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

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Abstract

Taking advantage of the powerful horizontal movement of ocean waves that are close to shore is one of the most efficient means of harvesting the energy in those waves.

The Oyster wave-energy power plant is designed to do just that. The base was installed on the seabed having a large, bottom hinged, buoyant oscillator measuring 12m x 26m (39ft x 85ft). This oscillator is driven forwards and backwards by the horizontal wave movement. Two hydraulic cylinders, connected to the oscillator, pump water-based hydraulic fluid via pipelines to an onshore installed Pelton turbine–generator unit with a design capacity of 800 kW.

The hydraulic cylinders in this application are submerged in salt water, use water-based hydraulic fluid, and are expected to operate continuously for 25 million cycles between planned servicing. To satisfy these requirements, modified seal and bearing elements, the Hunger Ultraplate offshore rod coating, and a stainless steel liner used for inner barrel corrosion protection were used. During the design and production phase, a test rig for the seal and bearing elements was built, 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 with branch operations in Ireland and Northern Ireland. The company is currently developing its flagship technology, a hydro-electric wave energy converter known as Oyster. The goal of Aquamarine Power is to develop commercial Oyster wave farms around the world and make marine renewable energy mainstream.

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

Figure 01: Oyster 1 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 (40 to 65ft) 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 energy into high pressure water-based hydraulic fluid. The hydraulic fluid is pumped to shore through a pipeline where it is converted to electrical power via a hydro-electric plant with a Pelton turbine.

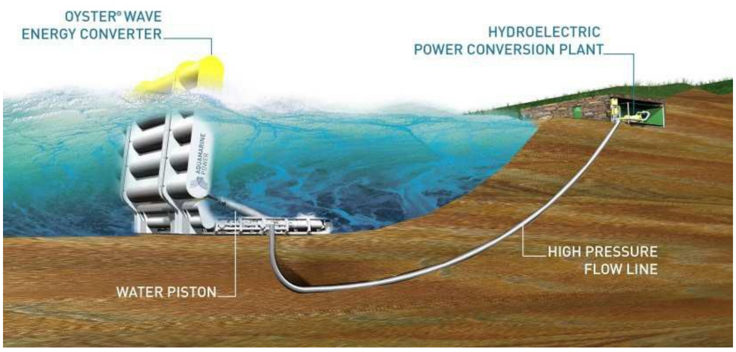

Figure 02: Principle of Oyster

Oyster 1 successfully operated for about 6,000 hours offshore prior to being decommissioned. The performance was closely monitored, and the data collected from the testing were 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. 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 condensed into two accumulator modules and two cylinder modules. These modules can be exchanged using relatively small vessels that are usually 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 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.

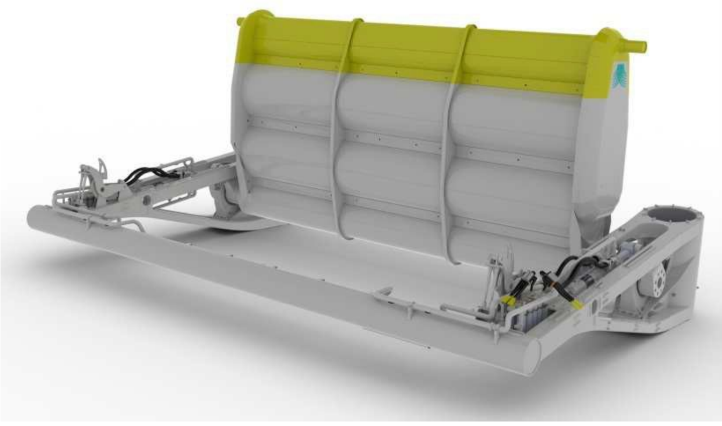

Figure 03: Oyster 800

Modeling of the installation of the machine in a wave tank facility at Queen’s University, Belfast enabled the testing of the cylinder seals for Oyster 800. The installation time has been reduced significantly by reducing the number of stationary piles from four to two. The avoidance of any large crane vessels further reduced the cost of the installation. 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 04: 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 must be designed to endure this service period. Additionally, a service friendly design with the possibility to refurbish main components of the cylinder were requested. **Figure 05** shows the main components of an Oyster 800 cylinder.

