भारतीय मानक

IS/IEC TS 62600-20 : 2019

Indian Standard

समुद्री ऊर्जा — तरंग, ज्वार और अन्य जल धारा परिवर्तक

भाग 20 महासागर तापीय ऊर्जा रूपांतरण (ओटीईसी) संयंत्र का डिज़ाइन और विश्लेषण — सामान्य मार्गदर्शन

Marine Energy —Wave, Tidal and Other Water Current Converters

Part 20 Design and Analysis of an Ocean Thermal Energy Conversion (OTEC) Plant — General Guidance

ICS 27.140

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Marine Energy Conversion Systems Sectional Committee, ETD 54

NATIONAL FOREWORD

This Standard (Part 20) which is identical to IEC 62600-20-2019 'Marine energy — Wave, tidal, and other water current converters — Part 20: Design and analysis of an ocean thermal energy conversion (OTEC) plant — General guidance' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Marine Energy Conversion Systems Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to International Standards for which Indian Standards also exist. The corresponding Indian Standard, which are to be substituted, is listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60079-0 : 2017 Explosive atmospheres — Part 0: Equipment — General requirements	IS/IEC 60079-0 : 2017 Explosive atmospheres: Part 0 Equipment — General requirements (*third revision*)	Identical

The Committee has reviewed the provisions of the following International Standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard:

International Standard	*Title*
IEC TS 62600-1	Marine energy — Wave, tidal and other water current converters — Part 1: Terminology
ISO 13628-5 : 2009	Petroleum and natural gas industries — Design and operation of subsea production systems — Part 5: Subsea umbilical
ISO 13628-11 : 2007	Petroleum and natural gas industries — Design and operation of subsea production systems — Part 11: Flexible pipe systems for subsea and marine applications
ISO 19900	Petroleum and natural gas industries — General requirements for offshore structures
ISO 19901-1	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating considerations
ISO 19901-7 : 2013	Petroleum and natural gas industries — Specific requirements for offshore structures — Part 7: Station keeping systems for floating offshore structures and mobile offshore units

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INTRODUCTION

Seventy percent of the Earth’s surface is ocean. Most solar energy striking the ocean is absorbed within the upper 100 m and is retained as thermal energy. Expanding slightly as it warms the surface seawater layer is reheated by additional sunlight resulting in temperatures often exceeding 25 °C in tropical latitudes. Deep seawater is much cooler, typically, about 4-5 °C at depths varying from 800 m to 1 000 m, as shown in Figure 1. This deep cold water is replenished from the polar regions by the thermohaline ocean circulation. From the temperature difference that exists between these upper and deep layers of the ocean, significant quantities of energy can be sustainably extracted by a process called Ocean Thermal Energy Conversion, OTEC.

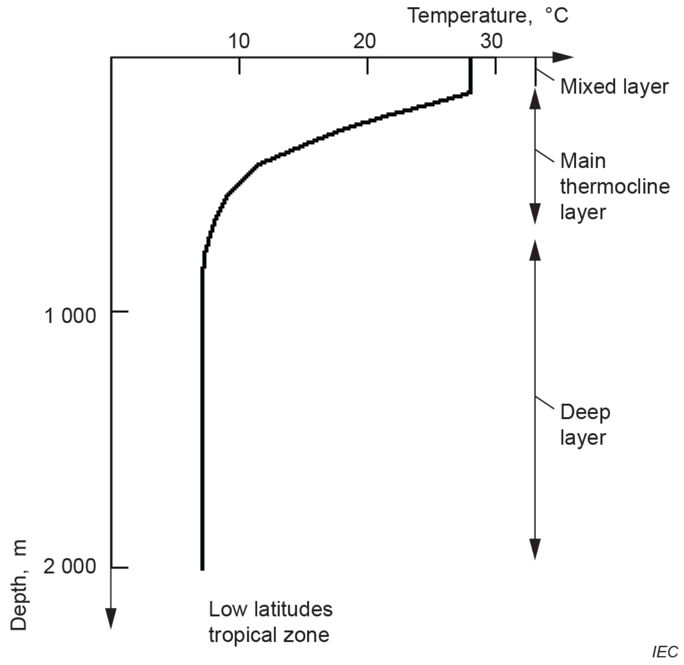

Figure 1 – Tropical ocean temperature-depth profile

The temperature difference between the ocean layers in the tropics changes very little during daily or even yearly cycles and shows a moderate and predictable seasonal variation. This steadiness creates an attractive characteristic in that OTEC can generate non-intermittent (sometimes referred to as ‘base-load’) power. Due to the relative simplicity of the process, OTEC is expected to have a very high capacity factor compared to most other forms or renewable energy. Capacity Factor is the ratio of actual electrical energy output over a given period of time, relative to the maximum possible electrical energy output over the same amount of time. The maximum possible energy output of a given installation assumes its continuous operation at full nameplate capacity over the relevant period of time. OTEC power output reliability and predictability is appealing when compared to the intermittency and hence low capacity factor of most renewable energy sources.

a) Working principle

OTEC converts a sustainable, low-grade heat source, ocean thermal energy, into electricity by applying a thermodynamic cycle. The theoretical maximum thermal conversion efficiency is determined by the Carnot cycle, where absolute ocean temperatures are applied in Kelvin. An example of the Carnot efficiency with a hot source of 27 °C and a cold source of 4 °C is:

$$\eta_{Carnot} = 1 - T_{cold}/T_{hot} = 1-(4+273,15)/(27+273,15) = 7,66\ \%$$

This efficiency assumes that the conversion is done by an ideal, reversible heat engine. In practice, the actual heat transfer is irreversible due to temperature differences in the heat exchangers and other factors. These heat transfer losses and the actual performance of the turbine and generator shall be accounted for when calculating the actual efficiency. The non-ideal, actual efficiency would thus be in the range of 3 % to 4 %.

The OTEC process can be configured with different cycles: open, closed and hybrid. The choice of which system will be optimum will normally be based on site characteristics, such as local power and fresh water demand.

b) Closed cycle

Closed-cycle OTEC systems are based upon the Rankine thermodynamic cycle and use a refrigerant-type process working fluid, contained within a closed piping system. Liquid working fluid is pumped into an evaporator heat exchanger where heat from the warm seawater causes the working fluid to vaporise. This vapour is piped to a turbine where its enthalpic energy drives a turbine-generator. The turbine's vapour exhausts to a condenser heat exchanger, where it condenses to a liquid by the cooling effect of the cold seawater. The liquid working fluid then drains to the working fluid pump, completing the cycle. Major components and flows of a Closed Cycle OTEC plant are illustrated in Figure 1 and Figure 2. Design considerations associated with these components will be discussed in Clause 5.

Within the evaporator, the warm seawater transfers its heat to the boiling working fluid, becoming less warm. Similarly, heat from the condensing vapour causes the cold deep seawater passing through the condenser to become less cold. The heat flow from warm water is 3 % to 6 % larger than the heat flow into the cold water. This difference is the energy usefully extracted by the turbine or lost due to friction.

The working fluid will have fluid properties that vary with the specific type used, such as R717 (anhydrous ammonia), R32, R134a or others. The evaporation and condensation properties and heat exchanger design performance should normally be selected to attain optimum efficiency for a particular working fluid. Within the process system, the highest pressure occurs at the working fluid pump outlet, the lowest pressure occurs in the condenser and the most significant pressure drop will take place within the turbine.

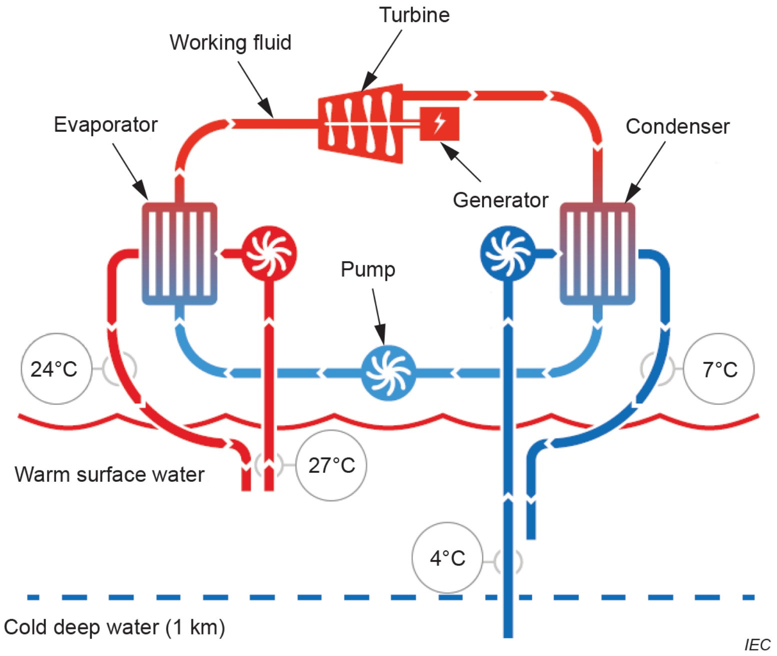

Figure 2 – Working principle of closed cycle ocean thermal energy conversion [2][1]

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[1] Numbers in square brackets refer to the Bibliography.

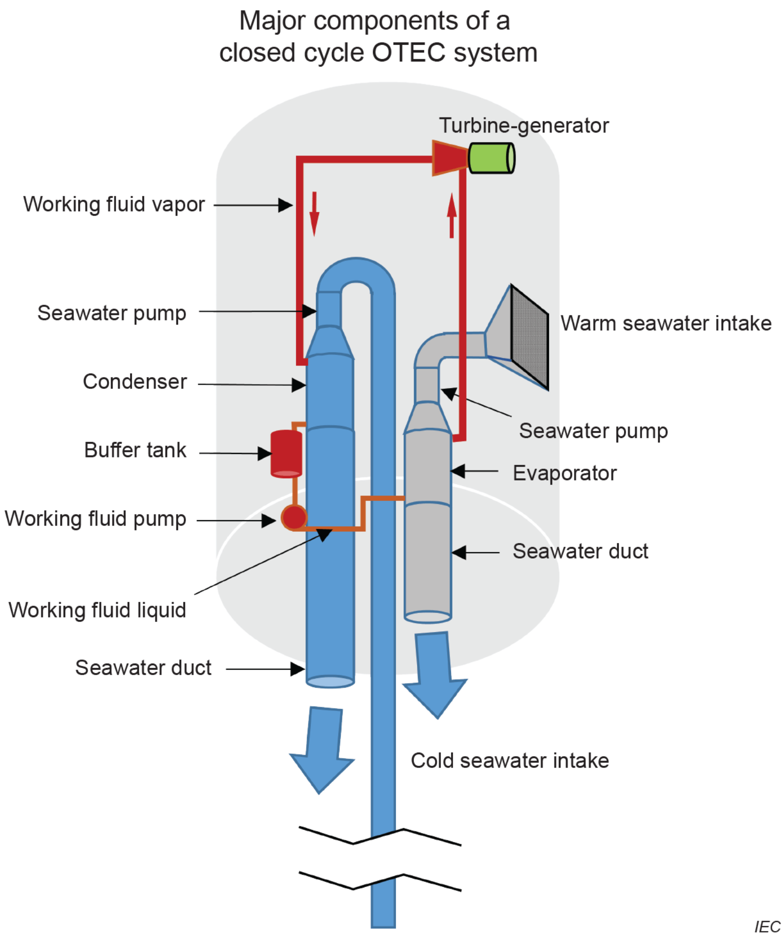

Figure 3 – Major power cycle components of a closed cycle OTEC plant

c) Open cycle

Open-cycle OTEC uses a vacuum process to exploit the different boiling pressures of warm and cold seawater. The working fluid is used only once and is continually replenished, hence the term “open” cycle. The process is as follows: Warm seawater enters a large evaporation chamber at approximately 96 % vacuum, where a small fraction of the seawater vaporizes to low pressure steam and the remaining seawater supplies the needed heat of vaporization. The cooled warm seawater is pumped from the evaporator. The low-pressure steam passes through a mist separator, drives a low pressure turbine and exhausts into the condensing chamber, which is maintained at approximately 98 % vacuum. The steam condenses directly onto cold seawater droplets within the condenser chamber and the slightly diluted cool seawater mixture is pumped from the condenser. Continuously-running vacuum compressors maintain the chamber vacuum by removing dissolved air and other trace gases that enter with the seawater flows.

