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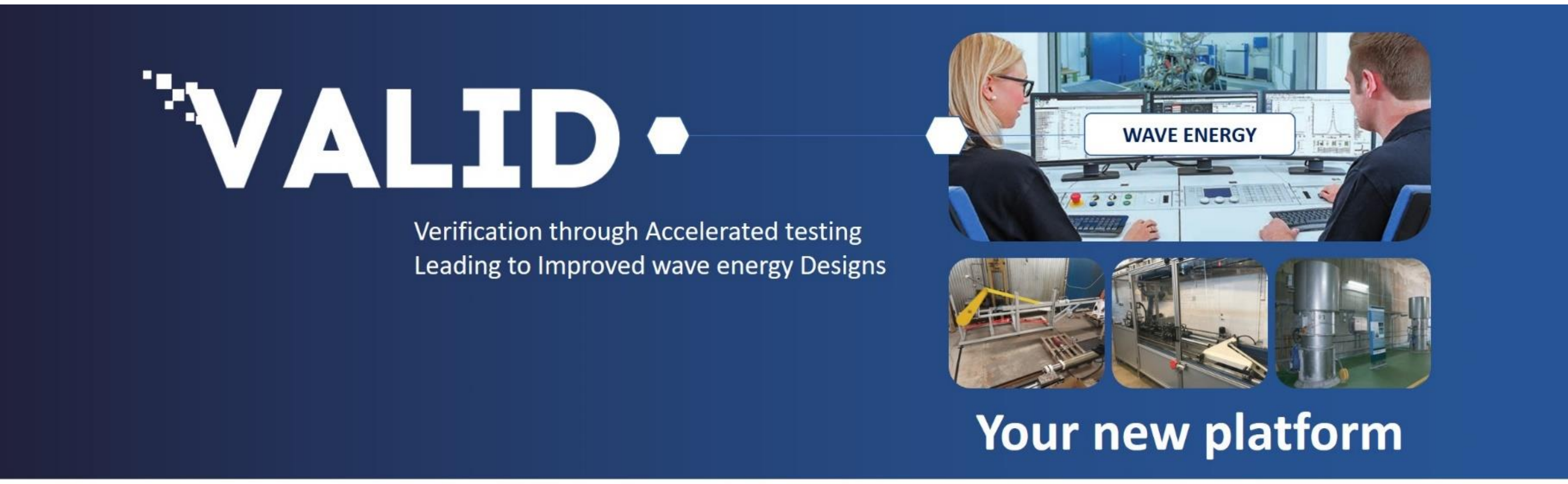
Verification through Accelerated testing Leading to Improved wave energy Designs



Deliverable 5.1

Definition of User Case #3

Version 2.0

2022-01-28

Lead participant: Wavepiston, AAU

Dissemination level: PU

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Executive Summary

The present report constitutes Deliverable 5.1 *"Definition of User Case #3"*, developed within WP5 of the VALID project. The overall aim of the report is to provide an overview of the topic dealt with in User Case #3, i.e., the reliability of seawater hydraulic pump seals used in wave energy converters (WECs). The specific case to be demonstrated in the VALID project is based on the Wavepiston WEC, which is a multi-body floating oscillating wave surge converter (OWSC) constructed by surging plates connected to a string made of drill pipe sections. The final objective of the present report is to establish a preliminary test plan for the hybrid testing that is to be used in the forthcoming work in WP5.

The reports start by giving a detailed account of the Wavepiston wave energy technology. This description lay the foundation for the later work on the test rig (Deliverable 5.2) as well as the wave-to-wire modelling (Deliverable 5.3). The description is for the sub-systems hydrodynamic; power-take off (PTO); control and power transmission.

The report further contains a discussion of components to be tested, namely the seals in seawater pumps used in the Wavepiston device. This includes a discussion of seals in the hydraulic pumps as well as literature study of seals in hydraulic pumps. The section also covers a thorough reliability and survivability assessment covering Root Cause Analysis and Bow Tie Analysis, leading up to a Failure Modes, Effect, and Criticality Analysis (FMECA). From the FMECA analysis, it was found that the highest risk priority numbers are:

- Early ending of seals' life
- Accelerated wear damage: Rod damage due to corrosion and biofouling
- Accelerated wear damage: too many suspended particles

The report then goes on to discuss relevant standards and best practices for wave energy simulations and tests. More importantly, the report covers how these practices are to be treated within the hybrid testing of User Case #3. The intended numerical set-up is discussed as well as the foreseen test rigs set-up. There will be a full-scale test using an entire hydraulic pump and a modified wear-bar test. The connection of the virtual models to the test rig using the MODEL.CONNECT framework is also considered.

Wavepiston is presently performing a full-scale test at the PLOCAN test site in the Canary Islands. Thus, the hybrid testing in WP5 will focus on this site. The environmental conditions of the PLOCAN site are reported and the relevant design load cases (DLC) are defined.

The report finishes with a discussion of the relevant metrics and parameters to be measured during the hybrid tests; and outlines the preliminary test matrices for the full-scale hydraulic pump tests and the modified wear-bar tests. It is understood that the test matrices will be updated and finalised in Deliverable 5.3.

Project partner names

- RISE Research Institutes of Sweden AB
- Fundacion Tecnalia Research and Innovation
- Corpower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
- Aalborg University
- AVL List GMBH
- Wavepiston AS
- Delft University of Technology
- Aquatera Sustainability Ireland LTD
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- Yavin Four Consultants, Unipessoal LDA
- Aquatera Atlantico
- Technical University of Denmark

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1 Overview of User Case #3

User Case #3 is mainly focused on the reliability of seawater hydraulic pump seals used in wave energy converters (WECs). The seals are typically found in hydraulic power take-off (PTO) sub-systems. The specific case to be demonstrated in the VALID project is based on the Wavepiston WEC, which is a multi-body floating oscillating wave surge converter (OWSC) constructed by surging plates connected to a string made of drill pipe sections. A surging plate is attached to a wagon that moves relative to a support beam. Two telescopic hydraulic pumps connect the wagon and beam. A unit of the plate, wagon, beam and pumps is named an Energy Collector (EC) (Figure 1, top). The Wavepiston WEC is to be made up of a string of up to 32 connected ECs. The string is held in position by two buoys at the ends, which are slacked moored to the seabed (Figure 1, middle). The hydraulic pumps in the ECs pressurise seawater into a transport pipe. The pipe leads the pressurised water to an onshore turbine and/or a reverse osmosis system. Wavepiston has deployed several scaled sea trials at the DanWEC test site, in Denmark [1] and is presently testing a full-scale system at the PLOCAN test site in the Canary Islands (Figure 1, bottom).

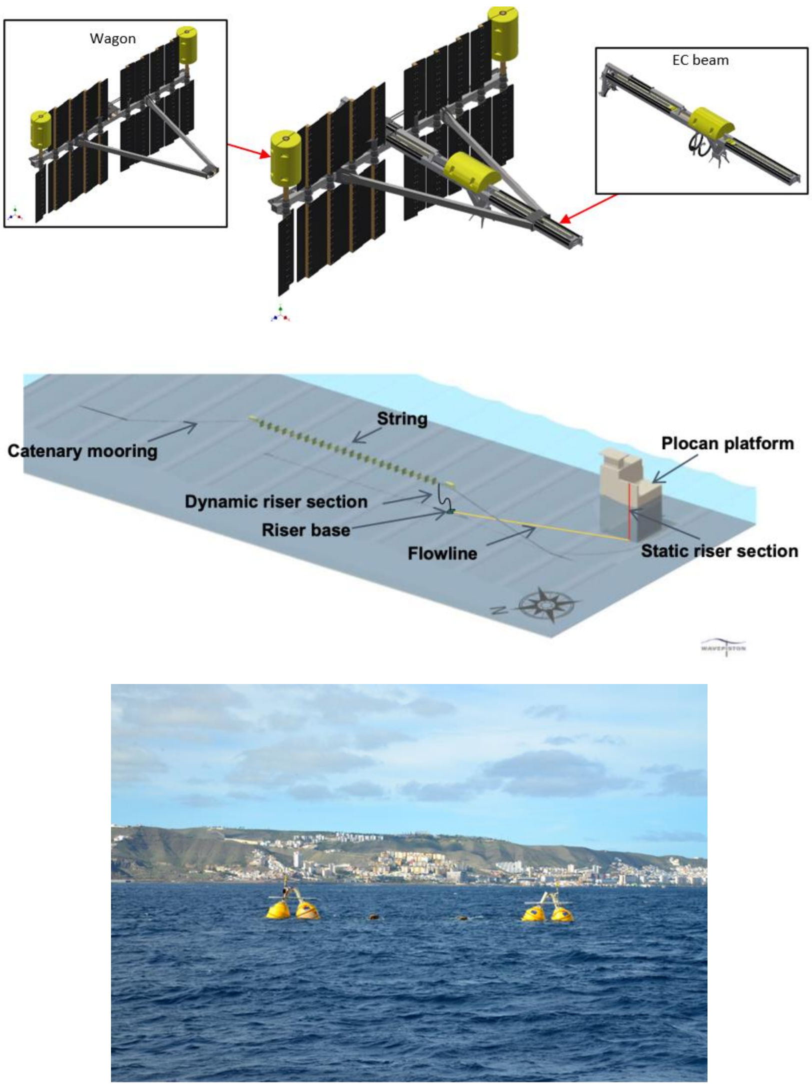

Figure 1: The Wavepiston floating oscillating wave surge converter.

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1.1 Introduction

The hydraulic pump unit has been identified as a critical factor for the Wavepiston device, see VALID Deliverable 1.1 [2]. The seals are a vital system part for the Wavepiston OWSC as the hydraulic pumps do not only generate power but also (i) make the ECs self-centering (i.e., providing the restoring force so the wagon will return to the equilibrium position); and (ii) are vital for the integrity of the structure by providing damping for the motion of the wagon.

The VALID hybrid testing approach means that some parts of the Wavepiston OWSC will be emulated by numerical and analytical means, while the seals will be represented in the physical test rig that is to be constructed. At a high level, the division between hardware and emulated parts for User Case #3 is presented in Figure 2.

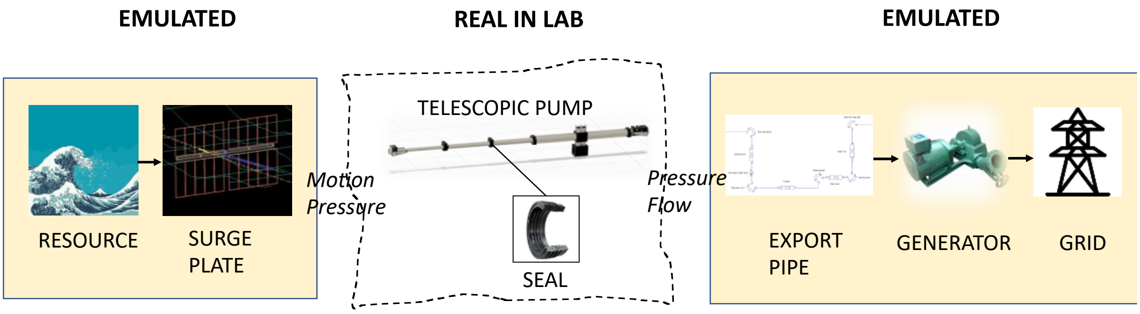

Figure 2: Emulated vs real parts in the VALID hybrid testing approach for seawater hydraulic seals.

Using Figure 2 as a visual aid, a spectral wave model is expected to simulate the environmental resources to provide boundary conditions to a wave2wire (W2W) model, consisting of several modules. The motion of the surge plates is to be simulated by a time-domain hydrodynamic model solving the Cummins equation using hydrodynamic coefficients obtained by a standard linear boundary element method (BEM) model. This module is expected to be developed in WEC-SIM/Orcaflex, see [3] for a more detailed description of the numerical models used by Wavepiston. The motion of the plates also depends on the PTO system and a module describing the dynamics of the hydraulic system, including the telescopic pumps and the transport pipe, is to be developed in Matlab/Simscape. A module of the control system for the generator is expected to provide the downstream boundary condition to the hydraulic model. The development of the emulated models is the focus of VALID Deliverable 5.3. Regarding the hybrid testing to be carried out in the VALID project, the complete W2W model will likely be too slow to be run in real-time. It is thus expected that the W2W model will give the time series of the plate motion to be used as input data to the test rig. The hydraulic model, which can be run in real-time, is expected to be linked to the physical test rig and used in a hybrid setting to provide realistic values of the pressure acting on the seals.

The design and construction of the seawater hydraulic seal test rig is the objective of VALID Deliverable 5.2. At a high level, it is expected that the pump unit with seals, check valves and accumulator will be tested by applying the reciprocating surge motion with a hydraulic actuator. An outline of the test rig is presented in Figure 3.

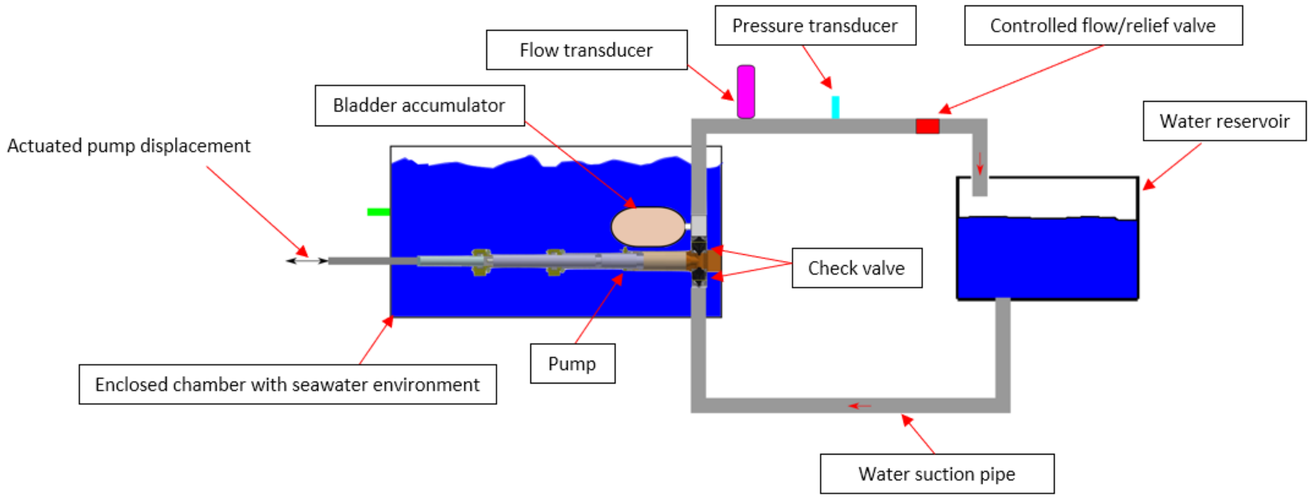

Figure 3: Outline of seawater hydraulic pump seal test rig.

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1.2 Definition of relevant WEC-components/sub-system parameters

WECs come in all shapes and forms but, as discussed in VALID deliverable 1.1 [2], from a sub-system point of view all WECs are built up from the same key sub-systems as illustrated in Figure 4.

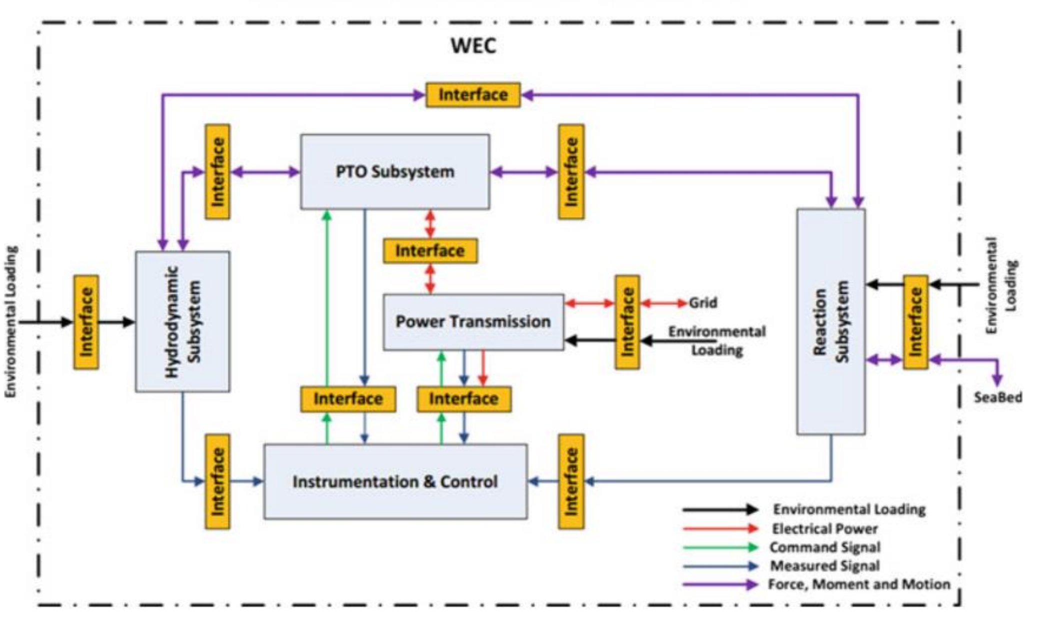

Figure 4: WEC system breakdown [4].

Following such nomenclature, the different sub-systems can be defined as [5]:

1. Hydrodynamic sub-system, responsible for the wave absorption and harvesting of the wave power. For the Wavepiston OWSC, this is the wave motion causing the surge motion of the wagons.
2. PTO sub-system, describing the conversion of mechanical power to electricity by a turbine or to fresh water by a reverse osmosis module. For the Wavepiston OWSC, this subsystem consists of a primary PTO in the shape of hydraulic pumps converting the motion of the wagons to high-pressure seawater and an electrical generator as secondary PTO that converts the high-pressure seawater into electricity.
3. Power transmission sub-system, which is the electric system that feeds the converted electricity into the grid.
4. Reaction sub-system, providing a reaction point for the PTO. For a Wavepiston EC, this is the support beam that in turn is kept in position by a slack mooring system.
5. Control sub-system. It consists of sensors, actuators, processing units, etc. for the electromechanical processes.

How these sub-systems appear in practice in the Wavepiston device are detailed in the following sub-sections. We focus here mostly on the PTO sub-system as that sub-system contains the hydraulic pumps and seals that will be subjected to testing in VALID.

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1.2.1 Hydrodynamic sub-system

The hydrodynamic sub-system of the Wavepiston WEC consists of several ECs. An EC consists of a wagon that slides relative to the support beam and two hydraulic pumps (as illustrated in Figure 1, top) that harvest the relative motion between the wagon and beam. The ECs are attached to a string made up of drill pipe sections (see Figure 5), referred to as drill string in the text below.

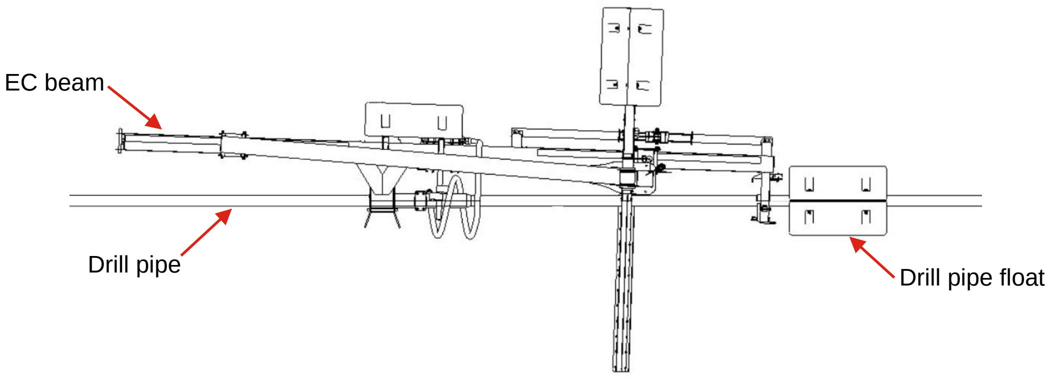

Figure 5: Side view of the EC module mounted on the drill string.

As illustrated in Figure 6, the surge plate connected to a wagon is made up of ten individual paddles. The paddles can rotate 90 degrees around their vertical axes to make the plate more transparent to the flow and consequently reduce the hydrodynamic loading on the Wavepiston system (the rotation of the plates is activated when the wagon hits the end stop). The wagon is connected with two telescopic pumps. During the surge motion of the wagon, one of the pumps is driving seawater into the drill string, and the other pump is filled with seawater. The dimensions of the paddles in the operating conditions (without flipped plates) are illustrated in Figure 7, while the main properties of the wagon are listed in Table 1.

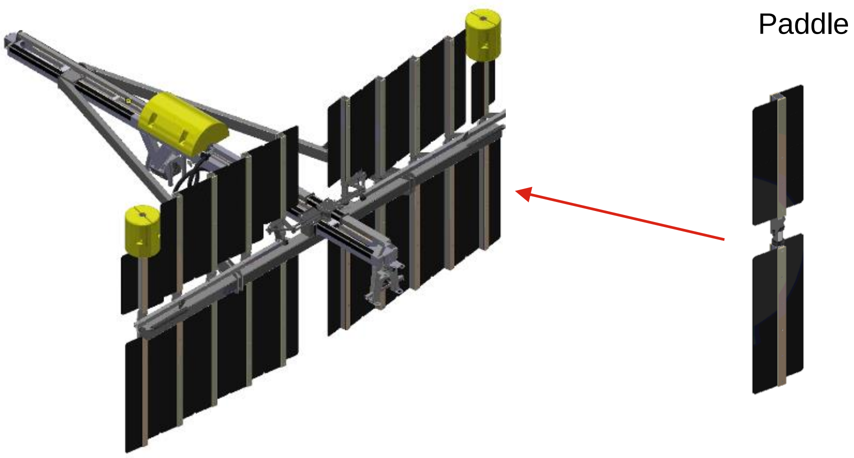

Figure 6: EC module.

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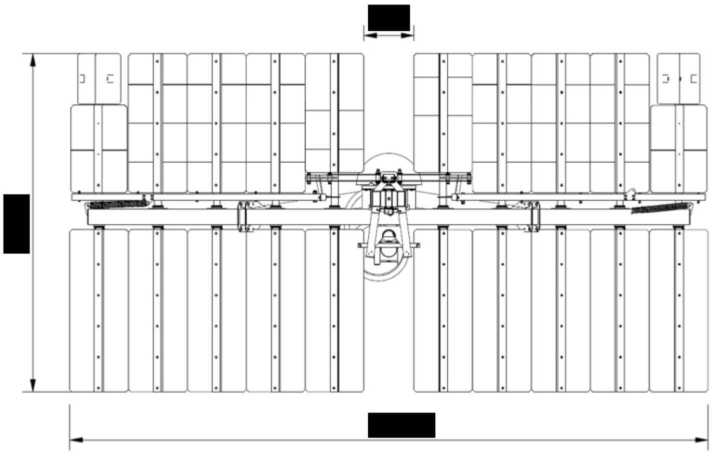

Figure 7: Dimensions of the EC drag area [mm].

Table 1: Wagon properties.

Property	Value
Height	[redacted]
Width	[redacted]
Wagon drag area	[redacted]
Mass	[redacted]

1.2.2 PTO sub-system

In the Wavepiston WEC, the PTO sub-system is defined to be the pump unit and the hydraulic pipe interface to the turbine, including the dynamic and static riser and flowline pipe. A sketch of the main components in the PTO sub-system is illustrated in Figure 8. Further details about the main components are provided in the following sub-sections.

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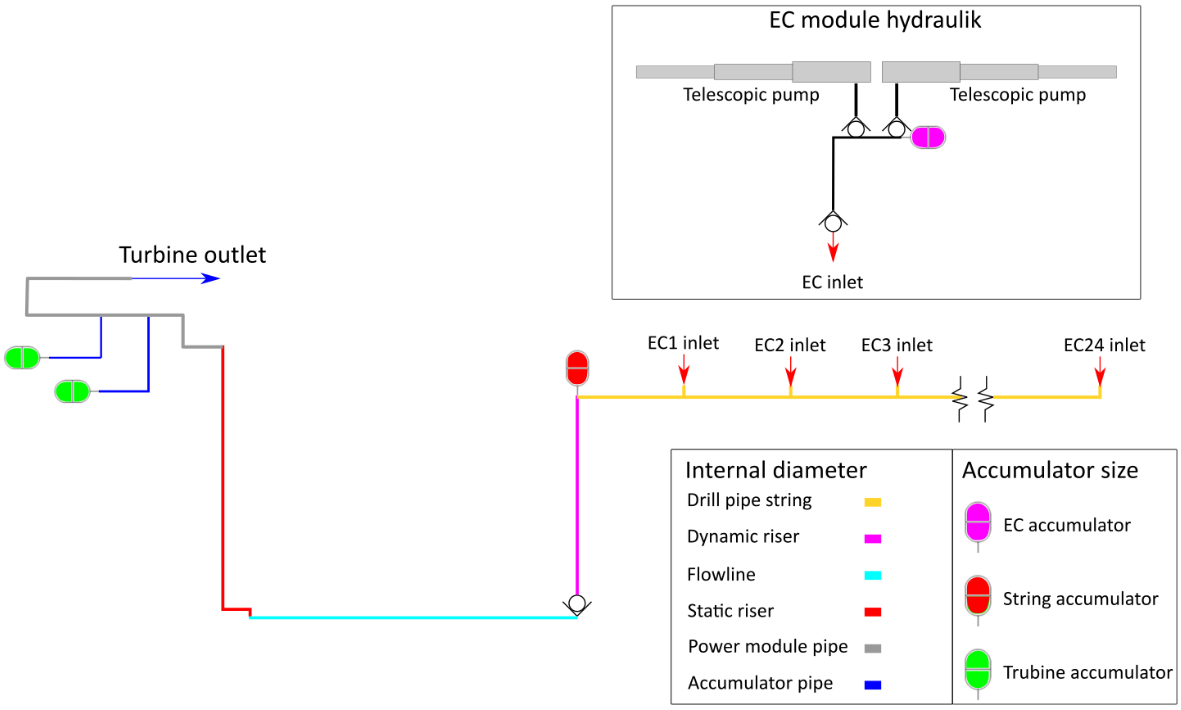

Figure 8: Sketch of the main components in the PTO sub-system.

