensure proper alignment of shafts. Calculations for shaft alignment should consider the following:

- bearing clearances
- bearing offsets from the defined reference line
- bearing deflections
- shaft deflections with respect to the defined reference line

The load conditions should include both extreme and fatigue loads. Details, such as fillets, keyways, radial holes, slots, surface roughness, shrinkage amounts, contact between tapered parts, pull up on taper, bolt pretension, protection against corrosion, welding details etc. as well as material types, mechanical properties, cleanliness and NDT specification should be defined and evaluated against the design requirement and loading.

Shaft design should take into account aspects to prevent fatigue failure and local deformation. DNV CN 41.4 offers detailed methods on how to assess the safety factor criteria mentioned in Table D1-1.

<i>Criteria</i>	<i>Safety factor, S</i>
Low cycle ( $N_c < 10^4$ stress cycles)	Peak stresses: 1.4 Reversed stresses in notches: 1.25
High cycle ( $N_c \gg 3 \cdot 10^6$ stress cycles)	1.6
Transient vibration when passing through a barred speed range: ( $10^4 < N_c < 3 \cdot 10^6$ stress cycles)	Linear interpolation ( $\log\tau$ - $\log N$ diagram) between the low cycle, peak stresses criterion with $S = 1.4$ and the high cycle criterion with $S = 1.6$ .

Table D1-1 Shaft safety factors

For applications where it may be necessary to take the advantage of tensile strength above 800 MPa and yield strength above 600 MPa, material cleanliness has an increasing importance. Higher cleanliness than specified by material standards may be required (preferably to be specified according to ISO 4947). Furthermore, special protection against corrosion is required.

Stainless steel shafts are to be designed to avoid cavities (pockets) where the seawater may remain uncirculated (e.g. in keyways). For other materials, special consideration applies to fatigue values and pitting corrosion resistance. The shaft safety factors for the different applications and criteria detailed in Classification Note 41.4 should be, at least, in accordance with Table D1-1. The safety factors should be applied to the response due to characteristic loads i.e. without load factor.

For a more detailed fatigue assessment see Guideline for Design of wind Turbines Section 6.1.3 Fatigue Strength. There it is presented the fatigue strength in terms of S-N curves and also the various factors influencing the definition of S-N curves from small specimens in laboratory tests.

## D1.1 Bearings

The design should consider all details as dimensions with tolerances, bearing types, material types, the lubrication system including oil cleanliness and oil temperature. The design should also consider the loading conditions including accelerations, deformations.

Bearing type should be selected based on the loads (axial, radial forces), rpm, motion, acceleration, relative deformations and misalignments of the shafts and their supports, lubrication, maintenance requirements and monitoring requirements. Experience from similar applications should also be considered.

The bearing loads are normally defined as a spectrum with associated operational and environmental conditions and expected number of operation hours.

Non-rubbing seals exhibit no friction and no wear and form a good supplement to other seals. Bearing seals may be important for retaining bearing lubrication and to keep out contaminants.

Bearing dimensions and design details are discussed in Ship Rules Pt.4 Ch.4 Sec.1 B900 and B1000 as well as in AGMA 6006-A03 for wind application.

## D1.2 Connections

Design of flange connections is addressed in Ship Rules Pt.4 Ch.4 Sec.1B 300. Shrink fit connections is addressed in B400, keyed connections in B500, clamping couplings in B600 and spline connections in B700.

## D1.3 Inspection

All shafts, coupling hubs, bolts, keys and liners should be tested and documented as specified in Table D1-2.

<i>Part</i>	<i>Chemical composition (ladle analysis)</i>	<i>Mechanical properties</i>	<i>Ultrasonic testing</i>	<i>Crack detection <sup>1)</sup></i>	<i>Hydraulic testing</i>	<i>Visual and dimensional check <sup>2)</sup></i>
Shafts <sup>3) 7)</sup>	Yes	Yes	Yes	Yes	-	Yes
Rigid couplings when torque	Yes	Yes	Yes	Yes	-	Yes
Keys, bolts and shear pins	Yes	Yes	-	-	-	Yes <sup>4)</sup>
Shaft liners	Yes	-	-	Yes <sup>5)</sup>	Yes <sup>6)</sup>	-
<ol style="list-style-type: none"> <li>1. By means of magnetic particle inspection or dye penetrant. To be carried out in way of all stress raisers (fillets, keyways, radial holes, shrinkage surfaces on propulsion shafts etc.). If especially required due to nominal stress levels, also the plain parts shall be crack detected. No cracks are acceptable</li> <li>2. The visual inspection shall include checking of all stress raisers (see above) with regard to radii and surface roughness, and for plain portions, the surface roughness. It is also to include the shaft's protection against corrosion, if this is provided prior to installation onboard. Dimensional inspection to be done in way of shrinkage surfaces (actual shrinkage amount or individual dimensions shall be documented).</li> <li>3. Any welds to be NDT checked (ultrasonic testing and surface crack detection) and documented.</li> <li>4. Can be omitted for keys, bolts and shear pins in reduction gears. Can also be omitted for friction bolts of standard type.</li> <li>5. In way of fusion between pieces.</li> <li>6. Test pressure 2 bar.</li> <li>7. However, not applicable for rotor shafts in generators.</li> </ol>						

Table D1-2 Requirements for documentation and testing

For shafts, hubs and liners that are assembled at the manufacturer's premises, the following should be verified:

- Liners mounted on the shaft with regard to tightness (hammer test) and that any specified space between shaft and liner is filled with a plastic insoluble non-corrosive compound.
- Shrink fit couplings mounted on the shaft with regard to the specified shrinkage amount (diametrical expansion, pull up length, etc.). For tapered connections the contact between the male and the female part shall be verified as specified.
- Bolted connections with regard to bolt pretension.
- Keyed connections with regard to key fit in shaft and hub.

Shafts for high speed rotation need to be dynamically balanced.

#### D1.4 Control and monitoring

In order to improve reliability and maintenance based on behaviour of the equipments, monitoring of main shaft parameters should be considered. Also, to avoid damage, alarms may be defined to define shut down of the operation or to indicate operations beyond the normal parameters for operation.

During inspections oil samples should be taken for oil lubricated shaft arrangements. Presence of water and contaminants should be checked. Water content should be limited to 0.5%. Oil volume should be checked (checking for leakage).

#### D1.5 Shaft Arrangement

The shafting system should be evaluated for the influence of:

- thermal expansion
- shaft alignment forces
- universal joint forces
- tooth coupling reaction forces
- elastic coupling reaction forces (with particular attention to unbalanced forces from segmented elements)
- hydrodynamic forces on moving parts or any input load on the shaft.
- forces due to movements
- forces due to whirling vibration
- forces due to distortion or sink-in of flexible pads.

#### D1.6 Installation Inspection

Clamp couplings should be checked with regard to tightening of the bolts. This should preferably be made by measuring elongation (applicable for through bolts).

Keyed connections should be checked with regard to:

- shrinkage amount between hub and shaft (applicable to cylindrical connections)
- contact between male and female tapered members, (full contact band at upper end required)
- push up force or pull up length of tapered connections
- key tight fit in shaft and hub (applicable to reversing plants).

Keyless shrink fit connections should be checked with regard to:

- circumferential orientation (marking) between the parts (not applicable to sleeve couplings)
- contact between male and female tapered members (not applicable for couplings certified as hub and sleeve together and contact checked at the manufacturer). As a minimum there should be a full contact band at the big end. For wet mounting, the contact may be improved by light grinding with a soft disc and emery paper in the hub (not the shaft). A test pull up may also be used to improve the contact.
- shrinkage amount, verified by diametrical expansion or pull up length
- draining and venting (by air).

Bearing clearances (for fluid film bearings) should be recorded. The protection against corrosion of shafts should be checked. The shaft alignment should be within the tolerances given in the shaft alignment specification.

Temperature in fluid film bearings and vibrations should be measured (see Pt.4 Ch.4 Sec. 11).

## D2 Gear Transmissions

Ship Rules Pt.4 Ch.4 Sec.2 describes the requirements for gear transmissions that should also comply with the general requirements for rotating machinery (Pt.4 Ch.2).

Some common gear types are spur and helical gears, epicyclic or planetary gears, bevel gears, worm gears and hypoid gears. The “involute teeth” is the form almost universally used in helical, spur, bevel and worm gears. The bearing types for gears may be ball bearings, cylindrical roller, spherical roller and tapered roller bearings.

### Design principles

The gearing may be verified on the basis of calculations and preferably combined with tests in workshop and field tests.

Calculation methods as given in Classification Note 41.2, comprising information on calculation of tooth root strength (root fractures), flank surface durability (pitting, spalling, case crushing and tooth fractures starting from the flank), and scuffing. Alternative methods to the ones given in Classification Note 41.2 may also be considered on the basis of equivalence.

The gear teeth should be designed with the minimum safety factors. The safety factors should be in the range as given in Table D2-1 for propulsion and auxiliary.

	<i>Auxiliary</i>	<i>Propulsion</i>
Tooth root fracture $S_F$	1.4 <sup>3)</sup>	1.55
Pitting, spalling and case crushing $S_H$ <sup>1)</sup>	1.15	1.20
Scuffing $S_S$ <sup>1) 2)</sup>	1.4	1.5
<ol style="list-style-type: none"> <li>1. These safety factors apply to medium and high speed gears designed for long lifetimes (e.g. <math>&gt; 10^6</math> load cycles). For slow speed gears with short design life time (e.g. <math>&lt;&lt; 10^6</math> load cycles) and where certain flank deterioration is acceptable, lower values may be considered.</li> <li>2. For medium and high speed gears as mentioned above, a minimum difference of 50°C between scuffing temperature and contact temperature applies in addition to the safety factor. However, if an oil inlet temperature alarm is installed, the minimum difference of 30°C between scuffing temperature and actual alarm level applies.</li> <li>3. If an auxiliary gear stage is arranged as a power take off from a propulsion gearbox, and a tooth fracture of the auxiliary gear stage may cause a consequential damage to the propulsion system, the tooth root safety factor shall be as for propulsion.</li> </ol>		

Table D2-1 Minimum safety factors

Due to the scatter of the FZG test results, the FZG level used in the calculations should be one level lower than the specified. Any gear utilising oils with specified FZG level above 12, the test results for the actual oil should be documented in a test report from a recognised laboratory, and/or oil supplier.