Alternately, a large condensing surface heat exchanger can segregate the steam from the cold seawater, yielding quantities of fresh water suitable for drinking water or irrigation. Thus open cycle OTEC can be configured to produce both electricity and fresh water.

Both closed cycle and open cycle OTEC use the Rankine thermodynamic cycle. The primary difference is that open cycle systems use large vacuum chambers and a very high-volume low pressure steam turbine, whereas closed cycle uses heat exchangers, a smaller turbine and a working fluid pump. A schematic diagram of the open cycle OTEC system is given in Figure 4

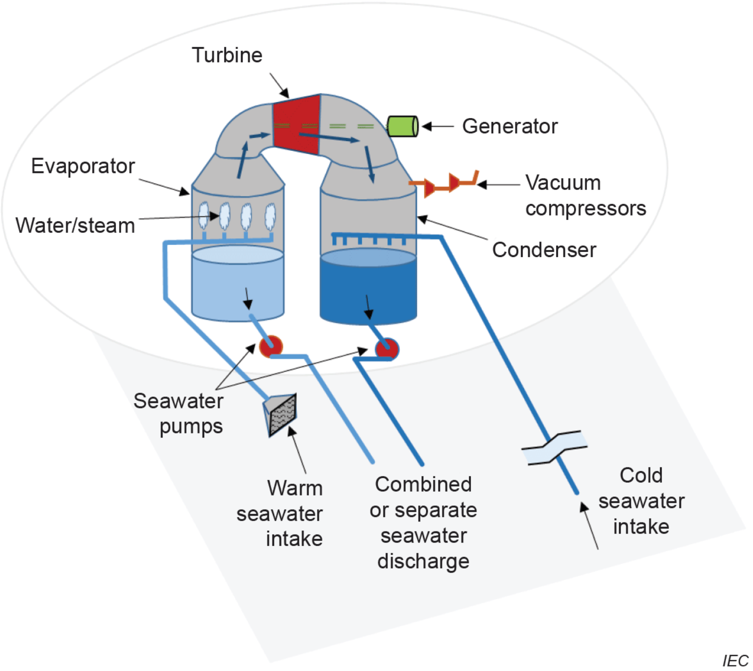

Figure 4 – Open cycle OTEC system

d) Hybrid cycle

A hybrid cycle combines features of both the closed-cycle and open-cycle systems to yield both electricity and desalinated water. Heat exchangers, vacuum chambers and other components may be arranged in numerous stages to extract additional thermal value from the "used" warm and cold seawater flows.

Indian Standard

MARINE ENERGY — WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS

PART 20 DESIGN AND ANALYSIS OF AN OCEAN THERMAL ENERGY CONVERSION (OTEC) PLANT — GENERAL GUIDANCE

1 Scope

This part of IEC 62600 establishes general principles for design assessment of OTEC plants. The goal is to describe the design and assessment requirements of OTEC plants used for stable power generation under various conditions. This electricity may be used for utility supply or production of other energy carriers. The intended audience is developers, engineers, bankers, venture capitalists, entrepreneurs, finance authorities and regulators.

This document is applicable to land-based (i.e. onshore), shelf-mounted (i.e. nearshore seabed mounted) and floating OTEC systems. For land-based systems the scope of this document ends at the main power export cable suitable for connection to the grid. For shelf-mounted and floating systems, the scope of this document normally ends at the main power export cable where it connects to the electrical grid.

This document is general and focuses on the OTEC specific or unique components of the power plant, particularly the marine aspects of the warm and cold water intake systems. Other established standards are referenced to address common components between the OTEC system and other types of power plants and floating, deep water oil and gas production vessels, such as FPSOs and FLNG systems. Relevant standards are listed within this document as appropriate.

The flow diagram, shown in Figure 5, illustrates the main design process associated with floating, shelf-mounted or land-based OTEC systems.

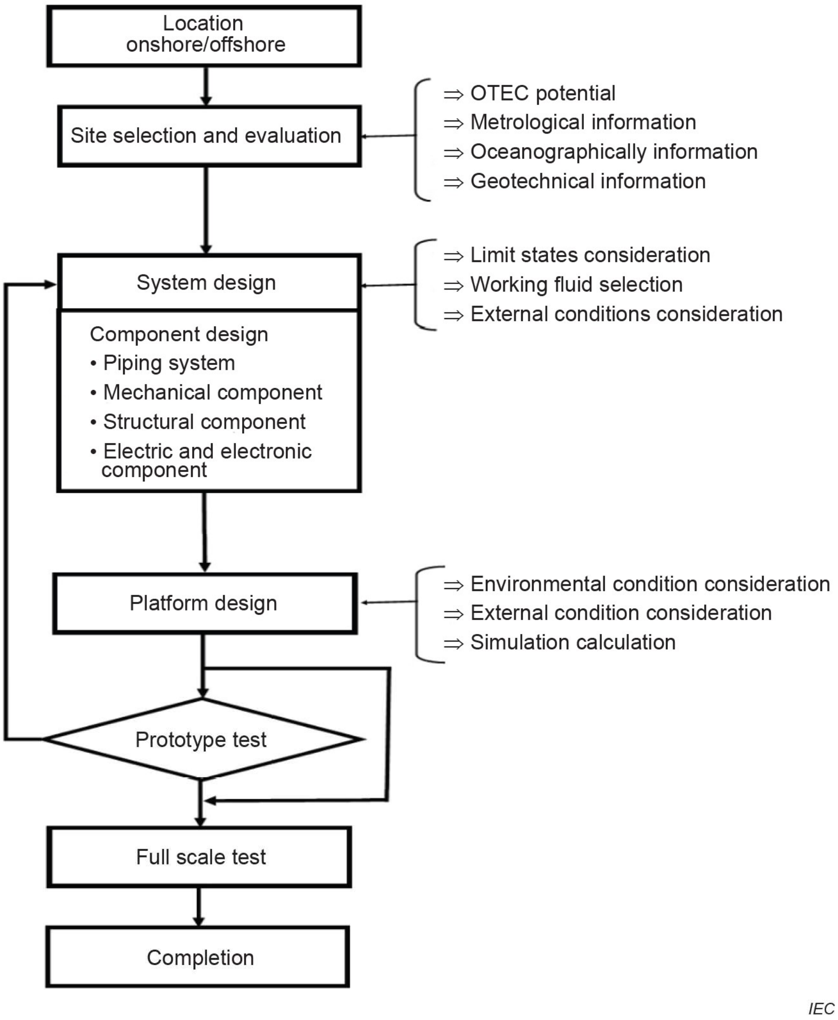

Figure 5 – Example of a typical process for developing and testing an OTEC system (land-based and floating)

2 Normative references

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

IEC 60079-0:2017, *Explosive atmospheres – Part 0: Equipment – General requirements*

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

ISO 13628-5: 2009, Petroleum and natural gas industries – Design and operation of subsea production systems – Part 5: Subsea umbilicals

ISO 13628-11: 2007, Petroleum and natural gas industries – Design and operation of subsea production systems – Part 11: Flexible pipe systems for subsea and marine applications

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

ISO 19901 (all parts): *Petroleum and natural gas industries – Specific requirements for offshore structures*

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

ISO 19901-7:2013*, Petroleum and natural gas industries – Specific requirements for offshore structures – Part 7: Station keeping systems for floating offshore structures and mobile offshore units*

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

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

ISO 19905 (all parts), *Petroleum and natural gas industries – Mobile offshore units – Jackups*

ISO 19906, *Petroleum and natural gas industries – Arctic offshore structures*

ISO 21650, *Actions from waves and currents on coastal structures*

3 Terms and definitions

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

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

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

3.1
seawater differential temperature
temperature difference between the warm surface and the cold deep ocean sea water

Note 1 to entry: Figure 6 illustrates how this temperature differential may vary during the course of a year.

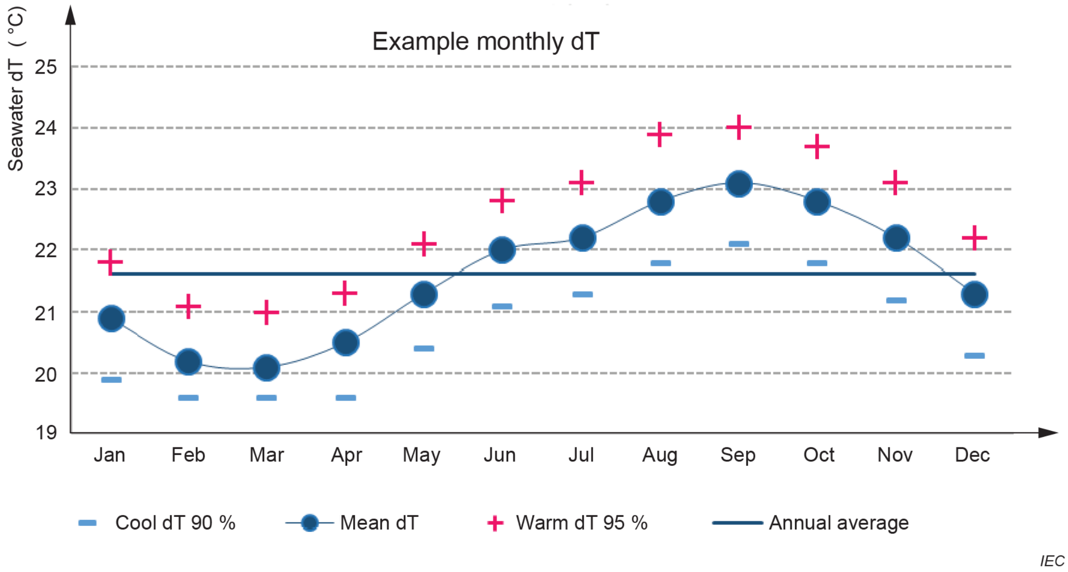

Figure 6 – Seawater differential temperature with 95 % confidence intervals

3.2
rated, nameplate or nominal capacity <for an OTEC plant>
maximum net power that can be generated by an OTEC plant

Note 1 to entry: Note the relationship between generated power and seawater differential temperature (compare Figures 6 and 7).

Note 2 to entry: In the example shown in Figure 7, the rated, nameplate or nominal capacity is 120 MW. The maximum gross power for the OTEC plant would be 160 MW (August, September and October), where gross power is the electric power generated at a defined set of seawater flows/temperatures and measured as the electrical output of the alternator or alternators. Net power should be measured at the interface to the electrical grid and is the power remaining after all system power losses (self-power, transmission losses, transformer losses) have been realized.

