Oyster- Wave Energy Power Plants: A new Challenge for hydraulic Cylinders

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Abstract

A very efficient method to use wave energy in close to shore sea areas is the use of the powerful horizontal movement of the waves. The Oyster wave energy power plant is installed on the sea bed and has a vertical installed flap of 12m x 26m which is driven forwards and backwards by the horizontal wave movement. Two hydraulic cylinders, connected to the tilting flap, pump water based hydraulic fluid via pipelines to an onshore installed Pelton turbine – generator unit with a design capacity of 800 kW.

For the hydraulic cylinders it is a very special challenge to permanently move in an underwater environment by using water based hydraulic fluid. The aspired 25 million cycles between the planned services represent very well the high requirements to the reliability of the whole system. To qualify the cylinder design to these requirements modified seal and bearing elements, the Hunger Ultraplate offshore rod coating and an inner barrel corrosion protection by a stainless steel liner were used. Parallel to the design and production phase a test rig for the seal and bearing elements was build and ran over millions of cycles to test the reliability and lifespan of the seals under simulated operation conditions.

KEYWORDS: hydraulic cylinder, offshore coating, Oyster, regenerative energy, rod coating, water based hydraulic fluid, water seal, wave energy,

1. Oyster – The wave energy power plant

Aquamarine Power is a wave energy company, with head offices in Edinburgh, Scotland and further operations in Ireland and Northern Ireland. The company is currently developing its flagship technology, a hydro-electric wave energy converter known as Oyster. Aquamarine Power's goal is to develop commercial Oyster wave farms around the world and make marine renewable energy mainstream.

The company has successfully deployed a full-scale 315kW near-shore wave energy device prototype (Oyster 1) at the European Marine Energy Centre (EMEC) in August 2009, and this device became the first grid-connected electrical power generation from a near-shore wave energy device in the world, in October 2009. The Oyster 1 prototype had a design life of two years and has been decommissioned in 2011 (**Figure 01)**.

Figure 1: Oyster in operation at EMEC

The principle of Oyster is based on a large bottom hinged buoyant oscillator, which occupies the complete water column from the seabed to the ocean surface (**Figure 02)**. It is typically located in 12 to 20m water depths to interact efficiently with the dominant surge forces encountered in the near-shore environment. The surge forces are moving the oscillator like an inverted pendulum, which can move through the full 180 degrees. The oscillator is connected to hydraulic cylinders converting the movement into high pressure water. The water is pumped to shore through a pipeline where it is converted to electrical power via a hydro-electric plant with a Pelton turbine.

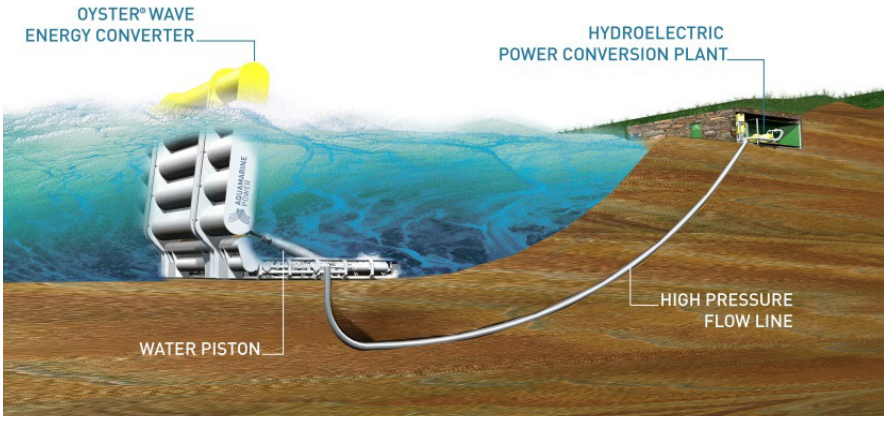

Figure 2: Principle of Oyster

Oyster 1 has successfully operated for about 6000hrs offshore prior to being decommissioned. The performance has been closely monitored and the results from the testing have been used for the design of the next generation commercial scale Oyster 800.