1.2.2.1 EC hydraulic

The components in the pump unit are illustrated in Figure 9**,** and a hydraulic diagram of the EC module is shown in Figure 10**.** The pump unit is connected to the drill string with a check valve, as indicated in Figure 10. The dimensions of the piping in the EC module are listed in Table 2.

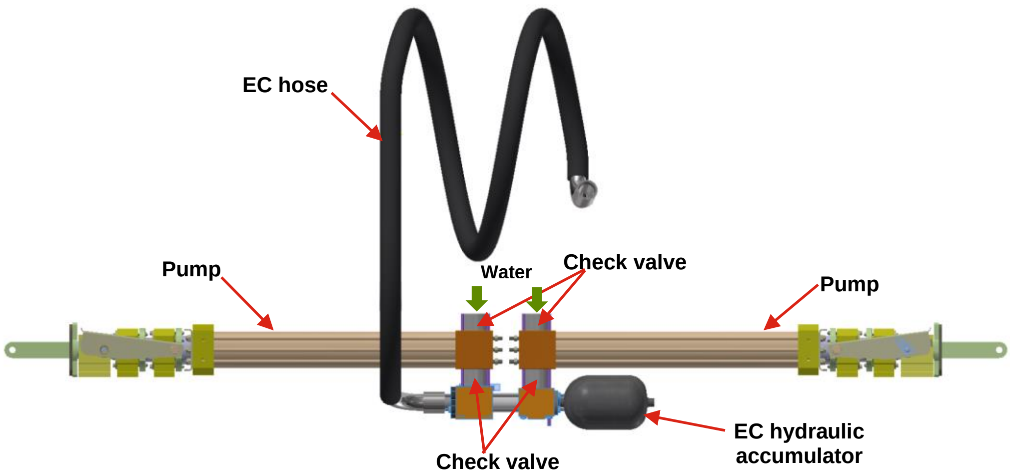

Figure 9: Pump unit.

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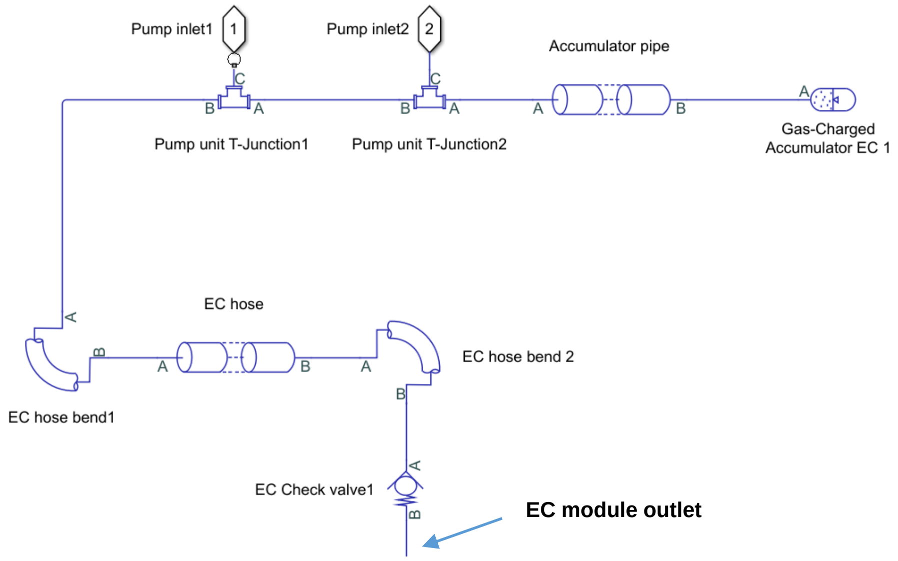

Figure 10: Hydraulic diagram of the EC hydraulic.

Table 2: EC hydraulic pipe dimensions.

Component	Dimension
EC hose	Diameter: [redacted] m Length: [redacted] m
EC hose bend	Diameter: [redacted] m Bending radius: [redacted] m
T-junction	Diameter AB: [redacted] m Diameter C: [redacted] m
Accumulator pipe	Diameter: [redacted] m Length: [redacted] m

Hydraulic pump

As mentioned above, the wagon is connected to the EC beam with two telescopic pumps. During the surge motion of the wagon, one of the pumps is driving pressurized seawater into the drill string, while the other pump is filled with seawater. The telescopic pump has three stages with different diameters (see Figure 11). The telescopic pump sequence is controlled, as illustrated in Figure 12. Letting the plate start at the maximum left position and moving towards the right, the left pump will become filled with water while the right pump will pump water into the drill string. First, the right pump is experiencing the smallest diameter, stage 1, and as it moves to the maximum position to the right it passes through stage 2 and 3 (and analogous for the motion to left for the left telescopic pump). Thus, as the wagon travels towards the end stop the pump diameter increases, giving a larger force to be overcome. Wavepiston owns a patent on the sequence mechanism of the telescopic pump [6].

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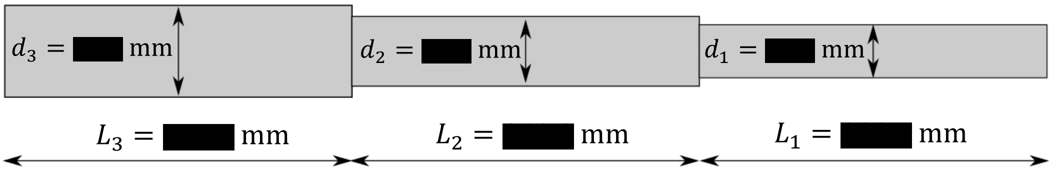

Figure 11: Telescopic pump dimensions.

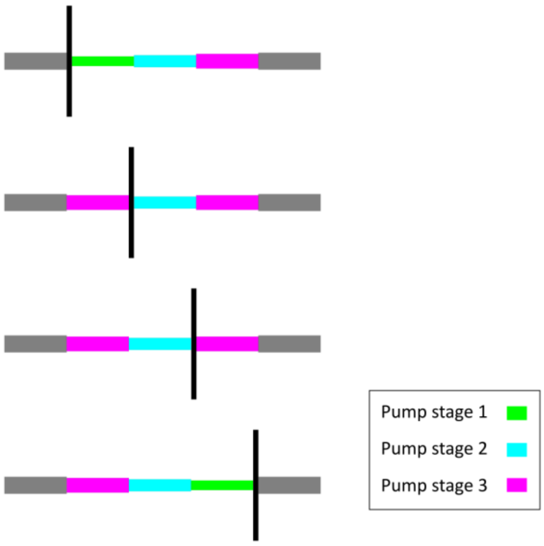

Figure 12: Illustration of the telescopic pump sequences for different plate positions.

1.2.2.2 EC hydraulic accumulator

The EC accumulator that is mounted on the pump module is illustrated in Figure 13 and the accumulator properties are listed in Table 3.

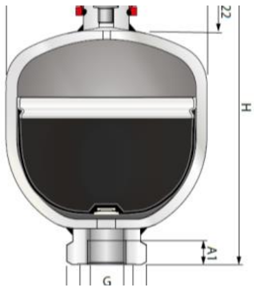

Figure 13: Illustration of the membrane accumulator mounted on the pump unit.

Table 3: EC accumulator properties.

Gas volume	Design pressure	Temperature range	Pressure ratio (Pmax/P0)	Pressure ratio (Pmax - Pmin)	G	A1
[redacted] L	[redacted] bar	[redacted] °C	[redacted]	[redacted] bar	[redacted] ”	[redacted] mm

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1.2.2.3 Drill string

The drill string consists of 24 drill pipes that are connected through hydraulic interfaces to the EC modules, as illustrated in Figure 14. An accumulator is mounted near the interface between the dynamic riser and the drill string in order to reduce the flow pulsation in the export pipe.

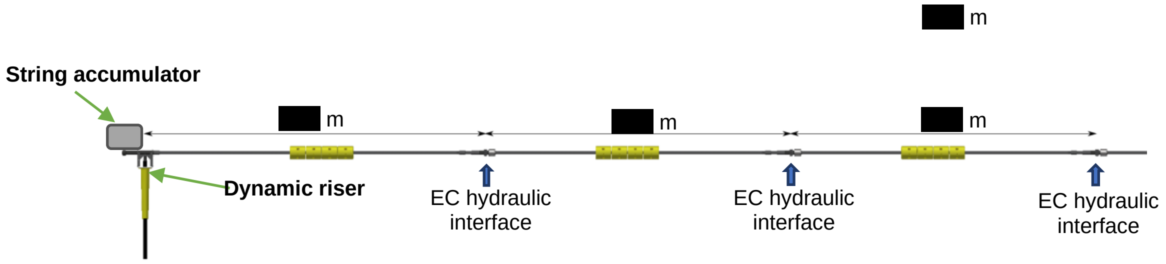

Figure 14: Illustration of the drill string.

Drill pipe

The drill string is made up of sections of drill pipes. The drill pipe dimensions are given in Figure 15, and a hydraulic diagram of the drill pipe and the interface to the EC module is illustrated in Figure 16. The dimensions of each component in the hydraulic diagram are listed in Table 4.

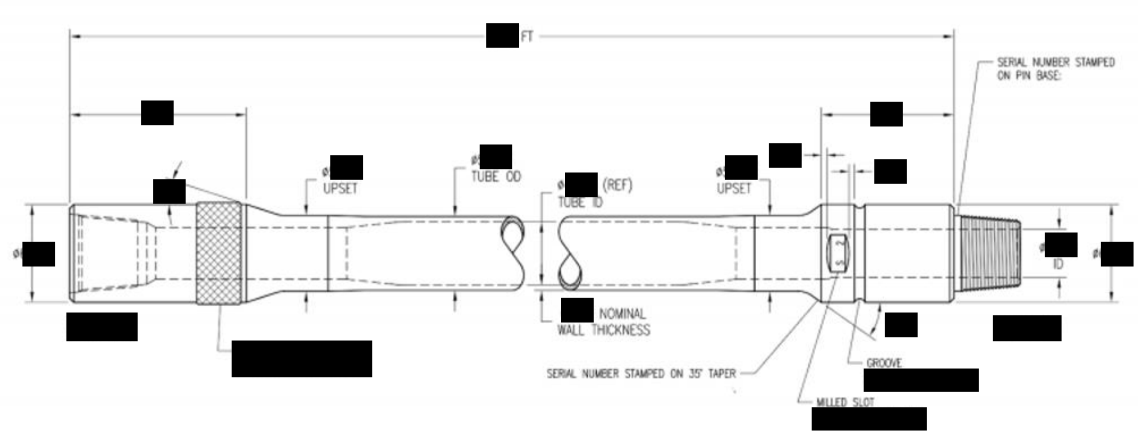

Figure 15: Machine drawing of the range 2 drill pipe with dimensions [FT/inch].

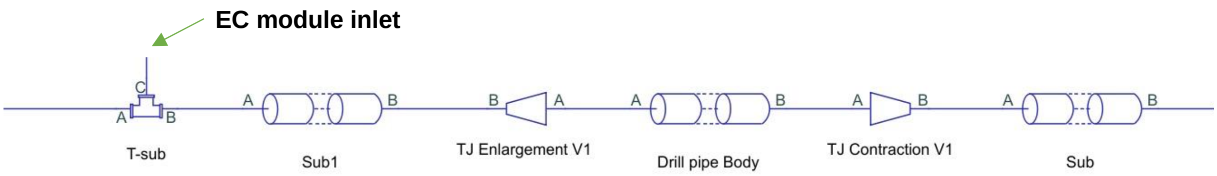

Figure 16: Hydraulic diagram of each set of sub and drill pipes.

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Table 4: Sub and drill pipe dimensions.

Component	Dimension
Sub1	Diameter: [redacted] m Length: [redacted] m
Enlargement	Cone angle of upset: [redacted] Diameter B: [redacted] m Diameter A: [redacted] m
Drill pipe body	Length: [redacted] m Diameter: [redacted] m
Contraction	Cone angle of upset: [redacted] Diameter A: [redacted] m Diameter B: [redacted] m
Sub	Diameter: [redacted] m Length: [redacted] m
T-sub	Diameter AB: [redacted] m Diameter C: [redacted] m

String accumulator

The string accumulator consists of 2 bladder accumulators, with design and properties as illustrated in Figure 17 and Table 5.

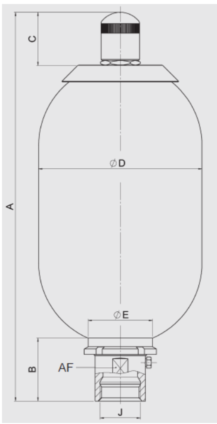

Figure 17: String bladder accumulator.

Table 5: String accumulator properties.

Nominal volume	Eff. gas volume	J (Thread ISO 228)	ØE	AF	Q
[redacted] l	[redacted] l	G [redacted]	[redacted] mm	[redacted] mm	[redacted] l/s

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1.2.2.4 Export pipe

The export pipe between the drill pipe string and the turbine located at the PLOCAN platform is made up of 3 parts: the dynamic riser, the flowline and the static riser. This is illustrated in Figure 18.

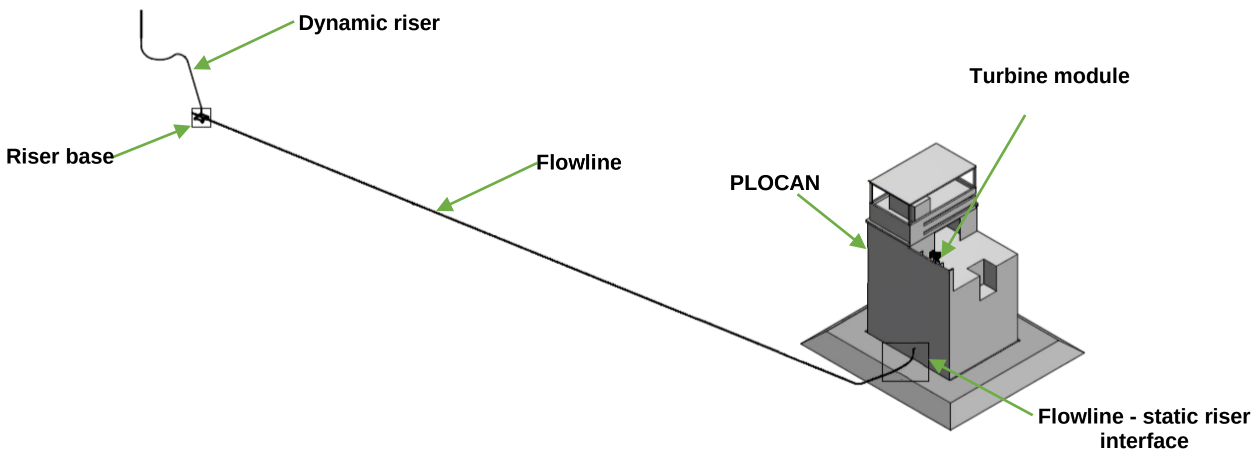

Figure 18: Illustration of the export pipe between the drill string to the platform.

A hydraulic diagram of the export pipe is shown in Figure 19, whereas the dimensions of the main components are listed in Table 6.

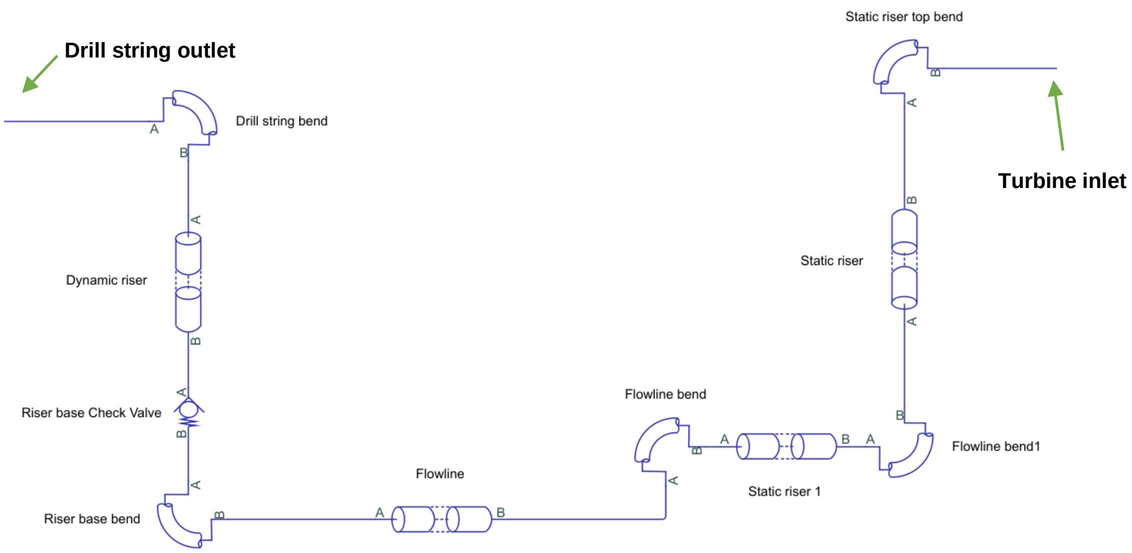

Figure 19: Hydraulic diagram of the export pipe.

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Table 6: Export pipe dimensions.

Component	Dimension
Dynamic riser	Length: [redacted] Diameter: [redacted] m
Flowline	Length: [redacted] m Diameter: [redacted] m
Static riser	Length: [redacted] m Diameter: [redacted] m Elevation gain from port A to port B: [redacted] m

1.2.2.5 Turbine module

The turbine module that converts the pressurized water to electrical power is illustrated in Figure 20, and a hydraulic diagram of the piping in the turbine module is illustrated in Figure 21. Two hydraulic accumulators with the properties listed in Figure 22 are used as pulsation dampers in the turbine module.

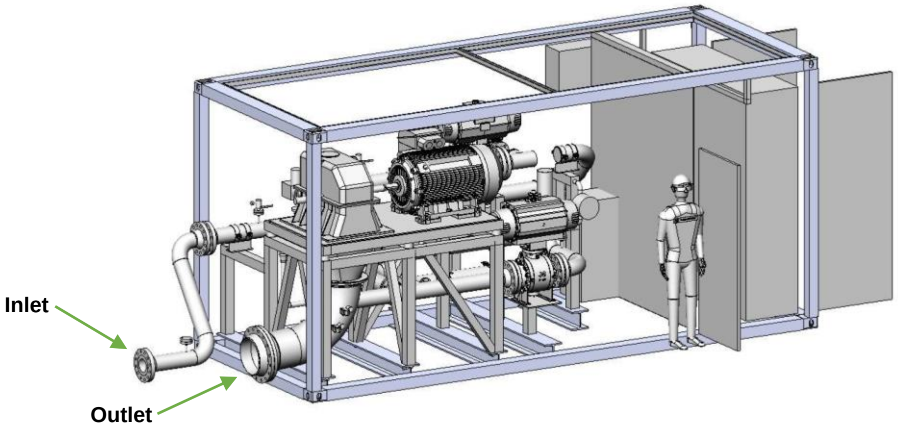

Figure 20: Illustration of the turbine power module located at PLOCAN.

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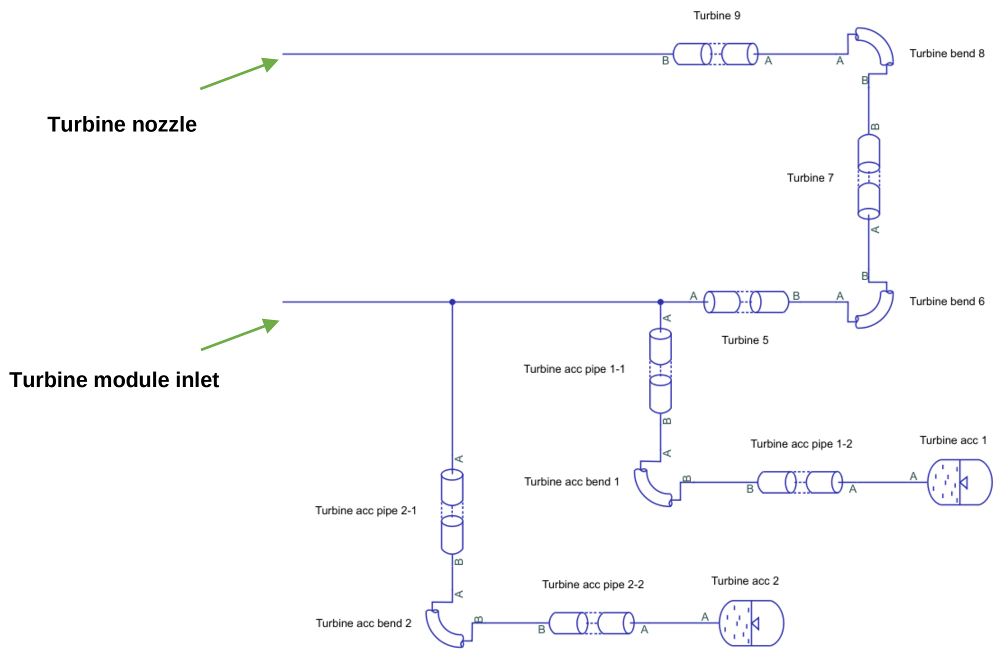

Figure 21: Hydraulic diagram of the turbine module.

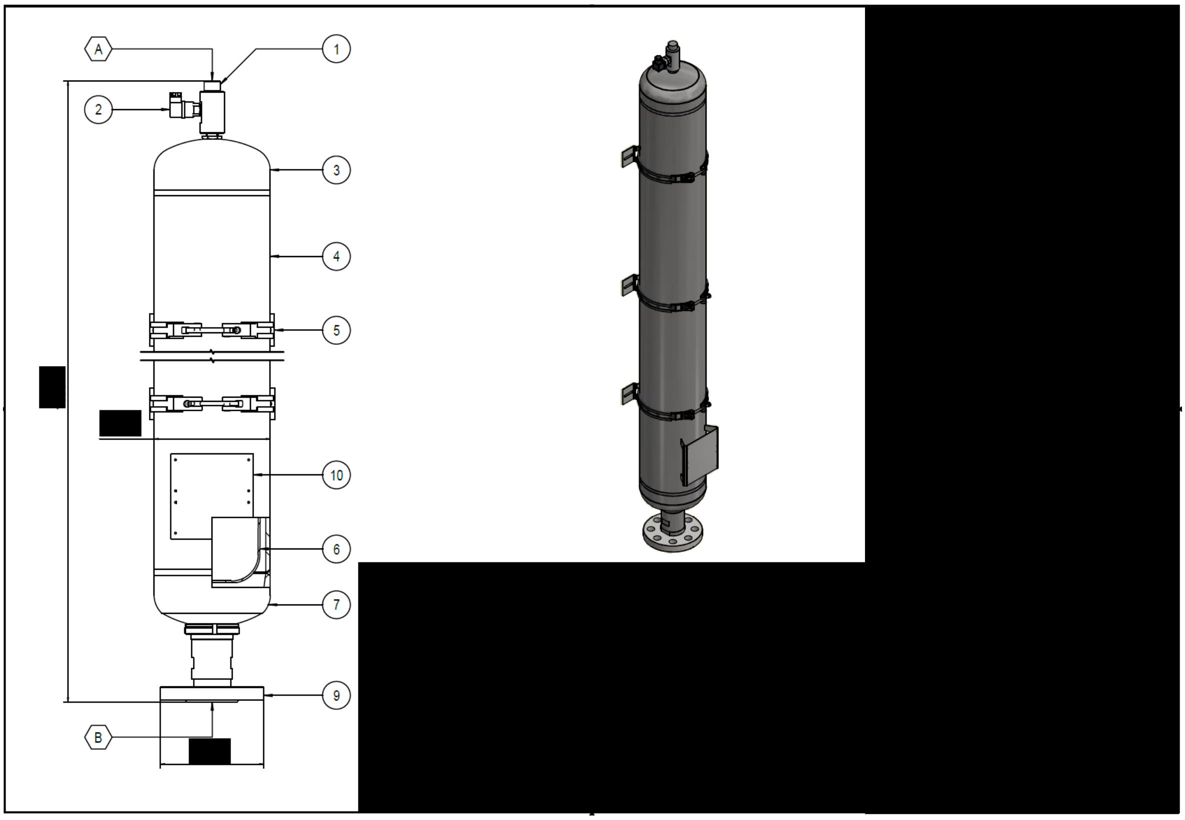

Figure 22: Properties of the hydraulic accumulators in the turbine module.