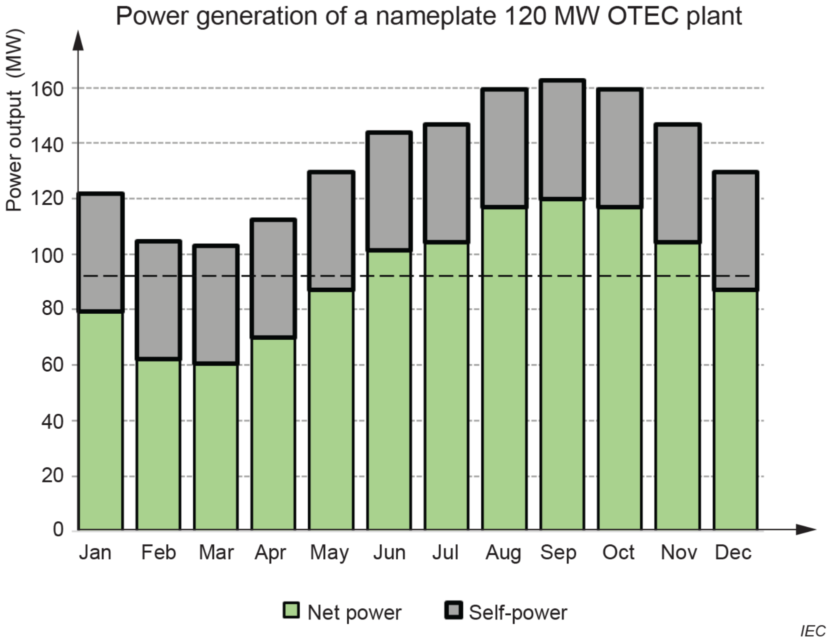

Figure 7 – Example of OTEC power definitions

3.3

working fluid

gas or liquid heat transfer medium, which drives the turbine

Note 1 to entry: Closed cycle OTEC systems use industrial refrigerants/working fluids such as anhydrous ammonia, R32, or other suitable fluids. Open cycle OTEC systems use vapour from the flash evaporation of warm sea water producing low pressure steam.

3.4

Front End Engineering Design

FEED

body of engineering that takes a conceptual design forward to allow a cost estimate for project control purposes to be derived

Note 1 to entry: Typically, it may represent between 20 % and 25 % of the total engineering of a project.

4 Abbreviated terms and acronyms

CWP	Cold Water Pipe
EJ	Exojoule (1.0E+18 Joules)
FMEA	Failure Mode Effect Analysis
FLNG	Floating Liquefied Natural Gas
FPSO	Floating, Production, Storage and Offloading
HX	Heat Exchanger
HIRA	Hazard Identification and Risk Assessment
IMO	International Maritime Organisation
IRM	Inspection, Repair and Maintenance
ROV	Remotely Operated Vehicle
SCADA	Supervisory Control and Data Acquisition
VIV	Vortex Induced Vibrations

5 Site specific and metocean design parameters

5.1 Environmental factors influencing design

5.1.1 General

The phenomena listed in 5.1.2 through to 5.1.10 shall, based on region specific data, be addressed in the design.

These phenomena shall be described by physical characteristics and supporting statistics. The joint occurrence of different values of parameters shall also be defined once suitable data are available. From this information, appropriate environmental design conditions shall be established that will consider the following:

a) The type of structure being designed.
b) The phase of development (e.g. construction, transportation, installation, etc.).
c) The limit-state considered.

Usually two sets of conditions should be established that take into consideration the following:

- Normal meteorological and oceanographic conditions that are expected to occur frequently during the life of the structure. These conditions are needed to design systems for fatigue, to plan field operations, such as inspection/maintenance operations and to develop the actions caused by the environment associated with particular operations or serviceability checks;
- Extreme meteorological and oceanographic conditions that recur with a given return period or probability of occurrence.

Extreme, normal and other meteorological and oceanographic parameters shall be determined from actual measurements at the site or by suitable validated hindcast model data.

5.1.2 Seawater temperature

Seawater temperature profiles should typically be measured at the site at least monthly for at least one year to optimise the selection of warm water intake depth, optimum cold water intake depth, and the mixing of discharged seawater.

Seawater temperatures at the selected intake and discharge depths should be measured at least hourly for at least one year to quantify daily and seasonal variability. Minimum, maximum and average temperatures should be reported.

Adequate data shall also be collected at high resolution (~ 1 min) to quantify dynamic temperature variations for warm and cold seawater caused by tides, storms or internal waves.

This data shall be evaluated with nearby long-term observations and/or validated hindcast data to calculate Annual Energy Production (AEP) and to support financial modelling. The data should also be used for environmental mixing studies as part of the permitting/licensing process. Guidance on additional data collection requirements should be obtained from relevant permitting agencies.

The warm water intake should be located deeper than typically 10 m to avoid flotsam and effects of surface waves. Cold seawater intake depth will generally be based upon an optimization of power output versus cold water pipe cost. The selected discharge depth is likely to depend upon the desired use of the discharge water and permitting considerations. Representative depths may be 15 m for warm water intake, 900 m to 1 100 m for cold water intake and 75 m to 100 m for a mixed discharge.

5.1.3 Wind

Actions caused by wind acting on a structure shall be considered for both the global and local design. Site-specific information on air density, wind speed, direction and duration shall be determined.

Wind is usually characterized by the mean value of its velocity over a given time interval at a given elevation above the mean water level. In specific cases (for example, design of flexible and compliant structures such as oil and gas flare-towers), the frequency content is of importance and shall be addressed.

Wind spectrum should be considered for moored floating OTEC systems, including second order slow drift effects.

The variability with elevation and spatial coherence shall be considered. Reference to ISO 19901-1 is highly recommended. Another beneficial reference is DNV GL RPC205 [5].

5.1.4 Waves

Actions caused by waves acting on a structure shall be considered for both the overall structure and mooring, as well as individual components that are exposed to wave forces. Waves are usually characterized by wave spectrum, significant wave height and peak period.

a) For land-based plants, data collected and analysis should conform to the procedures listed in ISO 21650 as well as ISO 19905 or ISO 19902 as relevant.

b) For plants sited in deep water, data collected and analysis should conform to procedures listed in ISO 19901-1. Also beneficial is DNV GL RP-C205 [5].

5.1.5 Water depth and sea level variations

The water depth shall be determined. The magnitude of the low and high tides and positive and negative storm surges shall be addressed.

The possibility of ground subsidence shall be considered when determining the design water depth.

5.1.6 Currents

Phenomena such as tidal, wind driven, cyclone induced, global circulation, solitons, loop and eddy currents shall be assessed to determine whether they should be considered in the design process.

Currents shall be described by their velocity (magnitude and direction), variability with water depth and persistence.

The occurrence of fluid motion caused by internal waves shall be considered.

5.1.7 Marine growth

Potential marine growth shall be considered and then defined by estimated thickness, roughness, density and variation with depth.

The design may rely on periodic marine growth cleaning or anti-fouling systems during the platform life. Any such reliance shall be documented and the cleaning program defined over the life of the platform including cost and feasibility. The consequences of not maintaining this program should be determined and formally documented taking into account the implications relative to the original design parameters.

5.1.8 Other meteorological and oceanographic information

Other environmental information such as precipitation, fog, and variability of the density and oxygen content of the sea water shall be assessed from a possible operational point of view and documented whether this is necessary to assess.

5.1.9 Water chemistry

For both warm and cold water the following information at intakes and proposed discharge zone depth range should be determined:

- Nutrient concentration.
- Turbidity.
- Micro and macro plankton.
- Oxygen, carbon dioxide, etc., content.

5.1.10 Third party (collision, anchor impact, trawling, Unexploded Ordinance (UXO)

These factors all can potentially affect an OTEC plant design and should be reviewed and addressed as required.

5.1.11 Soil/seabed conditions

Seabed conditions shall be precisely defined in the OTEC installation area by conducting geophysical surveys and geotechnical surveys. This includes surveys in the vicinity of mooring locations and along the cable route(s) or seawater pipe routes (for land or shelf-mounted OTEC systems). Geohazards shall also be assessed for the proposed installation site.

5.2 Biological impact

The following marine organisms have potential to affect the reliable and thermodynamically efficient operation of an OTEC system:

- Plankton.
- Fish.
- Plants.
- Coral and biofouling build up.
- Mammals in the location of the OTEC system.
- Other Benthic organisms.

Experience from the offshore oil and gas sector has shown that the potential effect from these biological factors can be controlled with considered initial design and careful in field operation. Because the thermodynamic efficiency of an OTEC system is low, small reductions in efficiency can significantly reduce power output and profitability. This illustrates the importance of controlling potential biological impacts and also ties in with the importance of prototype testing, which is covered in 12.2.2.

6 Floating OTEC – General information and guidance (closed cycle, deep water)

6.1 Seawater considerations

Figure 8 illustrates terms and possible seawater intake and discharge layouts for a generic floating OTEC plant, nominally based on a Spar buoy type hull form as an example. Many other types of hull form have also been proposed.

Primary design considerations include:

- Optimised architecture for construction, installation, operation, mooring/propulsion, maintenance/refit and decommissioning.
- Appropriate stability and strength during storms, and long-term structural fatigue capacity.
- Ensured crew safety and health during visits or long-term occupancy.
- Efficient seawater flow paths to minimize parasitic power losses.
- Seawater intake design optimised to manage entrainment and impingement of sea life addressing location, flow velocity and intake flow direction.
- Sea water discharge plumes located and directed to prevent their re-ingestion into the plant. This may involve careful consideration of the pros and cons of whether to direct the nutrient-rich deep water below the photic zone (the uppermost layer into which daylight penetrates in sufficient amounts to influence living organisms, especially by permitting photosynthesis).