One of the challenges encountered during the operation of Oyster 1 was the reliability of the cylinder seals, which were supplied first by a UK based company. Consequently the design efforts for Oyster 800 have been focused on reliability and ease of maintenance. The design has been modularized and all moving parts have been summarized in two accumulator modules and two cylinder modules. These modules can be exchanged by relatively small vessels, which are available in any harbor around the world. The general Oyster 800 design is shown in **Figure 03**.

Oyster 800 represents a step change in design, size and power output. The oscillator is about 50% wider (26m) in comparison to Oyster 1 but produces about 250% more energy because of the hydrodynamic design optimization. Oyster 800 will form part of an array comprising three wave energy converters, which will be connected to one single onshore hydro-electric plant, improving the overall economics dramatically.

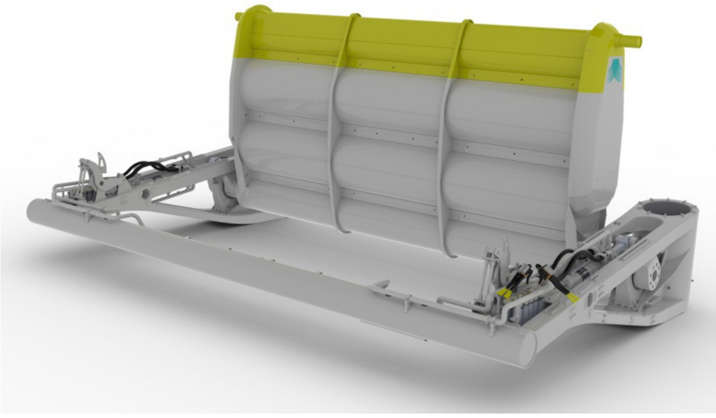

Figure 3: Oyster 800

The testing program for Oyster 800 included next the cylinder seal tests modeling of the installation of the machine in a wave tank facility at Queen's University Belfast. The installation time has been reduced significantly by reducing the number of piles from four to two. The avoidance of any large crane vessels further reduced the cost of the installation. Oyster 800 has been installed on the seabed at EMEC in August 2011. Severe weather conditions offshore have delayed the commissioning of the machine but at the time of writing first power is expected in early 2012. The cylinder modules and the whole wave energy converter have been heavily instrumented to deepen the understanding of the technical challenges and improve reliability for the future designs. **Figure 04** shows one of the cylinder modules already installed in the structure.

Figure 4: The cylinder module within Oyster 800

2. General cylinder design

The hydraulic cylinders had to be designed to move in an underwater environment where a service or even a simple seal change is impossible. During the specified system lifetime of 25 years the cylinders will experience approximately 120 million cycles. But to keep the system performance a five year service period is planned for the final Oyster system which corresponds to 24 million cycles. Therefore the typical wear parts of the cylinder have to be designed to endure this service period. Additionally a service friendly design and the possibility to refurbish main components of the cylinder were requested. **Figure 05** shows the main components of an Oyster 800 cylinder.

