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2 **1 Modernized cathodic protection system for legs of the production rig –**
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4 **2**
5 **3 evaluation during ten years of service.**

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32 **14 ABSTRACT**

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35 15 The modernization of cathodic protection system of the Baltic Beta platform legs is described.
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37 16 It was that the sacrificial anodes cone-shaped groups were to be placed on the seabed at a
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40 17 depth of 80 meters. The measurements results of cathodic protection effectiveness during its
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42 18 ten-years operation are presented. The effectiveness was assessed based on the potential value
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44 19 along the entire length of the legs from the sea surface to the seabed. The gained experience
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46
47 20 indicates that use of sacrificial anode systems mounted on the seabed can be an effective form
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49 21 of cathodic protection of offshore platforms legs. It is basically the only means of
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52 22 anticorrosion protection in case of a platform not able to leave its location for renovation
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54 23 works in a shipyard.

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59 25 **Keywords:**
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26 Gas and oil production rig

27 Sea platform

28 Corrosion

29 Cathodic protection

30 Sacrificial anode

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32 **1. Introduction**

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34 Gas and oil production rigs require effective and reliable corrosion protection, without
35 which the material degradation may lead to breakdowns or even disasters (Kiran, 2017;
36 Esaklul and Ahmed, 2009; Melchers, 2005; Wu, 2018). Such protection is achieved through
37 the combined use of protective coatings and cathodic protection. These technologies
38 complement each other: the better the barrier properties of coatings, the lower the demand for
39 cathodic protection current. The use of coatings drastically reduces the cathodic protection
40 current demand of the protection object and hence, the required sacrificial anode weight.

41 Cathodic protection of marine structures can be implemented using systems based on
42 sacrificial anodes (Szabo and Bakos, 2006a), systems with an external power source –
43 impressed current cathodic protection (Szabo and Bakos, 2006b) or by means of hybrid
44 systems combining the two technologies (Larsen, 2019; Hajigholami et al., 2017). Sacrificial
45 anodes designed to work in seawater environment are made of zinc- or aluminum-based
46 alloys. In the classic cathodic protection solutions, cores of anodes are welded to a protected
47 structure, and anodes are arranged so as to provide the protective potential on the entire
48 protected surface (Hartt et al., 2005; Lemieux and Hartt, 2006).

49 Cathodic protection of marine structures is a complex issue. There are no universal
50 solutions for protection systems of this kind. Each structure requires development of an

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individual concept for protection implementation. To design a protective installation properly, it is necessary to recognize the corrosion hazards in the facility and estimate the demand for protective current, which is related to the preservation of protective properties of the coatings, seawater temperature (Hong et al., 2018), its oxygenation and salinity (Zakowski and Narozny, 2014), depth, colonization of the constructions by marine organisms (Jeffrey and Melchers, 2003; Liu and Cheng, 2017) and precipitation of calcareous deposits (Zamanzade, 2007; Zakowski, 2013).

During the retrofit of cathodic protection system of the Baltic Beta rig legs, an concept for application of sacrificial anode groups placed on the seabed has been developed (Zakowski, 2011). It was basically the only means of protection in case of a platform not able to leave its location for renovation works in a shipyard. Such solutions have already been used, but in shallow seas (Hartt, 2012; Yin et al., 2019; Rossi, 1998). Meanwhile, the depth of the sea at the workplace of the Baltic Beta rig is about 80 meters.

This publication discusses the main operating experience of the platform's cathodic protection system obtained during its ten-year operation.

1.1 Characteristics of the Baltic Beta production rig

The Dyvi Beta rig (nowadays known as the Baltic Beta) was built for the Norwegian company K / S DYVI DRILLING by the French company Compagnie Francaise d'Entreprises Metalliques (CFEM) at the Dunkirk shipyard in 1975–77 under the ETA Houston Texas license. In the first period of its operation, it was used for development of the Norwegian oil field EKOFISK. Later, it was bought by the Norwegian company Smedvig and used for various purposes, such as construction of a port structure in the area of the Adriatic Sea. In 1994, it was purchased by the Polish company Petrobaltic. Before starting its journey to the

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76 Baltic Sea, the WEST BETA rig was put on a dry dock, where renovation was carried out
77 focusing mainly on the legs structure. Having moved the platform from the Mediterranean,
78 the Baltic Beta began working on the development of the Polish B3 oil field in the Baltic Sea.
79 Since 1995, the Baltic Beta continuously works on the same location. The depth of the Baltic
80 Sea in the area of the foundation of the oil producing rig is about 80 m.

81 The Baltic Beta rig extracts from beneath the bottom of the Baltic Sea oil, natural gas
82 and associated formation water. At first all three fluids are separated from each other, and
83 each one has its own destiny in a separate technological process. The system responsible for
84 this operations is called GEOSERVICE.

85 Oil is pumped true a underwater pipe line to a storech tanker ship moored near the rig.
86 Once the tanker has reached its capacity, it is sent onshore for discharge or a ship to ship
87 transfer operation is carried out, which allows for a constant production of oil.