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1.2.3 Control sub-system

The position of the spear nozzle illustrated in Figure 23 at the inlet manifold of the turbine is adjusted by a proportional-integral-derivative (PID) control loop which aims at keeping a constant head pressure of 55 bar. The pressure measurement which is used in the PID-loop is obtained just before the turbine inlet manifold, as indicated in Figure 24.

1.2.4 Power transmission sub-system

The (AC) power from the generator is rectified and subsequently re-converted to AC by power electronics. Hence, for the Wavepiston turbine/generator, the grid can be considered an ideal adaptive load, which momentarily adapts to the generator's output.

In the event of a grid failure, the Wavepiston PTO system will dump power into an onboard resistor while shutting the system down.

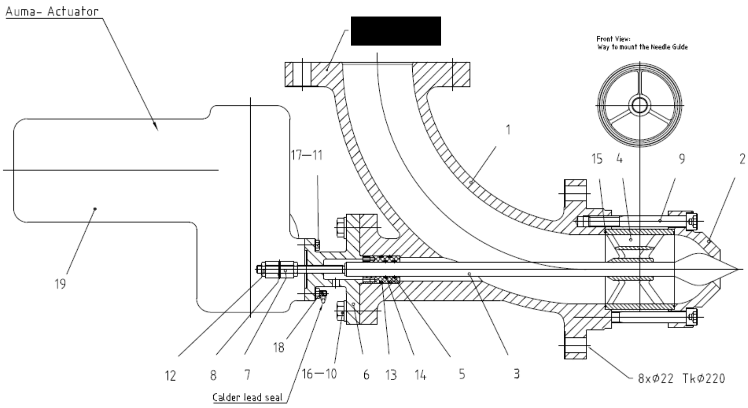

Figure 23: Cross-section of the turbine inlet manifold with spear nozzle.

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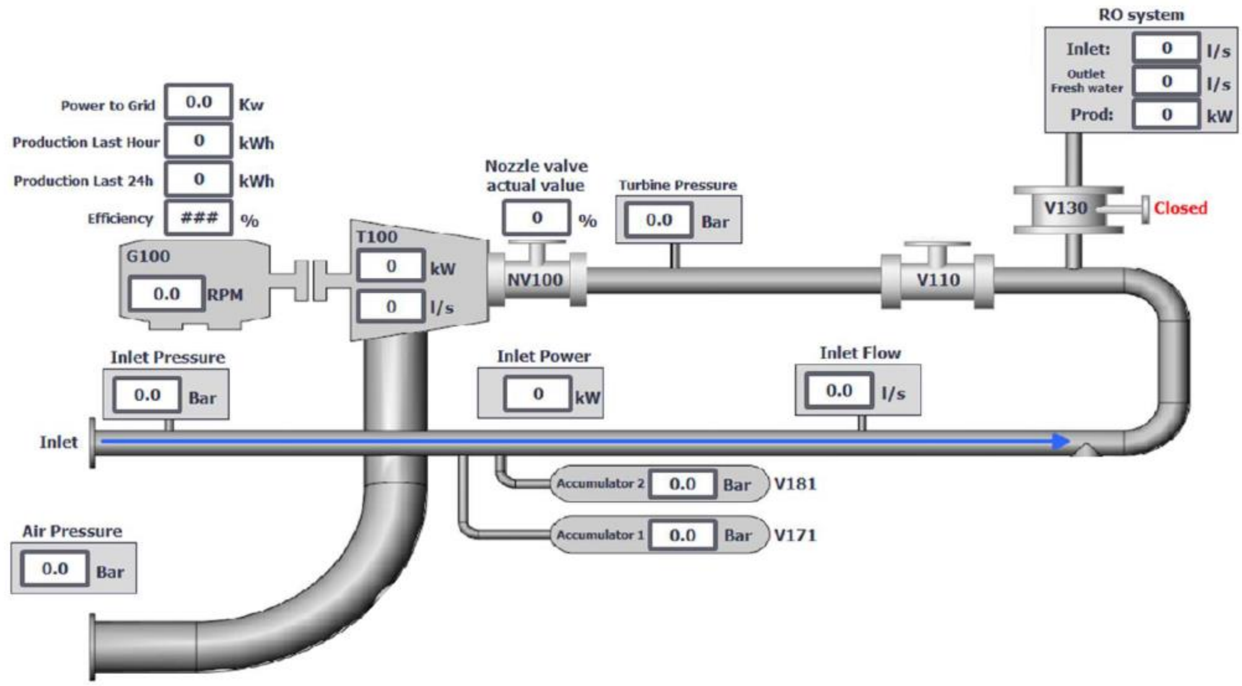

Figure 24: Diagram of the turbine power module located at PLOCAN with sensor positions.

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2 Components to be Tested

In this section the components to be tested are identifies and described. The key components were preliminary identified in Table 14 in VALID Deliverable 1.1 [2] as the PTO sub-system and especially the seals within the hydraulic pumps.

2.1 Identification of components to be tested

As detailed in Section 1, the Wavepiston system is based on vertical paddles as shown in Figure 25, which pull a wagon back and forth under the oscillatory action of the surge component of wave movement. The wagon carries the plates and interacts with hydraulic telescopic pumps, which convert the wave forces, acting on the paddles, into pressurized seawater.

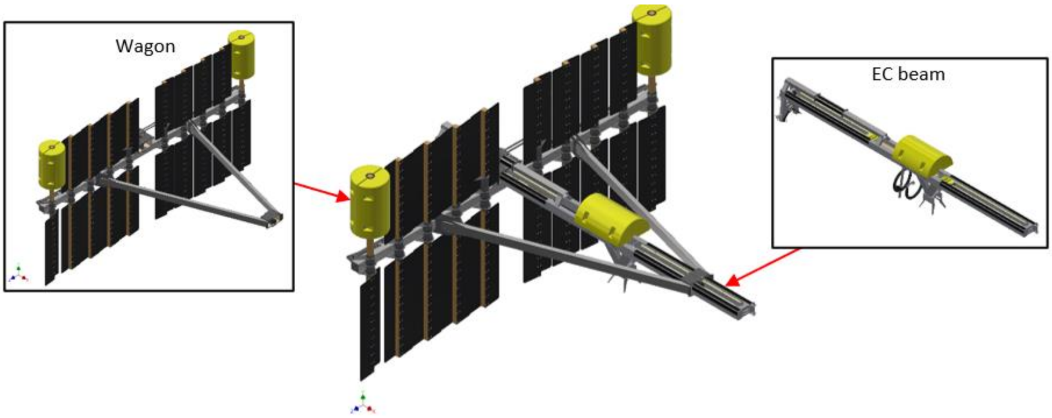

Figure 25: Wavepiston energy collector module.

Common to all moving, mechanically loaded surfaces on the Wavepiston system are that their movement is oscillatory and irregular. Furthermore, all wear surfaces in the Wavepiston system are lubricated using water. Although water, used as a lubricant, has a low viscosity, it is corrosive and thus less than optimal from an engineering point of view as compared to e.g., petroleum-based or mineral-based lubricants. Nevertheless, water lubrication has been chosen as a governing design principle throughout the entire Wavepiston system, to prevent leakage of environmentally dangerous substances in case of system failure.

The friction and wear of hydrodynamically lubricated systems depend, among other variables, on the viscosity of the lubricating fluid as well as the relative movement between surfaces to maintain a lubrication film. Thus, the low viscosity and the fact that the lubricated interface often stops will occasionally result in failure of the hydrodynamic lubrication film, leading to contact between the moving surfaces and hence contact wear.

To counteract wear, the development of the Wavepiston system has focused on minimizing the contact forces and the bending moments between the sliding wagon and its stationary counterpart, thus reducing wear on main bearing surfaces. Figure 26 shows the areas in the Wavepiston system which are subjected to sliding wear (marked with a yellow dot).

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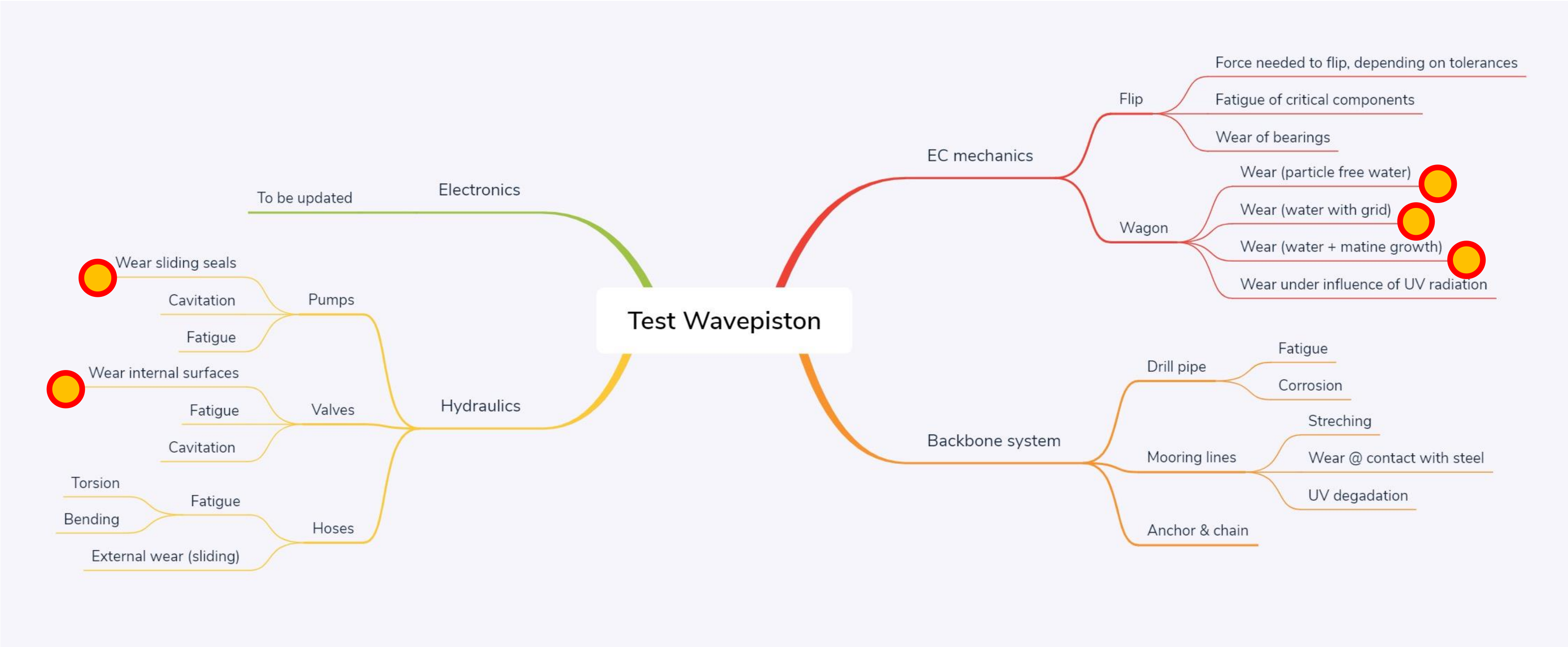

Figure 26: Identified wear surfaces in Wavepiston system subjected to oscillating wear.

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As an example of a wear counteracting measure, the plate structure is built to be symmetric around the load-supporting central pipe, and both the moving and the stationary part of the structure are made to be neutrally buoyant, thus minimising the static contact forces.

Although wear in most moving contact surfaces can be minimised through engineering design, there are fewer wear mitigation strategies available for the surfaces of the pump seals since the internal pressure of the pumps energizes these seals. Hence, the higher the pump pressure, the higher the load on the sliding seal contact surface. The hydraulic pumps in the Wavepiston system are operated at a nominal pressure of 60 bar. Due to this, the seal contact surfaces are intrinsically high loaded except when the sliding direction is changed.

In conventional hydraulics, the energizing fluid is a customized hydraulic fluid with good lubrication properties, and the piston is usually a surface coated with polished hard chrome. As the hydraulic pumps in the Wavepiston system must work in raw, aerated, seawater, polished hard-chrome surfaces are not suitable due to the lack of chemical stability of the hard chrome, which is degraded due to the influence of Chlorine ions (Cl^-). Chlorine ions are well known to be detrimental to stainless steel since Cl^- dissolve the passivating chromium oxide. Therefore, the hydraulic pistons are made from polished duplex steel pipes which are more resistant to aerated seawater.

When a hydraulic cylinder reaches the end of a stroke, the relative speeds between piston and seals reduce, and the viscodynamic lubrication film gradually breaks down. The effect of this is that the seals and the counteracting metal surface come into physical contact leading to both wear and other tribochemical phenomena that are poorly understood. An example of this is given in Figure 27, showing a steel piston rod from a reciprocating seal test. From the figure, it is evident that the chemical nature, and hence the tribological behaviour of the surface, has changed profoundly in the reversal zone.

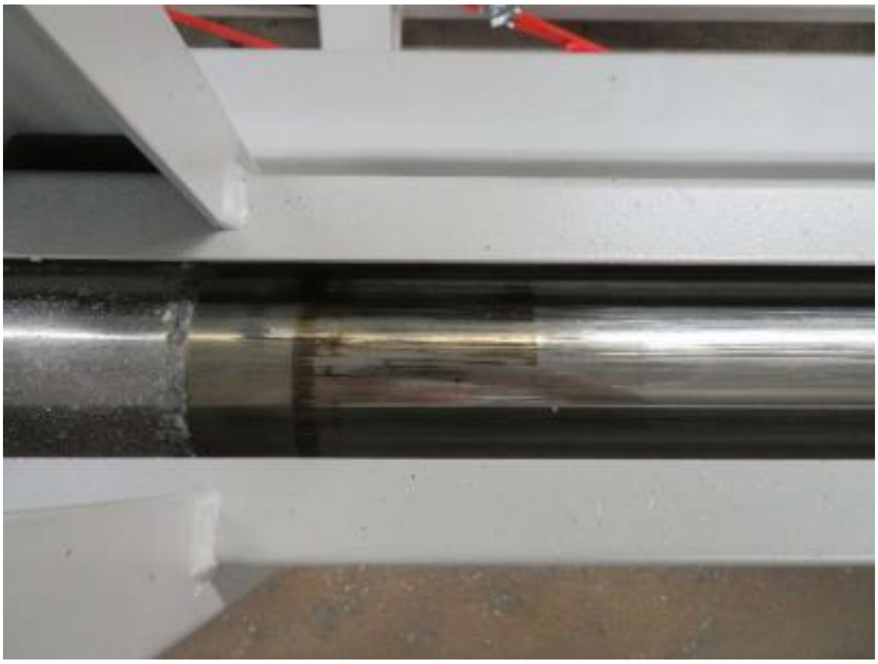

Figure 27: Wear and corrosion in pump rod.

Hence, and for a more complete assessment of the influence of critical components, the components to be tested in VALID are not limited to seals but must be expanded to seal/piston systems. For the seals, U-rings and chevron seals must be tested. Within each subgroup, materials will be varied.

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For the pistons, material choice is limited to duplex 2205. However, the use of different grinding strategies and various surface treatments to extend the life of the piston are within the scope of this project.

2.2 Identification of degradation processes

2.2.1 Deterioration in seals

Damage and failure of seals can present itself through different pathologies, coming from short- or long-term conditions around them such as temperature, pressure, weathering, seals' misfitting, suspended particles in fluids, the air-fluid ratio in lubricant or fluid, stroke speed, incompatibility of fluid and seals, seals' absorption, wrong installation, uneven load or friction, not enough lubrication and misfit between reciprocating component and seal. In Figure 28, the different seals' failures are shown:

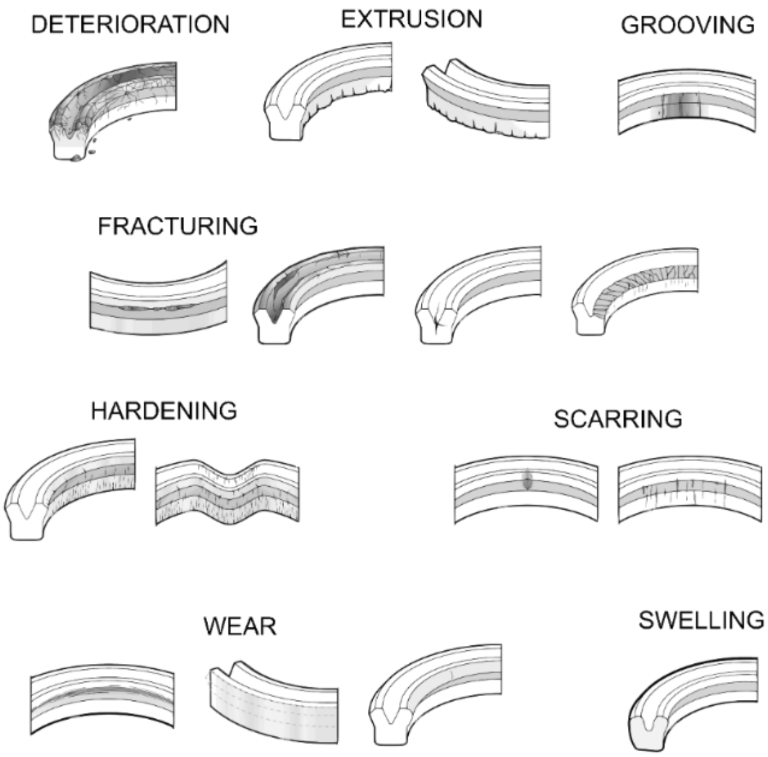


Figure 28: Pathologies related to the deterioration in seals, from [7].

The damage on seals is also related to their use: static, semi-static and dynamic. The use in User Case #3 is merely dynamic reciprocating movement. Figure 29 shows the diversity of uses of seals.

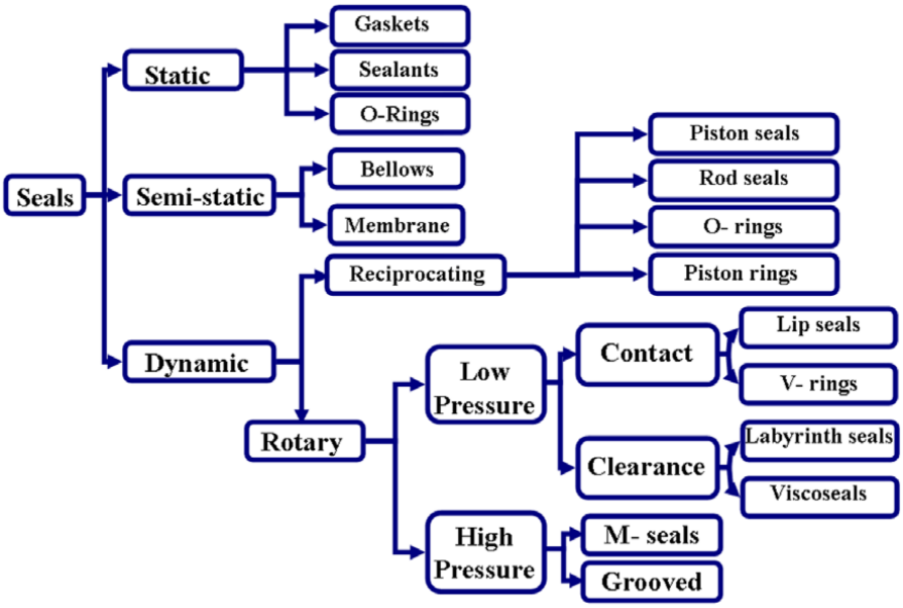
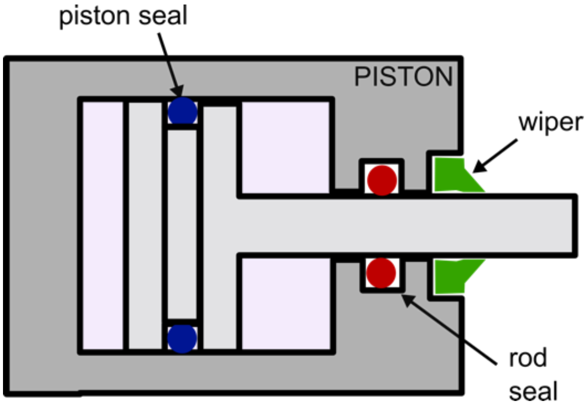


Figure 29: Seals classification in [8].

A piston's seals can be sub-classified as rod seals, piston seals, and wipers, see Figure 30a. In User Case #3, the seals are of the rod seal type. There are different cross-sections of ring seals such as O-rings, U-rings and V-rings, see Figure 30b. O-rings are known for having poor performance, and hence U-rings or V-rings are used. Alternatively, different rubber or metal springs can be used to energize the seal (see Figure 30b). Additional ways to improve the performance of the seals are:

- Combinations of different seals with a different cross-section.
- To use different materials, e.g., PTFE (Polytetrafluoroethylene) sealing, hardening materials (metal or polymers).
- To reduce the piston housing.



(a)

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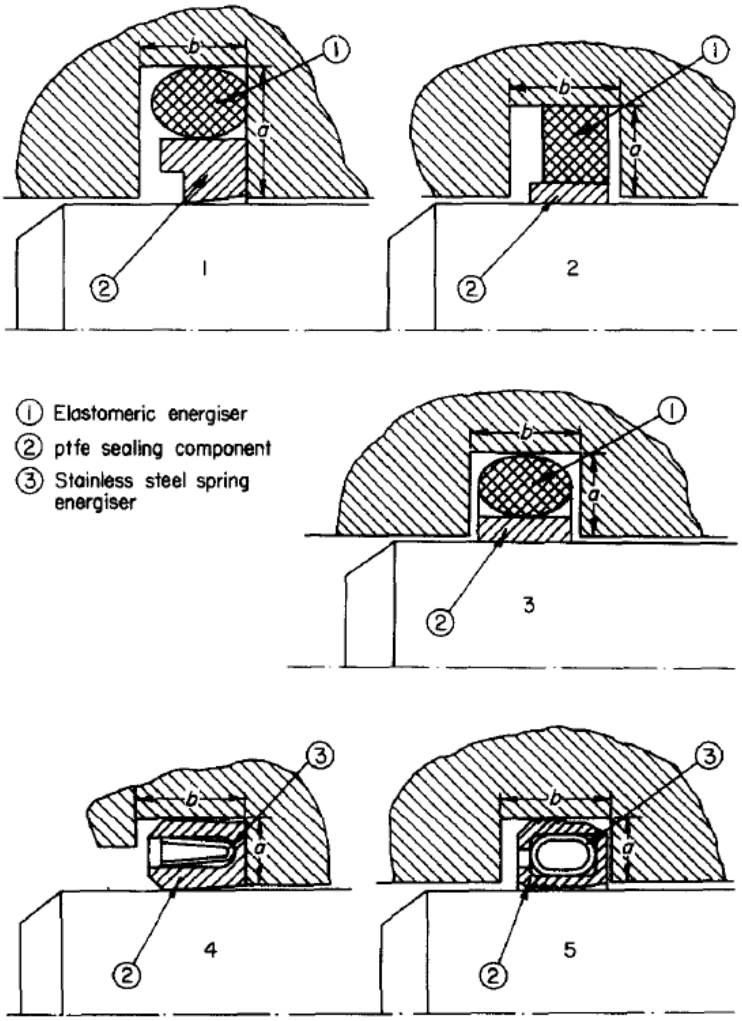

(b)

Figure 30: (a) Reciprocating seals in a piston. (b) Rubber or metal spring energizers with plastic seals to create an initial seal, taken from [9]

From the 70 papers identified in the literature review for seals technology and deterioration (see Appendix A), 15 papers were found relevant from the direct search. Additionally, an indirect search into the references cited in these 15 papers were conducted but did not reveal any additional relevant papers. Table 7 lists the relevant papers. The papers in Table 7 address the seals' materials, testing, and technologies for seawater lubricant that is relevant in User Case #3.

Table 7: Most relevant references found in literature search for seals technology and deterioration.