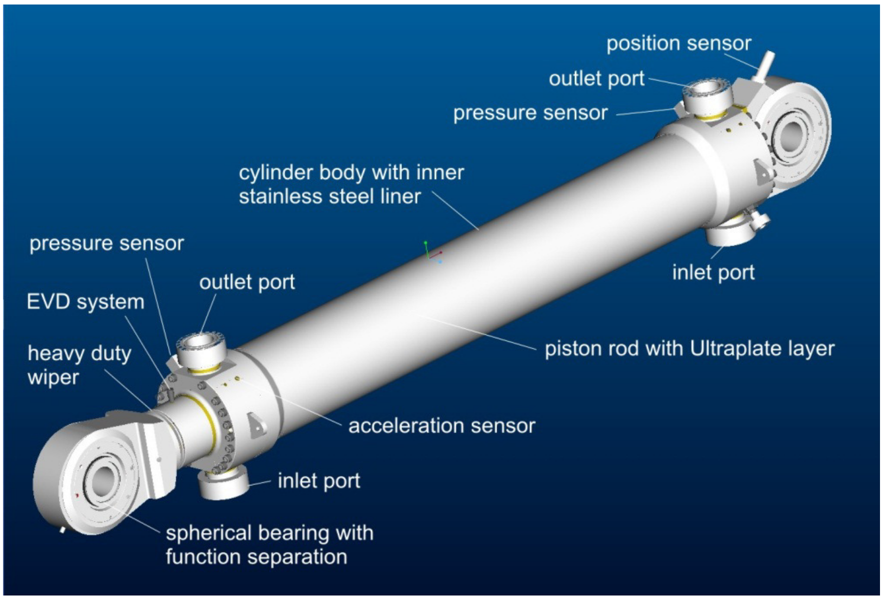

Figure 5: Oyster 800 cylinder - main components

The system pressure under full load condition is specified to 120 bar and for pressure peaks up to 160 bar. This might not be extreme but under consideration of the numbers of cycles the fatigue calculations led to a comparably strong design.

To correspond to the environmentally friendly technology of a wave energy power plant the hydraulic fluid for the hydraulic cylinders and the onshore installed Pelton turbine is specified to be a 95%- water based hydraulic fluid. In addition a partly contamination of the fluid with seawater has to be tolerated by the whole system. This requires a good corrosion protection of all inner cylinder parts. The piston rod is coated with the offshore approved Ultraplate layer and the cylinder bore surface got a stainless steel liner for long-term corrosion and wear protection. Also the seal and bearing elements had to be adjusted to the limited lubrication properties of a water based hydraulic fluid as well as to the expected lifetime. To investigate different promising seal materials and seal designs a scaled test rig was built which could simulate the main factors like water based fluid, system pressure and speed, water environment, sinus shape drive sequence and selected surface material. Also for the spherical bearings for rod end and rear end mounting no comprehensive experiences were available and therefore

new design and function ideas has been realized to correspond to the requirements. While a normal spherical bearing has one bearing surface for all load and movement conditions only the special designed spherical bearing for the Oyster 800 cylinders as shown in **Figure 06** has divided the functionality to three bearing levels. The intention was to improve the load stability and to divide the wear to more than one bearing surface only.

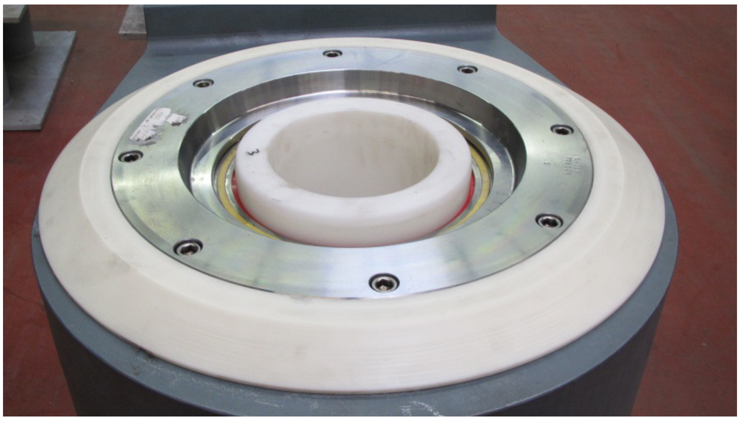

Figure 6: Oyster 800 spherical bearing

Finally different electronic sensors were installed to control main conditions of the cylinder like system pressures, stroke, speed and mechanical accelerations to the cylinder body. All sensors are designed to allow a change under water by a diver carried out service. The performance of all functions was tested during the acceptance test of the cylinders (**Figure 07**).