88 Formation water is specially prepared, it is deoxygenated, cleared from oil, special
89 chemical are added to kill any bacteria that can contaminate the oil reservoir. All of the
90 produced formation water is pumped back to the oil reservoir by a set of electrically driven
91 plunger pumps by a system called OIL PLUS.

92 The block diagram of the gas processing systems on board Baltic Beta is shown in Fig.
93 1. The natural gas separated from the crude oil is used on board Baltic Beta in three basic
94 processes. The first and most important is the electrical energy production process which
95 powers the rig itself. This is achieved by a gas turbine driving an electrical generator which
96 covers all of the rig power demand. This system is shown in Fig. 2 with field number five-
97 B2G8. The second process is related with the injection of sea water. In this process a second
98 gas turbine is used to drive a centrifugal pump, which injects specially prepared sea water to
99 the oil reservoir in order to sustain the oil pressure at a constant level, this system is called
100 BHPS. The third process uses all of the gas which was not used in the first two processes

101 mentioned above. This remaining gas is dried, filtered and compressed in a four stage
 102 electrically driven piston gas compressor. All component of this system are located on the
 103 stern of Baltic Beta and are shown in Fig. 2 with field number one- SSG.

105 **Tab. 1.** Gas characteristics separated on Baltic Beta.

Components	Unit	Parameters values		
		Min. Value	Max. Value	Average Value
Gas density (at 0 ° C)	kg/m ³	0,904	1,14	1,015
Gas chemical composition:				
CH ₄	% volume	43,4	51,48	46,6
C ₂ H ₆	% volume	22,92	30,26	26,37
C ₃ H ₈	% volume	13,25	18,99	16,2
i-C ₄ H ₁₀	% volume	0,76	1,43	1,06
n-C ₄ H ₁₀	% volume	1,27	4,42	2,91
neo-C ₅ H ₁₂	% volume	traces	0,026	0,002
i-C ₅ H ₁₂	% volume	0,16	2,28	0,48
n-C ₅ H ₁₂	% volume	0,17	1,27	0,48
C ₆ H ₁₂	% volume	0,02	0,73	0,18
C ₇ H ₁₆	% volume	traces	0,251	0,058
ΣC ₅ +	% volume	0,364	3,046	1,196
N ₂	% volume	3,27	7,18	5,45
CO ₂	% volume	0,03	0,52	0,19
He	% volume	traces	0,05	0,031
H ₂	% volume	traces	0,002	traces
Gas calorific value	MJ/m ³	51,26	56,99	54,63

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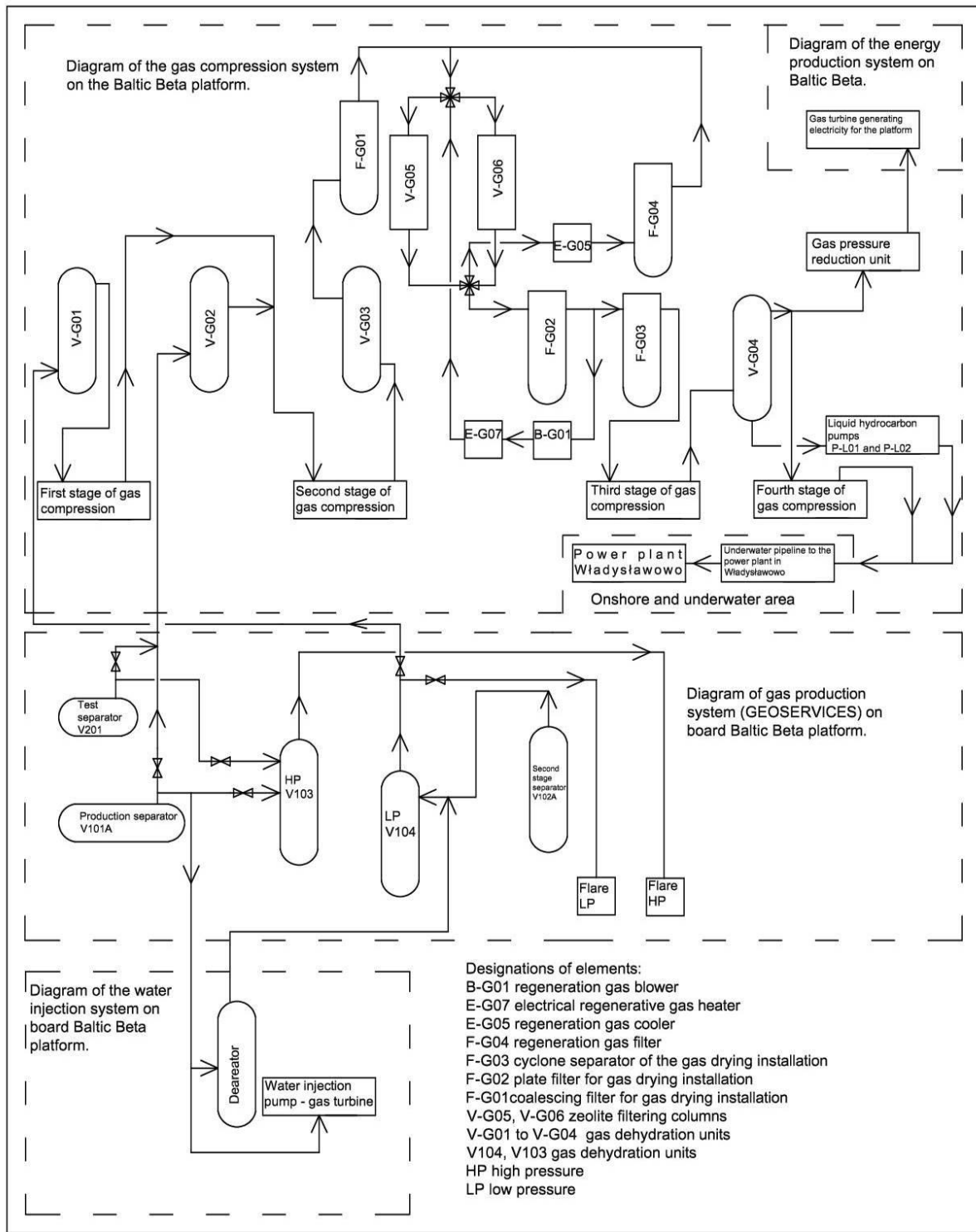