Year	Title	Reference
2019	Q. Han, Y. Zhang, H. Chen, J. Yang, and Y. Chen, "Analysis of Reciprocating Seals in the Wet-Mate Electrical Connectors for Underwater Applications," presented at the ASME 2018 International Mechanical Engineering Congress and Exposition, Jan. 2019. doi: 10.1115/IMECE2018-86988.	[10]
2016	C. Shen, M. Khonsari, M. Spadafora, and C. Ludlow, "Tribological Performance of Polyamide-Imide Seal Ring Under Seawater Lubrication," Tribology Letters, 2016, doi: 10.1007/s11249-016-0686-7.	[11]
2014	Z. Wang and D. Gao, "Friction and wear properties of stainless steel sliding against polyetheretherketone and carbon-fiber-reinforced polyetheretherketone under natural seawater lubrication," Materials & Design, vol. 53, pp. 881–887, Jan. 2014, doi: 10.1016/j.matdes.2013.07.096.	[12]
2013	Z. Wang and D. Gao, "Comparative investigation on the tribological behavior of reinforced plastic composite under natural seawater lubrication," Materials & Design, vol. 51, pp. 983–988, Oct. 2013, doi: 10.1016/j.matdes.2013.04.017.	[13]
2012	B. Chen, J. Wang, and F. Yan, "Comparative investigation on the tribological behaviors of CF/PEEK composites under sea water lubrication," Tribology International, vol. 52, pp. 170–177, Aug. 2012, doi: 10.1016/j.triboint.2012.03.017.	[14]
2012	B. Chen, J. Wang, and F. Yan, "Synergism of carbon fiber and polyimide in polytetrafluoroethylene-based composites: Friction and wear behavior under sea water lubrication," Materials and Design, vol. 36, Apr. 2012, doi: 10.1016/J.MATDES.2011.11.034.	[15]
2011	B. Chen, J. Wang, and F. Yan, "Friction and Wear Behaviors of Several Polymers Sliding Against GCr15 and 316 Steel Under the Lubrication of Sea Water," Tribol Lett, vol. 42, no. 1, pp. 17–25, Apr. 2011, doi: 10.1007/s11249-010-9743-9.	[16]
2010	Q. Tang, J. Chen, and L. Liu, "Tribological behaviours of carbon fibre reinforced PEEK sliding on silicon nitride lubricated with water," Wear, vol. 269, no. 7, pp. 541–546, Aug. 2010, doi: 10.1016/j.wear.2010.05.009.	[17]
2009	H. Shen, Q. Wen, and K. C. Lifer, "An Experimental Analysis on Rubber-Metal Contact Stress Corrosion in Seawater," Aug. 2009, pp. 635–638. doi: 10.1115/IMECE2008-67437.	[18]
2008	G. Zhang, C. Zhang, P. Nardin, W.-Y. Li, H. Liao, and C. Coddet, "Effects of sliding velocity and applied load on the tribological mechanism of amorphous poly-ether–ether–ketone (PEEK)," Tribology International, vol. 41, no. 2, pp. 79–86, Feb. 2008, doi: 10.1016/j.triboint.2007.05.002.	[19]
2008	M. Sumer, H. Unal, and A. Mimaroglu, "Evaluation of tribological behaviour of PEEK and glass fibre reinforced PEEK composite under dry sliding and water lubricated conditions," Wear, vol. 265, no. 7, pp. 1061–1065, Sep. 2008, doi: 10.1016/j.wear.2008.02.008.	[20]

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Year	Title	Reference
2004	J. Jia, J. Chen, H. Zhou, and L. Hu, "Comparative Study on Tribological Behaviors of Polyetheretherketone Composite Reinforced with Carbon Fiber and Polytetrafluoroethylene Under Water-Lubricated and Dry-Sliding Against Stainless Steel," Tribology Letters, vol. 17, no. 2, pp. 231–238, Aug. 2004, doi: 10.1023/B:TRIL.0000032449.32855.3d.	[21]
1999	J. P. Netzel and I. Freimanis, "Performance and wear testing of mechanical seals in sea water service," Lubrication Engineering, vol. 55, no. 7, p. 15, Jul. 1999.	[22]
1995	P. Baets, "Comparison of the wear behaviour of six bearing materials for a heavily loaded sliding system in seawater," 1995, doi: 10.1016/0043-1648(94)06540-3.	[23]
1991	J. W. M. Mens and A. W. J. de Gee, "Friction and wear behaviour of 18 polymers in contact with steel in environments of air and water," Wear, vol. 149, no. 1, pp. 255–268, Sep. 1991, doi: 10.1016/0043-1648(91)90378-8.	[24]

2.2.2 Identification of deterioration in seals

2.2.2.1 Findings in literature

To identify relevant facts and findings related to the deterioration process of the seals in the WEC-component (prior to hybrid/accelerated testing), the previous literature was identified and analysed (see Table 7). From the analysis, the relevant findings of the identification of seals can be detailed as follow:

1. There are seals´ materials that are gaining popularity for their wear performance:

- Nylon and Rubber, see reference [18].
- Metalic/alloy seals, Aluminium-bronze, Sintered-graphite-bronze, lamellar cast iron, Nodular cast iron, see reference [23].
- Plastic composite materials, see reference [14].
- Polyamide (PA), see reference [23].
- Polyamide-imide (PAI), see reference [11].
- Poly-ether-ether-ketone (PEEK), see references [12], [14], [15], [21].
    - CF/PEEK or CFRPEEK - Carbon Fiber Reinforced PEEK, see references [12], [14], [15], [21].
    - GF/PEEK or GFRPEEK - Glass Fiber Reinforced PEEK, see reference [20].
    - CF/PTFE/PEEK or CFRPEEK- Carbon Fiber - PTFE particles reinforced PEEK, see reference [21].
- Poly-ethylene-tere-phthalate (PETP), is also used as filler, see reference [23].
- Per-fluoro-ethylene propulene copolymer (FEP), see reference [16].
- Poly-imide (PI).
- Poly-phenyl p-hydroxy-benzoate (PHBA), see reference [16].
- Poly-phenylene sulphide (PPS).
- Poly-tetra-fluoro-ethylene (PTFE).

- Poly-oxy-methlene (POM).

2. A metric to measure the wear is the specific wear rate (*K*) of the specimens, which can be calculated with the formula *K= (V/(L d))*, where *V* is the wear volume loss (mm^3), *L* is the load (N) and *d* is the sliding distance (mm). Baets [23] found that PETP and PA have a starting friction coefficient of 0.09 and a maximum of 0.26, with the lowest specific wear rate ranging from 0.12 to 0.06 x 10^{-4} at the double of the number of cycles when in metal alloys specific wear rates range from 2.32 to 0.21 x 10^{-4} without considering seawater as a lubricant.
3. Mens at al. [24] found that the increase of temperature is increasing the wear rate, however, when fillers such as PTFE or Glass Fiber are used, this damaging characteristic is reduced, decreasing the friction coefficient and thus the wear.
4. The fact of water lubrication (see e.g. Jia et al. [21]) reduces the friction coefficient using CF-PTFE-PEEK. Also, the water lubrication reduces the wear rate in CF-PTFE-PEEK. Jia et al. [21] studied the case of seals and stainless-steel surfaces, finding that seals benefited from water lubrication and the cooling provided by the water medium. It was found that the oxidation of stainless steel continued with or without lubrication.
5. In the case of GF-PEEK (see Sumer et al. [20]), it was found that water lubrication is reducing the friction coefficient and specific wear rate.
6. Chen et al. [16] address the seawater as a lubricant getting relevant results when it is compared several polymers for two types of steel: i) GCr15 bearing steel is GB standard Alloy Bearing steel and ii) 316 steels. The findings are important, showing that PI has the lowest coefficient of friction and specific wear rate for GCr15 with seawater as lubricant; however, when the material is changed to 316-steel, FEP has the lowest friction coefficient and PEEK the lowest specific wear rate jointly with FEP. This is a relevant finding for the design and selection of the seal for the Wavepiston device.
7. Chen at al. [15] tested the filler/reinforcing of PI and CF into PTFE, finding that PTFE with 5% of PI and 15% CF is the type of reinforced PTFE with the lowest friction coefficient and specific wear rate when seawater is considered as a lubricant. The same authors (Chen et al. [14]) found that increasing sliding speed increases the friction and specific wear rates.
8. Wan & Gao [13] compared the wear performance of seals of three materials: ABS, CF-PAI and CF-PEEK with seawater lubrication, finding that CF-PEEK had microscopically smaller wear depth with a lower friction coefficient.

2.2.2.2 Deterioration in seals

The current literature addresses mainly the seals' wear performance in seawater lubrication without considering biofouling (the accumulation of microorganisms, plants, algae, or small animals –not wanted- on surfaces in marine environment) and corrosion effect in the rod. The literature considers different materials, temperatures, pressure and velocity of movement (rotational and reciprocating), finding that temperature and velocity of movement increase wear, while water lubrication reduces it. The best wear performance of seals is also related to the contacting metal and pressure of the seals with contacting material. In most of the mentioned papers, different reinforcing materials (filler material) were used, such as PTFE, CF, GF, and base materials such as PEEK, PTFE and PI.

As it is mentioned in Shen et al. [18] and from what is shown in Figure 27 in the first tests, the damage in the rod and seals depends on the contact area and pressure seal-rod. It is recommended to use some of the material presented in section 2.2.2.1 for seals considering different seal-rod pressure levels, piston pressures, characteristics velocity of WEC-pump and different temperatures close to the site temperatures.

According to different research work, the wear could develop future pathology characteristics (see Figure 28) coming from contacting metal, biofouling, tribocorrosion (see [25]) and rod rugosity; however, wear is the relevant deterioration process for seals and rods, that later developed in further not desired damage.

2.3 Risk Identification

2.3.1 Identification of triggers and Inputs

Triggers and inputs are indicators of existing and future issues on the seals that may need risk management/assessment activities for the User Case #3. The central topic is the accelerated damage of seals, and side topics are related to how it is possible to formulate reliability and survivability (R&S) assessment through accelerated testing with hybrid testing.

Accelerated testing with hybrid simulation is treated in this document as a necessary step without allocating uncertainty to this step. However, in the case of R&S, it is essential to mention the conditions related to the state-of-the-art for the seals' damage and assessment process. Three triggers/inputs are mainly identified for the device:

A. Economic

- A (input): OPEX vs. seal performance: Consideration for the seals' performance on the operational expenses, considering life cycle assessment, maintenance, and change of seals.

B. Regulatory and standards

- B (input): Achieve requirements/future changes in technical standards and regulations: reliability and survivability.

C. Technology, science, and research triggers

- C (input): Lack of information in the research/assessment/modelling:
  - Model of seals degradation for user case conditions: seawater (suspended particles and sea growth), pressure, friction coefficient and corrosion.
  - Assessment of seals for reliability assessment purposes
  - Experimental research/application in materials for seawater lubrication and pressure
  - Experimental research/application for rod materials and stroke velocity.
  - Experimental research/application for tribocorrosion in seal-rod materials
  - Experimental research/application for multi-factorial testing of the previous items.

2.3.2 Identification of WEC's hazards

To identify the harmful conditions for seals, a preliminary Root Cause Analysis (RCA) - the five why's method - is performed for the mentioned input A, B, and C. Later, the different issues are placed in a fishbone diagram (RCA by Ishikawa diagram)

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Root cause analysis for input A (OPEX):

"OPEX vs. seal performance: Consideration for the seals' performance on the operational expenses, taking into account life cycle assessment, maintenance, and change of seals"

- *Level 1: Why the OPEX vs. seals' performance comparison is a co-existing issue?* Because the seals' performance in terms of leakage and loss of pressure could trigger additional strategic (planning) and tactical (inspection and maintenance) actions for seals' care and assessment in-situ.
- *Level 2.a: Why is seals' performance an issue in this case?* Because seawater, corrosion, seals' wear, and piston pressure reduce the energy production performance.
- *Level 2.b: Why is OPEX a metric for comparison with seals performance?* Because in the case that seals are damaged more often, there is a need for strategic and tactical actions to maintain the energy production, increasing the OPEX, costly at offshore conditions.
- *Level 3.a (from 2.a): Why could seals underperform the factual in-situ condition?* Because environmental conditions [seawater and suspended particles (including sea growth) and corrosion] and an inappropriate design could lead to unsatisfactory seals' conditions, the damage is causing a drop in energy production.
- *Level 3.b (from 2.b): Why could OPEX increase?* Inspecting seals and maintenance operations for seals' exchange requires costs for in-situ actions that are expensive in the offshore context.
- *Level 4.a (from 3.a): Why an inappropriate design could lead to an unsatisfactory seals' state?* Because the seals' material, size, and level of damage must be assessed and considered in the design. The material type and size are constrained to industrial solutions; however, the level of damage must be evaluated according to given met-ocean conditions using degradation models where damage is quantified.
- *Level 5.a (from 4.a): Why met ocean conditions could lead to an inappropriate design?* Any change of met ocean conditions for different reasons (climate change, extreme event) or a not proper selection of met ocean conditions could lead to imprecise estimation of seals performance.
- *Level 5.b (from 4.a): Why do degradation models could lead to an inappropriate design?* There are no degradation models for seals that couple friction, pressure, seawater, and operational conditions of the target seals. Also, there is no reliability assessment for seals in these conditions. Therefore, the degradation model must be formulated considering the user case considerations and related uncertainty.

From this RCA, it is clear that the identification and use of the proper met ocean condition are relevant, and adequate seals degradation models are essential.

Root cause analysis for input B (Regulatory and standards):

"Achieve requirement/ future changes of technical standards and regulations: reliability and survivability."

- *Level 1: Why could any changes in technical standards and regulations lead to a harmful situation for the WEC?* Unmanned systems such as WEC do not impose a harmful situation for humans, but the fatal failure of the device could lead to the loss of the device. The standards and guidelines for design, assessment and certification proposed a minimum framework and level of safety that the device has to fulfil. Not accomplishing these guidelines could happen when the device fails before the estimated time or when the guidelines are modified in the context of WECs.

- *Level 2: Why the WEC seal design/assessment could not fulfil the guidelines?* Because the tools for design and assessment have to be formulated and matured with experimental information, research and modelling.

In this second RCA, it is identified again that the design and assessment method should be formulated and comply with guidelines in the case of seals' damage.

Root cause analysis for input C (Technology, science, and research triggers):

"Lack of information in the research/assessment/modelling"

- *Level 1.a: Why the lack of referential information is relevant in the case of seals degradation?* The state-of-the-art studies about seals performance are limited to finite element analysis (FEA) of seals in the reciprocating system where the stresses are estimated through the reciprocating movement (qualitative analysis); however, given stress for such analysis are only identified the local stresses in perfect ideal conditions where seals initial conditions are not considered, misfits in the piston are not subject of study and surface degradation are not existing. Also, while the current research addresses different materials, seawater condition, pressure, the velocity of testing, seals' reinforcement and tribocorrosion, there is no joint research where seawater lubrication is combined with tribocorrosion, piston pressure, rod deterioration, seal-rod contact pressure and sea growth-related rod deterioration. There are high-performance seal materials as reinforced PEEK or PTFE, but further research and application results are needed. Another feature of user case #3 is that seals are unidirectionally activated because, in the other direction of the reciprocating movement, the seal is allowing that seawater to enter.
- *Level 1.b: Why the different experimental work is needed?* Because it is expected that seals perform at their maximum lifetime when there is tribocorrosion in the seals and rod by the lubricant seawater, under specific pressure conditions and given seals' material.
- *Level 1.c: Why the lack of referential information is relevant in the case of seals reliability?* There is not a damage accumulation model in the present state-of-the-art of seals. As recent studies show, the friction coefficient, internal pressure and, reciprocating movement are critical indicators in the seals' performance that must be interrelated in the damage and reliability assessment methodology. There is vast research in the tribology of seals; however, reliability (not performance reliability) and damage models are not existing.
- *Level 1.c: Why the modelling of the seals' influence on the environmental loads is relevant in the estimation of damage?* Capturing the effects of loads is relevant at the WEC device level; however, to estimate the seals' damage, it is essential to identify global conditions that cause harmful local conditions, e.g., large waves could not impose more damage on seals as a specific train of waves in the WEC.

The question of this third RCA, related to each other, i.e., a model to quantify the seals' damage and R&S assessment method needs to be formulated.

Fishbone diagram from RCA

In the previous preliminary root cause analysis, seals damage is the central theme. The preliminary identified issues related to seals' damage, modelling, and R&S assessment can be summarised in Figure 31.

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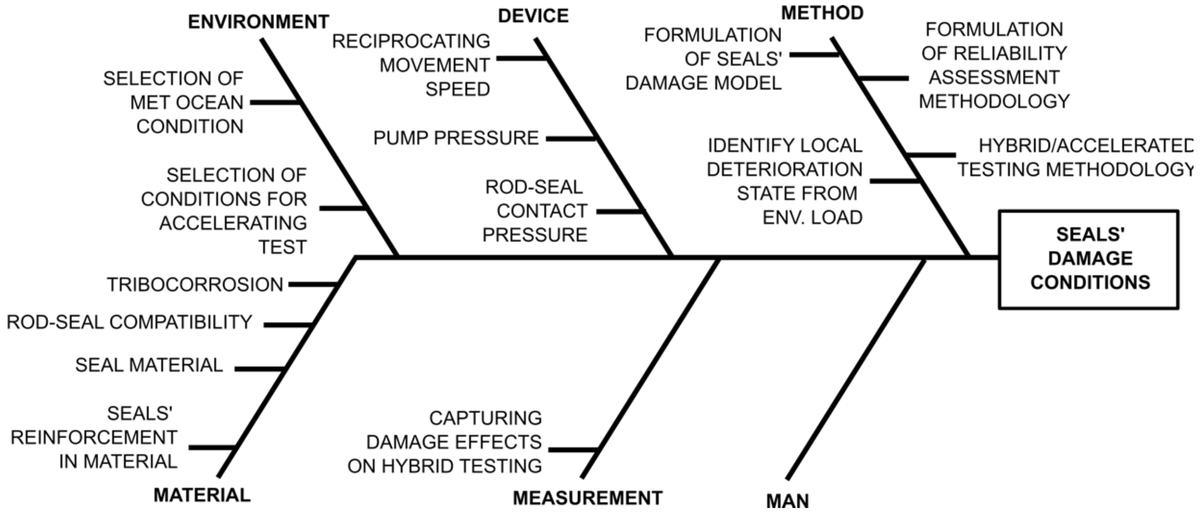

Figure 31: Fishbone diagram from RCA.

2.3.3 Uncertainty identification

From the previous issues in Figure 31, it is possible to identify uncertainties related to potential failure modes, causes/mechanisms, and phases in the process of assessing the seals. The uncertainties are the following:

1. Environment

- Selected met ocean conditions that impact the component: uncertainty related to the characteristics of wave loads that impact the WEC.
- Selected load conditions for accelerated testing into hybrid testing for having the highest impact in the investigated component.

2. Measurement

- Capturing damage effects on hybrid/accelerated testing.
- Measuring the loss of pressure as an indicator of wear in seals, using leak rate since a perfect sealing may not necessarily exist.
- Measuring deterioration in seals using different devices (microscope) or durometer (elasticity of the seal).
- Measuring parameters related to the specific wear rate, such as the wear volume loss, the load and the sliding distance, also the friction coefficient for the reciprocating cycles.
- rate of wear in seals due to suspended particles, i.e., seawater.

3. Method

- Formulation of seals' damage accumulation model. The found literature used mainly microscopic measurement of seals' surface that is a direct wear 3D view to the deterioration; however, there are no models considering the user case characteristics: seawater, rod-seal contact pressure, tribocorrosion, reciprocating velocity, pressure, rod corrosion, sea growth, etc.
- Identification of local deterioration mechanism from environmental load and modelling.
- Formulation of reliability and survivability assessment model and methodology.

- There is not a current hybrid/accelerated testing methodology for seals. Additionally, the formulated hybrid/accelerated testing methodology should contain the relevant seal' material and conditions.

4. Device

- The reciprocating movement speed is a vital characteristic for the seal condition, decreasing and increasing the wear.
- The pressure of the pump, like the velocity, is a major indirect factor to increase the wear. The pressure of the pump could have cycles of loading-unloading due to the nature of the pump, and the pressure efficiency could decrease during the seal's life.
- The seal size selection is relevant because the rod-seal pressure is changing according to this size, and the pressure could play a major role in the wear (tribocorrosion) and seal life.

5. Material

- Tribocorrosion topic is not widely addressed in experimental research for seals. Thus, any further experimental test would contain inherent tribocorrosion wear.
- The compatibility of rod-seal is relevant, causing the certain seals' materials to perform better than others, see the section of identification of deterioration.
- The variety of seal materials gives the possibility to test high-performance materials such as PEEK, PI, FE, PTFE, etc. Besides what is chosen, the other relevant characteristic added is the reinforcement, but the proportions of reinforcement or fillers should be calibrated for the contact material, lubricating medium, pressure and temperature.

2.3.4 Safeguard and barrier analysis

The bow tie analysis (BTA) is helpful to identify corrective barriers and preventive safeguards, and when the events happen, it supports identifying the mitigation barriers and recovery barriers. Using the RCA information and fishbone diagram above, a BTA diagram is presented in Figure 32 in parts. Figure 32a is extended in the hazard side by representing the triggers and inputs that precede the hazards and threats for seals. In Figure 32b, the corrective barriers and preventive safeguards are presented and in Figure 32c, the mitigation barriers and recovery barriers are shown.

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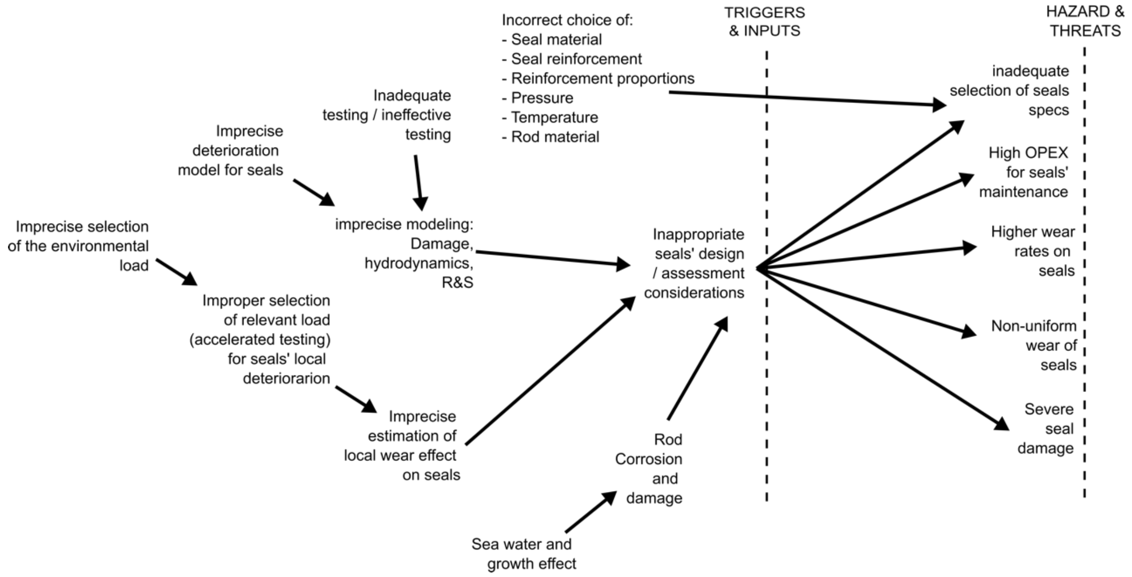
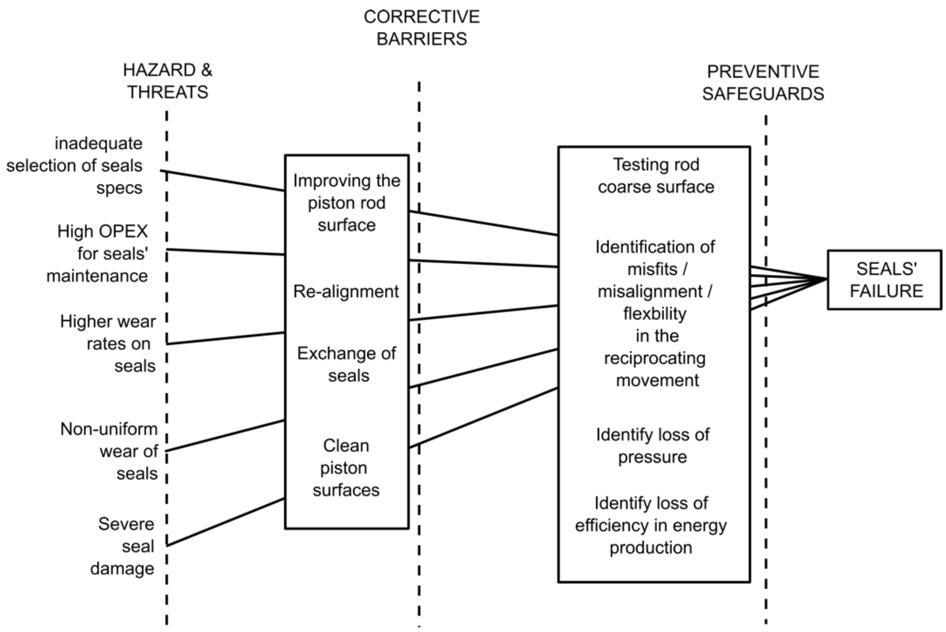


(a)



(b)

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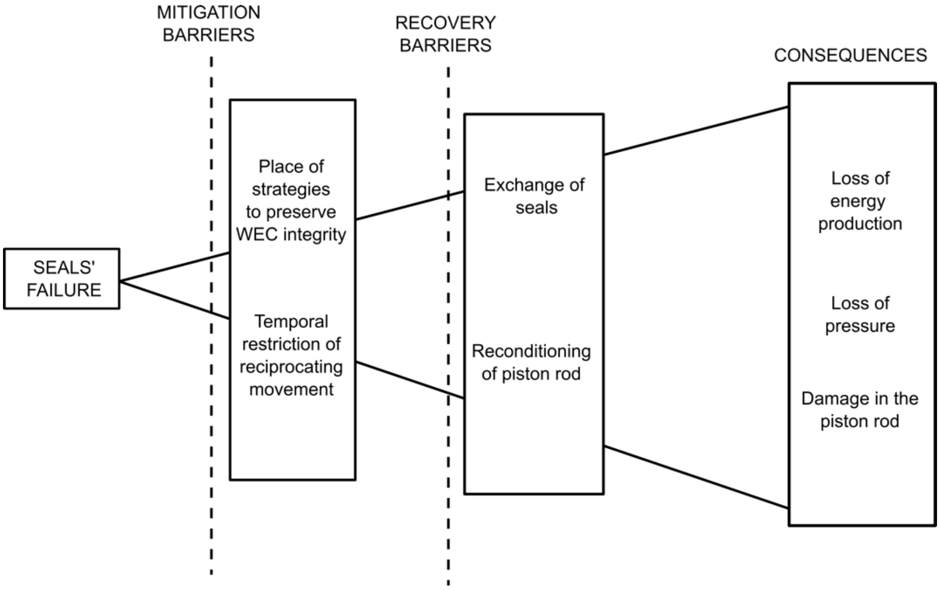

(c)

Figure 32: Piecewise bow tie diagram. (a) Triggers/Input + Harmful conditions. (b) Harmful conditions + Corrective barriers + Preventive Safeguards + Hazard. (c) Hazard + mitigation barriers + recovery barriers + consequences.