Figure 7: Oyster 800 cylinders on the hydraulic test rig

2.1. Piston rod coating

The Ultraplate piston rod coating is a plasma transferred arc (PTA) welded overlay on the piston rod providing excellent corrosion and wear properties under offshore conditions. Ultraplate is developed for hard offshore applications as per corrosion categories according to EN ISO 12944.2 like the splash-zone or for submerged conditions /1/. Its capabilities are tested and proven by many applications for more than ten years as well as by the DNV test program according to the "Guideline for qualification of wear and corrosion protective surface materials for piston rods and other components" /2/.

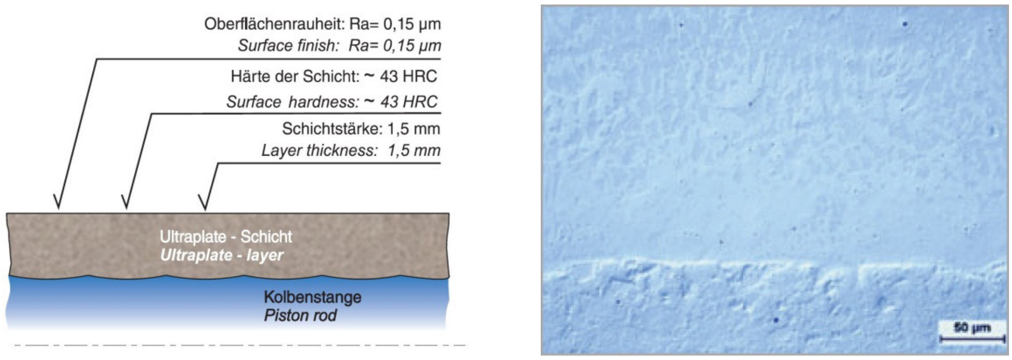

Figure 8: Ultraplate layer and bonding zone under magnification /3/

Figure 08 shows the layer composition and properties of the Ultraplate coating. The layer material is provided to the plasma welding torches in form of a powder and is welded with lowest possible dilution with the substrate material to keep the corrosion properties of the pure layer material. The result is a non-porous layer, highly bonded to the base material and offering unlimited seawater resistance and sufficient wear resistance. The performance of the Ultraplate coating is tested and certified by Det Norske Veritas (DNV) with regards to layer composition, hardness and corrosion resistance according the ASTM G48 pitting corrosion test. These tests are part of the Guideline for the qualification of piston rod coatings for offshore applications. To get additional information about sedimentation, rub off effects or biological growth on the Ultraplate coating in real sea environment the test piece shown in **Figure 09** was positioned in the sea beside an Oyster 1 installation.

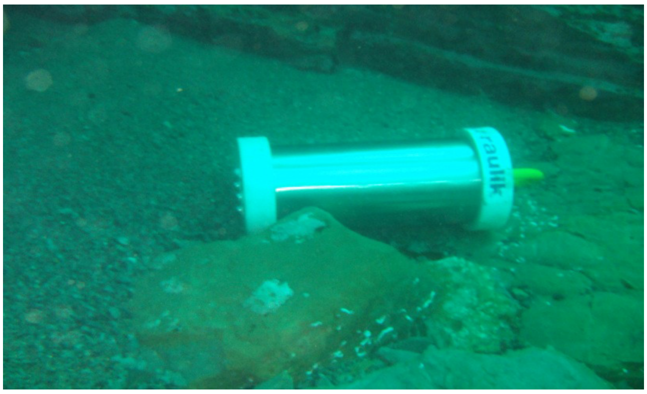

Figure 9: Test piece with Ultraplate layer in the North Sea

2.2. Composite tube with inner stainless steel liner

To protect the bore surface of the cylinder against corrosion a stainless steel liner in form of a thin tube is installed in a carbon steel made cylinder barrel. The stainless steel liner doesn't provide any stability to the cylinder but offers a reliable corrosion protection and good wear resistance. To get a rigid connection between the inner liner and the outer barrel both elements were distorted together on a special tube drawing machine (**Figure 10**).