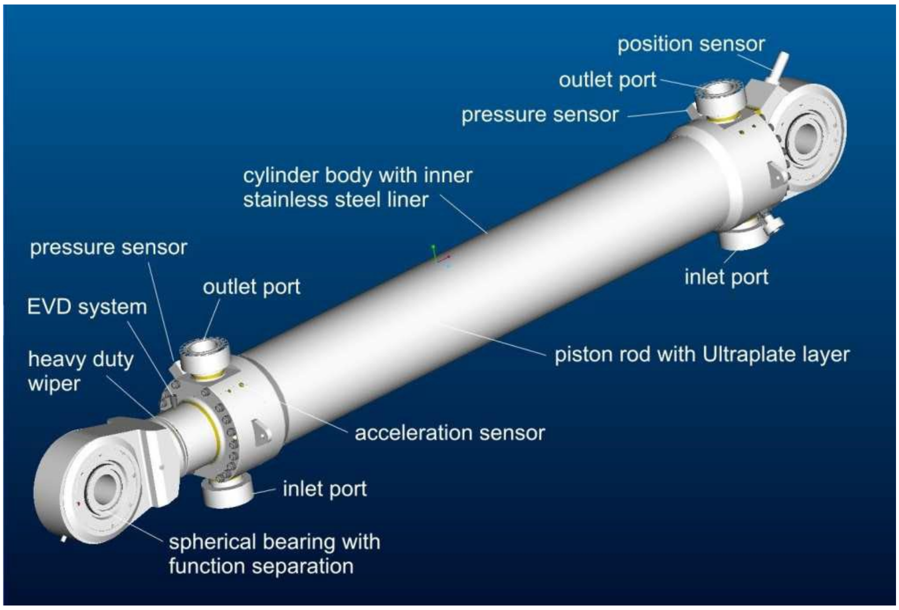

Figure 05: Oyster 800 cylinder - main components

The system pressure under full load condition is specified to 12 MPa (1,750 psi) and for pressure peaks up to 16 MPa (2,300 psi). This might not seem extreme but, considering the number of cycles, the fatigue calculations led to a comparatively robust 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, some contamination of the fluid with seawater must 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 has 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 data were available and therefore new design and function concepts were developed to meet the requirements. While a normal spherical bearing has one bearing surface for all load and movement conditions, the specially designed spherical bearing for the Oyster 800 cylinders, as shown in **Figure 06,** has divided the functionality to three bearing levels. This was done to improve the load stability and to distribute the wear over more than one surface.

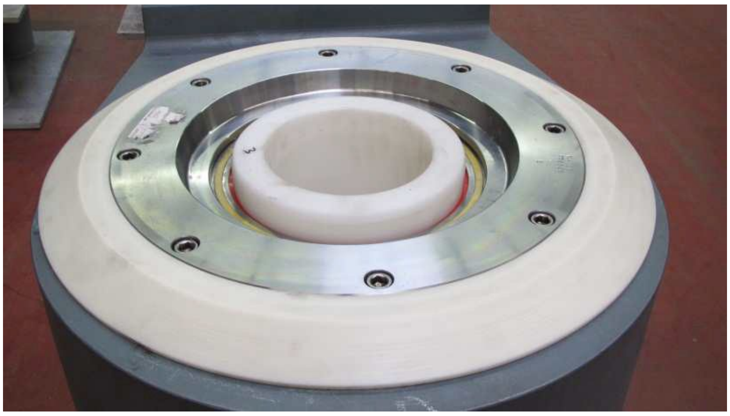

Figure 06: Oyster 800 spherical bearing

Finally different electronic sensors were installed to monitor and control the main cylinder conditions like system pressure, stroke, speed, and mechanical accelerations of the cylinder body. All sensors are designed to allow a diver to service and change under water.