2.3.5 Failure modes, effects, and criticality analysis (FMECA)

With the outcome from the root cause and the bow tie analyses, it is possible to formulate more in detail an FMECA (Failure Mode, Effect and Criticality Analysis). The FMECA table is presented in six tables:

- Table 8– Presents the Failure modes and contexts
- Table 9– Presents the effects
- Table 10 – Contains the qualitative analysis for estimating a risk priority number
- Table 11– Contains the probability rating for Table 10
- Table 12 – Severity rating for Table 10
- Table 13 – Present the consequence vs likelihood matrix + heat map providing the risk principle for acceptable and tolerable risk.

Table 8: Part 1 of FMECA Failure Modes.

ID	ITEM	POTENTIAL FAILURE MODE	POTENTIAL CAUSE(S) / MECHANISM	MISSION PHASE
1.a	Seals	Accelerated wear damage	Rod damage due to corrosion and sea growth (biofouling)	**Design/Testing:** Not considered/represented in the accelerated testing **Assessment:** Not considered in the formulation of damage model and R&S assessment **Operation:** Corrosion rate above the proposed / pitting rates above the proposed
1.b	Seals	Accelerated wear damage	Too many suspended particles (sea growth)	**Assessment:** Not considered in the formulation of damage model and R&S assessment **Operation:** Corrosion rate above the proposed / pitting rates above the proposed
1.c	Seals	Non-uniform wear damage	Misalignment of reciprocating movement	**Design/Testing:** Not considering/represented in the accelerated testing
1.d	Seals	Early ending of seal's life	Selection of environmental load	**Design/Testing:** Not considering the relevant weighted sea states for the seals' reciprocating movement

Table 9: Part 2 of FMECA's Effects + Detection.

ID	Local effects of failure	Next higher level effect	System-level end effect	Detection	Control factor* (C)
1.a	Accelerated wear	Loss of pressure	Loss of efficiency on energy production	Local pumped pressure/energy production	1000
1.b	Accelerated wear	Loss of pressure	Loss of efficiency on energy production	Local pumped pressure/energy production	1000

1.c	Non-uniform wear damage	Loss of pressure	Loss of efficiency on energy production	Local pumped pressure/energy production	100
1.d	More damage in the life cycle	Loss of pressure	Loss of efficiency on energy production	Local pumped pressure/energy production	10
*Control factor not used in this analysis					

Table 10: Part 3 of FMECA's Criticality Analysis.

ID	Probability (P)	Severity (S)	Risk Priority Number (RPN = P*S)
1.a	0.1**	0.3	0.03
1.b	0.1	0.1***	0.01
1.c	0.01	0.1	0.001
1.d	0.5	1****	0.5
** This has to do with light. Damage from growth can be mitigated by isolating the sealing surfaces from light *** lower severity to same damage type as wear from particles will be slow and predictable whereas rupture due to e.g. growth of barnacles may cause sudden failure **** this would result in "creeping" global failure on all components			

Table 11: Probability Rating for Table 10.

P-Rating	Meaning	Probability of failure on design life
A	Extremely unlikely (Virtually impossible/ No known occurrences)	1.0e-4
B	Remote (relative few failures)	1.0e-3
C	Occasional	1.0e-2
D	Reasonably Possible	5.0e-2
E	Frequent	0.1

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Table 12: Severity Rating for Table 10.

P-Rating	Meaning	Severity
I	No relevant effect on the reliability and survivability	0.01
II	No damage and only results in maintenance actions	0.1
III	Minor damage	0.2
IV	Critical damage causing a loss of primary function of piston	0.8
V	Global damage resulting in inoperative device	1

Table 13: Risk Matrix + Heat Map - Probability and Severity.

	I	II	III	IV	V
A	Low	Low	Low	Moderate	High
B	Low	Low	Moderate	High	Unacceptable
C	Low	Moderate	Unacceptable	Unacceptable	Unacceptable
D	Low	Moderate	Unacceptable	Unacceptable	Unacceptable
E	Moderate	Unacceptable	Unacceptable	Unacceptable	Unacceptable

2.3.6 Conclusion of risk identification

The section of risk identification was focused on the identification of trigger & inputs, hazards, barriers & safeguards and risk estimation through qualitative risk assessment tools, such as root cause analysis (The five whys and fishbone diagram), bow tie analysis and FMECA.

After the FMECA analysis, it was found that the highest risk priority numbers are:

- Early ending of seals' life
- Accelerated wear damage: Rod damage due to corrosion and biofouling
- Accelerated wear damage: too many suspended particles

These priority failure modes support the initial desire to test the seal conditions under accelerated/hybrid testing in the user case.

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3 Relevant Standards – Best Practices

3.1 Methodology for evaluating the environmental conditions

The environmental conditions are of paramount importance to wave energy design. See VALID Deliverable 1.2. [3] for a detailed description. For wave energy projects, the technical specifications IEC TS 62600-101 [26] and DNV-RP-C205 [27] deal specifically with how to estimate the wave climate. The wave energy resource is to be derived mainly from numerical simulations using spectral wave models, that have been successfully validated against measurement data. IEC TS 62600-101 divides the assessment into three categories depending on the stage of the study:

- Class 1: Reconnaissance.
- Class 2: Feasibility.
- Class 3: Design.

Within User Case #3, Class 3 is the most relevant, and thus, the uncertainty of the estimated environmental conditions needs to be low and the extent of the domain of interest in the order of 25 km. In the following, we will only discuss requirements for Class 3 studies.

If direct wave measurements are to be used, then the Measure-Correlate-Predict methods can be used. Here a short-term measurement campaign at the deployment site will be correlated to a set of existing long-term measurement in the region of interest. It is important that the two sites experience the same wind fields and wave systems. The measurement/s should give reliable estimates of significant wave height (precision greater than 0.3 m 95% of the time), energy period (precision greater than 1.0 s 95% of the time), omnidirectional wave power, spectral width (precision greater than 0.05 95% of the time) and directional spreading index (precision greater than 10 degrees 95% of the time)

More frequent than to directly use wave measurements is to generate synthetic data series using numerical spectral wave models. The spectral model needs to be validated, and thus wave measurements are required (where the measurement should have the above-mentioned accuracy). The numerical simulations should be carried out with a 3rd generation spectral wave model using a spatial resolution less than 50m, a temporal resolution less than 1 hour, not less than 25 wave components and not less than 48 azimuthal directions. At least ten years of wave data should be generated with a minimum of the step of 3 hours. Finally, a sensitivity analysis is required to be performed by turning on/off different solutions modules.

3.2 Methodology for evaluating the wave-structure interaction

From the given environmental conditions, the loads acting on the WEC and the subsequent motion and power production are typically obtained through experimental and/or numerical models. This step is described in detail in VALID Deliverable 1.2 [3] while VALID Deliverable 1.1 [2] lists some of the associated standards.

As User Case #3 will not rely on experimental tests the focus is on the numerical methodology. From the DNV guidelines DNVGL-OS-C101 [28] it is clear that the theoretical/numerical approach to evaluating the loads should be accompanied by model or full-scale tests if the uncertainties associated with the numerical model are large . Clearly the Wavepiston device falls under this category. In User Case #3 the numerical models will be compared to the full-scale Wavepiston WEC deployed at PLOCAN.

It is further stated in [28] that slender parts, like the drill string, can be evaluated using the Morison approach using drag and inertia coefficients as defined in DNV-RP-C205 [27]. On the other hand, the ECs plainly should be treated as large radiating/diffracting structures.

Also, the influence of the many closely located ECs (multi-body interactions) should be included in the analysis.

DNV-RP-C205 [27] details the computation of the loads, whereas DNV-RP-F205 [29], details the computations of the response. From the documents is clear that the Wavepiston device should be modelled in a coupled manner including system nonlinearities (mooring and PTO systems). The standard linear/nonlinear BEM approach should suffice, while CFD should be used to estimate drag coefficients as experimental model tests are missing. This is also the set-up most likely to be feasible for use in the hybrid testing, see the discussion in Deliverable 1.2 [3].

3.3 Methodology for testing

The industry practice method for testing seals that Wavepiston currently adapts is to mount two or more counter-facing seals in a stationary seal block that holds the seals under testing, as shown in Figure 33.

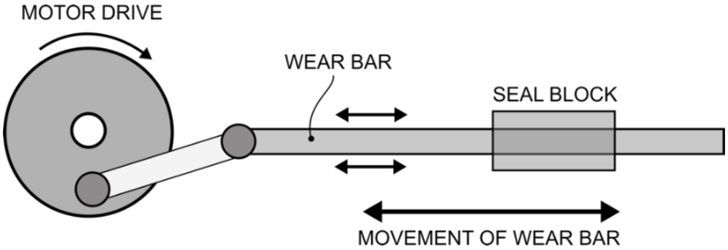

Figure 33: Stationary seal block with the movement of wear bar.

A round wear bar simulating the piston is then driven back and forth at a constant RPM by a geared motor, resulting in position, velocity and acceleration profiles as shown below in Figure 34.

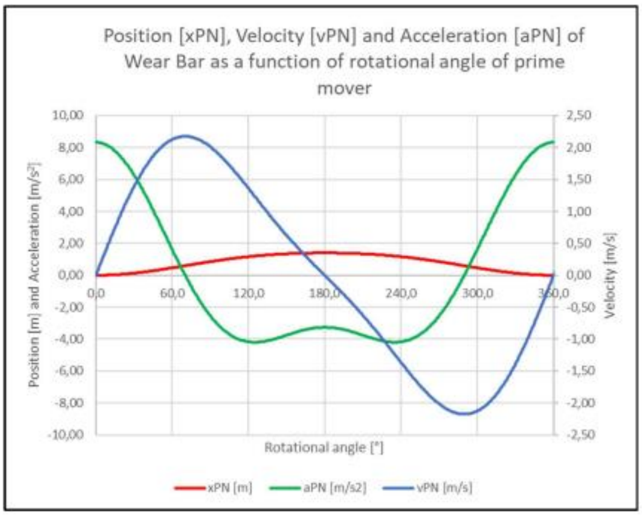

Figure 34: Typical displacement response from wear bar test, red: Wear bar velocity, acceleration, and position as a function of the rotational angle of the prime mover axis.

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Figure 35 shows the inner working of the seal block in larger detail (although simplified relative to actual testing equipment). The sealing block contains one or more pressurized compartments, each compartment sealed by two counter-facing seals. The sealing test pressure of the system is controlled by controlling the pressure in the enclosure. The condition of the seals during the test is generally monitored by cutting off the pressure feed to the enclosure and hereafter measuring the rate of pressure decline in the confined enclosure.

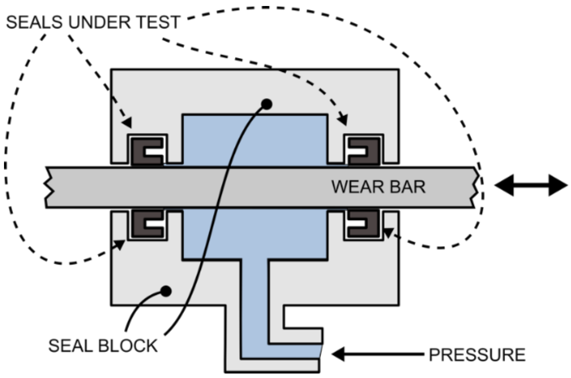

Figure 35: A simplified cross-sectional view of seal block.

For simplicity, the sealing block is shown in Figure 35 with a single entry. In actual measurements, it is common practice to circulate the hydraulic fluid in a closed-loop system to dissipate energy from the seals that may otherwise heat up due to frictional forces. Alternatively, the cooling of the system may be executed using a separate cooling circuit.

Figure 36 shows an actual test stand. The green lines are high-pressure lines whereas the transparent lines are cooling water. An advantage of this approach is that friction is easily monitored as forces emanating from the hydraulic pressure are cancelled out.

Figure 36: Seal block used by Wavepiston until now to test seals.

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From the description given above, it is clear that the conventional procedure for testing is oversimplified when comparing test and reality in a WEC similar to Wavepiston. The shortcomings are:

- The conventional setup assumes constant pressure in the hydraulic system. The effect of this is that the seals are energized when moving in both directions. This is very different from the seals found in a Wavepiston system, where seals are only energized when the piston is moving in one direction.

This effect makes conventional testing conservative.

- A further difference caused by the constant pressure is that the seals are energized at the onset of movement. Wavepiston seal surfaces are, at the onset of movement, not energized and do have far smaller initial friction than seals tested using the conventional approach.

This effect makes conventional testing conservative.

- The motor drive in the test is always running, making the shift in direction happen very fast. Thus, during the test, it is plausible that the lubricating film between piston and seal is maintained. This is very different from actual use, where the pistons move erratically and not all the time. Thus, during actual operation there is ample time to collapse the lubrication film, hereby increasing wear in the interface.

This makes conventional testing non-conservative.

- It is anticipated that stopping and change of direction increases wear. Thus, if the seal/piston under test is always stopped at the same position, localised increased wear is to be expected. This is in line with experimental findings (see Figure 26). For a Wavepiston piston, there is no distinct stop/reversal/start zone and thus no zone with highly increased wear. This makes conventional testing conservative

As can be seen from above, the current testing set-up is less than ideal for predicting the actual lifetime for sealed sliding interfaces in a Wavepiston system.

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4 Hybrid Testing

4.1 Methodology for evaluating the environmental conditions

User Case #3 focus mainly on the Wavepiston deployment at PLOCAN, Canary Islands. Here we have measured wave buoy data in very close proximity to the deployed Wavepiston device, see section 5.1.1. As the wave buoy data is less than one km from the deployment site, and the bathymetry is rather smooth, no MCP is deemed to be required. The measured data have been postprocessed in [30] and [31], hence, it is expected to use the measured data directly.

4.2 Methodology for evaluating the wave-structure interaction

The motion of the Wavepiston device will be modelled using a combination of the linear potential flow models accessible to Wavepiston, see Deliverable 1.2 [3]. The overall global motion including mooring restraints is to be setup in an Orcaflex model. This model however is based on the Morison approach and thus will not capture the body-to-body interaction of the ECs. Alongside the Orcaflex model, a WEC-SIM model with a reduced number of ECs (say 3 to 5) will be implemented. This model will be based on hydrodynamic coefficients and thus include interaction between the ECs. The boundaries for the WEC-SIM model will be provided by the time series given by the Orcaflex model. This approach serves not only to reduce the computational time but also to circumvent the need for the computer in the hybrid testing to run Orcaflex which is licensed software.

The drag coefficients will be very important for the resulting motion of the ECs including the hydraulic pumps and subsequent loading on the seals. While the shape of the plates might be simple, the fact that they move in close proximity to both the free surface and to other plats makes tabulated values uncertain. There are no experimental tests of the Wavepiston device to compare to. Thus, CFD simulations will be performed to provide calibration data for the drag coefficients.

4.3 Methodology for accelerated tests

The Wavepiston system uses seawater as a medium in a telescopic pump for conversion and carrier of power, as shown in Figure 37. Consequently, leaks in the Wavepiston system are acceptable from an environmental standpoint. Furthermore, as long as the leaks are relatively small and do not significantly impact system yield, leaking hydraulics are also acceptable from an operational and mechanical standpoint.

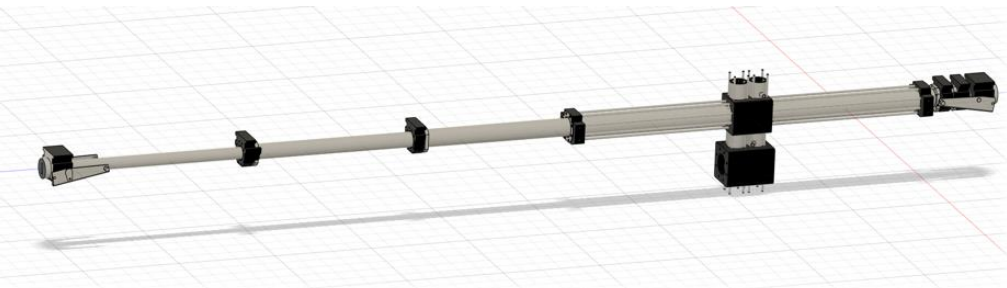

Figure 37: 3D drawing of pump unit with telescopic pumps.

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Typically, when hydraulic seals are tested, the way to access wear is to cut the flow to the sealed area and record how fast the pressure drops. However, this method is not an option in a leaky hydraulic system as pressure will almost immediately drop to zero. Thus, instead of simply measuring time and pressure, testing the performance of Wavepiston hydraulic systems will require measurement of both times, pressure and leak rate from the seal under test.

Often hydraulic seals are designed for low friction. Although low friction is a highly desirable feature, in the Wavepiston system low friction must be weighed against durability, as any seal failure will require refurbishment of an entire energy collector, which is a costly operation. Thus, a high friction seal with a long-expected lifetime may yield a system with a better overall economy, compared with a Wavepiston system fitted with low friction seals having only mediocre longevity.

As mentioned in Section 3.2, Wavepiston seals are only energized in the compression part of the hydraulic pump cycle. In Section 3.2 it is furthermore mentioned that the pressure build-up sequence may be essential to contact wear which happens when the sealing system starts to move from a standstill position. Thus, the accelerated test will require realistic pressure build-up during initial movement to ensure that wear is characterised from a standstill position.

A prominent feature of any Wavepiston system is the use of staged, telescopic pumps that ensures that the system is self-centering in irregular waves. Whenever the pumping action changes direction or the pump starts moving, there will be a pressure build-up as described above. However, when the hydraulic pumps shift from one stage to the next stage, there will be an upstart of the movement with the seals fully energized already at zero velocity. These two start-up sequences represent different tribological situations due to how the sealing lips are energised before piston movement is initiated. Thus, the test must include initial movement with fully energized seals and seals where the movement starts with non-energized seals.

4.3.1 Full-scale accelerated test

The full-scale accelerated test program is used to evaluate the performance of chevron seal different, which are the baseline seal design, and to validate the fatigue performance of the pump unit. A 3D sketch of the full-scale test rig is illustrated in Figure 38.

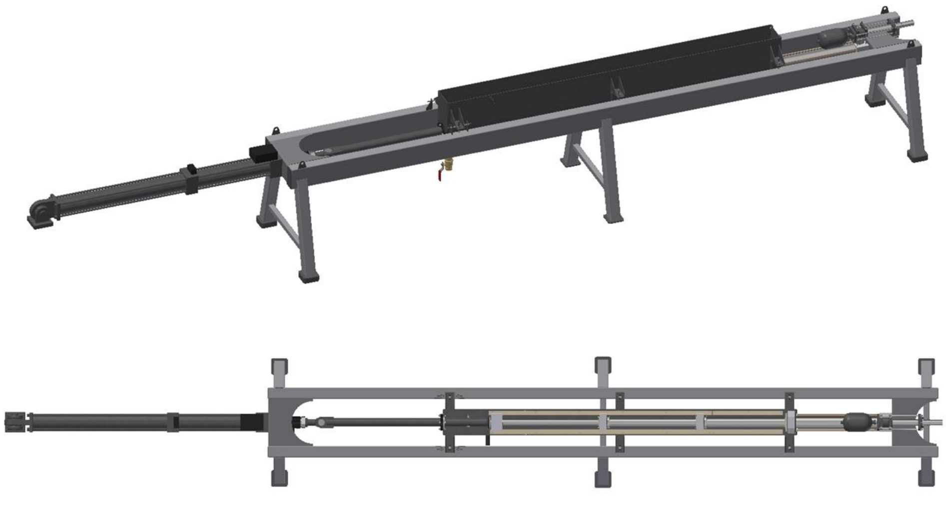

Figure 38: 3D sketch of the full-scale pump test rig.

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The dominating failure mechanism of seals is wearing as mentioned in the FMECA presented in Section 2.3.5 whereas fatigue failure of the pump unit is dominated by the number of pressure cycles. The main seal wear factor is the number of reversals where the viscodynamic lubrication film breaks down, leading to physical contact between the seals and the counteracting metal surface. The accelerated test of the seals and the pump unit is achieved by reducing the sliding distance combined with a high head pressure on the pump unit. The reduced sliding distance increases the frequency of the sliding reversals of the seals and pressure cycles in the pump unit. There is a risk that the water temperature will increase because of the accelerated test as mentioned in Deliverable 1.1 [2]. Therefore, the operating temperature of the seals will be monitored during the accelerated test.

A simple spring-controlled relief valve will be used to control the pump head pressure in the full-scale accelerated test. The following will be monitored during the accelerated test

- Pump head pressure (Pressure transducer)
- Internal pump pressure (Pressure transducer)
- Pump displacement (linear variable differential transformer LVDT)
- Pump actuation force (Load cell)

The pump actuation force will be compared to the internal pump pressure to evaluate the seal friction.

4.3.2 Modified wear bar test

It is expected that the wear bar test will be used to perform the accelerated test on seals. The advantage of using this modified wear-bar rather than the full-scale test rig with the actual pump unit is that the forces needed to activate the cylinder are comparably lower, thus allowing for simpler, cheaper and more energy-efficient actuators. The reduction in the actuation force can potentially enable the option for testing the seals with high acceleration and velocities compared to the full-scale test rig.

Two wear situations appear in the pumps; the first is the build-up of cylinder pressure during initial piston movement (followed by movement). The second is an initial movement with pressure already built up on sealing surfaces. The wear bar test rig will be split into two coupled test sections to distinguish between these two wear situations. The one section, which pressurizes the system, is used to study wear in the pressure build-up situation. Another section is used to study wear in situations where movement is always initialized with fully energized seals.

As shown in Figure 39, a modified wear bar is used to investigate wear in the situation where pressure is built up during initial movement.

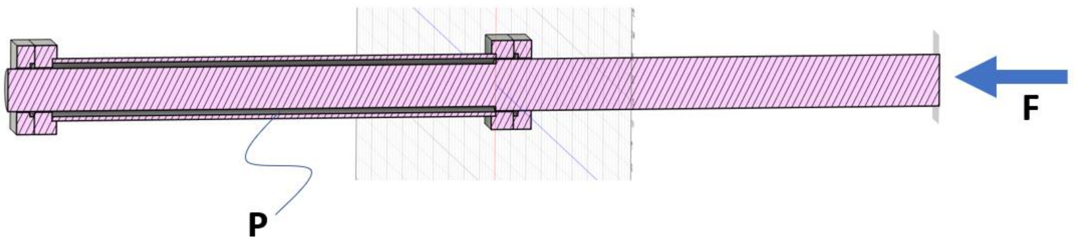

Figure 39: Modified wear bar seal test.

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A setup using a straight wear bar, as introduced in Section 3.2, is used to investigate wear in the situation where the system is already pressurized. Combining these two bars makes it possible to simulate both wear situations in a single experimental setup, as shown below in Figure 40.

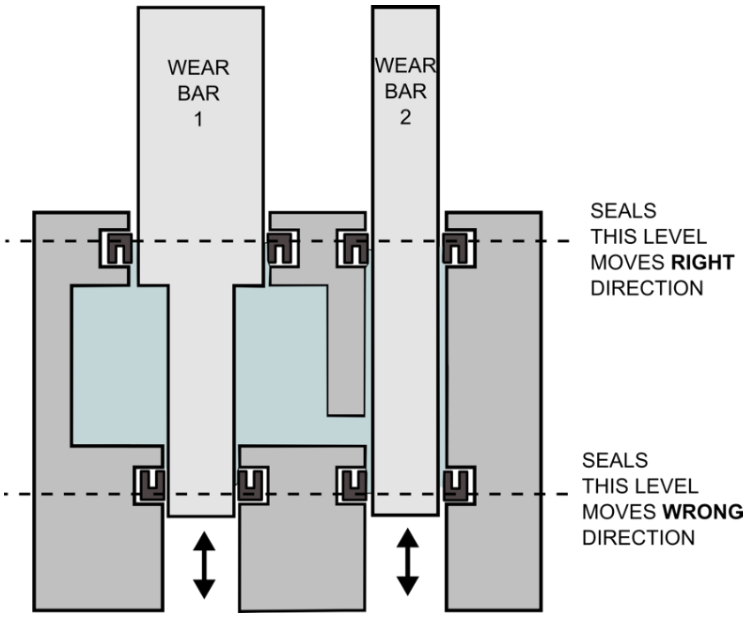

Figure 40: Combined wear bar test principle with modified wear-bar and straight wear-bar.