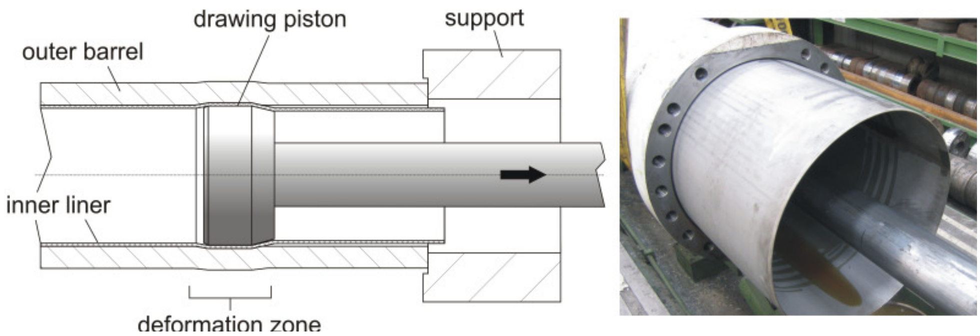

Figure 10: Composite tube technology

By an inner tool in shape of a piston which is drawn through the pre-fitted tubes both were expanded in a way that after releasing the stress behind the piston the two tubes clamp gap free together as a composite tube. After the drawing process the ends of both pieces will be machined and welded together to be sealed. After that the liner bore surface will be honed like a standard tube to the specified surface quality. Beside the very good corrosion properties another advantage of such a composite tube is that it can be removed and changed against a new one under usage of the outer cylinder barrel in case of deeper damages in the liner surface. In case of the Oyster cylinders 590 mm bore cylinder barrels were produced in this way.

2.3. Seal and guiding system

For the seal and guiding system of the Oyster cylinders requirements like long lifetime, good service accessibility, pollution tolerance, possibility of biological growth on the rod surface, reduced lubrication properties of the fluid and chemical compatibility were considered. To achieve this, modified seal and guiding elements from the Hunger DFE program were used and different elements were related to different functions. **Figure 11** shows a rod seal and guiding arrangement of an earlier Oyster cylinder.