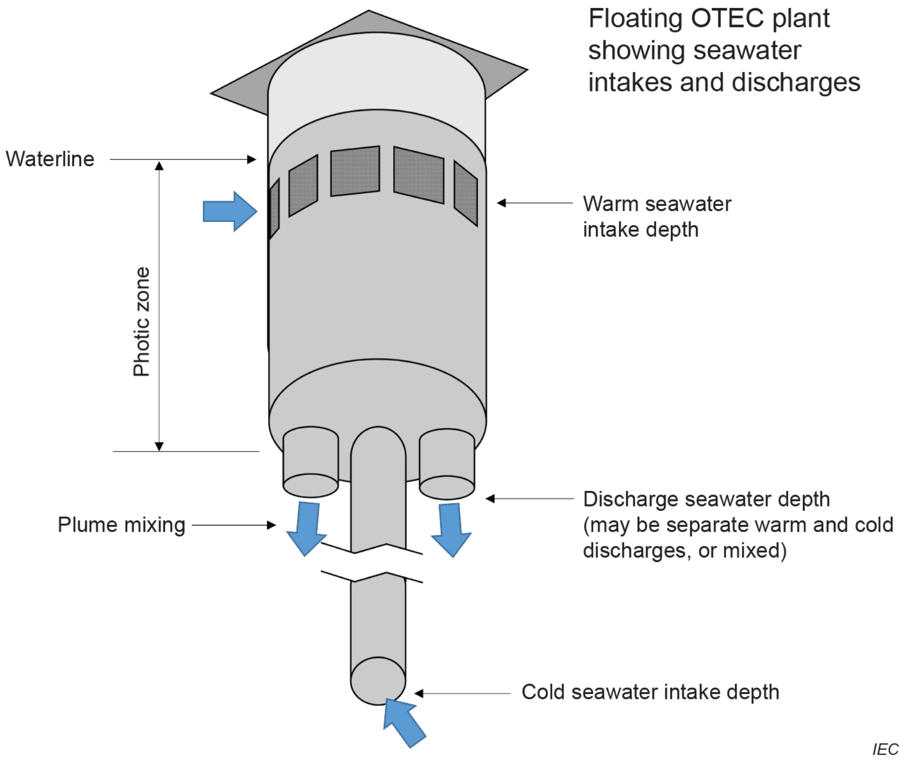

Figure 8 – Seawater flow considerations for floating OTEC

6.2 Cold seawater system

6.2.1 Systems engineering considerations

A large Diameter Cold Water Pipe (CWP) and its attachment to the surface platform is a feature unique to OTEC plants. The CWP shall be designed to withstand static and dynamic loads imposed by the pipe self-weight, the relative motions of the pipe and platform when subjected to wave and current loads (due to both design storm or smaller cumulative typical fatigue type motions) and the internal low pressure induced by water flow. The CWP shall be large enough to handle the required water flow with low internal drag loss; it needs to be of a material that will be durable in seawater and not form corrosion products that might induce heat exchanger corrosion or be environmentally unacceptable.

Due to these requirements, a CWP design engineer shall develop a design in concert with the power system and platform designer. A CWP shall access the depths to meet the design temperature, this is typically associated with 700 m to 1 200 m depths. The selection of CWP dimensions illustrate the numerous engineering considerations to determine the desired power output and a plant's thermal-mechanical-electrical conversion efficiency and resulting net/gross power ratio. Table 1 below lists the major cold water pipe design considerations needed to create a site specific optimum design.

Table 1 – Indicative design consideration in selecting Cold Water Pipe parameters

Cold Water Pipe feature	Pro	Con
Longer CWP length	Cooler sea water, more efficient power cycle	Increased CW pumping power and capital cost
Larger CWP diameter	Less CW pumping power	Increased capital cost and structurally more complex hull pipe interface
Increased cold seawater flow	Cooler sea water, more efficient power cycle	Larger CWP diameter and increased pumping power

6.2.2 Cold water pumping power considerations

The power required for pumping cold water through the OTEC condenser system is given by the product of the seawater mass flow rate times the total hydraulic head. The hydraulic head is the sum of several factors:

- Friction and minor losses: Hydraulic pumping power throughout the cold water ducting will be consumed due to inlet loss, exit loss, screens, valves, friction, and various dynamic losses due to abrupt area changes, bend radii and diffuser geometry, etc. Selecting a cold water path yielding an optimal blend of hydraulic performance, constructability, maintenance access and acceptable cost offers an opportunity for skilful design. An average 2 m/s flow velocity is a reasonable first iterative design step.
- Density static head: The cold water in the CWP is somewhat denser than the surrounding water column and will have a static equilibrium height of approximately 1 m below ambient sea level. This height shall be calculated on a case by case basis and overcome via pumping power.
- CWP friction: The power to force cold seawater along the friction-causing inner surface of the CWP.
- Condenser loss: The power to force cold seawater through the condenser heat exchanger’s small passageways.
- Losses due to inefficiencies of the pump/motor.

6.2.3 CWP dynamic response

Compared to steel and flexible riser pipes used on offshore oil and gas platforms, the CWP is of larger diameter and envelops much more fluid mass. Thus, the dynamic response of the CWP will substantially affect the dynamic response of the whole platform. Any numerical analysis should use an appropriately “coupled” hydrodynamic and structural model.

If the OTEC system is moored the potential interaction (impingement or clashing, entanglement) between the CWP, the umbilicial/power export cable and the mooring system shall be assessed. A suitable means to suspend the CWP from the floating platform or from an adjacent buoy shall be considered.

The CWP may be attached to the platform using either a rigid or “fixed” interface or via a gimbaled or “flexible” interface. Determining the right solution will require an engineering trade based upon a number of factors specific to each design and installation location and resulting bending and axial stresses and associated strain and material fatigue.

Effects from internal fluid flow inside the CWP should be assessed, and if of significance should be accounted for.

The following are recommended to be considered when analysing a CWP and its effect on overall system dynamics:

- The analysis should include static and dynamic effects.
- The analysis should include linear and non-linear wave effects, especially 2nd order effects such as slow-drift pitch motions of the platform and any resulting increase in maximum pitch motions.
- The analysis of the pipe dynamics should include modal damping as well as hydrodynamic damping due to viscous drag. The amount of damping will affect the maximum bending particularly for modal frequencies within the range of wave energy. Structural damping will be a function of materials and constructions. Full scale measurements are the best way to verify damping. In the absence of full scale data on similar structures an assessment of structural hysteresis may be used to estimate a damping coefficient. Sensitivity to damping should be investigated.

- The water inside the CWP represents significantly more mass than the pipe itself and its effect needs to be considered in the analysis.
- Any system dynamic analysis shall include the dynamic coupling between the pipe, platform and moorings. See DNV GL RPF205 [6].
- The entrained seawater mass is dynamically anisotropic which results in a varying response depending on the direction of the motion of the surface platform. In a heave environment, pressure fluctuations within the CWP shall be considered in the design. Hence, anisotropic mass effects need to be considered when computing axial stresses in the pipe wall due to platform motion.
- Hydrodynamic coefficients for the CWP should be reviewed for suitability for anticipated CWP flow conditions.
- Hydrodynamic model tests are recommended to validate numerical models of platform, pipe and mooring dynamics.
- The analysis should include an assessment of the susceptibility of the CWP to vortex induced vibrations.
- CWP design and development should address guidance provided regards limit states and safety factors provided in the following standards: API RP 2SK[16], DNVGL-OS-C501 (Composite Components)[7], DNVGL-ST-F201 (Dynamic Risers)[9]. Because of the large CWP diameter, limit states for shell buckling should also be considered: DNVGL-RP-C202[10] (Buckling strength of Shells-Rules and Standards). See also suction collapse below.

6.2.4 Static Loads and bending moments

Static longitudinal loads may result from the pipe's weight or pipe material specific gravity relative to seawater. Pipe internal pressure loads will result whenever the pipe is in operation.

Bending moments along the pipe may be static or dynamic. Static bending loads may be caused by a steady current or platform list. Dynamic bending loads are created by platform motion relative to the pipe (surge, heave, sway, roll, yaw, and pitch) as well as unsteady wind, current and waves. First and second order effects should be addressed (see DNVGL RP-F205[6]).

Vortex induced vibrations (VIV) also should be assessed. A modal analysis should identify mode shapes and frequencies and modal basis calculation should be undertaken to identify the risk of VIV according to the current profiles of the site. Multimodal responses in shear currents should be considered and the effect on strength, buckling and fatigue assessed. For non-axisymmetric cross section, possible Galloping phenomenon should be assessed.

6.2.5 Suction collapse

Suction collapse may occur when the operating static normal pressure exceeds the pipe's capacity to withstand exterior normal pressure loads. Note that these external loads may include a transient component due to surface platform heave. Material fatigue due to CWP bending and ovalling (non-circular deformation) shall be included when designing suction pipes.

Non-circular deformation can greatly reduce a pipe's ability to withstand suction collapse. The global and local design of the CWP shall counteract excessive ovalling, which needs to be carefully monitored during CWP manufacture and in situ behaviour.

6.2.6 Deflection by current and platform motions

A freely supported CWP attached to a moored platform subjected to steady ocean currents will adopt an angle representing a force balance between lateral moments imposed by the current profile and the restoring force due to the pipe weight. Estimation of the maximum angle allowed for a range of materials, pipe diameters and lengths using a reliable method is essential for a successful design. Since the drag coefficient is critical for the estimation of current loads and angle, consideration shall be given to the effects of Reynolds' number, pipe roughness, appendages and vortex induced motions on the drag coefficient, see DNV RP C205[5].

An inclined CWP in current may involve a significant horizontal offset of the entry of the CWP (bottom section) and therefore a vertical offset as well. It should be verified that the water depth reached by the bottom of the CWP still satisfies the required cold water in-take temperature.

6.2.7 Analysis of loads and displacements

Wave and wind forces on a floating OTEC platform will cause time-varying displacements of the top of the cold-water pipe. These will induce lateral and longitudinal motions along the length of the pipe, with magnitude dependent on the pipe's natural vibrational modes and damping from the structure and internal and external seawater. Additional loads will result from currents and platform motions. For pipes that are rigidly connected to the platform, the bending moments imposed by the platform's six degrees of freedom motion shall be included. For all platforms, gimballed or not, bending moments caused by heave acting on an inclined pipe (see DNVGL RP C205 [5] and DNVGL RP C202 [10]) shall be included.

Any analysis should include all static and dynamic loads on the platform and pipe simultaneously.

6.2.8 Recommendations for qualification of the Cold Water Pipe (CWP)

The CWP is a key component for the OTEC system, and at present there are no standards directly applicable to this type of structure. As several aspects of the CWP may be considered innovative, it is recommended that a new developer should undertake a process of qualification of the CWP and all ancillary equipment associated with the production, installation, and operation of the CWP. Guidance for performing such a new technology qualification process can be found in API 17N[12]. Additional relevant guidance for the qualification testing of flexible pipes (both bonded and non-bonded) may be found in API 17B[11] . Recommended guidance for ancillary components can be found in API 17 L1[13] and API 17 L2[14].

The qualification program shall be formalized at an early stage to define how the integrity of design, procurement, fabrication, testing and installation method will be maintained throughout.

6.2.9 Analysis approach

Time domain as well as frequency domain analyses need to be undertaken for computing various stresses on any CWP pipe bundle or individual pipe. Since the CWP is of a large diameter, the associated Keulegan-Carpenter (KC) number defining the oscillating fluid regime composed of floater imposed motions and waves may be low. It is well known that drag and lift coefficients are strongly affected at low KC and they shall be included accordingly, applied to the local relative fluid velocities. Assuming a strong influence of the CWP dynamics on the floater that leads to non-linear global responses in addition to this flow regime dependency, time domain computations should be conducted for at least a reduced load case matrix and model tests should be used for verification.

6.3 Warm seawater system

6.3.1 Warm water intake (screen)

Warm water is drawn from the mixed layer near to the surface. An inlet depth is selected that will give a suitable compromise among requirements for maximum water temperature, minimum pressure fluctuations due to waves, compatibility with platform design restrictions and acceptable, where applicable, biological impact.

The warm water for the evaporator heat exchangers passes through screens that bar entrance of marine animals and debris. The entrance area at the screen is typically designed to prevent fish from being impinged against the screen. Examples of best available technology for the Warm Water screen include:

a) maintaining slow (such as 15 cm/s) velocities,

b) having inlet flow directions generally horizontal, and

c) practical means to remove fish, biofouling or debris that become impinged on the screens over time.

6.3.2 Warm water ducting and pumps

The ducts to and from the pumps, plus pipework in general, should be designed to give a smooth flow path without sharp turns or contractions to minimize dynamic head losses.