For clarity, both wear bars are here drawn into the same seal block. In an actual setup, the system will comprise two seal blocks connected with a hydraulic hose. Note that the right-hand part of the wear-block mimics the wear situation in a regular hydraulic tester.

To measure the seal friction in the left-hand wear-block, the endcap pressure from the hydraulic fluid must be accounted for. The seal friction in the right-hand cavity can be measured directly.

Note that the bottom level seals are moving in the wrong direction and should be mounted such that they can be easily changed during testing.

Using WEC-Sim, the movement of the panels for certain sea states is calculated for irregular sea states. The telescopic pump has three pump stages which imply that only one pump piston is moving while the two others are stationary. The wear-bar test will only be testing one piston. To accelerate the wear in the seal test, the stationary time of the piston will be reduced by post-processing the displacement signal calculated with WEC-Sim. The wear bar test will be actuated by an actuator with the post-processed displacement signal to increase the usage which is recommended as an acceleration method in Deliverable 1.1 [2].

4.4 Full-scale hybrid test setup

The full-scale hybrid test rig will be performed by coupling the W2W model to the full-scale pump test rig illustrated in Figure 38.

4.4.1 W2W model used in the hybrid test

The W2W model is set up by coupling the hydrodynamic system model of the Wavepiston system to the hydraulic model by the AVL Model.Connect interface as illustrated in Figure 41. The hydrodynamic system model of the Wavepiston system

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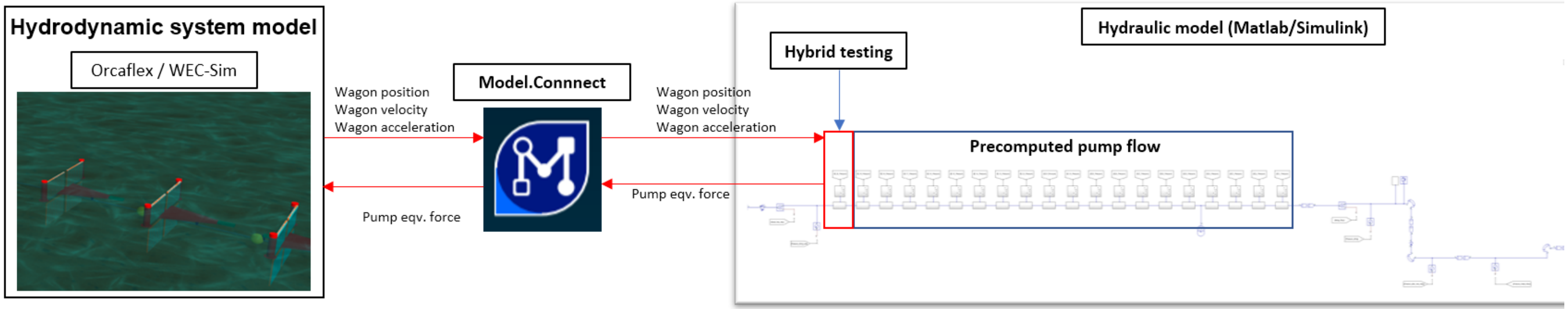

Figure 41: Wave-2-wire model used in the hybrid testing.

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computes the wave loading on each energy collector. The AVL Model.Connect interface sends the wagon position, velocity, and acceleration to the hydraulic model. The hydraulic model computes the equivalent pump force which is sent back to the hydrodynamic system model. The hydraulic model computed the equivalent pump force based on simulation of the hydraulic system. The following components are modelled in the hydraulic model

- Telescopic pumps
- Export pipe with pressure accumulators
- Pressure relief valve
- Turbine module

The hybrid testing will be performed on one pump unit as indicated in Figure 41. The equivalent pump force is coupled to the operation condition of all the other energy collectors through the hydraulic piping system which shall be accounted for in the hybrid testing. The full hydrodynamic system model with all energy collectors is computationally heavy and it can therefore not be used for real-time hybrid testing. It is, therefore, expected that the head pressure of the hybrid tested pump unit will be calculated in the hydraulic model with the precomputed pump flow of the remaining pump units in the system.

The full wave-to-wire model is not coupled with the Model.Connect interface at the current stage. The operating condition of the hydraulic system has, therefore, been simulated with the precomputed pump flow from the Orcaflex model with the assumption of the constant pressure of 60 bar in the pumps. The pump flow calculated with Orcaflex has been used in the hydraulic model to analyze the system pressure at different sea states. The maximum operating condition of the pump is listed for different sea states in Table 14. The maximum operating pressure increases with the significant wave height H_s. However, the annual occurrence at the PLOCAN site decreases with the significant wave height as shown in Table 16. Due to the annual occurrence of the sea states, it is expected that most of the seal wear will occur in H_s< 2 m.

Table 14: Operating condition of the pump based on precomputed pump flow from Orcaflex with constant 60 bar pump pressure.

Environmental loading						
Significant wave height, Hs [m]	1.0	1.5	2.0	2.5	3.0	3.5
Wave peak period, Tp [s]	8	8	8	10	10	12
Pump loading (Hydraulic model)						
Max pump pressure [bar]	61.8	69.7	76.2	79.1	88.1	89.0
Max pump force in Orcaflex [kN]	38.4	43.3	47.3	49.1	54.7	55.2
Actuator loading (Simplified Wave-2-wire model)						
Max pump stroke [m]	1.91	2.06	2.14	2.14	2.17	2.26
Maximum wagon velocity [m/s]	0.96	1.41	2.02	2.07	2.38	3.60
Maximum pump flow [l/s]	3.24	4.77	6.83	7.00	8.04	12.17

It is difficult to capture the real behaviour of the check valves and the pressure loss in the pump unit with the bladder accumulator. Therefore, the full telescopic pump unit with bladder

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accumulator and check valves illustrated in Figure 9 will be included in the hybrid testing program.

The full-scale hybrid test rig illustrated in Figure 42, will be used to test the performance of the pump unit and to test the seal wear in real operating conditions. The full-scale test setup will be used to verify the validity of the modified wear-bar test procedure and ensure that the seals will perform in with the pump in more realistic operating conditions. The actuation displacement and the head pressure of the pump module is set by the W2W-model the actuation force and then are then send returned to the W2W-model.

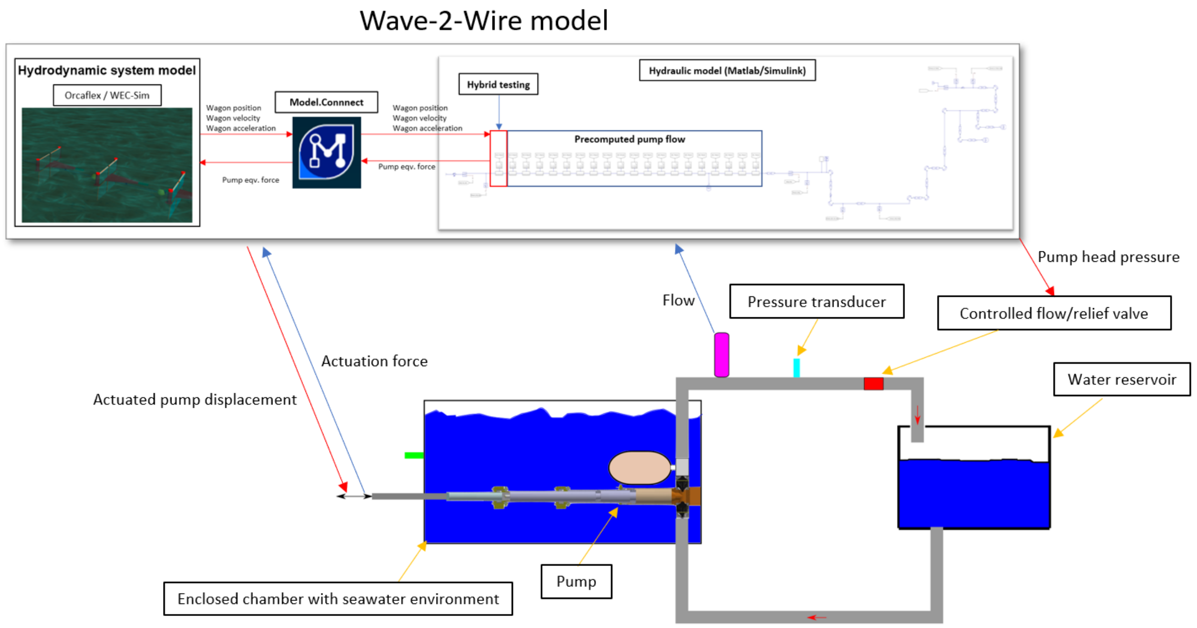

Figure 42: Sketch of the full-scale hybrid test rig.

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5 Design Load Cases

The methodology that defines the load and strength assessment of an offshore renewable energy converter is typically underpinned by a set of Design Load Cases (DLCs). The DLC is defined as combinations of operational modes and/or design situations with external conditions, providing a succinct representation of key input parameters that define relevant loading scenarios to be experienced by the structure during its design life, see Deliverable 1.1 [2].

5.1 Metocean design basis at PLOCAN

The environmental condition at PLOCAN test site will be used in the definition of the design load. The reason for using PLOCAN metocean data as input to the relevant design load case(s) is that Wavepiston will shortly deploy a test system at PLOCAN, which enables comparison between simulations and actual measurements. The environmental load data that will be used to define DLCs will be outlined in this section based on measured data at the PLOCAN installation site.

According to [32], the following environmental loads are the most important for the design of marine structures:

- Wave.
- Current.
- (Tide and storm surge).
- (Wind).

Tide and the storm surge affect the vertical position of the energy collectors and the pretension level in the Wavepiston system. It is anticipated that the wind loadings on the Wavepiston system are insignificant since most of the system is submerged. Wind, effects are, therefore, neglected when defining the design load cases of the system.

5.1.1 Wave buoy data

The wave data provided in this section is based on measurements from a wave buoy located at (Lat 28.0531 N, Lon 15.3970 W), which is approximately 850m Northwest of the Wavepiston system as shown in Figure 43. The seabed bathymetry is indicated with contour lines where the wave buoy is located at a water depth of 40m.

The following data are measured on an hourly basis at the buoy:

- Significant Wave Height, H_s (m).
- Maximum Wave Height, H_{max} (m).
- Mean period, T_{m02} (s).
- Peak Period, T_p (s).
- Wave direction, D (compass angle).
- Swell/elevation of low-frequency part of waves (m).

The historical hourly data can be downloaded there for the last 20 years from the Emodnet homepage [33]. The historical data is updated monthly at the end of each month.

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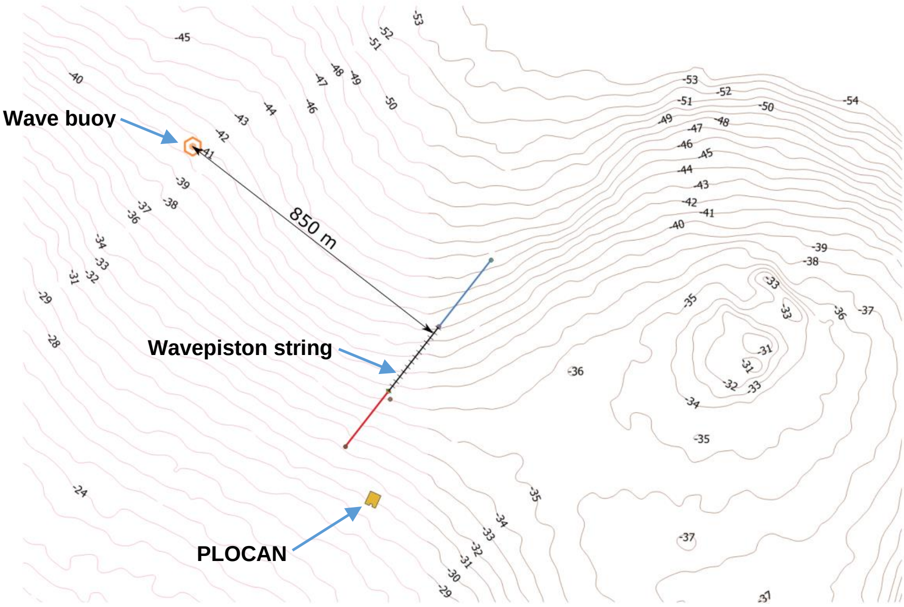

Figure 43: Seabed bathymetry and position of the wave buoy relative to the Wavepiston system.

5.2 Wave data

Significant wave heights (H_s) and peak periods (T_p), as well as corresponding maximum wave heights (H_{max}), are listed in Table 15 for various return periods T_R. The extreme wave parameters are based on a statistical analysis of H_s measured with the wave buoy indicated in Figure 43 between 1990 to 2001. The statistical analysis is performed with a three-parameter Weibull distribution [30]. The annual joint distribution of the significant wave height H_s and the wave peak period T_p is listed in Table 16. A wave rose that show the significant wave height H_s and the directionality measured at the PLOCAN test site in the period between January – September 2014 is shown in Figure 44.

Table 15: Extreme operational sea state (ESS) at PLOCAN estimated based on a three-parameter Weibull distribution. From [31].

	Symbol	H_{s10}	H_{s20}	H_{s50}	H_{s100}	H_{s200}	H_{s500}
Return period [years]	T_R	10	20	50	100	200	500
Significant wave height [m]	H_s	4.49	4.88	5.41	5.81	6.22	6.77
Maximum wave height [m]	H_{max}	7.18	7.81	8.66	9.30	9.96	10.83
Wave peak period [s]	T_p	11.1	11.4	11.9	12.2	12.5	12.9

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Table 16: Probability of occurrence significant wave height H_s and wave peak period T_p (annual average based on measurement period 1990-2001). From [31].

H_S(m)	Tp (s) ≤2,0	4,0	6,0	8,0	10,0	12,0	14,0	16,0	18,0	20,0	>20,0	Total
≤0,5	0,000	0,371	0,716	1,484	1,903	1,829	1,046	0,516	0,033	0,004	0,000	7,902
1,0	0,000	0,705	9,876	10,295	5,966	3,981	3,484	2,326	0,200	0,059	0,000	36,892
1,5	0,000	0,000	6,099	17,137	6,151	2,026	1,373	1,046	0,093	0,004	0,004	33,936
2,0	0,000	0,000	0,312	8,563	5,606	0,790	0,571	0,234	0,52	0,000	0,000	16,127
2,5	0,000	0,000	0,019	0,820	2,690	0,256	0,152	0,089	0,041	0,000	0,000	4,066
3,0	0,000	0,000	0,000	0,037	0,534	0,130	0,030	0,011	0,033	0,007	0,000	0,783
3,5	0,000	0,000	0,000	0,000	0,093	0,108	0,011	0,000	0,000	0,000	0,000	0,211
4,0	0,000	0,000	0,000	0,004	0,007	0,026	0,019	0,000	0,000	0,000	0,000	0,056
4,5	0,000	0,000	0,000	0,000	0,000	0,007	0,015	0,004	0,000	0,000	0,000	0,026
5,0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
>5,0	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Total	0,000	1,076	17,022	38,339	22,950	9,153	6,700	4,226	0,456	0,074	0,004	100

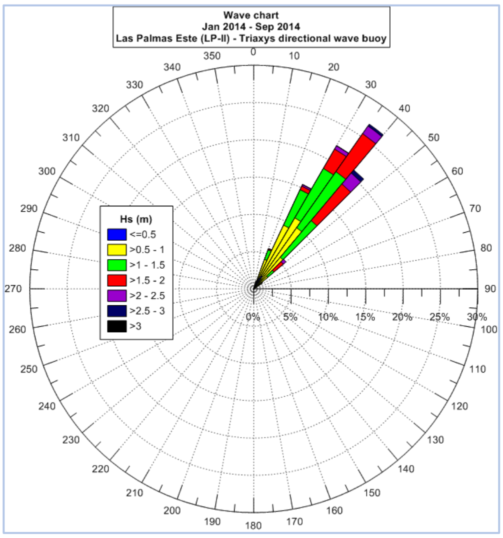

Figure 44: Wave rose Jan 2014 – SEP 2014 showing the incoming wave direction relative to the north which corresponds to 0 degrees. From [31].

The normal operational sea state (NSS) will be used that used to estimate the power production, fatigue, and wear on the components in the system. The normal operational sea state (NSS) is defined by binned sea states that represent the annual joint distribution of the significant wave height H_s and the wave peak period T_p listed in Table 15. The wave conditions listed in Table 17 will be used to simulate and test the normal operating condition. It can be seen that the binned sea states are covering 62.4 % of the events in the scatter diagram. The directional spread that will be considered in combination with the RNSS is 30-45° relative to the north based on the wave rose shown in Figure 44.

Table 17: Normal operational sea state (NSS).

Load case	H_s [m]	T_p [s]	Annual occurrence [%]
FLS 1	0.5	8	1.5
FLS 2	1.0	6	9.9
FLS 3	1.0	8	10.3
FLS 4	1.5	8	17.1
FLS 5	1.5	10	6.2
FLS 6	2.0	8	8.6
FLS 7	2.0	10	5.6
FLS 8	2.5	10	2.7
FLS 9	3.0	10	0.5
FLS 10	3.5	12	0.1
Total			62.4

Table 18: Reduced range normal operational sea state (RNSS).

Load case	H_s [m]	T_p [s]	Annual occurrence [%]
FLS 2	1.0	6	9.9
FLS 4	1.5	8	17.1
FLS 7	2.0	10	5.6
Total			32.6

5.2.1 Current Data

The current is essential for system performance since current may lead to higher pump velocities and increases in the drift effects of the plate when it is aligned with the Wavepiston system. Furthermore, off-axis directional currents will impose a catenary shape of the Wavepiston system, which increases the pretension level and changes the energy collector's direction relative to the wave heading angle. The current speed and direction measured at the PLOCAN test site in different periods at various water depths are given in Figure 45 to Figure 47. The effect of the current will be analysed based on the current speed, direction and velocity profile listed in Table 19. The current velocity profile that will be used for the PLOCAN site is uniform since the current does not vary significantly along with the water depth. The two current directions that will be analysed are illustrated in Figure 48 relative to the system orientation.

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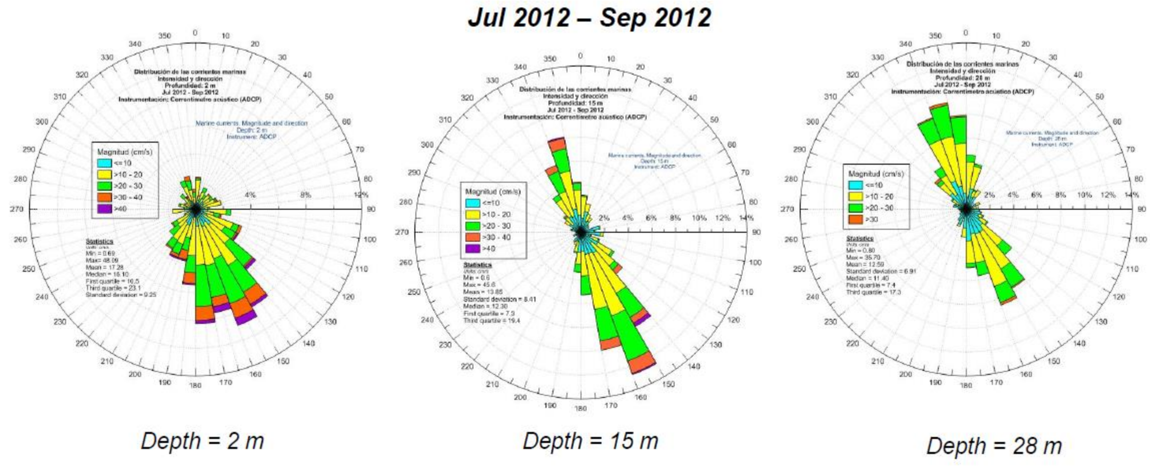

Figure 45: Current measurement at the PLOCAN test site in the period: July to September 2012. From [31].

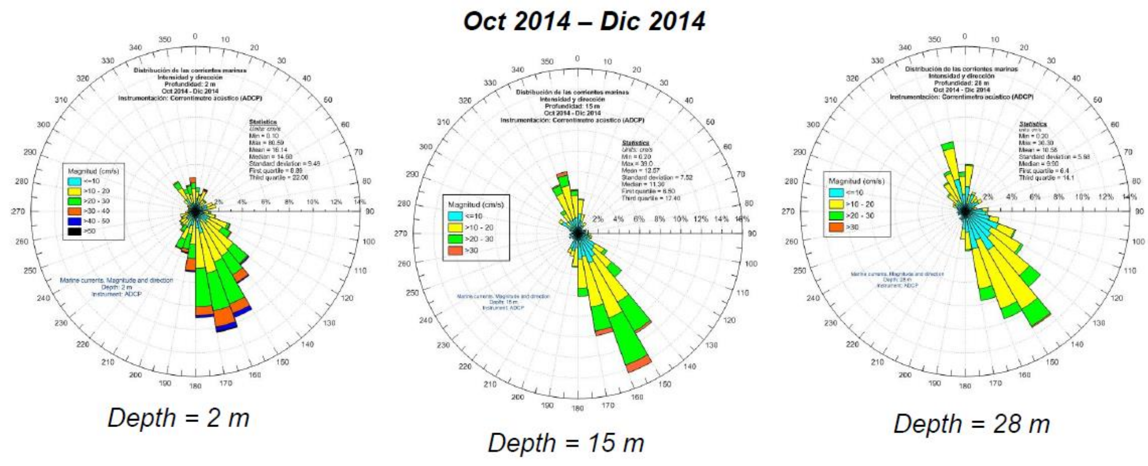

Figure 46: Current measurement at the PLOCAN test site in the period: October to December 2014. From [31].

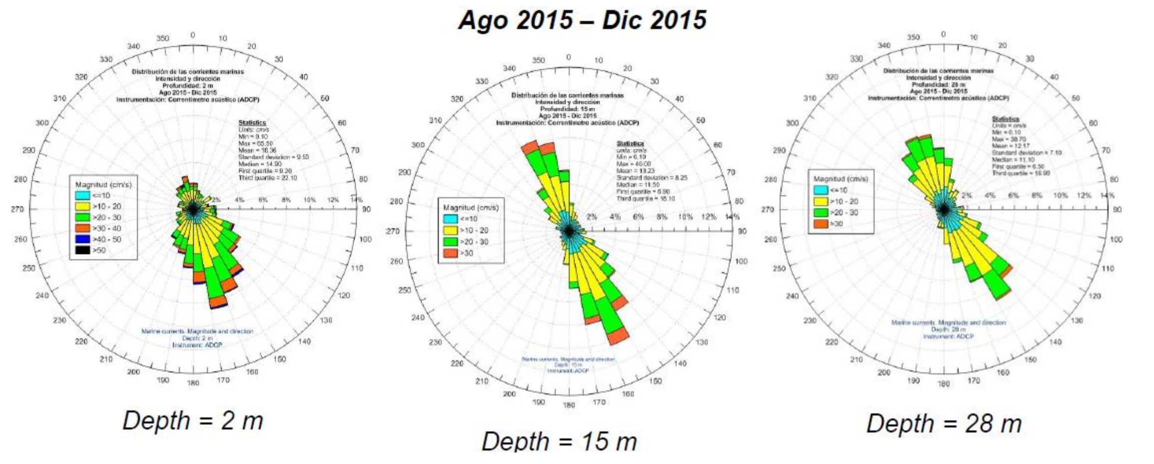

Figure 47: Current measurement at the PLOCAN test site in the period: August to December 2015. From [31].

Table 19: Normal current model (NCM).

Current	Current speed	Direction [°]	Velocity profile
NW current	0.5	355	Uniform
SE current	0.5	155	Uniform

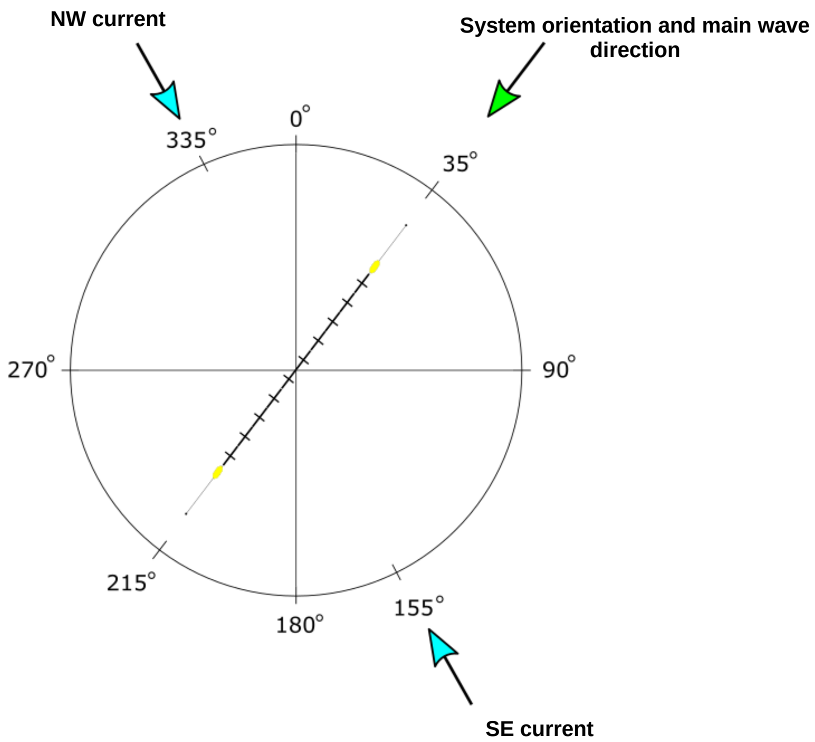

Figure 48: Orientation of the Wavepiston system at the PLOCAN test site current directions and the main wave direction.