The performance of all functions was tested during the acceptance test of the cylinders (**Figure 07**).

Figure 07: 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 was developed for hard offshore applications in accord with EN ISO 12944.2 for corrosion categories like the splash-zone or submerged conditions /1/.

Its capabilities have been tested and proven in 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/.

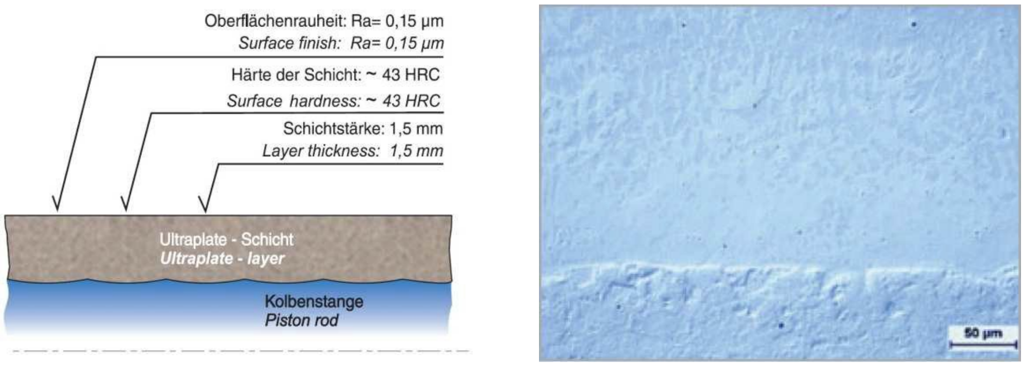

Figure 08: Ultraplate layer and bonding zone under magnification /3/

Figure 08 shows the layer composition and properties of the Ultraplate coating. The layer material is added 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 09: 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 the form of a thin tube is installed in a cylinder barrel made of carbon steel. 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**).

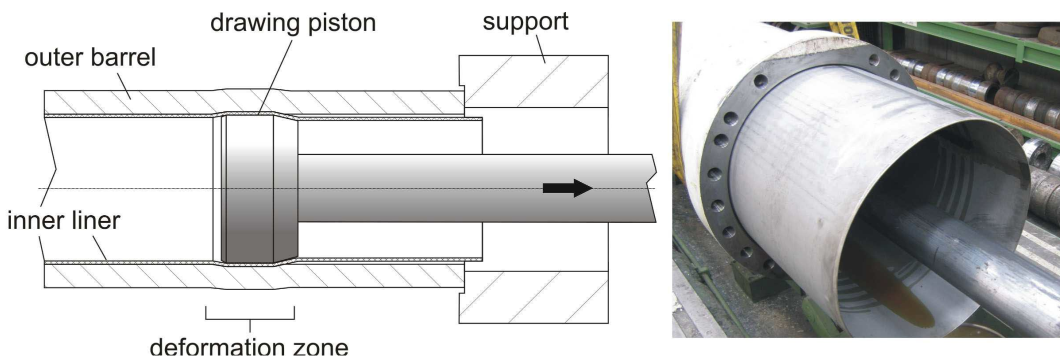

Figure 10: Composite tube technology

A piston shaped tool is drawn through the pre-fitted tubes where 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 are machined and welded together, sealing them completely . After that, the liner bore surface is honed like a standard tube to the specified surface quality. Besides the very good corrosion properties, another advantage of such a composite tube is that a damaged inner lining can be removed and changed instead of having to replace the entire cylinder barrel. The 590mm (23.2in) bore Oyster cylinder barrels were produced in this way.