The ducting arrangements are normally specific to a given site and plant design. Shore-based plants having one or more pipes in the surf zone will require special protection.

6.3.3 Biofouling control

Some type of active control measures will be required to prevent biofouling issues which arise with the warm water in various parts of the warm water system.

6.4 Seawater discharge arrangement and plume analysis

6.4.1 Seawater discharge ducts

The large sea-water flows emanating from an OTEC plant are at present a unique phenomenon because deep seawater is nitrate-rich, oxygen deficient and denser than the surface water. Details will vary by geographic location, discharge depth and plant design parameters. In contrast, most industrial seawater users take in surface water and add heat which lessens the density of the discharged water.

Enhanced growth of phytoplankton is likely if nutrient-rich deep water is discharged shallow enough for photosynthesis to occur. OTEC plants may use shallow discharge depths if developers desire this enhanced growth, or they may use longer ducts to minimize growth by discharging below the photic zone. This decision will affect the overall plant architecture.

The warm and cold seawater flows may remain separate or may be combined. If the flows are mixed prior to discharge, the cold water will be more dilute but warmer than if the flows are kept separate. The pros and cons of discharge pipes that release the seawater within, or below the photic zone shall be assessed on a case by case basis. Suitable numerical models of plume propagation and biological effect have been developed and should be applied. The importance of an environmental impact study cannot be overemphasized and time required for its proper conduct and consideration by stakeholders shall be included in project plans.

6.4.2 Seawater pumps

Seawater pumps (both cold and warm) will typically be of high-flow, low head design. Impellers will generally be of axial flow or mixed flow configuration. Such pumps have a high Net Positive Suction Head (NPSH) and are sensitive to inlet flow conditions of pressure, velocity, recirculation and vorticity. Designs should include a generous margin for available NPSH. In addition, consideration should be given to the orientation of the installed pumps and the associated implications due to platform motions. The position of the pumps in the system is shown in Figure 9.

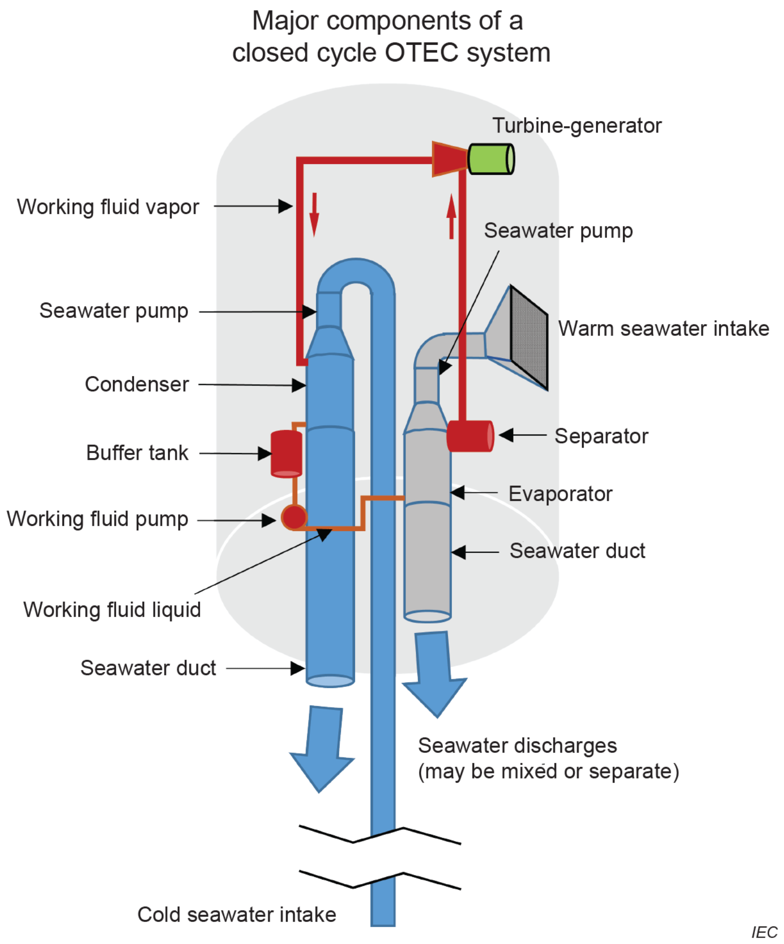

Figure 9 – Major components of a closed cycle OTEC plant working fluid process system

7 Process system

7.1 Working fluid selection

A closed cycle system can employ as a working medium any fluid with an appropriate vapour pressure at the temperature of the hot source and physical and chemical properties suitable for the total power system design. Most working fluids developed for air-conditioning or refrigeration systems are potential OTEC candidates.

Desirable characteristics of working fluids (closed cycle)

The major factors are:

- Typical vapour pressure in the range of 700 kPa to 1 400 kPa at 27 °C.
- Condensing pressure should be higher than atmospheric pressure.
- Enthalpy difference between the turbine inlet and outlet ports.
- Low volume flow of working medium per kilowatt of power produced.
- High heat transfer coefficient, that is, low thermal resistance to heat transfer from the bulk vapour to the heat exchanger surface through the liquid film.
- Chemical stability and compatibility with materials and structures of the power cycle, including heat exchanger, turbine, seals and lubricants.
- Ease of detection (safety).

- Acceptable toxicity and flammability (safety).
- Environmental acceptability.
- Availability.
- Acceptable cost.

7.2 Heat exchanger (HX) selection

Selection of heat exchanger area should be based on a cost optimised process to deliver maximum available power with acceptable risk. The selection of heat exchanger area is based upon a consideration of sea water flow, sea water velocity and working fluid heat transfer properties and HX geometry. HX selection needs to address corrosion, biofouling, HX configuration/type, and seawater and working fluid pressure losses as well as cost.

Ultimately heat exchanger and process system optimisation is related to a levelised cost of energy that includes operations and maintenance/replacement costs. This technical and economic optimization should seek to minimize pressure losses in the entire process circuit.

7.3 Materials compatibility

Practical use of the working fluid requires that it be compatible with materials of construction and handling. A high-level risk assessment using standards specific to the materials being considered shall be performed.

Corrosion protection needs to be addressed since deep cold ocean water tends to be biologically inert/nutrient rich and low in oxygen. This poses unique challenges to all systems which contact cold water. For example, although stainless steel and aluminium alloys tend to form a protective metallic oxide layer, the low-oxygen cold deep seawater may degrade this layer, leading to metallic pitting of components exposed only to deep seawater.

In addition, working fluids and elastomers shall be checked for compatibility, and heat exchanger mountings shall avoid dissimilar material so as to avoid galvanic corrosion, or use other corrosion protection methods.

7.4 Process system risks and hazards

A high-level risk assessment will be required as part of the front end design process to identify all possible process system risks and hazards. Steps should be put in place to make sure all risks are as low as reasonably practicable (ALARP).

The impact of possible release of working fluid should be considered with respect to preservation of the environment with associated mitigations.

At present it is likely that some extended duration testing of heat exchangers in a representative environment is required at an appropriate scale.

The design should consider isolation and venting requirements for heat exchangers and all aspects of the working fluid circuit, including on board storage, to preclude the potential for leaks to the environment.

8 Platform type

8.1 General

Selection of a suitable surface platform is vital for the successful long-term operation of an OTEC system. A wide variety of floating platform types have been proposed for OTEC use. Previous concepts and an extensive bibliography are given in [2]. Figure 10 identifies ISO offshore standards relevant to design and operations of an OTEC platform.

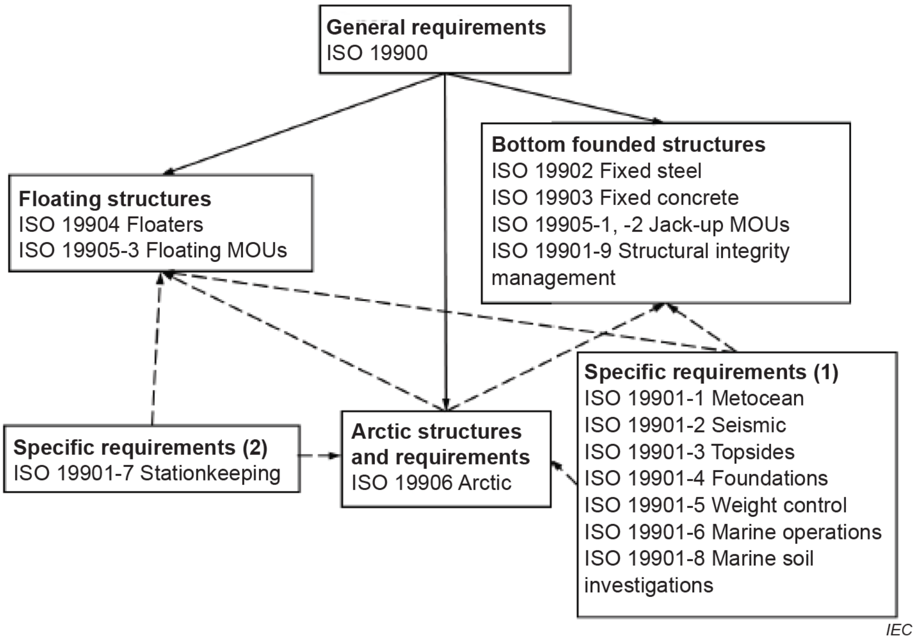

Figure 10 – ISO 19900 offshore standards relevant to OTEC platform design

A floating OTEC platform shall be large enough to contain the power plant, of which the heat exchangers are a major volume element due to the low sea-water temperature difference. Other large components, which shall be supported by the OTEC platform, include large seawater pumps, turbine-generator sets, power conditioning equipment, and other auxiliary equipment.

The platform shall support the cold water pipe and water discharge, and warm and mixed water ducting and provide space for energy transfer systems, operating personnel, and conventional equipment for seakeeping, safety, navigation, etc.

The floating plant shall be assessed as a floating substructure subjected to hydrodynamic loading, vertically supported by the buoyancy of the structure itself and the horizontal forces induced by wave, current, wind. The horizontal forces will be resisted by the station keeping system, typically a mooring system or thrusters or a combination of both. Non-moored Grazing systems are also another option based on surface temperature updates from satellites, thus helping to maximise power output.

8.2 Mooring/Station keeping

8.2.1 Grazing OTEC plants (no power export cable required)

Unmoored OTEC plant ships in normal operation will graze typically at an average speed of 0,4 to 0,5 knots up to a maximum speed of 1,0 knot, changing position from day to day to keep the plant-ship in a region of optimal surface temperature. The propulsion system shall also be able to maintain ship heading and stability in waves and winds of the severity predicted for the location while addressing a likely classification society approved metocean data return period. Note that concepts for grazing plants have been considered for which the vessels have no propulsion plants at all. The concept put forward in a US DoE study used drifters that could be periodically relocated by tugs when they strayed too far outside of their designated harvesting area.

8.2.2 Non-grazing OTEC plants

Direct transmission of OTEC power to shore requires that floating OTEC plants be maintained at a fixed location by mooring or dynamic positioning. Both procedures have been considered; however, dynamic positioning, unlike a mooring system, consumes power thus reducing the net power output of the OTEC plant. If some form of thruster system is adopted (e.g., thruster to maintain heading for a weathervaning system) engineering design data and assessment methodology can make use of the extensive technology developed for the offshore oil industry.