5.3 Tide levels

The tide level affects the mean tension in the drill string. This governs the overall dynamic behavior of the energy collectors in a nonlinear way. It is therefore not certain that the highest tide is a conservative choice to use for the design load case. The average low and high tide are selected for analysis to capture the effect of tidal variation.

Table 20: Measured astronomical tide at the port of Las Palmas.

	Maximum [m]	Minimum [m]	Average [m]	Standard deviation
High tide (HAT)	3.11	1.73	2.38	0.26
Low tide (LAT)	1.41	0.13	0.78	0.25

5.4 Seawater properties

The seawater properties are outlined in this section based on seasonal measurements performed at the PLOCAN test site. The seawater parameters presented in this section form the operating corrosive environment of the pump unit.

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5.4.1 Temperature

The seawater temperature measure with a multiparametric probe at the PLOCAN test site is plotted as a function of the water depth in Figure 49 in the period May 2011 - October 2013. The pumps are operating near the sea surfaces where the temperature varies between 18-24°C.

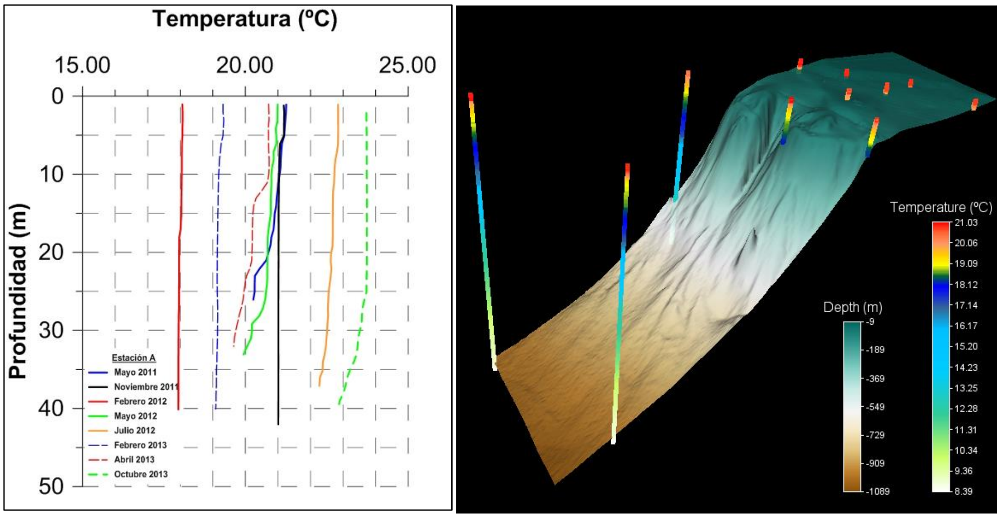

Figure 49: The seawater temperature as a function of the water depth measured at the PLOCAN test site in the period between May 2011 - October 2013. From [31].

5.4.2 Salinity

The seawater salinity measure at the PLOCAN test is plotted as a function of the water depth in Figure 49 in the period May 2011 - October 2013. The pumps are operating near the sea surfaces where the salinity varies between 36.70 psu – 36.95 psu.

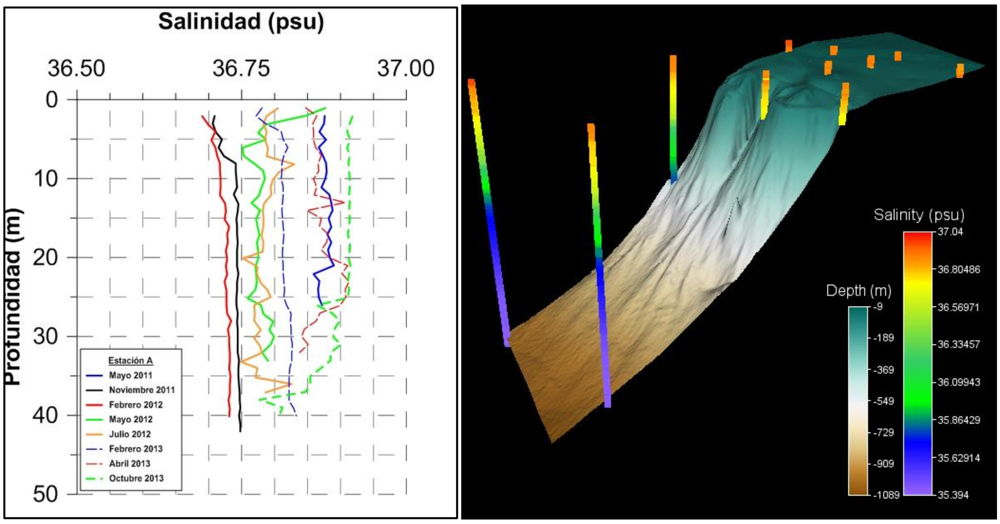

Figure 50: The seawater salinity as a function of the water depth measured at the PLOCAN test site in the period between May 2011 - October 2013. From [31].

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5.4.3 Dissolved oxygen at the sea surface

The dissolved oxygen at the sea surface is measured with a Niskin bottle at various locations within the PLOCAN test site. The dissolved oxygen level is plotted for measurements performed in the period Marts 2011 – November 2015 in Figure 51. The dissolved oxygen level is varying between 6.5 – 9.5 mg/L.

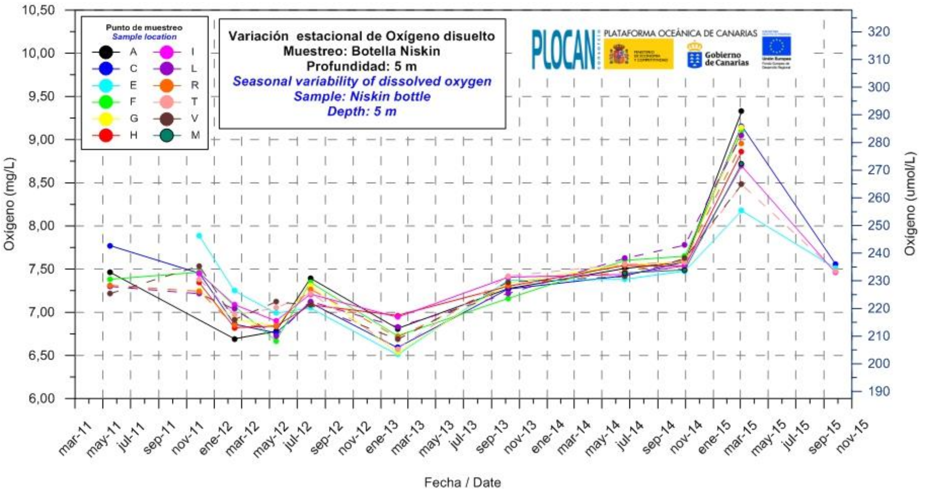

Figure 51: Dissolved oxygen level for measurements performed in the period Marts 2011 – November 2015 with a Niskin bottle. From [31].

5.5 Marine growth

Marine growth will affect the performance of the seals in the pump. The marine growth rate at PLOCAN test site is unknown at the current stage and needs to be further investigated.

5.6 Partial safety factor

The four load design categories are outlined in Table 21 are defined based on the recurrence period of external conditions. In turn, and to assist with the definition of the type of load and partial safety factor to apply, the design categories can be related to design situations. The abnormal and the transport and installation design category is not considered in this study.

Table 21: Design categories: recurrence period and design situation From [34].

Design category	Recurrence period	Design situations
Normal (N)	≤ 1 year	Normal operation Normal operation plus fault Parked "Survival" configuration
Extreme (E)	≤ 50 years	Parked Fault in parked condition "Survival" configuration
Abnormal (A)	≤ 500 years	System pressure loss
Transport and installation (T)	≤ 1 year	Installation Maintenance

The design methodology of the system is performed based on the offshore standard DNVGL-OS-C101 [28]. DNVGL-OS-C101 provides design principles and overall requirements for the structural design of offshore structures.

5.6.1 ULS

The ultimate limit state (ULS) design check ensures that the probability of failure during the design life is acceptable. The design loads F_d for the ULS condition, see (1), are obtained by multiplying the characteristic loads F_k by a ULS load factor γ_F according to Table 22:

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

Table 22: Load factor for ULS. From [28].

Combination of design loads	*Load categories*			
	G	*Q*	*E*	*D*
a)	1.3	1.3	0.7	1.0
b)	1.0	1.0	1.3	1.0

Load categories are:
G = permanent load
Q = variable functional load
E = environmental load
D = deformation load

For description of load categories see Sec.2.

5.6.2 FLS

The load factor γ_f in the FLS condition is 1.0. However, the design fatigue factors (DFF) shall be applied to the design life to reduce the probability of fatigue failure. The calculated fatigue life shall be longer than the design life T_{life} multiplied with the DFF. The EC operates in the splash zone and no inspection is planned during the design life. The value of the DFF of the EC module is defined according to Table 23.

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Table 23: Design fatigue factors. From [28].

	DFF related to survey cycle	
Structural element	5-year inspection interval, carried out in dry dock	5-year inspection interval, carried out afloat
External structure, accessible for regular inspection and repair in dry and clean conditions	1	1
External structure, accessible for inspection but not accessible for repair in dry and clean conditions	1	2 [1) 2)]
Internal structure, accessible and not welded directly to the submerged shell plate	1	1
Internal structure, accessible and welded directly to the submerged shell plate	1	2
Non-accessible areas, not planned to be accessible for inspection and repairs during operation	3	3

[1)] For units that are planned to be inspected afloat at a sheltered location:

— DFF of 1 from 1 m above lowest inspection waterline and upwards.
— DFF of 2 from 1 m above the lowest inspection waterline and downwards.

[2)] For units intended for prolonged stay at location:

— DFF of 1 above the splash zone.
— DFF of 2 below the splash zone.
— DFF of 3 in the splash zone.

Splash zone is the area that not is accessible, due to typically waves and current. The splash zone shall be defined for the unit, as relevant.

5.7 Description of the design load cases (DLCs)

The design load cases are described in detail in this section, and it is furthermore summarized in Table 23 and Table 25.

5.7.1 Power Production

In this design condition, the WEC is in operation mode and connected to the electrical grid. The control system is operating in normal power production.

DLC 1.1: At this point, the normal operational sea states (NSS) listed in Table 17 will be analysed. The effect of the directional spread and the current will not be considered for the NSS. DLC.1.1 will be used for fatigue analysis of the system and assessment of the power production.

DLC 1.2: The wave directional spread and current representative for the installation site are addressed for the sea states listed in Table 18 to quantify the effect on the power production and the system loading.

DLC 1.3: Loading combinations resulting from a range of spectral shapes, including bimodal spectra with two widely spaced frequency and/or directional components are considered. In this study, the Ochi-Hubble wave spectrum will be used and the JONSWAP spectrum will be analysed to check for sensitivity for the RNSS listed in Table 18.

DLC 1.4: DLC 1.4 covers large wave groups that may occur during operational sea states (using focused wave groups). The random phasing assigned to the DLC 1.1 sea states may not lead to the generation of these as part of the normal operational time series and so these loading effects are accounted

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for with the focused wave groups. This approach reduces the need to run lengthy sea state simulations with multiple random wave phases.

DLC 1.5: In DLC 1.6 the operation of the Wavepiston system with substantial marine growth is considered for a subset of DLC 1.1 operations conditions. The level of marine growth will depend on the frequency of maintenance operations and the water conditions in the proposed deployment sites.

5.7.2 Power Production Plus Occurrence of a Fault

Any fault in the control, safety system, or internal fault in the PTO system that is significant for WEC loading is assumed to occur during power production is analysed in this DLC category. It will be assumed that independent faults do not occur simultaneously.

DLC 2.1: Control system faults that can be considered as normal events are covered in this DLC.

5.7.3 Start-up

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

DLC 3.1: Start-up of the machine during a sub-set of operational sea states deemed to meet the environmental start-up criteria for the system. The start-up control sequence will be applied to the turbine module and the operational condition will be analysed.

5.7.4 Normal Shutdown

This DLC category includes all the events resulting in loads on the WEC during normal transitions from power production to a standby condition (standstill or idling).

DLC 4.1: This DLC represents cases where the device operator shuts down the WEC. Shutdown times at a range of different instants during a focused wave group may be considered.

5.7.5 Emergency shutdown

This load case corresponds to the manual actuation of the emergency stop push button. Two emergency shutdown conditions will be checked. The first is the bypass conditions where water is bypassing the turbine and dumped directly into the sea. In the second emergency shutdown condition, the water flow is blocked completely before the turbine module and the system will be put into survival mode.

5.7.6 Parked / Storm protection

The EC wagon is parked in extreme conditions in significant wave conditions to protect the system against extreme loading.

DLC 6.1: The parked conditions of the wagon are analysed with extreme wave sea states with a recurrence period of up to 50 years in DLC 6.1.

DLC 6.2: The parked conditions of the wagon are combined with extreme wave sea states with a recurrence period of up to 50 years is combined with wave directional spread and current to study the operational condition of the EC.

DLC 6.3: The expected number of hours of non-power production time in parked conditions will be considered to assess fatigue damage on critical components (investigate if significant fatigue damage can occur in the locking mechanism).

5.7.7 Fault conditions

DLC 7.1: Fault conditions of the EC wagon locking mechanism will result in power production in the extreme sea state. The fault condition of the EC wagon locking mechanism where the system is producing power is combined with the extreme wave sea states with a recurrence period of up to 50 years.

DLC 7.2: Fault conditions on the export pipe will lead to system pressure loss. In case of pressure loss, it will be checked if the wagon end stop and locking mechanism safely can put the EC wagon into parked conditions.

Table 24: Abbreviation used in the overview Table 25.

Abbreviation	Description	Data in
NSS	Normal Operational Sea States	Table 17
RNSS	Reduced Range Normal Operational Sea States	Table 18
ESS	Extreme Operational Sea States	Significant wave heights *(Hs)* and peak periods (T_p), as well as corresponding maximum wave heights (*Hmax*), are listed in Table 15 for various return periods *TR*. The extreme wave parameters are based on a statistical analysis of H_s measured with the wave buoy indicated in Figure 43 between 1990 to 2001. The statistical analysis is performed with a three-parameter Weibull distribution [30]. The annual joint distribution of the significant wave height *Hs* and the wave peak period *Tp* is listed in Table 16. A wave rose that show the significant wave height *Hs* and the directionality measured at the PLOCAN test site in the period between January – September 2014 is shown in Figure 44. Table 15
H_{s50}	Significant wave height with a recurrence period of 50 y	Significant wave heights (*Hs*) and peak periods (T_p), as well as corresponding maximum wave heights (*Hmax*), are listed in Table 15 for various return periods *TR*. The extreme wave parameters are based on *a* statistical analysis of H_s measured with the wave buoy indicated in

		Figure 43 between 1990 to 2001. The statistical analysis is performed with a three-parameter Weibull distribution [30]. The annual joint distribution of the significant wave height Hs and the wave peak period Tp is listed in Table 16. A wave rose that show the significant wave height Hs and the directionality measured at the PLOCAN test site in the period between January – September 2014 is shown in Figure 44. Table 15
NCM	Normal Current Model	Table 19
U	Ultimate strength analysis	-
F	Fatigue strength analysis	-
*	Fatigue partial safety factor	Table 23
E	Extreme partial safety factor	Table *22*

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Table 25: Overview of the design load cases (DLCs).

Design situation	DLC	Wave condition	PTO condition	Other condition	Analysis type
1. Power production	1.1	NSS	Power Production	LAT	F
	1.2	RNSS	Power Production	LAT NCM	F U
	1.3	RNSS	Power Production	Ochi-Hubble JONSWAP	U
	1.4	FWG	Power Production		
	1.6	RNSS	Power production	Marine growth	U
2. Power production plus the occurrence of a fault	2.1	RNSS	Power production	Fault in control system	U
3. Start-up	3.1	RNSS	Start-up Procedure		F U
4. Normal shut-down	4.1	RNSS	Normal shut-down procedure	Vary the shut-down time of different points during the wave group	F
	4.2	H_{s1}	Normal shut-down procedure		F U
5. Emergency shutdown	5.1	FWG ESS -H_{s50}	Power production	Bypass condition Turbine blocking condition	U
6. Parked / Storm protection	6.1	ESS -H_{s1}	Parked	NCM	U
	6.2	ESS -H_{s50}	Parked		U
	6.4	NSS	Parked		U
7. Fault conditions	7.1	ESS -H_{s50}	Power Production	Fault on the wagon locking device	U
	7.2	RNSS	Power Production	System pressure loss	A

6 Parameters for Different Metrics

6.1 Hybrid exchange parameters

6.1.1 Accelerate/hybrid testing concept

Accelerated testing can be classified into three approaches:

1. Time-acceleration
2. Selective-acceleration
3. Condition-acceleration

The time-accelerated tests are the test in which it is possible to reduce the time intervals of imposed conditions to accelerate the deterioration process or reduce the time to failure of the specimen, e.g., when a test coupon needs to be tested rapidly, and there is the possibility to increase the loading frequency, to complete the test in reduced time.

Selective-testing or cycle acceleration for fatigue case; is a testing strategy in which only some complete tests are performed and later the test coupon capacity is extrapolated using the partial gained information, e.g., when there is a complete fatigue testing campaign of a specific material. For example, one could focus on the high-stress ranges and a low number of cycles to extrapolate the fatigue capacity in the low-stress ranges with the higher number of cycles for testing.

Finally, the condition-accelerated testing is the popular type of accelerated testing, in which external conditions or agents are modified in such a way that the testing specimen increase their deterioration rate, or the life cycle is reached faster than in normal conditions, e.g., when wear is investigated, the lubricant can be exchanged by a lubricant with more suspended particles that would increase the wear of the specimen. It could also be the case that the increase of stresses (overstressing acceleration) is a particular case of this condition accelerated test. Each of the previous three approaches needs failure criteria and related parameters to define the type of accelerated testing selected. There are two types of accelerated testing:

- Accelerated life testing, ALT.
- Accelerated deterioration testing, ADT.

When ALT is selected this means that the experiment is looking for the ending of the life of the test specimen, given by a specific criterion, e.g., when the piston pressure is below 20% from the initial state, or the friction coefficient has decayed more than 50%, without paying attention to any parameter related to the deterioration process. When ADT is selected, this means that during the experiment, the deterioration process is observed and measured, establishing a more complex way to define failure, from the nature of ALT and ADT, it is expected that ADT is more complex to be carried out, containing higher phenomenological and epistemic uncertainty in the models when the deterioration process is supervised, measured and models are developed from ADT. ALT contains a simplistic approach where the testing process could only need the failure time with all the implicit intra- and inter-specimen. The references [35]–[40] are examples of the condition-accelerated testing when lubricants and suspended particles are added to the medium when seals are tested. The reference [35] is an example of a time-accelerated test.

In User Case #3, the time acceleration is selected as the testing acceleration approach for ALT of the seals at 1:1 scale.

6.1.2 Accelerated/hybrid testing and parameters

In the case of rod seals in piston or pumps, there are four groups of relevant variables or parameters:

- Pump parameters
  - Chamber pressure
  - Lubricant, in this case, seawater
  - Rod rugosity and material
  - Reciprocating movement – relative position
- Seal parameters
  - Seal base material
  - Seal reinforcement or filler in the main material
  - Seal reinforcement proportions
  - Seal-rod pressure
- Test conditions
  - Time
  - Velocity in the test
  - Load for wear testing
- Test outcome parameters
  - Rod-seal compatibility
  - Sliding distance
  - Friction coefficient,
  - Specific wear rate
  - Measured wear damage (microscopic damage) parameters

Each of the previous groups contains relevant parameters or variables to obtain from the testing setup or outcome from the test. The pressure in the pump is related to the reciprocating movement. The reciprocating movement consists of two stages where the seawater enters the pump in one direction and when the movement shift to the other direction, the pump gets closed to pump the seawater out. The pressure value is related to the location of the rod in the reciprocating movement.

The rod rugosity and material are related to the compatibility of the rod seal. It is demonstrated in current research that the material of the rod makes specific seals' material perform better as an outcome of the test. The seal base material, reinforcement, and reinforcement proportions have to be selected according to the decay of the friction coefficient and specific wear rate for the given lubricant, reciprocating velocity, pressure and rod material.

For hybrid, testing is vital to consider the exchange parameter or variables from the virtual side to the physical side and vice versa. The prospective parameters to exchange can be:

- Virtual to Physical side
  - Model-relative position in the reciprocating movement
  - Theoretical estimated pressure in the pump

- Physical to the virtual side
  - Experimental pressure in the pump, see Figure 42
  - Loss of pressure/leakage of seawater
  - Experimental-relative position in the reciprocating movement, see Figure 42

It is vital to establish a metric of comparison between virtual parameters such as pump pressure and relative location in the reciprocating movement.

6.2 Performance/diagnostic related parameters

In the case of rod seals in pumps, there are three groups of relevant variables or parameters for the performance/diagnosis:

- Pump parameters
  - (Desired) Chamber pressure
  - Seal R_o/R_i ratio
  - Rod material and surface finish
- Test conditions
  - Time
  - Velocity in the test
  - Temperature
- Test outcome parameters
  - Sliding distance
  - Friction coefficient,
  - Leakage from pump seals
  - Specific wear rate
  - Measured wear damage (microscopic damage) parameters (post-run diagnostic)

6.3 Reliability and Survivability related parameters

6.3.1 Reliability and Survivability parameters

In the case of rod seals in piston or pumps, there are three groups of relevant variables or parameters:

- Pump parameters
  - Chamber pressure
  - Rod rugosity and material
  - Reciprocating movement – relative position
- Seal parameters
  - Seal base material
  - Seal reinforcement or filler in the main material
  - Seal reinforcement proportions

  - Seal-rod pressure
- Test conditions and outcome parameters
  - Time
  - Velocity in the test
  - Load for wear testing in K
  - Rod-seal compatibility
  - Sliding distance in K
  - Friction coefficient,
  - Specific wear rate (K)
  - Measured wear damage (microscopic damage) parameters

The section on the deterioration of seals in this document mentions the relevant finding in the literature where some of the previous parameters are discussed and mentioned.

6.3.2 Potential application of the reliability and survivability parameters

The previous reliability and survivability parameters can support the creation and application of reliability assessment in User Case #3. These parameters can be used in the following way:

- The decay process of the friction coefficient during the time of reciprocating movement can be helpful to fit a Bayesian non-linear model to the process in which the multi-variate context can be considered, i.e., seal parameters and pump parameters.
- The specific wear rate jointly with the friction coefficient in the time of reciprocating movement can be helpful to correlate the wear condition and leakage problems in the seals.
- The loss of pressure or leakage conditions can be used as failure criteria for reliability and survivability purposes.

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7 Preliminary Test Plan

The main goal of the test program is to devise a test strategy that can be used to validate that the probability of wear failure of the seals and fatigue damage of the pump unit is acceptable. The current draft test plan will be presented in this section for both the full-scale test rig and for the small-scale wear-bar test. Furthermore, the acceptance criteria and the expected operating conditions will be outlined in this section.

7.1 Full-scale test rig

The full-scale test program will be carried in the three phases listed below:

1. *Initial accelerated test:* Accelerated tests of the seals will be performed on the full-scale pump unit with short stroke and high head pressure on the pump unit.
2. *Accelerated short pump test:* Accelerated test of reduced length three-stage telescopic pump to verify the design and the fatigue performance of the telescopic pump and sequence mechanism.
3. *Full-scale hybrid testing of the seals in the telescopic pump unit:* The seals and the pump unit will be subjected to hybrid-testing

The full-scale accelerated test program is used to evaluate the performance of baseline seal designs and to validate the fatigue performance of the pump unit. The hybrid test program will be used to validate the performance of the best performing seal identified in the accelerated test program under more realistic operating conditions. A new test rig has been designed in the VALID project to perform a full-scale hybrid test of the pump unit. Each test phase will be outlined following subsections.

The initial test program is based on the best knowledge at the current stage implies that the matrix is dynamic and will be refined as the test results sharpen our knowledge.

7.1.1 Initial accelerated test of the seals and the pump unit

This section outlines the initial accelerated test of the seals and the pump unit. The initial accelerated test will, furthermore, serve as the initial run-in of the test rig which will be used to verify the performance and setup of the test rig. The EC pump unit design has been updated recently and it has therefore not been subjected to a cyclic fatigue test. It is important to notice that the seals are a subcomponent in the pump unit. This implies that it will not be possible to perform the full-scale hybrid test of the seals if the pump unit fails before the seals. The test parameters of the initial accelerated test and the short pump accelerated test are listed in Table 26. In the initial accelerated test, a pump displacement of the pump is 100 mm combined with a randomized offset. The randomized offset is added to the displacement signal to distribute the stop/reversal/start zone along the pump piston to avoid localized wear. In the short pump stage, the full actuator stroke length of 900 mm will be used to test the short pump. It is suggested to scale the wagon displacement based on the length ration between the full pump and the short pump for a relatively large sea state in order to distribute the start and stop position along the pump.