Gear designs may be limited by other criteria as those mentioned in above. For example if service experience indicates that failure modes other than those above become a problem (such as oblique fractures starting from the active flank, grey staining developing to pitting etc.), hence, a gear design may be inappropriate even though the criteria above are fulfilled.

Gear designs should take into account all relevant load conditions such as dynamics. If transient load conditions result in reverse torque, this influence should be considered.

Quenched and tempered steels and all surface hardened steels should have a level of cleanliness that is suitable for the permissible stress level for high cycle fatigue. A suitable level in this context is e.g. chart/diagram index 2 for all groups A - DS in ISO 4967.

### D2.1 Shrink fitted pinions and wheels

While shrunk on pinions or wheels avoid the possibility of key-slot stress raisers they should be designed to prevent detrimental fretting, macro slippage and micromovements. The criteria for macro slippage and fretting are given in Pt.4 Ch.4 Sec.1 B400 (shrink fit connections). The influence of axial forces and tilting moments should be considered. Shrink fitted rims should have a minimum safety of 2.0 against micromovements based on the specified peak torque. The coefficient of friction  $\mu$  may be taken from Table D2.2

Application	Hub material (Shaft material = steel)		
	Steel	Cast iron or nodular cast iron	Bronze
Oil injection	0.14	0.12	0.13
Dry fit on taper	0.15	-	0.15
Glycerine injection (parts carefully degreased)	0.18	0.16	0.17
Heated in oil	0.13	0.10	-
Dry heated/cooled (parts not degreased or protected vs. oil penetration; nor high shrinkage pressure applied)	0.15	0.12	-
Dry heated/cooled (parts degreased and protected vs. oil penetration; or high shrinkage pressure applied)	0.20	0.16	-
Special friction coating	To be specially evaluated		

Table D2.2 Static coefficients of friction,  $\mu$

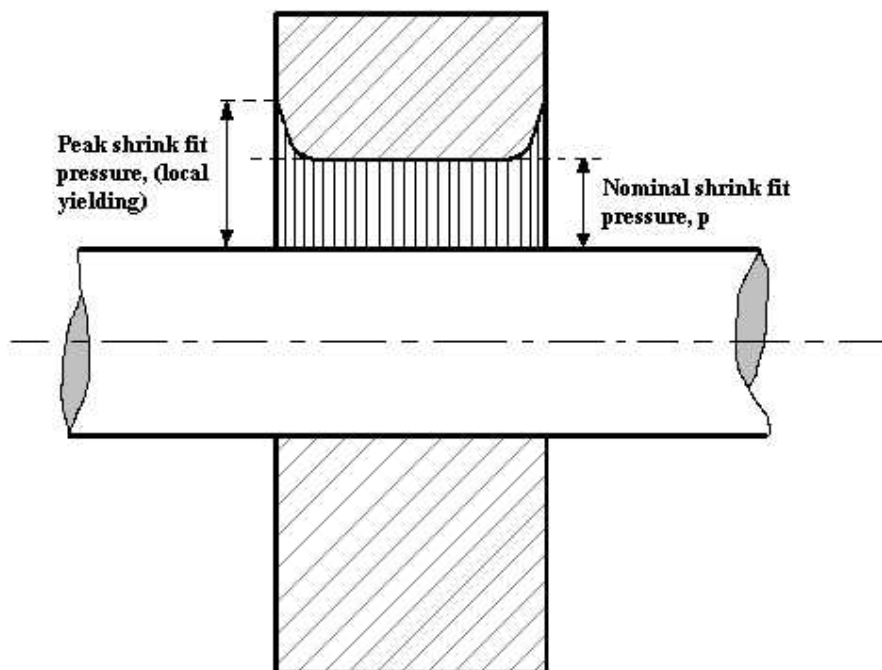


Fig. D2.1 Shrink fitted body with especially high surface pressure (only applicable for shafts protruding on each end)

The safety against micromovements is:

$$S = (p + \sigma) \mu / \tau = F_{lim}/F.$$

## D2.2 Shafts

Shafts should be designed to prevent fatigue. Detailed criteria are given in CN 41.4 - Calculation of Shafts in Marine Applications. When gear transmissions are designed for long lifetime (i.e.  $\gg 10^6$  cycles), the shafts should be designed to prevent detrimental fretting that may cause fatigue failures.

Practically, shafts with significant bending stresses such as pinion and wheel shafts are dimensioned with regard to stiffness (gear mesh considerations) and high cycle fatigue,

but hardly ever for low cycle fatigue because the two first will prevail. For short shafts made by blanks cut from forged bars without further forging, see Pt.4 Ch.2 Sec.3 A205.

### D2.3 Bearings

Fluid film bearings should be designed with bearing pressures that are suitable for the bearing metals. The calculation of bearing pressures should include the application factor  $K_A$ .

Ball and roller bearings should have a minimum  $L_{10a}$  (ISO 281) life time that is suitable with regard to the target design life and maintenance requirements. The influence of the lubrication oil film may be taken into account for  $L_{10a}$ , provided that the necessary conditions, in particular cleanliness, are fulfilled. For grease lubrication and oil lubrication without filter, the contamination factor  $\eta_c$  should not be chosen higher than 0.2. For oil lubrication with off-line filtering the contamination factor of 0.5-0.7 may be considered. Large bearings are less sensitive to contamination particles of a certain size than smaller bearings. See also D2.5.

The static safety factor  $C_0/P_0$  based on the extreme load cases including load safety factors should not be lower than 3.

In general for WECs rolling bearings should be designed for the target design life which is normally defined as 20 years. For low speed rotating bearings, the required basic rating life  $L_{10h}$  should exceed 100000 hours using the specified load conditions. The modified rating life  $L_{10mh}$  should at the same time reach at least the target design life. Other rating methods may be applied and the calculated bearing life should always exceed the target design life.

### D2.4 Casing

Inspection openings should be provided in order to enable inspection of all pinions and wheels (measurements of backlash and application of lacquer for contact pattern verification) as well as for access to clutch emergency bolts (if applicable). For special designs (e.g. some epicyclic gears) where inspection openings cannot be provided without severely affecting the strength of the design, holes for endoscope inspections may be a substitute to openings. Such holes should be positioned to enable endoscope inspection of all gearing elements. Easy access to all inspection openings should preferably be provided. This means that no piping or coolers etc. should be positioned to prevent access. In order to prevent rust, the gear casing should be provided with proper ventilation.

### D2.5 Lubrication system

The lubrication system should be designed to provide all bearings, gear meshes and other parts requiring oil with adequate amount of clean oil for both lubrication and cooling purposes. This should be obtained under all environmental conditions as specified for the WEC. The lubrication system may contain at least:

- an oil pump to provide circulation
- a filter of suitable fineness for gearing, hydraulics and bearings

Specification of a pressure filter for maintaining suitable fluid cleanliness may be 16/14/11 according to ISO 4406:1999 and  $\beta_{6-7(c)} = 200$  according to ISO 16889:1999.

if necessary, a cooler to keep the oil temperature within the specified maximum temperature when operating under the worst relevant environmental conditions. Heater may be needed depending on the minimum temperature when operating the device.

For gear transmissions where idling may be detrimental and considered as a normal working condition, there should be either:

- a shaft brake designed to hold (statically) twice the highest expected idling torque, or
- an extra oil pump which should not be the same pump as the standby pump.

The chosen version should be automatically activated as soon as possible after cut out of the generator.

Use of flexible hoses in the lubrication system should only be used when necessary in order to allow for relative movements (e.g. when resiliently mounted).

## D2.6 Inspection and test

Advice for Inspection and Testing may be found in DNV Rules for ships Pt4. Ch.4 Sec. 2C.

### D2.6.1 Pinions and wheels

Advice for inspection and testing of material (quenched and tempered steels, flame hardening or induction, nitriding, case hardening, surface hardened steels) are given in Pt.4 Ch.4 Sec. 2C 200-213.

All teeth should be inspected for cracks. Normally, gears are checked by means of the wet fluorescent magnetic particle method. However, nitrided or not surface hardened gears may be checked by the liquid penetrant method. For batch production a reduced extent of crack detection may be considered. The crack detection must be made prior to any shot peening process.

For case hardened gears grind temper inspection should be carried out randomly. This inspection may be done by:

- nital etching per ISO 14104 or ANSI and or AGMA 2007-B92 (grade B temper permitted on 10% of functional area (FB1)), or
- a calibrated magneto-elastic method (acceptance criteria subject to special consideration)

The tooth accuracy of pinions and wheels according to ISO 1328 as follows:

- for specified grade 4 or better, all pinions and wheels should be measured
- for specified grade 5 <sup>1)</sup> at least 50% should be measured
- for specified grade 6 <sup>1)</sup> at least 20% should be measured
- for specified grade 7 or coarser at least 5% should be measured.

<sup>1)</sup> When a wheel cannot be measured due to its size or weight, at least every mating pinion should be measured.

If other standards (e.g. DIN 3962 or ANSI/AGMA 2015-A01) are specified, measurement program equivalent to the above may be applied (with respect to pitch, profile and lead errors).