A stationkeeping system shall be designed to hold the plant within a specified circle above the selected geographical position without interfering with the power cable, in water depths exceeding 1 000 m. It shall also ensure that the platform can withstand the design site and metocean conditions. The relevant international standard is ISO 19901-7. (Other recognized standards include BV-NR-493[15]; DNV GL OS E301 Position Mooring[8]; and API RP 2SK[16].) Deep water moorings are complex and full use should be made of the experience gained from the design and long term operation of FPSO and semi submersible moorings. Moorings degrade over time and a mooring integrity review should be undertaken at the design as well as the operational stage making use of API RP 2SK [16].

9 Power export

9.1 General

This subclause outlines the main design considerations and requirements for the power/energy export subsystem of the OTEC plant. It assumes the following:

- The OTEC plant is mounted on a floating offshore platform.
- The OTEC plant is exporting power to a remote location (typically on shore, but it could be to another ocean based installation).

9.2 Design considerations

The power/energy export subsystem is defined as everything downstream from the generators (driven by the turbines/expanders of the Rankine cycle) up until the power is delivered to a customer at a contracted voltage. A portion of the generated power will need to be split off and made available for OTEC plant operations and for other platform power requirements (hotel loads, etc.) and is not explicitly addressed in this subclause.

Three categories of equipment comprise the power export sub-system: platform based equipment; transmission cable and land based equipment.

9.3 Platform based equipment

Basic power conditioning equipment typically includes:

- Transformers.
- J-tube (or other device) for connection of a dynamic cable to the moving platform plus suitable bell mouth.

9.4 Transmission cable

A high voltage power transmission line will need to include the following:

- A dynamic portion from the platform to the seafloor.
- A static portion along the seafloor to shore or to another remote destination.
- The associated cable protection equipment (shields, burial, suspension methods, etc.).
- A shore crossing.

Selection of DC or AC depends on voltage, distance of power transmission and other factors such as user requirements. A high voltage power transmission line may include the following:

- Power core(s)

- Fibre optics for data transfer/control
- Other compenents depending on system configuration

Specifics for the seafloor portion for a particular installation are very site specific. In some locations, horizontal directional drilling to “tunnel in” under possibly sensitive areas near shore may be required to “land” the cable and provide protection through the surf zone.

Note that subsea dynamic power cables at power ratings and voltages likely for an OTEC power export application should be qualified. ISO 13628-5, API 17B[11] and ISO 13628-11 include guidance for qualification testing.

9.5 Land based equipment

This will consist of power conditioning equipment, transformers and an associated protective building.

NOTE Applicable regulations for land based equipment may well depend on local authorities. See also IEC standards and local power grid codes.

10 Energy storage and transfer system

10.1 General

OTEC plant ships which are far from shore (not cable connected) may be designed to produce hydrogen, ammonia, methanol, or other energy intensive products. Energy transfer will involve on board storage of the energy product for periods of perhaps one month, followed by transfer of the product to a special tanker type vessel for transport to world ports for storage or delivery to the consumer. The basic equipment and procedures required for transfer of these energy products are generally in use in the offshore oil and gas sector, for example shuttle tankers working with FPSOs. However, the approach will need adaptation for a specific OTEC system and should be specified per relevant (IMO and similar) safety codes, depending on the plant’s actual location (e.g. on the high seas or in a state's exclusive economic zone).

10.2 Hydrogen

Hydrogen has a very low density, both as a gas and as a liquid and also an extremely low boiling point. Cryogenic or high-pressure storage is required if hydrogen is to be transferred in liquid form. Shuttle tanker transfer technology developed for Floating Liquefied Natural Gas (FLNG) systems may be helpful for cryogenic use of hydrogen.

10.3 Ammonia

An attractive method of storing and transporting OTEC hydrogen is to combine it with nitrogen on the plant ship to form ammonia, NH3, which can be easily liquefied, transported, and stored by existing methods and equipment. Liquid ammonia is nine times as dense as liquid hydrogen and can be stored at ambient temperature.

10.4 Methanol

Methanol (CH3OH) is made by combining two volumes of hydrogen with one volume of carbon monoxide (CO) in the presence of a suitable catalyst. Process designs are available from a number of proprietary sources. Designs should be carefully reviewed and modified as necessary for shipboard use. This may have particular impact on columns and separators or tanks with significant inventories.

10.5 Battery storage

The weight of battery storage is much less of an issue for a floating vessel compared, say, to an electric land vehicle. Thus, with continuing developments in battery technology this is a promising technology for OTEC power storage/transportation. The safety and interaction of any battery system with the process and utility plant on the OTEC vessel will need careful consideration. Electrically propelled shuttle tankers containing many battery banks, rather than oil tanks, may merit further assessment.

11 Land and shelf-based OTEC

11.1 General information and guidance

Mechanical system design of land-based or shelf-based OTEC systems will be generally similar to a floating system as described in the previous chapter. Compared to floating OTEC plants, land or shelf based plants will have longer seawater pipes, but simpler arrangements for power cables.

A land-based OTEC system has all major systems located in proximity to the shoreline. Land-based systems may be suitable at locations having a seabed profile that is generally steep. Seawater pipe anchoring in depths less than 40 m will be extensive, usually requiring burial. Primary design considerations will be:

a) protecting the plant components from extreme storms, and
b) minimizing wasted seawater pumping power due to lifting seawater high above sea level.

A shelf-based OTEC plant founded offshore in relatively shallow water may be appropriate for a site having a long distance from shore to the steep seabed. Portions of a shelf-based OTEC plant may well use a steel jacket with steel or concrete piles. Design of jacket based shelf mounted platforms is well established in the offshore oil and gas industry. This includes all geotechnical aspects of the piling operations and metocean loading. Designs should incorporate the ISO standards listed in Figure 10.

11.2 CWP design for land and shelf-based OTEC plants

The design and construction of cold water pipes for land and shelf-based OTEC plants involves several issues not encountered with vertically suspended CWPs, such as:

a) The design needs to be site bathymetry specific.
b) The design needs to address detailed historical information at the site concerning ocean waves and currents for three (or more) depth zones.
    - The near shore zone is often associated with high waves and currents and may require heavy structures and/or pipe emplacement below the sea floor.
    - A middle zone beyond the near shore, where effects of surface waves are felt, but exponentially diminish with depth.
    - A deep zone to extending down to the cold water intake depth. Typically, the total pipe length ranges from ~2 km at the steepest sites to 5 km to 10 km at other possible locations. In general, the shorter route the lower capital cost, although local obstructions shall always be addressed with respect to pipeline route.
c) Detailed bathymetry and morphological information about the sea bottom is required, whether the pipe is designed to be tethered above the seabed or firmly anchored to the bottom or buried in a trench.

Presence of local features, such as coral, local land and sea life, infrastructure, etc. shall be taken into account during route selection. Other users of the ocean should be consulted and their requirements assessed and addressed as required.

Relevant engineering information is also available from municipal sewage systems and electric power plants that discharge effluents through large underwater pipes extending to considerable depths and distances from shore. Such information and practical experience should be utilised.

Depending on location water pumping power may be substantially increased if the plant is placed on the shore at a height above storm wave limits.

12 Risk based approach for the design and operations of OTEC plants

12.1 Risk assessment

Risk is classically defined as the product of the likelihood of a negative event occurring, and its consequences. Rain is a common, even frequent occurrence, whose consequences are mostly trivial in an offshore setting. No out of the ordinary risk control is required. An uncontrolled fire at an offshore facility is potentially a frequent-enough occurrence that regulatory bodies require both preventive measures, such as detailed attention to controlling sources of ignition, fuel and, in some cases even oxygen, and corrective measures, such as permanently installed fire suppression equipment.

Risk is controlled by managing both frequency and consequence of possible events. An extreme tropical cyclone is a relatively rare event at any given geographical location, whose consequences could be devastating. An offshore facility can be designed and constructed to survive almost any storm, but the cost of doing so might be uneconomic. In such a scenario, designers shall seek to understand the severity of likely storms and their likely consequences to judge risk tolerance and possible mitigations. This is addressed by applying a typical risk matrix as shown in Figure 11.

In assessing likelihoods, designers/managers and risk assessment teams shall recognize the role that multiple, sequential or simultaneous failures can play in initiating or exacerbating an initial event. They shall further recognize the role played by human error and endeavour to include systems to minimise this very real danger.

RISK MATRIX					Consequence ratings for • Safety, • Environmental Impact • Financial Impact • Public Disruption
Probability	**Consequence**				
	1	2	3	4	
1				░	**Risk Score/Ranking**
2		░	░	▓	**1-3: Low Risk, minimal action required**
3		░	▓	▓	░ **4-6: Moderate Risk, Mitigation recommended**
4	░	▓	▓	▓	▓ **8-16: High Risk, Mitigation necessary**

IEC

Figure 11 – Simple risk evaluation matrix

Applying risk assessment techniques early in a design cycle of a new facility, using what is sometimes called a preliminary hazard assessment or hazard identification process, allows engineering focus to ultimately generate risk based design and operations. The process can involve experience-based measures, such as failure modes and effects analyses (FMEA) combined with statistical measures, such as mean time between failures for mechanical devices. When devices or methods are novel, and experience or statistical data are lacking, a more subjective process can be engaged. A risk assessment workshop can be convened, which relies on a small team of subject matter experts, led by a facilitator to arrive at a consensus on likelihood and consequence. When high-risk activities are identified, this same team can provide ideas for how to mitigate risk, and re-score the risk profile if mitigation is required.

12.2 Risk based design

12.2.1 Risk assessment process

Structured approaches for conducting risk assessments are described in many, widely available publications, such as [4].

12.2.2 Prototype testing

Prototype testing to obtain reliable operational performance data is vital to any project. Not only can it be used to quantify failure probabilities contributing to negative events, it can also provide assurance for the investment community and possibly government, that is likely to provide financial support for OTEC projects. Due to the cost associated with full scale testing, prototype testing at a reduced scale may be more appropriate.

Reduced scale prototype testing is an established technique for developing new engineering designs. To ensure a successful prototype testing programme it is necessary to define the scale up process and the confidence associated with this process. The documentation should be peer reviewed to confirm that the proposed process is valid. Adopting such a process will increase the probability that good results are obtained which, when scaled up, result in a successful design.

12.3 Risk based operational guidelines

12.3.1 Floating plant

There are unique risks associated with the operation of any floating plant. Fortunately, millennia of navigational experience, coupled with offshore operations experience provides us with the basis for ALARP safe design. Regulatory requirements, Classification rules and international treaties have evolved to mitigate these risks and will need to be incorporated in the design requirements.

Examples of mature and continuously evolving guidance are the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL).

12.3.2 Operating plant

Working and other fluids in OTEC plants are potentially hazardous. Ammonia, for instance, is flammable and immediately dangerous to life and health in concentrations as low as 300 ppm in air. Fuel for emergency and start-up power generation is obviously flammable. Operating and maintenance guidelines shall ensure that fluids are contained and that spaces where fugitive vapours can collect are monitored. Escape from and response to gas hazards shall be an integral part of design, training and operation.

The OTEC process equipment is made up of a myriad of ducts and rotating machines, any one of which can present a unique hazard to personnel. Risk identification and countermeasures shall be an integral part of design, training and operation.