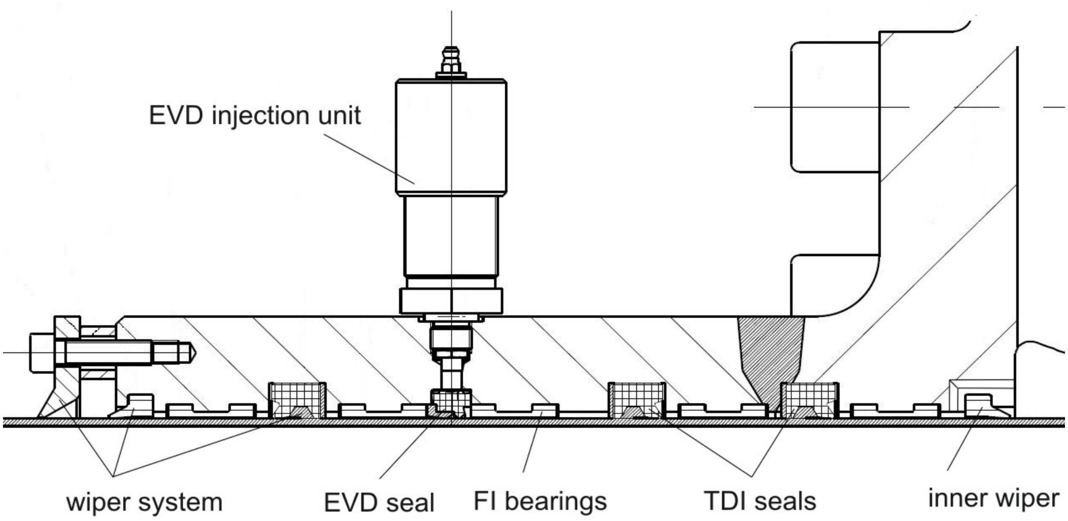

Figure 11: rod seal and guiding arrangement of an Oyster cylinder

Beginning from inside the first element is a wiper to avoid that possible pollution of the fluid could penetrate into the seal and guiding system. To avoid pressure differences over the wiper element small bypass drill holes are foreseen. The piston rod is guided by material modified FI bearing rings. Because of their special step shaped profile these elements offer the advantage of an increased support surface against displacements in moving direction and an increased clearance between the piston rod and the cylinder head steel part. Even under high side load conditions or advanced wear on the guide elements a sufficient clearance to avoid metal to metal contact is guaranteed. The material composition of the FI bearing elements is selected to guarantee emergency running properties even without any fluid.

The sealing system consists of two Hunger TDI type seals. The first seal on the pressure side is specified to be the main seal, followed by an identical further TDI. Whereas the pressurized main seal will show the expected wear behavior, the secondary seal runs non-pressurized with less wear as long as the main seal is full in function. If the main seal is worn out, the secondary seal will still have a remaining wear capacity to seal the cylinder. The intention behind this concept is not to have a 100% sealed system but rather an extended life span. To find the right seal profile and seal material a long-term test run as described in the following article was carried out.

The two TDI seals are followed by an externally adjustable seal system EVD. This kind of an already installed spare seal consists of a seal element which is installed with no pretension to the piston rod and an activation unit. This system offers the opportunity to reseal the cylinder in case of worn out TDI seals. To activate the system a diver has to turn the cap of the injection unit mounted to the cylinder head and pressurize by this the EVD system with a special gel. The seal lip of the EVD seal will be pressed against the piston rod surface and the cylinder is sealed again.

The next three elements, a to the outside directed TDI seal, a AI wiper element and an outer stainless steel scraper share the task to keep out sea water, wipe off smaller pollution from the rod and break away hard stuck pollution.

3. Seal test rig

To test the preselected seal elements before the Oyster system starts to run a scaled test rig was designed and build which can simulate the main operation and environment conditions of the seals. As shown in **Figure 12**, the test rig consist of a speed controlled drive unit with gear box and lever arm which drives a piston rod in a sinus shaped form. This simulates the oscillating rod movement by the Oyster flap. The test rod is guided and sealed in a cylinder tube which is pressurized with the 95% water content fluid by an accumulator unit. The whole cylinder body is submerged in a water basin for cooling purpose and to simulate the environment for the seal elements. With the test rig hydraulic seals can be tested under pressure up to p= 70 bar and with an adjustable cycle frequency of $0{,}5\ Hz < f_T < 0{,}7\ Hz$.