Bevel gears (that are not covered by ISO 1328) should be measured regarding pitch and profile errors if required in connection with the approval. Generally, all bevel gear sets should be checked for accuracy in a meshing test without load. The unloaded contact pattern should be consistent with the specified, and documentation thereof should follow the gear set to the assembly shop.

Visual inspection of the pinions and wheels should be carried out with special attention to:

- surface roughness of the flanks
- tooth root fillet radius
- surface roughness of tooth root fillet area
- possible grinding notches in the root fillet area. Any grinding (or any other machining) of the root area is not accepted unless this has been especially approved.

#### D2.6.2 Ancillaries

Pumps, electric motors, coolers, piping, filters, valves, etc. that are delivered as integral parts of the lubrication, hydraulic operation and cooling systems on the gearbox, should be checked by the gear manufacturer's quality system as found relevant.

#### D2.6.3 Assembling

Balancing of rotating parts and subassemblies of rotors should be documented and shall be within the specification. Cylindrical shrink fitting of pinions, wheels, hubs, clutches, etc. should be documented with regard to shrinkage amount. The diameters (and therewith the shrinkage amounts) should be checked at various positions along the length of the shrinkage surface. If conicity or ovality in a connection with length to diameter ratio  $> 1$  result in:

- a shrinkage amount near the minimum tolerance value at the torque transmission end, and
- an amount near the maximum tolerance value at the opposite end,

the shrinkage specification should be reconsidered with respect to possible fretting near the torque transmission end. (If the non-torque end is subjected to bending stresses, possible fretting must be considered here too.)

Tapered shrink fit connections should be documented with regard to contact area and pull up distance or push up force or diametrical expansion (whichever is the approved specification).

The contact between the male and female parts should be checked with a thin layer of contact marking compound (e.g. toolmaker's blue). There should be full contact at the end with torque transmission (which is normally the upper end). If this is not obtained, light correction grinding with a soft disc and emery paper may be done in the female part only (if wet mounting). Alternatively a test pull up may deform small irregularities and result in an improved contact.

Keyed connections should be checked with regard to:

- key fit in shaft and hub (for connections where the torque may be reversed the key should have a tight fit in both shaft and hub)
- shrinkage amount

- push up force

Spline connections should be checked with regard to:

- tight fit if of the "fixed" type
- lubrication if of "working" type.

Bolted connections such as bolted wheel bodies or flange connections should be checked with regard to:

- tightness of fitted bolts or pins
- pre-stress as specified.

Access through inspection openings to gearing and clutch emergency bolts (if applicable) should be verified.

## D2.7 Workshop Testing

### D2.7.1 Gear mesh checking

The accuracy of the meshing should be verified for all meshes by means of a thin layer of contact compound (e.g. toolmaker's blue).

When turning through the mesh, the journals should be in their expected working positions in the bearings. This is particularly important for journals which will assume a position in the upper part of the bearings (and the bearing clearances are different), and when external weights (such as clutches) may cause a pinion to tilt in its bearings.

For small and medium gears with ground or skived flanks on both pinion and wheel it is sufficient to check this at one position of the circumference.

For large gears (wheel diameter > 2 m) and for all gears where an inspection after part or full load (in the workshop) cannot be made, the contact checking should be made in several (3 or more) positions around the circumference of the wheel.

For bevel gears the contact marking should be consistent with the documented contact marking from the production, see Pinions and wheels - tooth accuracy D2.6.1.

For highly loaded gears it may be required to carry out such a mesh contact test under full or high part load by slow turning through a full tooth mesh at 3 or more circumferential positions.

The result of the contact marking should be consistent with that which would result in the required face-load distribution at rated load.

For gears connected to shafts in excess of 200 mm diameter, and for all multi-pinion gears, the contact marking of the final stage should be documented by tape on paper or photography. The backlash should be documented for all gear meshes.

All gear transmissions should be spin tested. Prior to the spin test some teeth at different positions around the circumference of all gear meshes should be painted with an oil resistant but low wear resistant test lacquer. For multi-mesh gears the lacquer should be applied to the flanks that mesh with only one other member.

After the spin test the initial contact patterns should be documented by sketches. The position of the initial contact should be consistent with that which would result in an acceptable load distribution at rated torque.

For gears that are workshop tested with a part load sufficient to verify the load distribution at rated torque, the testing in above may be waived, except for backlash measurements. Such part load testing should be representative for the full load condition as installed if the in- and out-put shafts are connected to systems that will not impose significant bending moments or forces. Furthermore, the part load should be so high (normally 40% torque or more) that reliable extrapolation to rated torque can be made.

During the running test the gearbox should be inspected for leakage. Noise and vibration tests should be carried out. The acceptance criteria should be based on test results from the testing of the prototype.

The lubrication system should be function tested at least for a prototype. Relevant measurements may include bearing temperature, oil flow, oil sump temperature. Oil cleanliness should be documented for each manufactured gear. All equipment delivered with the gearbox regarding indication, alarm and safety systems should be function tested.

#### D2.7.2 Clutch operation

For clutches delivered integral with the gearbox the clutching-in function should be tested. For oil operated clutches the testing should be made with the oil at normal service temperature.

The pressure - time function shall be within the specification and the end pressure at the specified level. No pressure peaks beyond the nominal pressure should be allowed. The clutch operation pressure should be measured as closely as possible to the clutch inlet.

#### D2.8 Control and Monitoring

Essential and important systems should be so arranged that a single failure in one system of one unit cannot spread to another unit (e.g. by use of selective fusing of electrical distribution systems).

Failure of any remote or automatic control systems should initiate shut down or an alarm. The generic requirements for control and monitoring systems are presented in Ship Rules Pt.4 Ch.9. These cover: general requirements, design principles, system design, additional requirements for computer-based systems, component design and installation and user interface.

The gear transmissions should be fitted with instrumentation and alarms at least for bearing temperature, oil pressure, oil inlet temperature and filter.

#### D2.9 Arrangement

The gearbox should be arranged so that appropriate alignment and running conditions are maintained during all operating conditions. Piping etc. should not be arranged to obstruct access to inspection openings.

All pipe connections should be screened or otherwise protected as far as practicable in

order to avoid oil spray or oil leakage into machinery air intakes or onto potentially hot surfaces.

## D2.10 Vibration

The vibration of the gearbox foundation (except when flexibly mounted) is normally not to contain gear alien frequency components with amplitudes exceeding 10 mm/s. Alien frequencies are those that are not rotational frequencies of any gear internal parts. Higher amplitudes may be accepted if resolved in the gear design.

## D2.11 Installation Inspection

### D2.11.1 Application

This section applies to inspections in connection with installation of complete gearboxes. Regarding external couplings and shafts, and internal clutches, see respective sections.

### D2.11.2 Inspections

The following inspections should be carried out:

- shaft alignment
- support of gearboxes
- flushing, applicable if the system is opened during installation. Preferably with the foreseen gear oil. If flushing oil is used, Residual Flushing oil should be avoided.
- lubrication oil should be as specified (viscosity, FZG class, etc.) on maker's list
- pressure tests to nominal pressure (for leakage) where cooler, filters or piping is mounted after installation
- clutch operation

## D2.12 After Installation

### D2.12.1 Gear teeth inspections

To prevent initial damage on the tooth flanks (scuffing) and bearings, the gear should be carefully run in according to the gear manufacturer's specification. After approximately 500 hours of operation, all teeth should be checked for possible failures as scuffing, scratches, grey staining, pits, etc.

### D2.12.2 Bearings and lubrication

Lubricating oil and bearing temperatures (as far as indication is provided) should be checked after installation at normal operating conditions. All temperatures should reach stable values (no slow gradual increase) without exceeding the approved maximum values.

## D3 Clutches

### D3.1 General

This section applies to clutches, both for use in shaft-lines and in gearboxes. Clutches of standard design should have the design assessed by third party and be compatible with type of application, environmental conditions and maintenance regime define in the specification. Track record for the equipment should be provided.

The following aspects should be investigated and documented for each clutch:

- connection to external shafts
- type of material
- mechanical properties
- heat treatment of splines etc.
- stress raisers
- activation system.
- static friction torque (with corresponding working pressure)
- dynamic friction torque (with corresponding working pressure)
- maximum working pressure
- minimum working pressure
- pressure for compressing return springs
- permissible heat development and flash power when clutching-in (upon request when case-by-case approval)
- the control and monitoring system, including set-points and delays

For each application the clutching-in characteristics with tolerances (pressure as function of time) including max. engaging speed, should be considered.

## D3.2 Design

### D3.2.1 Strength and wear resistance

The relevant parts such as flange connections, shrink fits, splines, key connections, etc. should meet the requirements given in connections in the shafting section.

If a disc clutch is arranged so that radial movements occur under load, the possible wear of the teeth and splines should be considered. This may be relevant for clutches in gearboxes where a radial reaction force may act on the discs. Such radial forces may occur due to bearing clearances in either an integrated pinion and clutch design or shafts that are moved off centre due to tooth forces.

Trolling clutches are subject to special consideration.

### D3.2.2 Emergency operation

Clutches may need to be designed to enable sufficient torque transmission to be arranged in the event of loss of power supply.

## D3.3 Inspection and Testing

### D3.3.1 Inspection and testing of parts

Power transmitting parts as hubs, flanges and outer parts should be documented regarding chemical composition of the material and mechanical properties. Surface hardened (> 400 HV) zones with stress raisers such as keyways, radial holes, splines, etc. as well as shrinkage surfaces should be crack detected by means of magnetic particle inspection or dye penetrant. This should be documented.

### D3.2.2 Ancillaries

Pumps, electric motors, coolers, piping, filters, valves, etc. that are delivered as integral parts of the hydraulic/pneumatic system of the clutch, should be checked by the manufacturer's quality system as found relevant.