For emerging technologies, such as OTEC, Classification societies can offer critical review under an approval-in-principle (AIP) program. This requires significant effort in cross-education between the classification society and the system designers during the documentation submittal and review process to obtain maximum benefit from the process.

12.3.3 Product export risks/hazards

OTEC plants may produce electricity or a synthesized energy storage medium for export. They may be used to produce fresh water or simply provide cooling water for export. The export of any OTEC product presents unique risks requiring review, if not mitigation. For electricity, sent by cable, striking the cable could be damaging, disruptive or deadly. Cable strikes can occur as a result of fishing activities, ship anchoring, other cable laying and/or trenching activities in the area, as well as any active geophysical environment. Further guidance on this subject can be found in the ISO 19900 series.

One concept for OTEC energy export is the synthesis of ammonia. The process of transferring ammonia to a tanker and transporting it to a delivery port involves multiple transhipments, each one of which has its own unique risks. The least hazardous export from an OTEC plant could be fresh or cold water, but this also presents potential risks. Once reliance on OTEC as a source for these commodities is developed, any disruption from a broken pipeline or system shutdown could be economically damaging.

13 Transportation and installation (T&I)

Transportation and installation require considerable planning, as it can involve many different approaches, although local availability of tugs and installation vessels will tend to influence the decision-making process. Early consultation with transportation and installation (T&I) contractors is recommended to identify feasible cost-effective solutions early on. It is also highly desirable to have a marine specialist as part of the project management team. Once an outline T&I methodology has been developed it should be reviewed by the project team to confirm that it is fit for purpose and that it is not expected to adversely affect plant operations. Factors which need to be taken into account in the decision-making process include:

- Should the moorings be pre-installed prior to hook-up to the OTEC platform? Depending on the type of mooring lines, they may need to be subsea buoyed off for protection (if using fibre rope) or they can be laid on the seabed (if using wire/chain) for later ready retrieval.
- Where is the hull to be fabricated, how should it be transported to the site, and in what stage of commissioning?
- Should the cold water and discharge pipes be fabricated on site or off-site and delivered for upending and installation?
- How will the deep-water sections of the export cable be laid and the shore crossing traversed? How will the dynamic cable between the platform and the seabed be installed? If fresh water production or cold water supply for sea water air conditioning are to be included, how will pipelines be laid and at what stage of the entire installation?

Whatever installation sequence is developed to meet the design requirements, a detailed plan with itemised method statements will be required as part of the engineering process. As discussed in Clause 8, non-standard operations should be subjected to rigorous Hazard Identification and Risk Assessment (HIRA) review by multidisciplinary teams under the chairmanship of an experienced facilitator. This group should review all procedures and classification of all vessels to be employed and the experience and qualifications of key installation team members to confirm their suitability for the work.

An independent check of all engineering calculations associated with installation should be carried out. It may be prudent to engage the services of an independent marine warranty surveyor company for review and approval. Although such a review historically is conducted to protect the interests of insurance underwriters, this critical, disinterested third party review of transport and installation engineering and procedures can be invaluable to the project team.

14 Commissioning and handover

Similar to sea trials for a newly-built ship, but probably far more involved, a commissioning plan, including checks of all safety and shutdown systems, shall be developed on a systems basis. The system architecture will dictate at which level each system, subsystem and component will be identifiable, commissionable and isolatable. Test plans shall be developed to enable functional confirmation at the lowest level first. Individual components should be tested first, before their subsystem and system. The goal is to perform as much of the system integrity testing before leaving the assembly yard. As with any good quality assurance plan, documentation and repeatability are critical. A sequenced method for commissioning, as well as integrated function tests, should be included in the test plans and signed off system-by-system by manufacturers, builders, integrators and operators.

Loading of all bulk fluids, such as fuel oil, hydraulic oil, refrigerants or working fluids, fire-fighting foam concentrates, lubricants and coolants, shall be carefully considered, as shall the pre-charging of each fluid or vapour system. In virtually all liquid and vapour systems, cleanliness is paramount, and commissioning plans shall include a means for verifying system cleanliness, integrity and proper purging and pre-charge.

The commissioning period can be viewed as a training opportunity for the operations team prior to handover from the builder/integrator. Suitable practice drills for making safe after emergency shutdown and re-starting in a proper sequence, should be included in these pre-handover routines.

Handover shall include a full documentation set including all manuals, spares lists, procedures, manufacturers' recommendations for inspection and maintenance, final signed test sheets and the inevitable, punch list of minor outstanding repair items. A plan for completion of the punch list should also be provided and agreed with the operations team.

Both the OTEC plant and the power export cable should be tested prior to connection to a grid. The OTEC site may well be logistically remote from the power cable manufacturer. How to test the OTEC power system and export cable shall be addressed during both the front end and detailed design process to ensure that the required system performance is achieved.

15 Operations, inspection and maintenance

15.1 General

This clause outlines the main aspects of requirements for the operations, inspection and maintenance phase of OTEC plant operation. It is based upon the following precepts:

- The plant may be mounted on a floating offshore platform, shelf-based or land-based. The overall plant may be considered in the following system groupings:
    - Cold and warm seawater supply and discharge systems, such as ducts and pumps
    - Process modules – Ammonia (or other working fluid) circulation including turbines; pumps; heat exchangers; controls and shutdown systems
    - Electrical systems including generators, transformers, power distribution and protection, and power export cable
    - Safety and habitability systems (fire-fighting, potable water, sewage, escape, etc.).
    - Bio-fouling control systems
    - Corrosion protection systems
    - Hull (or foundation), bilge and ballast systems
    - Position-keeping systems such as mooring equipment, or dynamic positioning
    - Transfer systems such as boat handling equipment and cranes
    - Control systems
    - Auxiliary systems

15.2 Operations

Operation of an OTEC plant will be similar to operation of industrial refrigeration facilities, offshore facilities or electricity generating plants. The standards, training and procedures from these industries should generally be adopted for use with OTEC plants.

As part of the plant design and operations plan, a list of required qualifications, manning and operational procedures shall be developed and implemented.

Industry or equipment-specific training qualifications will be relevant and shall be incorporated into the OTEC plant’s operational procedures. Any OTEC-unique variations from existing standards should be reported to regulators and the classification agency.

The Supervisory Control and Data Acquisition (SCADA) system shall have capability of recording operational history, displaying overview and detailed schematics of process and electrical systems, displaying alarms, in a hierarchical manner, giving additional weight (visually and audibly) to the important safety-critical alarms and allowing informative alarms and status alarms to be reviewed by the operators in a practicable time frame. An event recorder within the SCADA system shall be able to distinguish first-up alarm or trip signals to aid diagnostic activity during possible emergency OTEC power system shutdowns.

Notwithstanding the recording capability of the SCADA, it is advisable to ensure that operators fill in a summary log sheet of key parameters – this may be paper or electronic and will help to ensure and record that the essential overview of the system’s performance is taking place. A written log of relevant events and unusual observations should be maintained shift-by-shift; reference to this should be included in the review of the inspection and maintenance regime on a periodic basis.

It is possible that normal operation for nearshore installations could, after some extended experience with manned systems, become unmanned with remote control exercised from an onshore control centre. Operators should be required to practice emergency routines on a regular basis; whilst much of this can be via a simulated approach, a live scramble to attend the offshore facility if it is running unmanned should be included at least once annually, to preserve familiarity with emergency procedures.

15.3 Inspection and maintenance

It is important that a planned Inspection/Repair/Maintenance (IRM) integrity preservation scheme should be initiated from the beginning of the front-end design phase. This should take account of manufacturer recommendations, although not necessarily precisely follow them long term, except where a breach of warranty could occur. The overall intent should be to review the IRM scheme with a view to optimising inspection and planned activity in line with cost-effective operation, as experience of plant behaviour is obtained and documented.

Reliability centred maintenance (RCM) should be considered as a systematic approach to adoption of an IRM as an approach to limit uncertainties due to the extent of new or novel technologies involved in an OTEC system.

The IRM scheme should include, but not necessarily be limited to:

- External inspection of CWP, external hull and other submerged piping shall be performed at regular intervals, probably using ROVs. Particular vigilance should be maintained for signs of corrosion, cracking, excessive marine growth or damage around intakes and discharge points and on the mooring lines and connections. Fatigue sensitive areas should be subject to cleaning off of marine growth and close visual inspection for potential fatigue induced cracking taking into account any known fatigue hot spots.
- Repair of corrosion or removal of marine growth should normally follow a carefully developed plan and be adjusted in the light of field experience and developments in knowledge. For example, it may be found that certain materials are subject to premature ageing or stress induced cracking.
- Process systems should be regularly visually inspected. Reliance should not be placed only on installed monitoring systems and CCTV; the human ability to see or hear or smell “something not quite normal” should always be appreciated and applied.
- Monitoring of power drawn, bearing temperatures, and other condition parameters on key items of machinery including expander/generator, water pumps, and pressure differentials across heat exchangers to monitor fouling and availability signals from safety critical protection systems should all be utilised to aid with planning of routine maintenance, as well as major overhauls/life extension refits.

- Planned maintenance on major equipment items using FMEA and performance data techniques to avoid breakdown repairs, as far as possible, should be applied.
- Review of any process incidents or upsets to evaluate any potential impacts on maintenance requirements should be carried out.
- Keeping records of IRM activity including visual records of internal inspections of Heat exchangers, pumps, etc. Feedback of unusual/unexpected inspection findings to manufacturers should be undertaken to allow future design improvements to be implemented.
- Experienced evaluation, on perhaps an annual basis, of the IRM scheme, to possibly reduce frequencies of maintenance, wherever suitable, to optimise life cycle costs. This should address past operational experience and also the criticality of specific components. Such a review may show for certain instances that an increase in inspection or maintenance may be appropriate, particularly as equipment ages.
- Records of process interruptions and breakdowns shall be analysed to ensure that maintenance levels are still appropriate and any underlying causes are identified and rectified.

15.4 Hazards and safety

15.4.1 Hazards

Due to the use of hazardous materials, such as ammonia, a suitable safe haven for operators should be provided from which a safe means of escape can be made and which is in accordance with statutory regulations and class requirements, such as SOLAS and IMO. This may be by lifeboat, crew-boat or helicopter as appropriate. The safe haven shall contain all personal protective equipment required (e.g. breathing apparatus) to ensure that operators can egress in safety. The atmosphere in a safe haven shall be independently supplied and controlled, such that it will not be contaminated by toxic gas or liquid from an external source during an emergency. Full training in the use of safe haven systems shall be provided.

Particular care should be taken to ensure that procedures for leaks of toxic fluids (e.g. ammonia) are well understood and tested. Safety equipment should be available at appropriate points around the facility, which should be checked regularly and documented.

Hazardous circumstances, that alone or in combination with normal conditions could cause the serviceability limit state or ultimate limit state to be exceeded, shall be addressed. The measures taken to counter such hazards basically consist of:

- Careful planning during all phases of development and operation;
- Avoiding the structural effects of the hazards by either eliminating the source or bypassing them;
- Minimizing the consequences; or
- Designing for the hazards.

In considering a specific hazard, a design situation shall be defined. This design situation will normally be dominated by one hazardous occurrence with expected concurrent normal operating conditions. Early in the front-end design phase of a project a HAZOP (Hazard Operability) assessment should be undertaken. This should be repeated during the detailed design phase to confirm that all identified hazards have appropriate mitigations, which have been suitably peer reviewed.