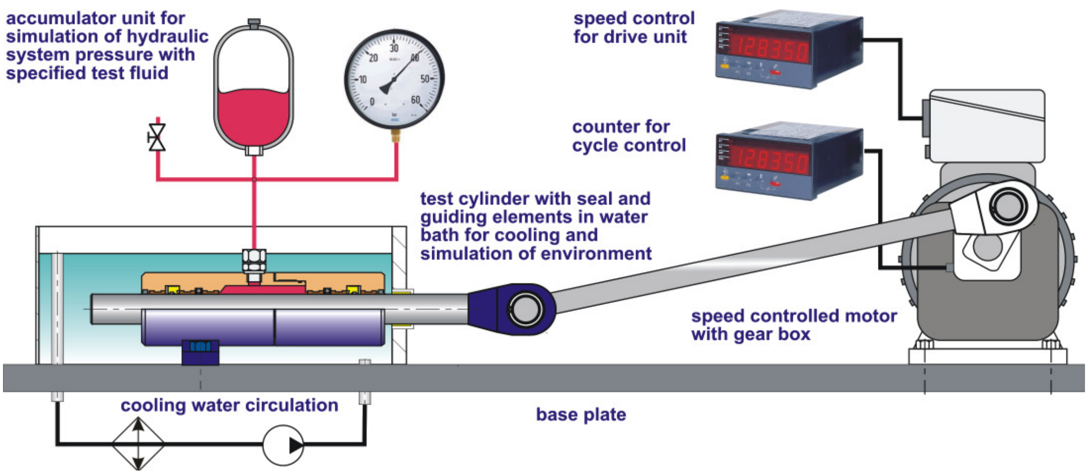

Figure 12: Test rig for seal examinations

With this test rig different seal materials and seal designs were tested over in total five million cycles so far. The test results were directly transferred to the Oyster I, Oyster 800 and Oyster 801 designs.

3.1. Test results

To start the tests a promising seal design and material was selected from the Hunger DFE program (seal design A). These seals were pressurized with the 95/5% water/glycol fluid under p= 50 bar and the test speed was adjusted to v= 0,16 m/min what corresponds to the average real cylinder speed. Already after 30.000 cycles the first test run had to be interrupted because of too high leakage. The examination of the seals showed a totally worn out seal body with additional mechanical damages because of high friction and some bypass stream damages (**Figure 13**).

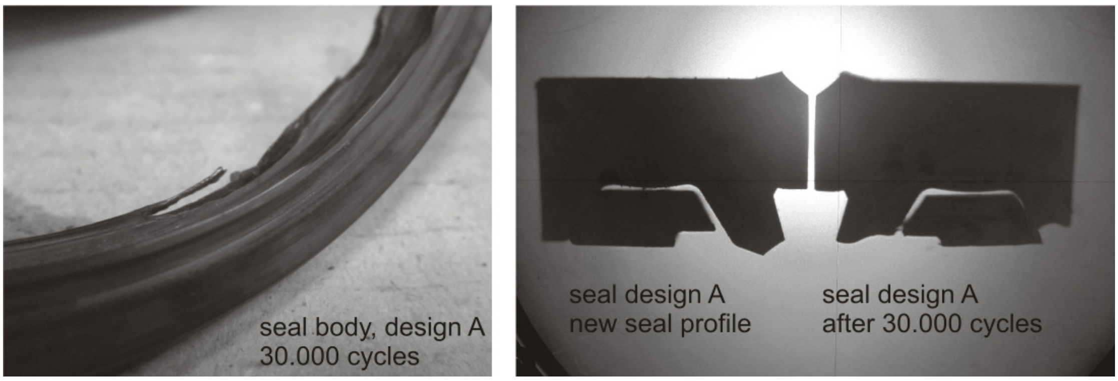

Figure 13: seal design A after 30.000 cycles and new seal profile

After better results with an improved seal design, containing an adjusted profile shape and new material, it was tried to increase the test speed from v= 0,23 m/sec to 0,45 m/sec, what is around three times quicker than in reality, to get faster results. The seal arrangement failed within short time and the examination showed that the seal elements were destroyed by cavitation and blow by effects.

Following these initial disappointments, a new seal design C has been developed, which has proven to run multi-million cycles with acceptable wear and tear. **Figure 14** shows the condition of such a tested seal. In current tests its durability is further tested and will be compared to the real-life results of Oyster 800 in the sea.