### D.3.3 Workshop Testing

Function testing: the clutch should be function tested. If the clutch is delivered with the activation control, the pressure - time function for clutching-in should be verified. If the clutch is oil operated this should be made with a representative oil viscosity.

### D3.4 Arrangement

Clutches should be arranged to minimise radial support forces.

### D3.5 Vibration

Engaging operation: the calculation of the engaging process should result in torque, flash power and heat development as functions of time, and should not exceed the permissible values for the clutch or any other element in the system.

### D.3.6 Installation Inspection

Alignment: clutches not integrated in a gearbox, should be checked for axial and radial alignment.

### D3.7 After Installation Testing

For the operating of clutches the following should be checked:

- when engaged, the operating pressure to be within the approved tolerance
- access to the emergency operation device, if applicable
- during engaging, the operating pressure as a function of time to be according to the specified characteristics.

The clutch engaging, as mentioned above, should be made at the maximum permissible engaging speed. The pressure indication should be representative for the operating pressure, i.e. measured close to the rotating seal and without throttling between the instrument and operating pressure pipe. No pressure peaks beyond the specified maximum pressure should occur.

## D4 Bending Compliant Couplings

### D4.1 General

Bending compliant couplings are membrane couplings, tooth couplings, link couplings, universal shafts, etc., i.e. all couplings that have a low bending rigidity, but high torsional rigidity. Couplings combining both low bending and low torsional rigidity should fulfil the requirements in both this section and the section of torsionally elastic couplings.

Couplings of standard design should have the design assessed by third party and be compatible with type of application, environmental conditions and maintenance regime define in the specification. Track record for the equipment should be provided.

The following aspects should be considered and documented:

- the type of material and mechanical properties
- surface hardening (if applicable)
- shot peening (if applicable)

- design details as keyways, bolt connections, or any other stress concentration.
- the permissible mean torque
- the permissible maximum torque (impact torque)
- the permissible vibratory torque for continuous operation
- the permissible angular tilt for continuous operation
- the permissible radial misalignment or reaction force (if applicable) for continuous operation
- the permissible axial misalignment for continuous operation
- the angular (tilt), radial and axial stiffness (as far as applicable)
- the maximum permissible r.p.m.

For power transmitting welds a full NDT specification including acceptance criteria should be submitted. For tooth couplings the tooth accuracy (ISO 1328) is to be specified.

For high-speed couplings (for connection to high speed turbines) the maximum residual unbalance should be specified.

#### D4.2 Design - Criteria for dimensioning

The couplings should be designed with suitable safety factors against fatigue ("suitable safety factors" will depend on the method applied, but typically be about 1.5).

For connections as flanges, shrink fits, splines, key connections, etc. see the requirements for connections in the Shafts Section:

For membrane, link or disc couplings the safety against fatigue should be documented:

- All relevant combinations of permissible loads should be considered
- The calculations may be combined with results from material fatigue tests
- The safety against fatigue may also be documented by fatigue testing of the complete coupling. If so, the load and the kind of loading (or combinations thereof) should be selected to document the safety when all permissible loads are combined.

Tooth couplings should be designed to prevent tooth fracture, flank pitting and abrasive wear.

The maximum permissible radial reaction force, the permissible mean and vibratory torque, the angular misalignment and the lubrication conditions should be combined in the calculations.

Universal shafts with power transmitting welds should be designed for a high safety against fatigue in the weld. The calculation should consider the maximum permissible loads and the specified weld quality.

The stresses in the welds combined with the maximum permissible defects according to the NDT specification should not cause a stress intensity of more than  $2\text{MPa}\sqrt{\text{m}}$ .

Ball and roller bearings should have a minimum  $L_{10a}$  (ISO 281) life time that is suitable with respect to the target design life for the component.

### D4.3 Inspection and Testing

Power transmitting parts as hubs, sleeves, shaft tubes, flanges and flexible elements should be documented regarding chemical composition of the material, mechanical properties and surface hardness (if surface hardened).

Zones with stress raisers such as keyways, holes, teeth, splines, etc. as well as shrinkage surfaces should be crack detected by means of magnetic particle inspection or dye penetrant.

Welds should be documented in accordance with the specification.

### D4.4 Workshop Testing

#### D4.4.1 Balancing

The couplings should be balanced in accordance with the specification.

#### D4.4.2 Stiffness verification

For membrane, link and disc couplings verification of the specified stiffness in angular and axial directions should preferably be carried out by means of static measurements. This applies to one coupling out of the serial production.

### D4.5 Arrangement

Couplings should be arranged to avoid any design limitations identified being exceeded. Furthermore, the reaction forces from couplings on the adjacent elements should be taken into account. All permissible operating conditions should be considered.

### D4.6 Installation Inspection

The coupling alignment (axial, radial and angular) should be checked. The alignment should be within the tolerances for the coupling as well as any other limitation specified in the shafting arrangement drawings (in particular for the high speed side).

The alignment should be made under consideration of all adjacent machinery.

## D5 Torsionally Elastic Couplings

### D5.1 General

Torsional elastic couplings mean steel, rubber and silicone couplings designed for a low torsional rigidity. Couplings combining both low torsional rigidity and bending flexible elements as membranes or links should fulfil the requirements in both in this section and the section of bending compliant couplings.

Couplings of standard design should have the design assessed by third party and be compatible with type of application, environmental conditions and maintenance regime define in the specification. Track record for the equipment should be provided.

The following aspects should be investigated and documented:

- type of material and mechanical properties
- surface hardening (if applicable)
- shot peening (if applicable)
- design details as keyways, splines or any other stress concentration

- rubber shore hardness H (laboratory test on rubber plates)
- permissible mean torque  $T_{KN}$  with the corresponding highest nominal shear stress in the elastomer and the bonding stress
- permissible maximum torque  $T_{Kmax1}$  for repetitive loads as transient vibration, typically during clutching in etc., see Fig. D5-1
- permissible maximum torque range  $\Delta T_{max}$  for repetitive loads as transient vibration, typically as passing through a major resonance during start and stop etc., see Fig. D5-2
- permissible maximum torque  $T_{Kmax2}$  for rare occasional peak loads, e.g. short circuits in generators
- permissible vibratory torque<sup>1)</sup> for continuous operation  $T_{KV}$ , see Fig. D5-3
- permissible power loss<sup>1)</sup> (heat dissipation)  $P_{KV}$
- permissible angular tilt, radial and axial misalignment for continuous operation
- angular (tilt), radial and axial stiffness<sup>1)</sup>
- permissible permanent twist of rubber element (applicable to progressive couplings)
- maximum permissible r.p.m.
- quasi-static torsional stiffness<sup>1)</sup>
- dynamic torsional stiffness<sup>1)</sup> including production tolerance
- damping characteristics<sup>1)</sup> including production tolerance.

For power transmitting welds a full NDT specification including acceptance criteria should be submitted.

<sup>1)</sup> as a function of the main parameters.