15.4.2 Safety

15.4.2.1 General

OTEC contains unique features such as large-scale ammonia process, storage (for temporary storage during maintenance activities and for top up capability) and transfer facilities. These may have similar requirements to facilities for the storage processing and handling of hydrocarbons in an offshore context. Area classification rules such as IEC 60079-0 will apply to prevent fire and explosion, etc.

A safety technical specification for the design shall be established covering area classification and equipment for use in hazardous atmospheres. A command station on the OTEC platform shall be integrated to allow for an on-site crew to monitor the health and safety of the various subsystems that compromise the OTEC plant and enable immediate corrective action to be taken in the event of an emergency. The location of the command station shall be carefully considered including, if appropriate, attention to potential marine hazards and the benefits of good external visibility as well as escape routes in the case of a major emergency.

15.4.2.2 Safety at sea

An offshore OTEC plant shall be equipped with appropriate navigation warning signs and lights, radar reflectors, life boats/life rafts and any other equipment consistent with national (flag state) and IMO regulations. If a unit has no flag, then local authorities are to be consulted.

15.4.2.3 Accidental events

The possibility of accidental events shall be carefully considered, and suitable criteria shall be established. Possible accidental events include, for example, vessel collision, dropped objects, crane failure, explosion, fire and flooding, etc.

15.4.2.4 Special requirements

All special operational, construction and maintenance requirements that can affect the safety of the structure shall be specified, together with their expected concurrent environmental conditions.

The limiting environmental conditions specific to certain operations shall be specified, for example mating of the CWP to the hull structure, depending on the proposed construction methodology.

15.4.2.5 Location

The site location and structure orientation (nominal heading) shall be specified. For plants designed to be relocatable or for grazing plants, the range of limiting environmental conditions and water depths shall be clearly stated on-board and agreed with the appointed classification society.

The site for the structure in latitude and longitude shall be identified early so that the appropriate environmental conditions and associated return periods can be sourced. The importance of obtaining accurate metocean data early on in a potential project cannot be over stated.

16 Decommissioning

At the end of its useful life, the installation will most likely have to be decommissioned rather than abandoned in place, although the possible beneficial impact of the structure on the local marine eco-system should also be addressed. Decommissioning is essentially the reverse of installation and commissioning and should be considered during the original front-end design process to try to make the process as safe, simple and straight forward as possible.

The scope of work associated with decommissioning typically includes:

- Disconnection, retrieval and disposal of the cold water pipe, power cable(s), warm water discharge, etc. Plastics in particular are not candidates for at-sea disposal. Certain components such as electrical cables may be suitable for reuse.

- Disconnection, retrieval and proper disposal of mooring lines, subsea buoys and clump weights, that may not be candidates for at-sea disposal. Ground tackle, i.e. anchors or piles, may be candidates for abandon in place, with the approval of regulatory authorities.
- Disconnection and tow-away of the offshore OTEC facility to a facility for emptying of all process fluids in a safe manner, cleaning and dismantling for disposal or recycling.
- Drilled or buried shore landings for pipelines and cables should be reviewed on a case by case basis to determine the least detrimental procedure for their decommissioning. A case by case assessment should be carried out, based on an energy balance environmental basis to determine what needs to be recovered or filled or perhaps reused for a new or upgraded system.

Decommissioning should be carefully planned in the same manner as installation including method statements, risk assessments and detailed procedures all being reviewed and agreed by a suitable expert team.

Post removal final site inspection, including ROV inspection of seabed and cable route(s) is likely to be carried out and documented if necessary.

Continued monitoring of the environmental restoration processes following decommissioning may be required by Regulators. Plans for such continuing, non-revenue-producing activities, if required, should be part of the decommissioning plan.

Annex A
(informative)

OTEC potential and its history

A.1 OTEC potential

The ocean thermal energy resource exists in tropical waters, roughly between latitudes 23º North and 23º South. Between these lines of latitude large parts of the ocean fulfil OTEC's requirement for a typical temperature difference of at least 20°C during the whole year. Past studies identified 98 nations and territories with access to the OTEC thermal resource within their 200 nautical mile exclusive economic zone. See Figure A.1.

The International Energy Agency reported that in 2012 world electrical consumption was 22,668 terawatt-hours, giving an average electric power consumption of 2,6 terawatts [1]. Research done by various independent sources suggests the sustainable OTEC resource is considerably larger than the world's present electrical production.

These sources include:

- The University of Hawaii estimates that there could be produced annually between 7 and 30 terawatts of OTEC electric power without adversely impacting the earth's natural thermal currents [3].
- The International Institute for Applied Systems Analysis (IIASA) reported a gross potential before electrical conversion estimated to be approximately 3150-30000 EJ/year. Assuming a 3 % net efficiency for an OTEC plant, this would furnish 3,3 to 30,5 terawatts.
- The Intergovernmental Panel on Climate Change estimates a net electricity potential of 108-324 EJ/year, which converts to 3,4 – 10,3 terawatts.

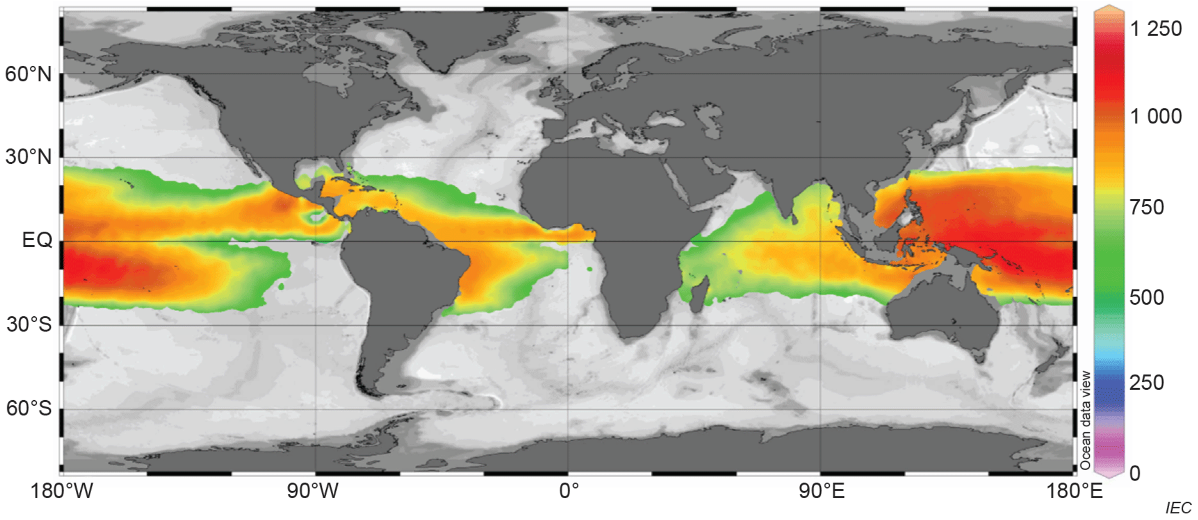

Figure A.1 – Density of OTEC potential around the world, in kW/km²

Much of the world's population is located within coastal regions and many live in the tropics. Promising initial markets for OTEC are tropical islands and coastal regions. In the future, electricity generated by OTEC may be used to synthesize a chemical energy fuel for widespread worldwide utilisation.

Depending on the actual warm and cold temperatures, OTEC plants require 5 m^3 to 10 m^3 of seawater per second to generate one megawatt of usable power. This water flow is comparable to low head run-of-the-river hydroelectric dams and thus require large pipelines and engineered infrastructure. Studies generally agree that OTEC plants, at large (>50 MW) scale can be technically and economically viable when using an average temperature difference of at least 20 °C. Present OTEC developers are investigating small OTEC plants for niche markets that have high existing electricity generating costs and a large seawater temperature difference easily accessible close to shore. Revenue from fresh water generation can also assist project economics.

A.2 Installation sites

OTEC power plants can be installed at three types of sites: onshore, shelf-mounted, or floating.

The feasibility of an onshore or shelf mounted OTEC system is highly dependent on the local seabed profile, i.e. if the cold water intake pipeline can reach adequate deep cold water with a not too long pipeline. For an onshore plant, the warm seawater supply pipes, cold seawater supply pipes and all return seawater pipelines transit the surf zone.

A shelf mounted or near-shore plant is fixed to the seabed (bottom founded) in a shallow area offshore, significantly shortening the length of all three pipes that shall transit the shallow water zone compared to an onshore plant. Installation of seawater pipes down a steep slope (> 20°) has been performed for diameters of 1 m to 2 m. At present larger diameter slope mounted pipes are expected to require additional engineering studies and testing.

Finally, a floating plant minimizes the length of seawater pipes and maximizes site/anchoring flexibility, but incurs the cost of the buoyant hull structure, mooring or propulsion systems, increased staffing costs due to on site living and power export cable to shore.

A.3 Previous OTEC projects

OTEC research systems of less than 250 kW have been built and operated multiple times, as shown below in Table A.1. Technology development has been funded by the United States, Japan, the Republic of S. Korea, France, India, and Malaysia and numerous companies. Further information can be obtained from the OTEC Foundation, Hawaii National Marine Renewable Energy Centre, Technical University of Malaysia, Saga University, and others. Technical, historical and economic data is summarized in [2], which is recommended to anyone new to this subject.

Table A.1 – Notable OTEC systems – Past and present

Year	Sponsor	Name	Location	Description
1928	Georges Claude	Ougree-Marhaye	Belgium	50 kW open cycle
1930	Georges Claude	Matanzas Bay	Cuba	22 kW open cycle
1978	State of Hawaii	Mini-OTEC	Kona, Hawaii	53 kw gross closed cycle
1979	Japan	Ocean Discover	Shimane Prefect	1 kW closed cycle
1980	US Dept. of Energy	OTEC-1	Kona, Hawaii	38 000 kWt (thermal test)
1982	TEPCO	Nauru	Island of Nauru	100 kW closed cycle
1993-8	US Dept of Energy	NPPE	Kona, Hawaii	250 kW open cycle
2011	Reunion Region	Naval Energie	St Pierre, La Reunion	500 kWt closed cycle test bench
2013	Japan	Okinawa Deep Seawater/OTEC Project	Kumejima Island	Two 50 kW closed cycle
2015	United States	Ocean Energy Research Centre	Kona, Hawaii	105 kW closed cycle

A.4 Open cycle OTEC

Open cycle plants have been demonstrated and have technical appeal because the warm and cool working fluids can, depending on design, exchange heat efficiently without an intervening heat exchanger surface. Because the steam working fluid is at very low pressure, its density is low and thus resulting component dimensions are large. A large diameter turbine will likely operate effectively on land, but may experience dynamic loading effects due to motions on a floating platform and this will need to be assessed and addressed.

Vacuum compressors will require several intercooled stages to efficiently remove non-condensable gases continuously from the seawater.

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(*Continued from second cover*)

International Standard	*Title*
ISO 19901 (all parts)	Petroleum and natural gas industries — Specific requirements for offshore structures
ISO 19902	Petroleum and natural gas industries — Fixed steel offshore structures
ISO 19903	Petroleum and natural gas industries — Fixed concrete offshore structures
ISO 19905 (all parts)	Petroleum and natural gas industries — Mobile offshore units — Jackups
ISO 19906	Petroleum and natural gas industries — Arctic offshore structures
ISO 21650	Actions from waves and currents on coastal structures

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