2.3. Seal and guiding system

For the seal and guiding system of the Oyster cylinders, the requirements of long life, good service accessibility, pollution tolerance, biological growth on the rod surface, reduced lubrication properties of the fluid, and chemical compatibility had to be met. To achieve this, modified seal and guiding elements from the Hunger DFE program were used with different elements used for different functions. **Figure 11** shows an example of a rod seal and guiding arrangement of an Oyster cylinder.

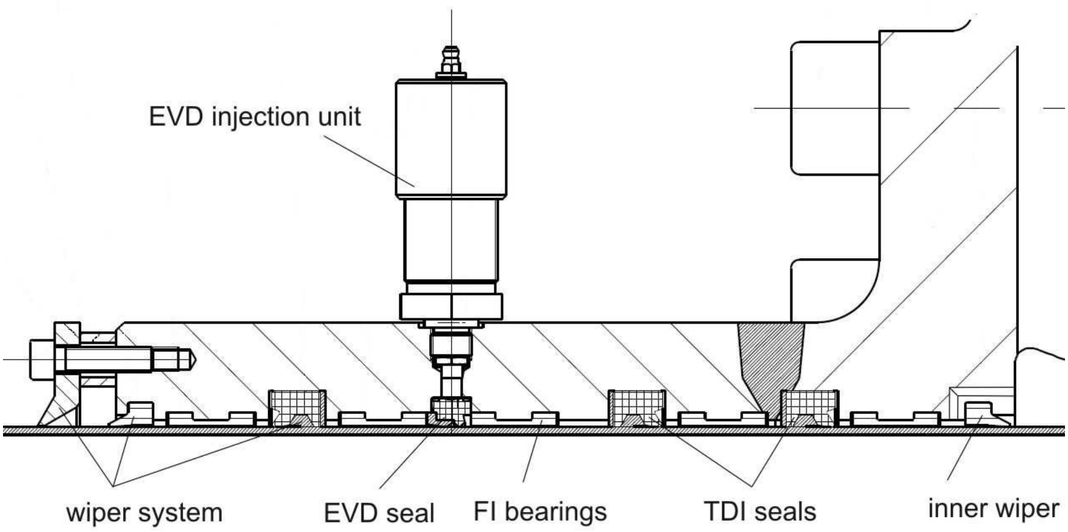

Figure 11: rod seal and guiding arrangement of an Oyster cylinder

Beginning from inside, the first element is a wiper to minimize the ingression of pollutants into the seal and guidance system. To avoid pressure differences over the wiper element, small bypass drill holes (not shown) may be used. The piston rod is guided by material modified FI bearing rings. Because of their special step shaped profile, these bearings offer the advantage of an increased support for the moving surfaces, 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. 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 fully functioning. 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 seal consists of a seal element with an activation unit and is installed with no pressure against the piston rod. This enables the cylinder to be resealed if both TDI seals become worn out. To activate the system, a diver would be needed to turn the cap of the injection unit mounted to the cylinder head. This pressurizes 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, an outside directed TDI seal, an 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 built which can simulate the main operation and environment conditions of the seals. As shown in **Figure 12**, the test rig consists 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 purposes and to simulate the environment for the seal elements. With this test rig, hydraulic seals can be tested under pressure up to 7 MPa (1,000 psi) and with an adjustable cycle frequency from 0,5 Hz to 0,7 Hz.