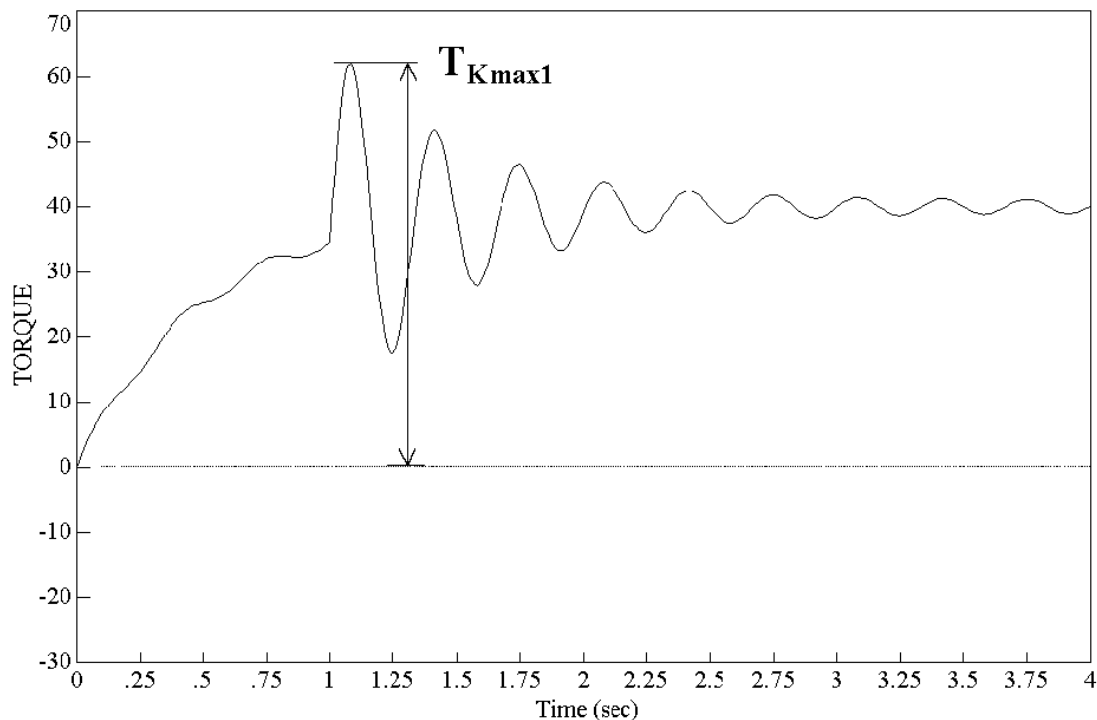


Fig. D5-1  $T_{Kmax1}$  at transient vibration

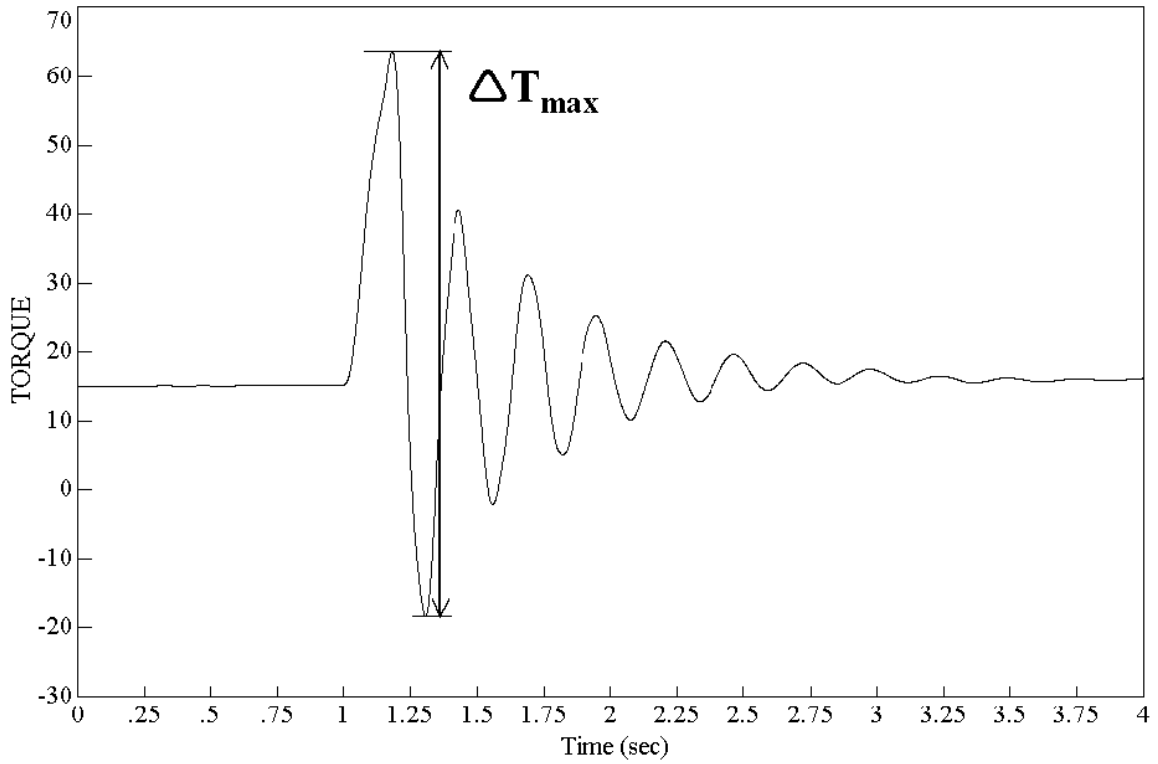


Fig. D5-2  $\Delta T_{max}$  at transient vibration

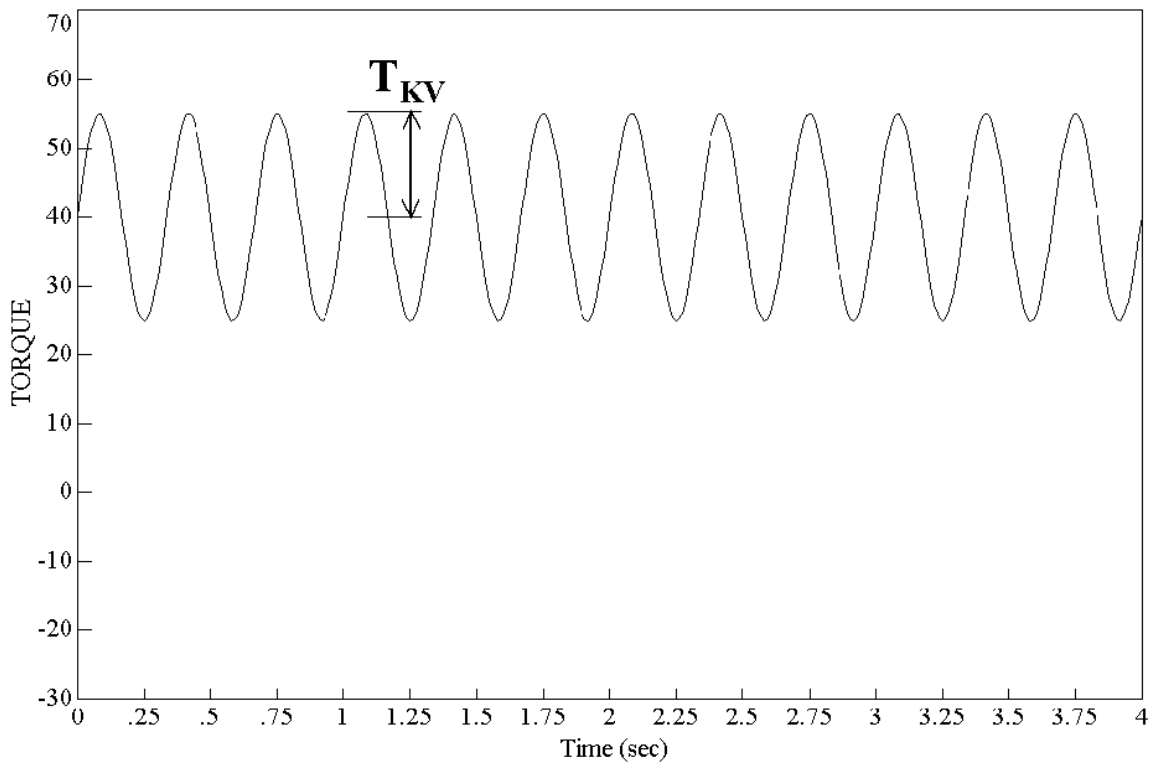


Fig. D5-3  $T_{KV}$  at continuous operation

Definitions of stiffness and damping are:

A) For linear couplings

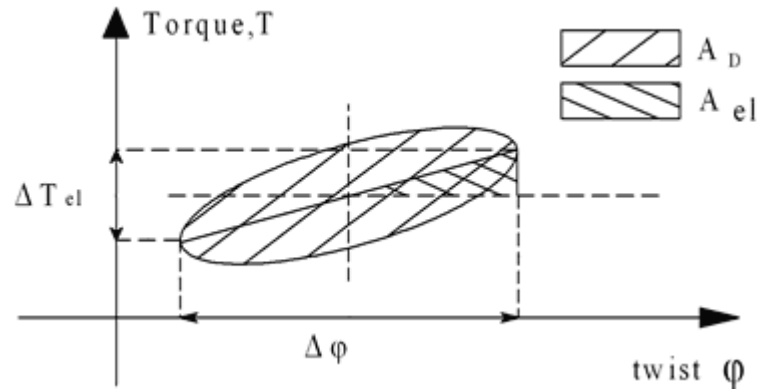


Fig. D5-4 Linear couplings

The stiffness  $K$  ( $K = \frac{\Delta T_{el}}{\Delta \phi}$ ) is the gradient of a line drawn between the extreme points of the twist as indicated in Fig.D5 -4.

For hysteresis plots that deviate from the ellipse (pure viscous damping) the line that determines  $K$  should be drawn through points determined as midpoints between the upper and lower part of the hysteresis curve, see Fig.D5 -5.

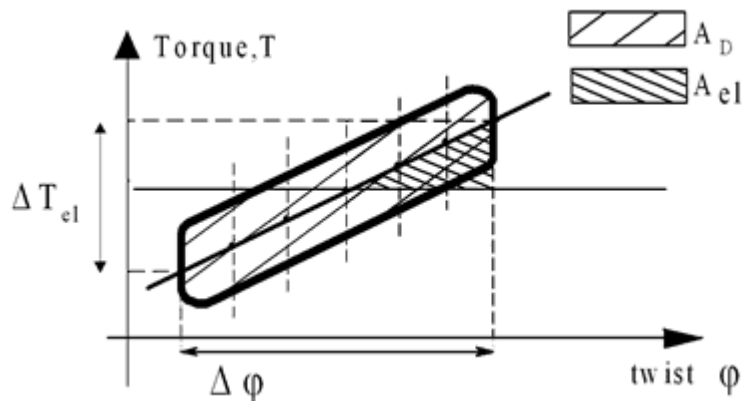


Fig. D5-5 Hysteresis curve

The damping is the ratio between the area described by the hysteresis loop  $A_D$  and the elastic work  $A_{el}$ ,

$$\psi = \frac{A_D}{A_{el}}$$

For couplings with typical elliptical hysteresis curves, other definitions may be considered.

B) For non-linear couplings

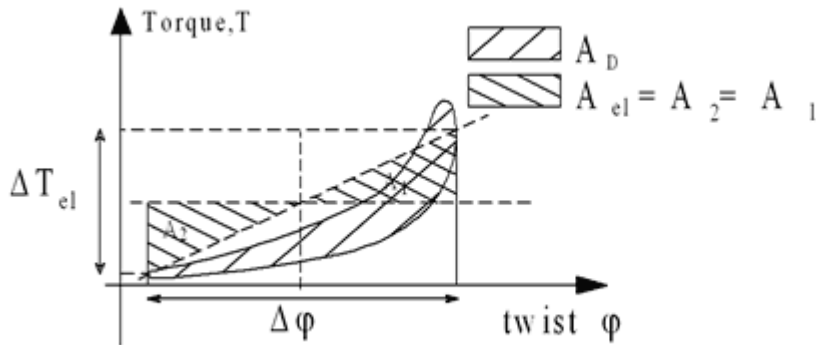


Fig. D5-6 Non-linear couplings

Plants with non-linear couplings may be calculated either by simulation (numeric time integration) in the time domain or in the frequency domain by linear differential equations. In the first case the torque – twist plots can be used directly. In the second case (more common method) representative linearised coupling properties must be used in the calculation. For this purpose the following applies.