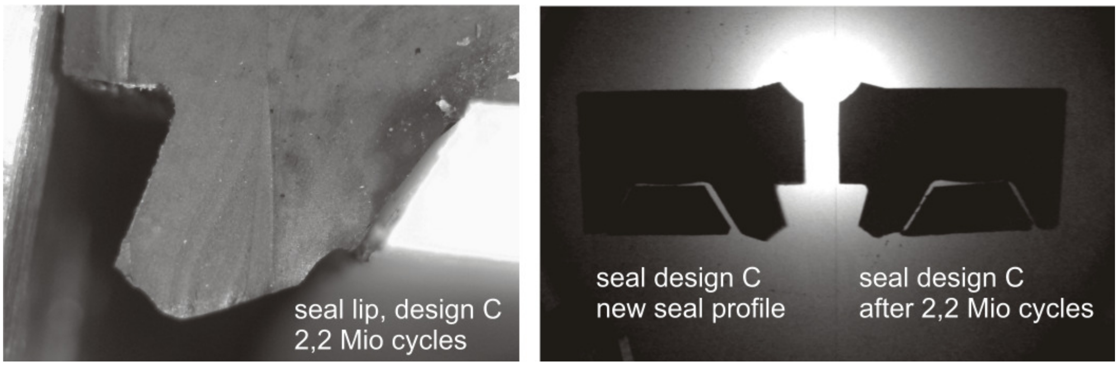

Figure 14: seal design C after 2.2 million cycles

During each test run also the leakage rate was measured as a pre-indicator for wear and tear of the seals. The curve in **Figure 15** shows how the seal leakage has developed over the test run. The general trend to a continuously increased leakage corresponds with the progressive wear on the seal lip. But the leakage rate reached in the test is for the real application of low importance and no failure criteria because it represents less than a ten millionth of the pumped fluid of each cycle only.

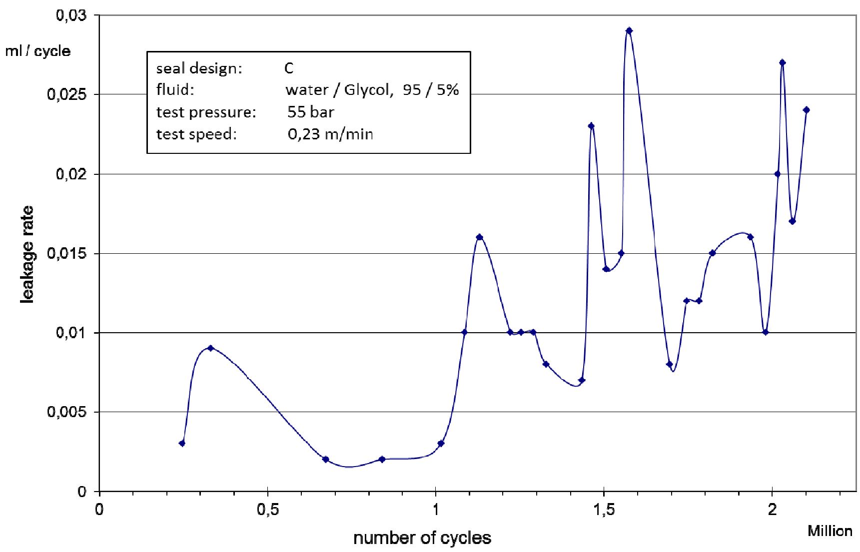

Figure 15: leakage rate per cycle of improved seal design

3.2. Outlook

Parallel to the test period of the Oyster 800 system the engineering of the Oyster 801 is pushed forward. This also includes a new cylinder design which is based on the previous cylinders but in a larger scale and with some detail improvements. Also the seal test rig is continuously running to gain as much as possible data and have a lead over the real system. From the Oyster 801 system two units will be installed to allow parallel feeding of hydraulic energy into one generator unit for the first time. Further systems with the need for special hydraulic cylinders are planned over the coming years. Future developments will involve an increased reliability, longer service life times, a further scaled up size and an operation with pure water, in perspective maybe with seawater in an open circuit.

4. Literature

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/2/ Guideline for qualification of wear and corrosion protective surface materials for piston rods and other components, Report no. 2009-3295, Rev. 0, Det Norske Veritas (DNV) Veritasveien, Norway

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4.1. Symbols

f_T	test frequency	Hz
p	pressure	bar
T	temperature	K
v	speed	m/sec
V_L	leakage rate	ml/cycle