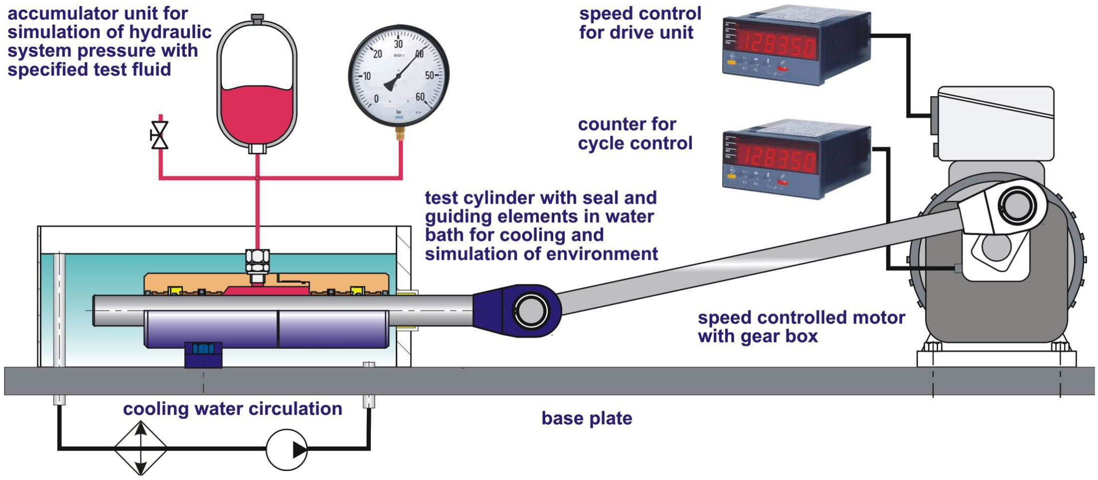

Figure 12: Test rig for seal examinations

With this test rig different seal materials and seal designs were tested for over five million cycles. 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 5 MPa (725 psi) and the test speed was adjusted to 0,16 m/sec (0.5 ft/sec) which corresponds to the average real cylinder speed. After 30,000 cycles, the first test run had to be interrupted because of too high leakage. 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**).

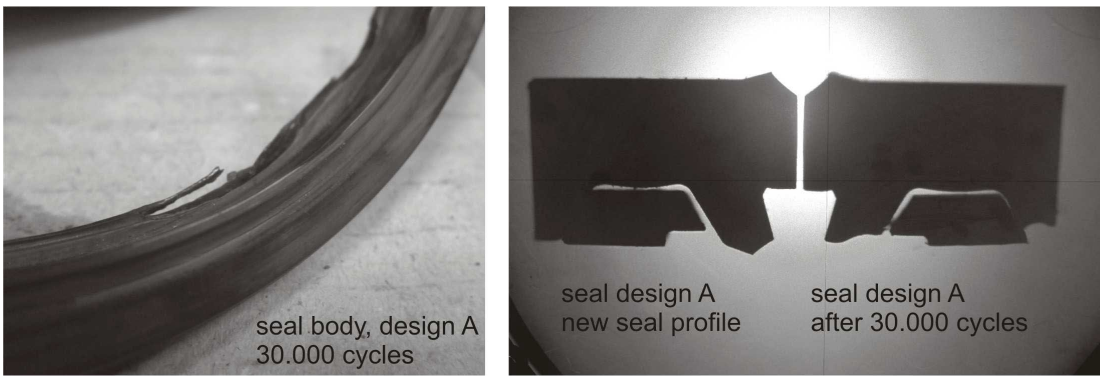

Figure 13: seal design A after 30,000 cycles and new seal profile

Better results were found with an improved seal design. It had an adjusted profile shape and new material. To get faster results, the test speed was increased from 0,23 to 0,45 m/sec (0.75 to 1.48 ft/sec), which is around three times the average velocity, The seal arrangement failed within a 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 was developed, which was able to run multi-million cycles with acceptable wear. **Figure 14** shows the condition of this seal after testing.