The (linearised) stiffness  $K$  is the gradient between the extreme points of the twist as indicated above.

For determination of the damping  $\gamma$  the elastic work  $A_{el}$  must be determined so that the above indicated areas of  $A_{el}$  are equal ( $A_1 = A_2$ ). Then the same definition as for linear couplings applies.

## D5.2 Design

### D5.2.1 Criteria for dimensioning

The couplings should be designed with suitable safety factors against fatigue and overheating (rubber). For connections as flanges, shrink fits, splines, key connections, etc. see the requirements for connections in the Shafts Section.

For steel spring couplings the safety against fatigue should be documented. All relevant combinations of permissible loads should be considered. The calculations may be combined with results from material fatigue tests. The safety against fatigue may also be documented by fatigue testing of the complete coupling. If so, the load and the kind of loading (or combinations thereof) should be selected to document the safety when all permissible loads are combined. Prevention of fretting is to be considered on vital elements.

Couplings should not have rigid torsional deflection limiters (buffers) within the permissible  $T_{Kmax2}$ . Furthermore,  $T_{Kmax2}$  should not be less than  $1.4 T_{KN}$ .

For elements that are not designed to avoid local strain concentrations, stricter values for the criteria given below may apply. For silicone couplings special considerations apply.

For rubber couplings with shear loaded rubber elements the shear stress (MPa) due to  $T_{KN}$  should not exceed the smaller value of: 1% of the shore hardness value or 0.65 MPa

The corresponding shear stress in the steel-rubber bonding surfaces is normally not to exceed 0.45 MPa.

The shear stress due to the permissible vibratory torque for continuous operation should not exceed 0.25% of the shore hardness. This shear stress is superimposed to the shear stress due to  $T_{KN}$ . The corresponding peak value is not limited by  $T_{Kmax1}$  in the paragraph below.

When not substantiated by means of an approved fatigue testing combined with FE analyses, the following applies:

Permissible torque  $\Delta T_{max}$  and  $T_{Kmax1}$  for transient operation (50.000 cycles) are limited to:

- a. A nominal shear stress  $\Delta\tau_{max}$  not to exceed  $\Delta\tau_{max} < 0.24 \cdot 10^{-3} H^2$
- b. A nominal shear stress  $\tau_{max1}$  not to exceed in any direction  $\tau_{max1} < 0.2 \cdot 10^{-3} H^2$  and limited to  $T_{Kmax1} \leq 1.5 T_{KN}$

Note that  $T_{Kmax1}$  is not limiting the shear stress due to  $T_{KN} + T_{KV}$ .

The strength of the emergency claw device (if required) should be documented by calculations. This device should be designed for a minimum lifetime that is sufficient to bring the unit in safe mode and combined with all permissible misalignments.

Couplings of natural rubber should not be subjected to ambient temperatures above 70°C.

#### D5.2.2 Component testing

Component testing applies to all rubber and silicone couplings, but also for special kinds of steel spring couplings.

Steel spring couplings that are designed such that the damping properties are essentially non-viscous (e.g. mainly friction damping), should be dynamically tested in order to establish the dynamic characteristics (stiffness and damping) as functions of their main parameters.

Rubber and silicone couplings should be documented with regard to compatibility with the characteristics and permissible loads. This should be made with both calculation and testing:

- The dynamic torsional stiffness and the damping should be verified by testing.
- The necessity for test documentation of the angular (tilt), radial and axial stiffness depends on the corresponding values for permissible misalignment.
- For component approval of a coupling series where the coupling sizes only differ by a scale factor, the documentation testing for stiffness and damping of only one size (per rubber type) may be sufficient. However, if power loss testing applies, this testing should be made with at least two different coupling sizes in order to extrapolate for inclusion of the whole series.
- Quasi-static tests should be made with the same elements as used for the dynamic testing, and prior to it. The purpose should establish reference values for certification testing.

The purpose for the testing of stiffness and damping is to establish the relations between

the quasi-static tests mentioned above and the dynamic behaviour of the coupling. Furthermore, the component testing should establish the dynamic torsional stiffness and damping (for the relevant rubber qualities of relevant element sizes) as functions of the main parameters such as:

- Mean torque  $T_M$ , normally at steps as

$T_M/T_{KN} =$	0.0	0.25	0.50	0.75	1.00
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- Vibratory torque  $T_V$ , normally at steps as

$T_V/T_{KV} =$	0.50	1.0	2.0 *
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(\* for the purpose of transient vibrations)

- Vibration frequency, normally at steps as

2 Hz	10 Hz	20 Hz
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and for elements loaded in compression, also at 40 Hz

- Temperature of the element. This is for the purpose of establishing representative stiffness and damping values under various ambient temperatures as well as under high power losses. Normally at:

reference condition, e.g. 30°C

25% of permissible  $P_{KV}$  \*

100% of permissible  $P_{KV}$  \*

\*  $P_{KV}$  as for rotating or non-rotating coupling, whichever is relevant for the laboratory

It is not required to test all the possible combinations of the conditions mentioned above. Normally reference conditions as e.g. the bold values above, are kept constant when one parameter dependency is tested. However, for typically progressive couplings (stiffness increasing with torque) all permissible combinations of mean and vibratory torque should be tested.

The test results should be presented as torque-twist plots, together with the details of the evaluation method.

The testing of the permissible power loss should be made by means of at least one temperature sensor in the rubber core at the expected (calculated) position of maximum temperature (position to be approved prior to the testing).

The core temperature during pulsating of the element should be plotted as a function of time until the end temperature is stabilised. The maximum permissible core temperature is 110°C for natural rubber and 150°C for silicone.

The permissible power loss  $P_{KV}$  is defined as the power loss that results in the maximum permissible core temperature.  $P_{KV}$  is normally tested at an ambient temperature of 20°C and should be linearly interpolated to zero at maximum permissible core temperature as a function of operating ambient temperature. For coupling series where the sizes only differ by a scale factor, interpolation and extrapolation may be done by the following formula:

$$P_{KV} = a T_{KN}^b$$

where the constants a and b can be determined by testing two or more different sizes of couplings in a series.

The power loss is normally to be measured by means of torque-twist plots and applied frequency. Alternative methods may be considered if their relevance can be documented and the results are estimated to the safe side.

When a steady state condition is reached, e.g. not more than 1°C increase per hour, the actual power loss is determined from a torque-twist plot as  $P_{KVtest} = A_D \cdot f$  (Hz). If the core temperature during this test  $\vartheta_{test}$  is different from the permissible value  $\vartheta_p$ , the  $P_{KV}$  is determined as:

$$P_{KV} = P_{KVtest} \cdot \frac{\vartheta_p - \vartheta_{Aref}}{\vartheta_{test} - \vartheta_A}$$

$\vartheta_A$  = ambient temperature during test  
 $\vartheta_{Aref}$  = reference temperature in catalogue.

Alternative methods to torque-twist pulsating may only be accepted if the evaluation of  $P_{KV}$  is made conservatively (to the safe side). If rotating with radial or angular misalignment is used, the assessment of the actual power loss in the elements must consider all possible increase of other losses (e.g. in bearings).

Further, the different temperature field versus the real one in torque-twist must be taken into consideration by e.g. finite element analyses or preferably by comparison measurements in order to arrive at a correlation factor between the applied method and the real torque-twist condition.

### D5.3 Inspection and Testing

Power transmitting parts as hubs, sleeves, shaft tubes, flanges etc. should be documented regarding chemical composition of the material, mechanical properties and surface hardness.

Surface hardened (> 400 HV) zones with stress raisers such as keyways, holes, splines, etc. as well as shrinkage surfaces should be crack detected by means of magnetic particle inspection or dye penetrant.

Welds should be documented in accordance with the specification.

### D5.4 Workshop Testing

#### D5.4.1 Stiffness verification

Each rubber or silicone coupling or elastic element should be verified with regard to quasi-static torsional stiffness. This should be done by twisting the coupling or by subjecting the elastic elements to a load that is equivalent to the coupling twist. The test torque should be at least 1.5  $T_{KN}$ . The resulting deflection should be within the tolerance and the deviation should be specified.

For segmented couplings the assembling of a coupling with segments from different

charges (possibly different stiffness) should be within the tolerance range for segment differences.

#### D5.4.2 Bonding tests

For couplings with bonded rubber or silicone elements the bonding should be checked. The coupling or elastic element should be loaded in at least one direction to the  $1.5 T_{KN}$ . At this load the element should be inspected for any signs of slippage in the bonding surface. Additionally the corresponding torque-deflection curve should be smooth and show no signs of slippage in the bonding.

The bonding may also be documented by alternative tests as e.g. tension where the tensile stress should be at least as high as the shear stress under  $1.5 T_{KN}$ .

For couplings that have a limitation of the permanent twist (all progressive couplings) should be marked so that the actual permanent twist and the limit twist are legible during service inspections.

#### D5.4.3 Balancing

Couplings for PTO/PTI branches should be single plane balanced when:

- tip speed > 30 m/s
- unmachined surfaces and tip speed > 10 m/s

#### D5.5 Arrangement

Couplings should be arranged to avoid that any design limitations identified to be exceeded. Furthermore, the reaction forces from couplings on the adjacent elements should be taken into account. All permissible operating conditions should be considered.

#### D5.6 Vibration

Torsional and lateral vibration should be considered.

Lateral vibration calculations of arrangements with segmented couplings may be required. The calculations should consider the rotating forces due to possible unbalanced tangential forces (1.0 order) at full torque as well as corresponding forces due to torsional vibration. Stiffness variations, in accordance with the approved tolerance for the segmented coupling, should be assumed.

The coupling data as stiffness and damping used for torsional vibration analysis should be representative for the actual ambient temperature as well as the temperature rise due to power loss. Further, the specified production tolerances should be considered.