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Table 26: Full-scale accelerated test - preliminary test matrix.

Test parameters	Initial accelerated test	Accelerated test of short pump
Seal design	Chevron seal	Chevron seal
Seal material	Cotton fabric & NBR rubber	Cotton fabric & NBR rubber
Rod material	Duplex steel	Duplex steel
Surface finish	to be defined	to be defined
Suspended particles	No	No
Fluid medium	Seawater*	Seawater*
Temperature	20°C	20°C
Pump head pressure	65 bar	65 bar
Reciprocating movement	100 mm stroke with randomized offset	900 mm stroke (Sea state scaled)

*Standard artificial seawater according to ASTM D1141-98 (2021)

7.2 Wear-bar test rig

The wear-bar test will be used for evaluating the different sealing configurations listed in Table 27. The test procedure which will be used in the evaluation are listed below

1. Initial test
   - The initial tests are relatively short test runs of all the seal design configurations listed in Table 27.
2. Initial wear inspection
   - Visual inspection of the wear pathologies by optical microscope.
   - Evaluation of the friction force.
   - Selection of the most promising seal configuration based on the visual inspection and the initial test performance.
3. Test to failure criteria
   - The seal configurations that look promising after the initial test be restarted if possible and tested until the leakage exceeds the acceptance criteria. The metallic wear-bar will be refurbished on the surface and fresh seals will be installed if it is not possible to restart the test.

Table 27: Small-scale hybrid wear-bar test - preliminary test matrix.

Test parameters	Baseline (1)	U-ring – Polyurethane (2)	POM (3)	POM/PTFE (4)	As (3)	PEEK-CF-PTFE (6)
Seal design	Chevron seal	U-ring	Depending on the previous outcome	As (3)	As (3)	As (3)
Seal material	Cotton fabric & NBR rubber	Polyurethane	POM	POM/PTFE	PEEK-CF-PTFE	PEEK-CF-PTFE
Rod material	Duplex steel	Duplex steel	Duplex steel	Duplex steel	Duplex steel	Duplex steel
Surface finish	to be defined	to be defined	to be defined	to be defined	to be defined	to be defined
Suspended particles	No	No	No	No	No	No
Fluid medium	Seawater*	Seawater*	Seawater*	Seawater*	Seawater*	Seawater*
Temperature	20°C	20°C	20°C	20°C	20°C	20°C
Load case	to be defined	to be defined	to be defined	to be defined	to be defined	to be defined

*Standard artificial seawater according to ASTM D1141-98

7.3 Evaluation criteria

The Wavepiston system uses seawater as fluid flow medium and minor leakages do not cause environmental issues as mentioned in Section 4.3. Therefore, from a performance perspective, Wavepiston accepts a flow loss of 1% in a pump stroke which is used as seal test failure criterion.

8 Nomenclature

Abbreviations

ALT	Accelerated life testing
ADT	Accelerated deterioration testing
BTA	Carbon Fiber
BEM	Boundary Element Method
CF	Carbon Fiber
DanWEC	Danish Wave Energy Center
DNV	Det Norske Veritas
EC	Energy Collector
ESA	European Space Agency
EU	European Union
FEA	Finite Element Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FEP	Per-fluoro-ethylene propulene copolymer
FLS	Fatigue Limit State
H2020	Horizon 2020
ITTC	International Towing Tank Conference
NBR	Nitrile Butadiene Rubber
OPEX	Operational expenditure
PA	Polyamide
PAI	Polyamide-imide
PEEK	Poly-ether-ether-ketone
PHBA	Poly-phenyl p-hydroxy-benzoate
PI	Poly-imide
PPS	Poly-phenylene sulphide
PTFE	Polytetrafluoroethylene
PLOCAN	Plataforma Oceanica de Canarias
RANS	Reynolds-averaged Navier–Stokes
RCA	Root Cause Analysis
Re	Reynolds number
RPN	Risk Priority Number
R&S	Reliability and survivability
ULS	Ultimate Limit State
W2W	Wave2Wire

WEC	Wave Energy Converter
WP	Work Package

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VALID

Annex A – Search for the literature review and clustering analysis

Literature review for identification of relevant topics in seal deterioration for the case context

In order to identify the prospective deterioration process (before hybrid/accelerated testing) in the specific seals' application of this WEC-component, a search in current literature (white and grey literature) was carried out. The following groups of keywords were identified:

- Group 1, seal and (water/sea water) piston application:
  - TS/TI: "seal", "seals", "rod seals", "rod seal", "pump seal", "pump seals", "pump ring", "pump rings" "piston rings", "piston ring", "piston seal", "piston seals", "o-ring", "o-rings", "o ring", "o rings", "u-ring", "u ring", "v-ring", "v ring", ("seal" AND "rod"), ("seal" AND "piston")
  - AND/TS: seawater, sea water, ("water AND "piston"), ("water" AND "pump"), ("sea water" AND "piston"), ("seawater" AND "piston"), ("sea water" AND "pump"), ("seawater" AND "pump"), ("sea water" AND "seal"), ("seawater" AND "seal"), ("seawater" AND "rod seal"), ("sea water" AND "rod seal"), ("sea water" AND "rod seals"), ("sea water" AND "rod seals")
  - NOT/TS (medical and biology related keywords): "medical", "vascular", "veterinary", "dentistry", "surgery", "medicine", "oral surgery", "teeth", "patient", "injury", "artery", "restoration", "death", "DNA", "female", "male", "child", "species", "fishery", "fish" , "animal", "cell", "tissue", "protein", "infection", "disease", "mouse", "bacteria", "bacterium"
  - NOT/TS (other technical words): "engine", "combustion", ("engine" AND "piston"), "pavement", "asphalt", "soil", "clay", "rotor", "bentonite", "vein", "erosion", "reactor", "nuclear", "cement", "concrete", "resin", ("concrete" AND "porosity"), "basin", "reservoir", "rock", "shale"
- Group 2, degradation process and mechanical use of seals:
  - "degradation", "deterioration", "damage", "grooving", "wear", "extrusion", "fracturing", "hardening", "scarring", "swelling", "tribology", "failure", "reciprocating", "reciprocating movement", "reciprocating motion"

The search of information was performed in the formal largest database of indexed documents (books, journals papers, conferences papers and reports) on the web, web of science. The queries to search relevant work are:

Number	ID	Query	Results
1	Q1	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")))	260

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		AND TS= ("sea water" OR "seawater" OR ("water" AND "piston") OR ("water" AND "pump") OR ("sea water" AND "piston") OR ("seawater" AND "piston") OR ("sea water" AND "pump") OR ("seawater" AND "pump") OR ("sea water" AND "seal") OR ("seawater" AND "seal") OR ("seawater" AND "rod seal") OR ("sea water" AND "rod seal") OR ("sea water" AND "rod seals") OR ("sea water" AND "rod seals")) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR "tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT TS=("basin" OR "reservoir" OR "rock" OR "shale")	
2	Q2	TS=("degradation" OR "deterioration" OR "damage" OR "grooving" OR "wear" OR "extrusion" OR "fracturing" OR "hardening" OR "scarring" OR "swelling" OR "tribology" OR "failure" OR "reciprocating" OR "reciprocating movement" OR "reciprocating motion")	Broad and very general
3	Q1+Q2	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston"))) AND TS= ("sea water" OR "seawater" OR ("water" AND "piston") OR ("water" AND "pump") OR ("sea water" AND "piston") OR ("seawater" AND "piston") OR ("sea water" AND "pump") OR ("seawater" AND "pump") OR ("sea water" AND "seal") OR ("seawater" AND "seal") OR ("seawater" AND "rod seal") OR ("sea water" AND "rod seal") OR ("sea water" AND "rod seals") OR ("sea water" AND "rod seals")) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR "tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT	70

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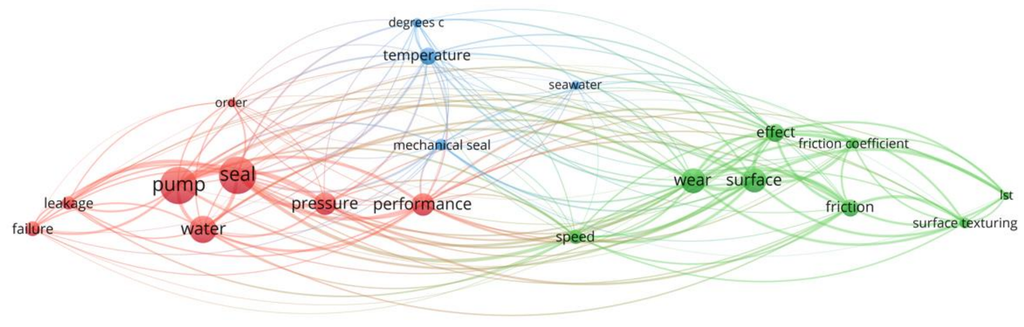
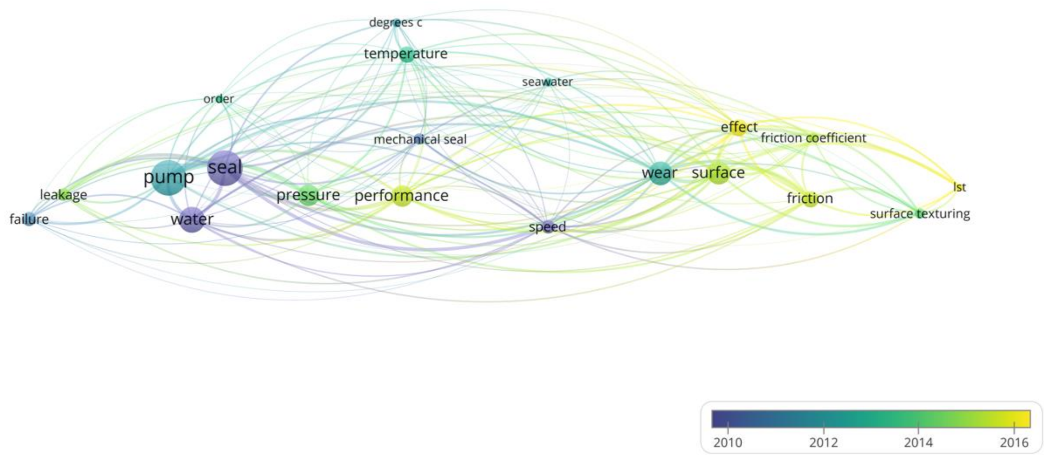
		TS=("basin" OR "reservoir" OR "rock" OR "shale") AND TS=("degradation" OR "deterioration" OR "damage" OR "grooving" OR "wear" OR "extrusion" OR "fracturing" OR "hardening" OR "scarring" OR "swelling" OR "tribology" OR "failure" OR "reciprocating" OR "reciprocating movement" OR "reciprocating motion")	

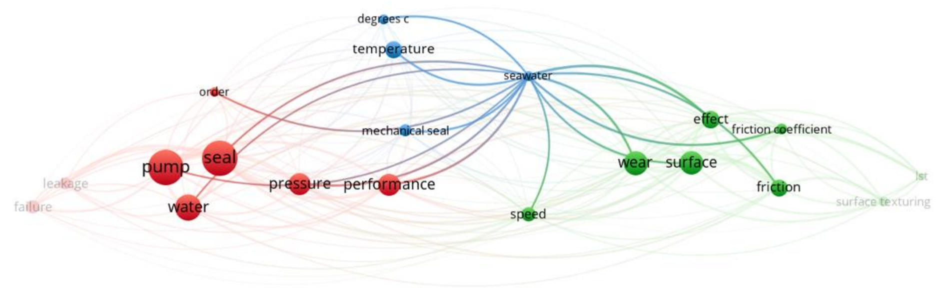
From the table above, it is evident that less than 100 documents are relevant in the topics related to seals and deterioration in the context of this user case #3. When clustering analysis is performed for the combination of query Q1+Q2, the following cluster network image is generated, see figure A.1.a.



(a)



(b)



(c)

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Figure A.1. (a) Clustering analysis of literature for (Q1+Q2). (b) Temporal information of the research-related keywords. (c) Relation of "seawater" with other topics related to seals.

In the cluster network in figure A.1.a, three clusters were found. The red cluster is research work focused on pump and seal related research. The green is focused on the tribology of seals. The blue cluster contains keywords related to sealing conditions such as seawater and temperature. In the temporal analysis of the cluster (see figure #103.b), the latest research is focused on the tribology of seals in pistons or pumps rather than in the other clusters. When one is focused on the keyword "seawater" (see figure #103.c), it links the red and green cluster, showing that there is research in tribology and pump or piston context. The general topics where the found research is located can be summarized in the following figure:

Literature review for hybrid/accelerated testing-related topics

In order to identify a prospective methodology (before hybrid/accelerated testing) and relevant parameters for accelerated/hybrid testing, a search in current literature was carried out. The following groups of keywords were identified:

- Group 3, seal and (water/sea water) piston application:
  - TS/TI: "seal", "seals", "rod seals", "rod seal", "pump seal", "pump seals", "pump ring", "pump rings" "piston rings", "piston ring", "piston seal", "piston seals", "o-ring", "o-rings", "o ring", "o rings", "u-ring", "u ring", "v-ring", "v ring", ("seal" AND "rod"), ("seal" AND "piston")
  - NOT/TS (medical and biology related keywords): "medical", "vascular", "veterinary", "dentistry", "surgery", "medicine", "oral surgery", "teeth", "patient", "injury", "artery", "restoration", "death", "DNA", "female", "male", "child", "species", "fishery", "fish" , "animal", "cell", "tissue", "protein", "infection", "disease", "mouse", "bacteria", "bacterium"
  - NOT/TS (other technical words): "engine", "combustion", ("engine" AND "piston"), "pavement", "asphalt", "soil", "clay", "rotor", "bentonite", "vein", "erosion", "reactor", "nuclear", "cement", "concrete", "resin", ("concrete" AND "porosity"), "basin", "reservoir", "rock", "shale"
- Group 4, Hybrid testing:
  - TS: "hybrid testing", "hybrid simulation", "hardware in the loop", "Hardware-in-the-loop", "hardware-in-loop", "hardware in loop", ("HIL" AND "hardware")
- Group 5, Accelerate testing:
  - "accelerated testing", "accelerate life testing", "accelerate deterioration testing", "accelerate damage testing", ("ADT" AND "accelerate damage testing"), ("ALT" AND "accelerated life testing")

The search of information was performed in the formal largest database of indexed documents (books, journal, conference and reports) on the web, web of science. The queries to search relevant work are:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

Number	ID	Query	Results
4	Q3	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston"))) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR "tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT TS=("basin" OR "reservoir" OR "rock" OR "shale")	25,120
5	Q4	TS=("hybrid testing", "hybrid simulation" OR "hardware in the loop" OR "Hardware-in-the-loop" OR "hardware-in-loop" OR "hardware in loop" OR ("HIL" AND "hardware"))	8,461
6	Q5	TS=("accelerated testing" OR "accelerate life testing" OR "accelerate deterioration testing" OR "accelerate damage testing" OR ("ADT" AND "accelerate damage testing") OR ("ALT" AND "accelerated life testing"))	1,962
7	Q3+Q4	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston"))) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR	2

		"tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT TS=("basin" OR "reservoir" OR "rock" OR "shale") AND TS=("hybrid testing", "hybrid simulation" OR "hardware in the loop" OR "Hardware-in-the-loop" OR "hardware-in-loop" OR "hardware in loop" OR ("HIL" AND "hardware"))	
8	Q3+Q5	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston"))) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR "tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT TS=("basin" OR "reservoir" OR "rock" OR "shale") AND TS=("accelerated testing" OR "accelerate life testing" OR "accelerate deterioration testing" OR "accelerate damage testing" OR ("ADT" AND "accelerate damage testing") OR ("ALT" AND "accelerated life testing"))	18
9	Q4+Q5	TS=("hybrid testing", "hybrid simulation" OR "hardware in the loop" OR "Hardware-in-the-loop" OR "hardware-in-loop" OR "hardware in loop" OR ("HIL" AND "hardware")) AND TS=("accelerated testing" OR "accelerate life testing" OR "accelerate deterioration testing" OR "accelerate damage testing" OR ("ADT" AND "accelerate damage testing") OR ("ALT" AND "accelerated life testing"))	No results

When the global research in accelerated testing (Q5) is analysed through clustering, it is possible to get the following figure:

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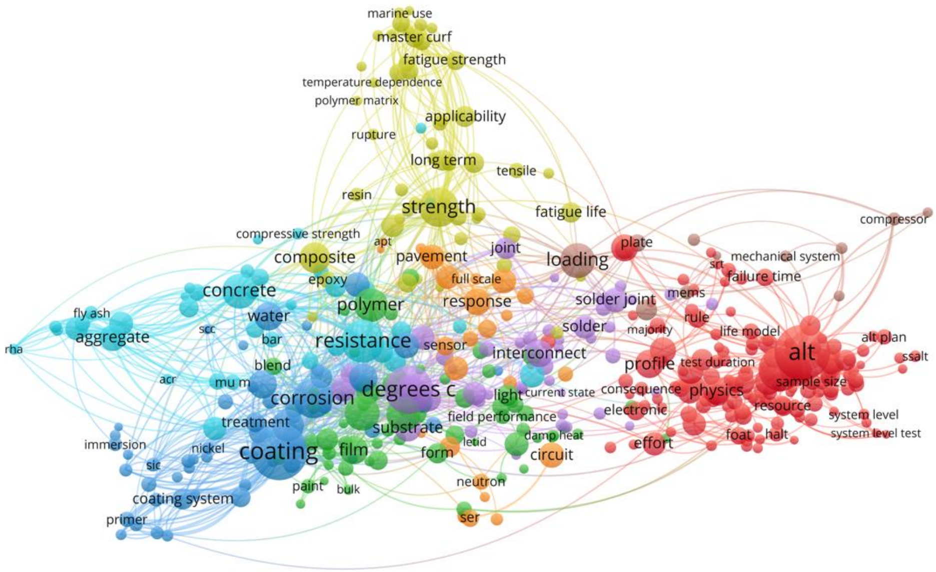

Figure A.2. Clustering network of accelerated testing on the web of science.

Figure A.2 shows that accelerate testing is a research topic in different areas. The red cluster is research work in engineering mechanics, the yellow cluster represents the research in composites, the light blue cluster represent the research in construction and civil engineering, the blue cluster is research in coating and corrosion, the orange cluster contains work in civil engineering pavements, and roads and green cluster is work related to physics. The existing gap between the red cluster and the other cluster could refer to a research gap where engineering mechanics is using particular terms and methodologies not related to other areas.

The fact that there are no research terms in the relation between hybrid testing and accelerated testing indicates that there is no current research going on in that area, being a research gap covered in this project.

Focusing on the current work-related to accelerate/hybrid testing and seals, one could take the work with the strings (Q3+Q4) and (Q3+Q5). There are 20 papers found in the search with the queries (Q3+Q4) and (Q3+Q5), six papers were found relevant. The table below provides the information on the relevant papers.

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Num.	Year	Title
1	2019	C. Zhang, L. Pan, S. Wang, D. Liu, M. Tomovic, and IEEE, "Accelerated Life Test Model by Time-Varying Dependence for Rotary Lip Seals," presented at the 2019 ANNUAL RELIABILITY AND MAINTAINABILITY SYMPOSIUM (RAMS 2019) - R & M IN THE SECOND MACHINE AGE - THE CHALLENGE OF CYBER PHYSICAL SYSTEMS, 2019.
2	2017	X. Lu, X. Chen, Y. Wang, and Y. Tan, "CONSISTENCY ANALYSIS OF DEGRADATION MECHANISM IN STEP-STRESS ACC ELERATED DEGRADATION TESTING," EKSPLOATACJA I NIEZAWODNOSC-MAINTENANCE AND RELIABILITY, vol. 19, no. 2, pp. 302–309, 2017, doi: 10.17531/ein.2017.2.19.
3	2016	L. Farfan-Cabrera, E. Gallardo-Hernandez, J. Pascual-Francisco, C. Resendiz-Calderon, and C. de la Rosa, "Experimental method for wear assessment of sealing elastomers," POLYMER TESTING, vol. 53, pp. 116–121, Aug. 2016, doi: 10.1016/j.polymertesting.2016.04.021.
4	2014	H. Kim, R. Kim, K. Chung, J. An, H. Jeon, and B. Kim, "Effect of test parameters on degradation of polyurethane elastomer for accelerated life testing," POLYMER TESTING, vol. 40, pp. 13–23, Dec. 2014, doi: 10.1016/j.polymertesting.2014.08.004.
6	2012	S. Lee, S. Yoo, D. Kim, B. Kang, and H. Kim, "Accelerated wear test of FKM elastomer for life prediction of seals," POLYMER TESTING, vol. 31, no. 8, pp. 993–1000, Dec. 2012, doi: 10.1016/j.polymertesting.2012.07.017.
7	2010	B. Klein, D. Kirschmann, W. Haas, B. Bertsche, and IEEE, "Accelerated Testing of Shaft Seals as Components with Complex Failure Modes," presented at the ANNUAL RELIABILITY AND MAINTAINABILITY SYMPOSIUM, 2010 PROCEEDINGS, 2010.

Literature review for reliability and survivability topics

In order to identify the relevant parameters that can be used as reliability and survivability estimates in the specific seals' application of this WEC-component, a search in current literature was carried out. The following groups of keywords were identified:

- Group 1, seal and (water/sea water) piston application:
  - TS/TI: "seal", "seals", "rod seals", "rod seal", "pump seal", "pump seals", "pump ring", "pump rings" "piston rings", "piston ring", "piston seal", "piston seals", "o-ring", "o-rings", "o ring", "o rings", "u-ring", "u ring", "v-ring", "v ring", ("seal" AND "rod"), ("seal" AND "piston")
  - AND/TS: seawater, sea water, ("water AND "piston"), ("water" AND "pump"), ("sea water" AND "piston"), ("seawater" AND "piston"), ("sea water" AND "pump"), ("seawater" AND "pump"), ("sea water" AND "seal"), ("seawater" AND "seal"), ("seawater" AND "rod seal"), ("sea water" AND "rod seal"), ("sea water" AND "rod seals"), ("sea water" AND "rod seals")
  - NOT/TS (medical and biology related keywords): "medical", "vascular", "veterinary", "dentistry", "surgery", "medicine", "oral surgery", "teeth", "patient", "injury", "artery", "restoration", "death", "DNA", "female", "male", "child", "species", "fishery", "fish" , "animal", "cell", "tissue", "protein", "infection", "disease", "mouse", "bacteria", "bacterium"
  - NOT/TS (other technical words): "engine", "combustion", ("engine" AND "piston"), "pavement", "asphalt", "soil", "clay", "rotor", "bentonite", "vein", "erosion", "reactor", "nuclear", "cement", "concrete", "resin", ("concrete" AND "porosity"), "basin", "reservoir", "rock", "shale"
- Group 6, Reliability and survivability terms:
  - TS: "reliability", "survivability", "probabilistic"

The search of information was performed in the formal largest database of indexed documents (books, journal, conference and reports) on the web, web of science. The queries to search relevant work are:

Number	ID	Query	Results
10	Q6	TS=("reliability" OR "survivability" OR "probabilistic")	Too broad
11	Q1+Q6	(TS=("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston")) OR TI= ("seal" OR "seals" OR "rod seals" OR "rod seal" OR "pump seal" OR "pump seals" OR "pump ring" OR "pump rings" OR "piston rings" OR "piston ring" OR "piston seal" OR "piston seals" OR "o-ring" OR "o-rings" OR "o ring" OR "o rings" OR "u-ring" OR "u ring" OR "v-ring" OR "v ring" OR ("seal" AND "rod") OR ("seal" AND "piston"))) AND TS= ("sea water" OR "seawater" OR ("water" AND "piston") OR ("water" AND "pump") OR ("sea water" AND "piston") OR ("seawater" AND "piston") OR ("sea water" AND "pump") OR ("seawater" AND "pump") OR ("sea water" AND "seal") OR ("seawater" AND "seal") OR ("seawater" AND "rod seal") OR ("sea water" AND "rod seal") OR ("sea water" AND "rod seals") OR ("sea water" AND "rod seals")) NOT TS=("medical" OR "vascular" OR "veterinary" OR "dentistry" OR "surgery" OR "medicine" OR "oral surgery" OR "teeth" OR "patient" OR "injury" OR "artery" OR "restoration" OR "death" OR "DNA" OR "female" OR "male" OR "child") NOT TS=("engine" OR "combustion" OR ("engine" AND "piston") OR "pavement" OR "asphalt" OR "soil" OR "clay" OR "rotor" OR "bentonite" OR "vein" OR "erosion" OR "reactor" OR "nuclear" OR "cement" OR "concrete" OR "resin" OR ("concrete" AND "porosity")) NOT TS=("species" OR "fishery" OR "fish" OR "animal" OR "cell" OR "tissue" OR "protein" OR "infection" OR "disease" OR "mouse" OR "bacteria" OR "bacterium") NOT TS=("basin" OR "reservoir" OR "rock" OR "shale") AND TS=("survivability" OR "probabilistic" OR ("reliability" AND "probability") OR ("reliability" AND "probabilistic"))	3

After searching the previous strings and looking through different literature from the search, the conclusion is that the term "reliability" is used in the found papers as a synonym of "performance" of the seals, and these papers were not giving a metric, method or parameters for reliability and survivability assessment.