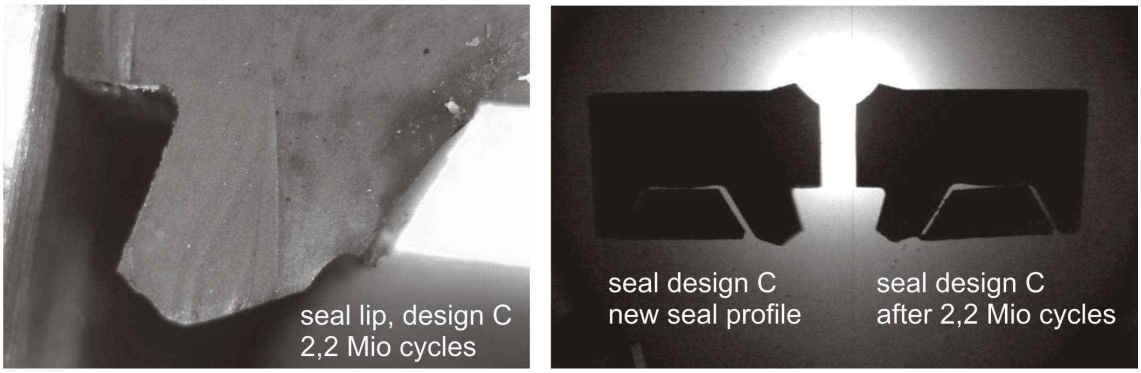

Figure 14: seal design C after 2.2 million cycles

During each test run, the leakage rate was measured as a pre-indicator for wear of the seals. The curve in **Figure 15** shows how the seal leakage developed over the test run. The leakage rate revealed in the test does show a predictable increase as the seal began to wear, but the actual leakage rate is only one ten millionth of the pumped fluid in each cycle and is therefore insignificant.

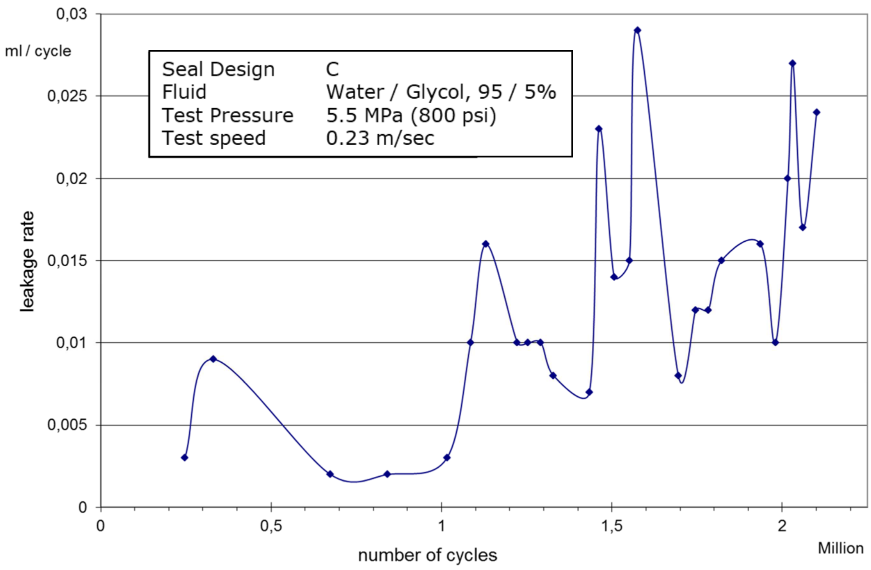

Figure 15: leakage rate per cycle of improved seal design

1.1. 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 on a larger scale and with some detail improvements. Also, the seal test rig is continuously running to gain as much data as possible. 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, a further scaled up size and an operation with pure water, or even seawater in an open circuit.

2. Literature

/1/ Kolbenstangenbeschichtungen für maritimen Einsatz, Dr.-Ing. MBA Ingo Rühlicke, Tagungsband Oberflächentagung Bremen 2009, Germany

/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

/3/ Ultraplate Reference List 2011, Walter Hunger GmbH & Co. KG - Hydraulikzylinderwerk, Lohr am Main, Germany, www.hunger-hydraulik.de

4.1. Symbols

f_T	test frequency	Hz
p	pressure	MPa (psi)
T	temperature	K
v	speed	m/sec (ft/sec)