#### D5.7 Installation Inspection

The coupling alignment (axial, radial and angular) should be checked. The alignment should be within the specified tolerances for the coupling as well as any other limitation specified in the shafting arrangement drawings.

The alignment should be made under consideration of all adjacent machinery.

#### D5.8 After Installation Testing

After approximately 500 hours of operation all rubber elements should be visually checked. No cracks or deterioration are acceptable.

# APPENDIX E - INSPECTION

## E1 Steel Inspection

In OS-C401, reference is also made to ANSI/AWS D1.1, ASME, ASTM G48, ASTM E562, BS 7448-2, EN 287, EN 1418, ISO 148, ISO 898, ISO 6507-1, ISO 8501-1, ISO 9606, ISO 10042 and NACE MR0175.

Also referred in OS-C401 is the IACS Shipbuilding and Repair Quality Standard. This is a fabrication standard agreed between the main Classification Societies for use with ships, and should be familiar to most shipyards.

The OS-C401 Chapter 2 Section 1 gives the requirements regarding welding procedures and welding procedure tests for C-Mn steel, low alloy steel, aluminium and stainless steel, and qualification of welders.

Inspection category of welds is defined in OS-C101 Section 4 C300. The requirements are based on the consideration of fatigue damage and assessment of general fabrication quality. The inspection category is by default related to the structural category according to the table (in descending order) below:

<i>Inspection category</i>	<i>Structural category</i>
I	Special
II	Primary
III	Secondary

Table E1.2 : Inspection Categories

The weld connection between two components shall be assigned an inspection category according to the highest of the joined components. For stiffened plates, the weld connection between stiffener and stringer and girder web to the plate may be inspected according to inspection category III.

If the fabrication quality is assessed by testing, or is of well known quality from previous experience, the extent of inspection required for elements within structural category *primary* may be reduced, but not less than for inspection category III.

Fatigue critical details within structural category *primary* and *secondary* shall be inspected according to requirements in category I. Welds in fatigue critical areas not accessible for inspection and repair during operation shall be inspected according to requirements in category I during construction.

Requirements for fabrication and tolerances are given in OS-C401 Chapter 2 Section 2. It is assumed that:

- fabrication of structural members is carried out within a documented and implemented quality system according to ISO 9000 or equivalent, and
- workmanship is carried out as per tolerances specified in OS-C401 Chapter 2 Section 2, following written procedures agreed upon.

Inspections should cover the following aspects:

- correct identification and documentation and use of materials,
- qualification and acceptance of fabrication procedures and personnel,
- inspection of preparatory work (assembly, fit-up form work, reinforcement, etc.),
- welding inspection,
- inspection of fabrication work for compliance with specifications and procedures,
- witnessing NDT, control and testing,
- inspection of repairs,
- inspection of corrosion protection systems, and
- functionality of examination or testing equipment and of recording and/or measuring devices vital for correct functioning of equipment and machinery used in fabrication.

Allowable misalignments and straightness is given in OS-C401 Chapter 2 Section 2. Tolerances for compression members which are based on calculations according to RP-C201 or RP-C202 shall not exceed the values given in OS-C401 Chapter 2 Section 2 E100 - Table E2. The buckling strength of a fabricated structure with larger imperfections may be determined by use of the actually measured imperfection. For devices that could be considered to be ship shaped units complying with OS-C102, acceptable tolerances are given in the IACS Shipbuilding and Repair Quality Standard.

Recommendations for regarding assembly, welding, heat treatment and repairs are given in Chapter 2 Section 2 F. For testing of welds the requirements for fracture mechanic tests and non-destructive testing are given in OS-C401 Chapter 2 Section 3.

All tanks should be checked for watertightness (see OS-C401 Chapter 2 Section 4). In terms of structural tests (also Section 4), the standard requires that at least one of several identical tanks to be tested. Pressure should be calculated taking into account the tank design conditions and filling system. If there are only void compartments in the device, an air test combined with soap solution for detection of leaks may be acceptable without a structural water pressure tests.

Closing appliances for access openings, in decks and bulkheads which shall be watertight, shall be separately tested before installation. Structural testing of other parts outside tanks may be required.

Requirements for corrosion protection systems (coating, sacrificial anodes or impressed current) are given in OS-C401 Chapter 2 Section 5.

## **E2 Inspection of Concrete**

Information regarding fabrication of concrete structures are available in OS-C502 Section 7.

In order to differentiate the requirements for inspection according to the type and use of the structure, the OS-C502 (Section 7 D) defines three inspection classes (in ascending order);

- IC 1: Simplified inspection,
- IC 2: Normal inspection, and
- IC 3: Extended inspection.

Inspection class may refer to the complete structure, to certain members of the structure or to certain operations of execution. For wave device structures it is recommended to apply Normal Inspection for most of the structure with critical parts opting for Extended Inspection.

For the Normal Inspection class it is required to inspect;

- the materials and products (materials for formwork, reinforcing / pre-stressing steel, fresh concrete, precast elements and embedded steel components), and
- the fabrication (scaffolding, formwork and falsework, ordinary reinforcement, embedded items, erection of precast elements, site transport and casting of concrete, curing and finishing of concrete, stressing and grouting of pre-stressing reinforcement; as-built geometry, documentations of inspection).

### **E3 Inspection of Composites**

Requirements regarding fabrication of composite structures with normal and high safety class are given in OS-C501 Section 11.

Differently from other materials, composite laminate and sandwich structures are normally produced as the component is built. The material properties depend not only on the raw materials but also on the specific way they are laid up. Laminates and sandwich structures should be built with a consistent quality. Process parameters and production machine parameters should be controlled.

OS-C501 Section 11 defines the following:

Traceability of raw materials, care regarding storage of materials, quality control of mould (tolerances, discontinuities, surface finish, compatibility of mould release agents with the material, structural stability, heating control, mould deformations and stresses, accidental condition), curing system, viscosity of the resin, accuracy of lay-ups of fabrics, tolerances for gaps between cores, overlap lengths and surface preparations in joints, alignment of components in joints and tolerances and requirements for QA and QC are defined in OS-C501 Section 11.

### **E4 Inspection of Equipment and Systems (all other integral parts of the WEC device)**

General requirements for equipment and systems are covered in the DNV Offshore standards referenced. Special attention (i.e. improved procedures, enhanced specifications and extended inspection) should be given to components and areas of systems (connections, non-redundant parts, etc) which will contribute to the reliability of the system. Where equipment is likely to be subject to harsh or onerous environments special tests should be requested as per DNV Approval Scheme 2.4.

## APPENDIX F - RELEVANT ELECTRICAL AND MECHANICAL ITEMS

### F1 Electrical Systems

Selected items from the OS-D201 contents list that may provide relevant guidance is presented below. This will in many cases have to be modified or adapted to the WEC design being considered.

#### Chapter 2 TECHNICAL PROVISIONS

##### Section 2 System Design

- A. Power Supply Systems
- B. Main Electric Power Supply System
- C. Emergency Power Supply System
- D. Battery Installation
- E. Generator Prime Movers

##### F. Electric Power Distribution

- F 100 Distribution in general
- F 200 Lighting

##### G. Protection

- G 100 System protection
- G 200 Circuit protection
- G 300 Generator protection
- G 400 Transformer protection
- G 500 Motor protection

##### H. Control

##### I. Vessel Arrangement

- I 100 General
- I 200 Switchboard arrangement
- I 300 Rotating machines
- I 400 Battery installations
- I 500 Cable routing
- I 600 Lightning protection
- I 700 Earthing of aluminium superstructures on steel vessels

##### J. Cable Selection

- J 100 General
- J 200 Cable temperature
- J 300 Choice of insulating materials
- J 400 Current rating
- J 500 Correction factors
- J 600 Parallel connection of cables
- J 700 Additional requirements for A.C. installations, and special D.C. installations
- J 800 Rating of cables

##### Section 3 Equipment in General

- A. General Requirements
- A 100 References
- B. Environmental Requirements

##### B 100 Inclinations

- B 200 Vibrations and accelerations
- B 300 Temperature and humidity
- C. Equipment Ratings
- C 100 Electrical parameters
- C 200 Maximum operating temperatures
- D. Mechanical and Electrical Properties
- D 100 Mechanical strength
- D 200 Cooling and anti-condensation
- D 300 Termination and cable entrances
- D 400 Equipment protective earthing
- D 500 Enclosures ingress protection
- D 600 Clearance and creepage distances
- E. Marking and Signboards
- F. Insulation
- F 100 Insulation materials

##### Section 4 Switchgear and Controlgear Assemblies

- A. Construction
- B. Power Circuits
- B 100 Power components in assemblies
- B 200 Batteries
- B 300 Additional requirements for high voltage assemblies

##### C. Control and Protection Circuits

- C 100 Control and instrumentation

##### D. Inspection and Testing

##### Section 5 Rotating Machines

- A 100 References
- A 200 Requirements common to generators and motors
- A 300 Instrumentation of machines

##### B. Additional Requirements for Generators

- B 100 General
- B 200 Voltage and frequency regulation
- B 300 Generator short circuit capabilities
- B 400 Parallel operation

##### C. Inspection and Testing

## Section 6 Power Transformers

### A 100 General

A 200 Design requirements for power transformers

### B. Inspection and Testing

## Section 7 Semi-conductor Converters

### A. General Requirements

A 200 Mechanical requirements

A 300 Design requirements, electrical, for semi-conductor assemblies

### B. Inspection and Testing

## Section 8 Miscellaneous Equipment

A 100 Battery boxes and lockers

A 200 Socket outlets and plugs

A 300 Lighting equipment

A 400 Heating equipment

## Section 9 Cables

### A 100 General

### B. General Cable Construction

### C. High Voltage Cables

### D. Low Voltage Power Cables

D 100 Cables rated 0.6/1 kV and 1.8/3 kV

D 200 Protective sheaths

D 300 Wire braid and armour

D 400 Switchboard wires

D 500 Lightweight electrical cables

### E. Control Cables

### F. Instrumentation and Communication Cables

### G. Fibre Optic Cables

## Section 10 Installation

### A. General Requirements

### B. Equipment

B 100 Equipment location and arrangement

B 200 Equipment enclosure, Ingress Protection

B 300 Batteries

B 400 Protective earthing and bonding of equipment

B 500 Equipment termination, disconnection, marking

B 600 Neon lighting

### C. Cables

C 100 General

C 200 Routing of cables

C 300 Penetrations of bulkhead and decks

C 400 Fire protection measures

C 500 Support and fixing of cables and cable runs

C 600 Cable expansion

C 700 Cable pipes

C 800 Splicing of cables

C 900 Termination of cables

C 1000 Trace or surface heating installation requirements

### D. Inspection and Testing

D 100 General

D 200 Equipment installation

D 300 Wiring and earthing

D 400 Distribution system properties

## Section 11 Hazardous Areas Installations

### B. Documentation

### C. Equipment Selection

C 200 Ex protection according to zones

C 300 Additional requirements for equipment and circuit design

### D. Installation Requirements

D 100 General

D 200 Cabling and termination

## **F2 Mechanical and Marine Systems**

Selected items from the OS-D101 contents list that may provide relevant guidance is presented in below. This will in many cases have to be modified or adapted to the WEC design being considered.

### **Chapter 2 TECHNICAL PROVISIONS**

#### **Section 1 Design Principles**

- A. Arrangement
  - A 200 Prevention of inadvertent operations
  - A 500 Fire protection
  - A 600 Piping systems
  - A 700 Operation of valves
  - A 800 Valves on sides and bottom
  - A 900 Fittings on watertight bulkheads
  - A 1000 Requirements dependent upon damage stability calculations
- B. Construction and Function
  - B 200 Environmental conditions
  - B 300 Functional capability and redundancy
  - B 400 Failure effects
  - B 500 Component design
- C. Personnel Protection
  - C 100 General

#### **Section 2 General Piping Design**

- A 100 Application
- B. Materials
- C. Design Conditions
- D. Pumps
  - D 200 Hydrostatic tests
  - D 300 Capacity tests
- E. Valves
- F. Flexible Hoses
- G. Detachable Pipe Connections
- H. Socket Welded Joints and Slip-on Sleeve Welded Joints

#### **Section 3 Platform Piping Systems**

- A 100 Scope
- A 200 Location of piping and control systems
- B. Ballast, Bilge and Drainage Systems General etc.
- E. Air, Overflow and Sounding Pipes

#### **Section 4 Machinery Piping System**

- A 100 Redundancy and capacity
- B. Cooling Systems
- C. Lubricating Oil System
- F. Feed Water and Condensation Systems
- H. Hydraulic Systems
- I. Pneumatic Power Supply
- K. Heating, Ventilation and Air Conditioning (HVAC)

### **Section 5 Machinery and Mechanical Equipment**

- A 100 Principles
  - B. Recognised Codes and Standards
    - B 100 Unfired pressure vessels
    - B 300 Atmospheric vessels
    - B 400 Heat exchangers
    - B 500 Pumps
    - B 600 Compressors
    - B 900 Shafting
    - B 1000 Gears
    - B 1100 Couplings
    - B 1200 Lubrication and sealing
  - C. General Marine Equipment
    - C 300 Boilers, pressure vessels, thermal oil installations and incinerators
    - C 400 Anchoring and mooring equipment
  - E. Turret Machinery

### **Section 6 Pipe Fabrication, Workmanship, and Testing**

- A 100 Objectives
- A 200 Application
- B. Welding
- C. Brazing of Copper and Copper Alloys
- D. Pipe Bending
- E. Joining of Plastic Pipes
- F. Hydrostatic Tests of Piping
- G. Functional Testing

## **F3 Instrumentation and Control Systems**

Selected items from the OS-D202 contents list that may provide relevant guidance is presented in below. This will in many cases have to be modified or adapted to the WEC design being considered.

### Chapter 2 TECHNICAL PROVISIONS

#### Section 1 Design Principles

##### A. System Configuration

A 200 Field instrumentation

A 300 System

A 400 Integrated systems

A 500 Redundancy

##### B. Maximum Unavailable Time

B 200 Continuous availability (R0)

B 300 High availability (R1)

B 400 Manual system restoration (R2)

B 500 Repairable systems (R3)

##### C. Response to Failures

##### D. Emergency Operation

##### E. User Interface

##### F. Tests

F 200 Software module testing

F 300 Integration testing

F 400 System testing

F 500 On-board testing

#### Section 2 System Design

##### A. System Elements

A 200 Automatic control

A 300 Remote control

A 400 Safety

A 500 Alarm

A 600 Pre-warning

A 700 Indication

A 900 Calculation, simulation and decision support

##### B. General Requirements

B 100 System operation and maintenance

B 200 Power distribution

##### A. General Requirements

A 100 System dependency

A 200 Storage devices

A 300 Computer usage

A 400 System response and capacity

A 500 Temperature control

A 600 System maintenance

A 700 System access

##### B. System Software

B 100 Software requirements

B 200 Software manufacturing

##### C. User Interface

##### D. Data Communication Links

D 200 Local area networks

D 300 Redundant local area networks

D 400 Instrument net

D 500 Interconnection of networks

#### Section 4 Component Design and Installation

A 100 Environmental strains

A 200 Materials

A 300 Component design and installation

A 400 Maintenance, checking

A 500 Marking

A 600 Standardisation

##### B. Environmental Conditions, Instrumentation

B 200 Electric power supply

B 300 Pneumatic and hydraulic power supply

B 400 Temperature

B 500 Humidity

B 600 Salt contamination

B 700 Oil contamination

B 800 Acceleration

B 900 Vibrations

B 1000 Inclination

B 1100 Electromagnetic interference

B 1200 Miscellaneous

##### C. Electrical and Electronic Equipment

C 200 Mechanical design, installation

C 300 Protection provided by enclosure

C 400 Cables and wires

C 500 Cable installation

C 600 Power supply

C 700 Fibre optic equipment

##### D. Pneumatic and Hydraulic Equipment

D 100 Pneumatic equipment

D 200 Hydraulic equipment

#### Section 5 User Interface

E 800 Safety of personnel

## APPENDIX G – STEEL GRADE CONVERSION

Conversions between NV grades and steel grades used in the EN10025 and EN10113 standards are given in Table A4 and A5 in OS-J101 Design of Offshore Wind Turbines (as reproduced below). The number of one-to-one conversions between NV grades and EN10025 grades given in Table G.1 is limited, because the E-qualities of the NV grades are not defined in EN10025 and because no qualities with specified minimum yield stress  $f_y$  greater than 355 MPa are given in EN10025.

<i>NV grade</i>	<i>EN10025 grade</i>
NVA	S235JRG2
NVB	S235J0
NVD	S235J2G3
NVE	-
NV A27	S275J0
NV D27	S275J2G3
NV E27	-
NV A32	–
NV D32	–
NV E32	–
NV A36	S235J0
NV D36	S355K2G3 and S355J2G3
NV E36	-
NV A40	-
NV D40	-
NV E40	-
NV D420	-
NV E420	-
NV F420	-
NV D460	-
NV E460	-
NV F460	-

Table G.1 : Steel Grade Conversions (from OS-J101)

### Guidance Notes:

Important notes to the conversions between NV grades and EN10025 grades:

NV grades are, in general, better steel qualities than comparable EN10025 grades. For example, all NV grades except NV A and NV B, are fully killed and fine grain treated. This is the case only for the J2G3 and K2G3 grades in EN10025.

The delivery condition is specified as a function of thickness for all NV grades, while this is either optional or at the manufacturer's discretion in EN10025.

The steel manufacturing process is also at the manufacturer's option in EN10025, while only the electric process or one of the basic oxygen processes is generally allowed according to the DNV standard.

For the grades NV A, NV B and NV D, an average impact energy of minimum 27 Joule is specified for thicknesses up to and including 50 mm. For larger thicknesses, higher energy

requirements are specified. EN10025 requires an average impact energy of minimum 27 Joule regardless of thickness.

Concerning NV A36 and NV D36, minimum 34 Joule average impact energy is required for thicknesses below 50 mm, 41 Joule for thicknesses between 50 and 70 mm, and 50 Joule for thicknesses above 70 mm. EN10025 specifies 27 Joule average impact energy for the S355J0 and S355J2G3 grades and 40 Joule for the S355K2G3 grade.

In EN10025, minimum specified mechanical properties (yield stress, tensile strength range and elongation) are thickness dependent. The corresponding properties for NV grades are specified independently of thickness.

<i>NV grade</i>	<i>EN10025 grade</i>
NVA	-
NVB	-
NVD	-
NVE	-
NV A27	-
NV D27	S275N
NV E27	S275NL
NV A32	-
NV D32	-
NV E32	-
NV A36	-
NV D36	S355N
NV E36	S355NL
NV A40	-
NV D40	-
NV E40	-
NV D420	S420NL
NV E420	-
NV F420	-
NV D460	S460N
NV E460	S460NL
NV F460	-

Table G.2 : Steel Grade Conversions (from OS J101)

Guidance note:

Important notes to the conversions between NV grades and EN10113 grades:

- The conversions are based on comparable requirements to strength and toughness.
- Because EN10113 specifies requirements to fine grain treatment, the EN10113 grades are in general better grades than corresponding grades listed in EN10025 and can be considered equivalent with the corresponding NV grades.