Fig. 1. Block diagram of the gas processing systems on board Baltic Beta.

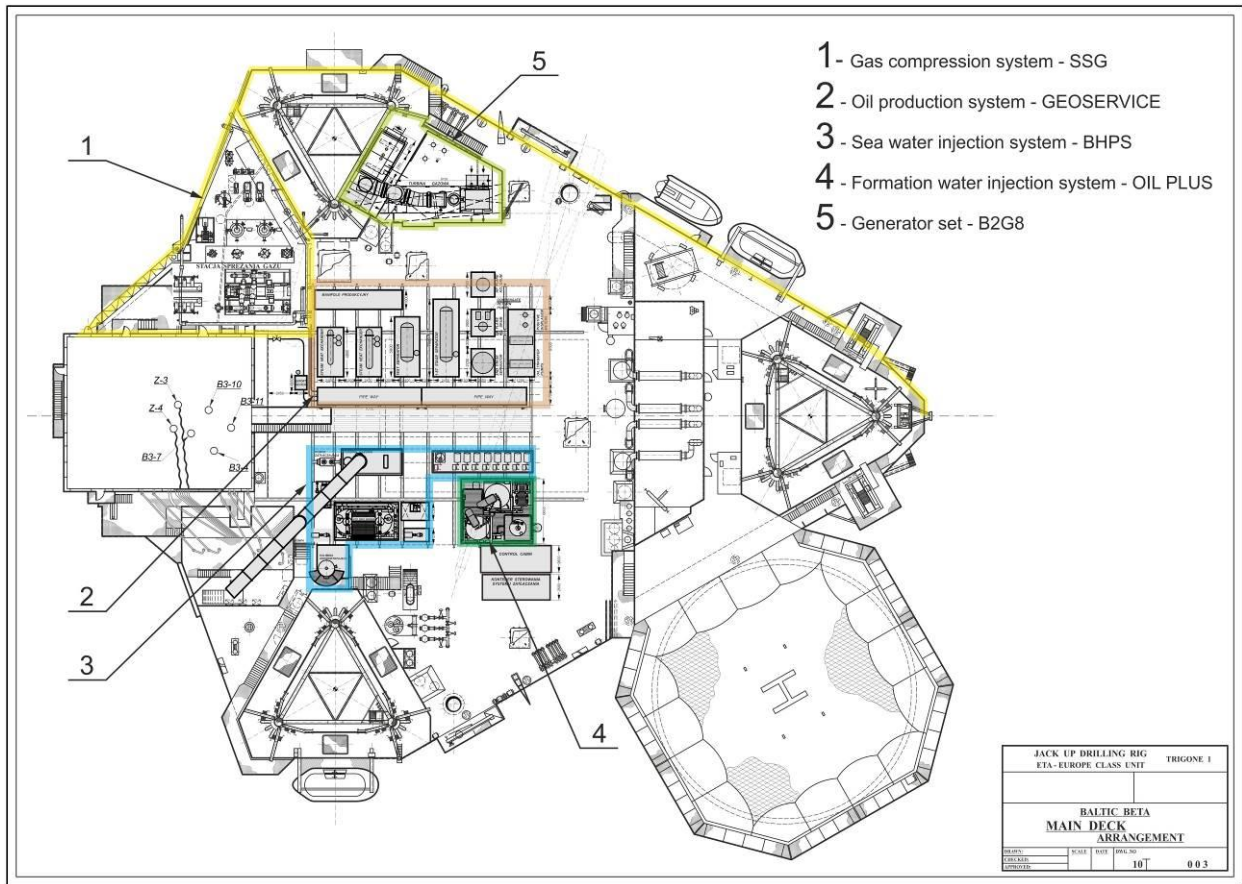
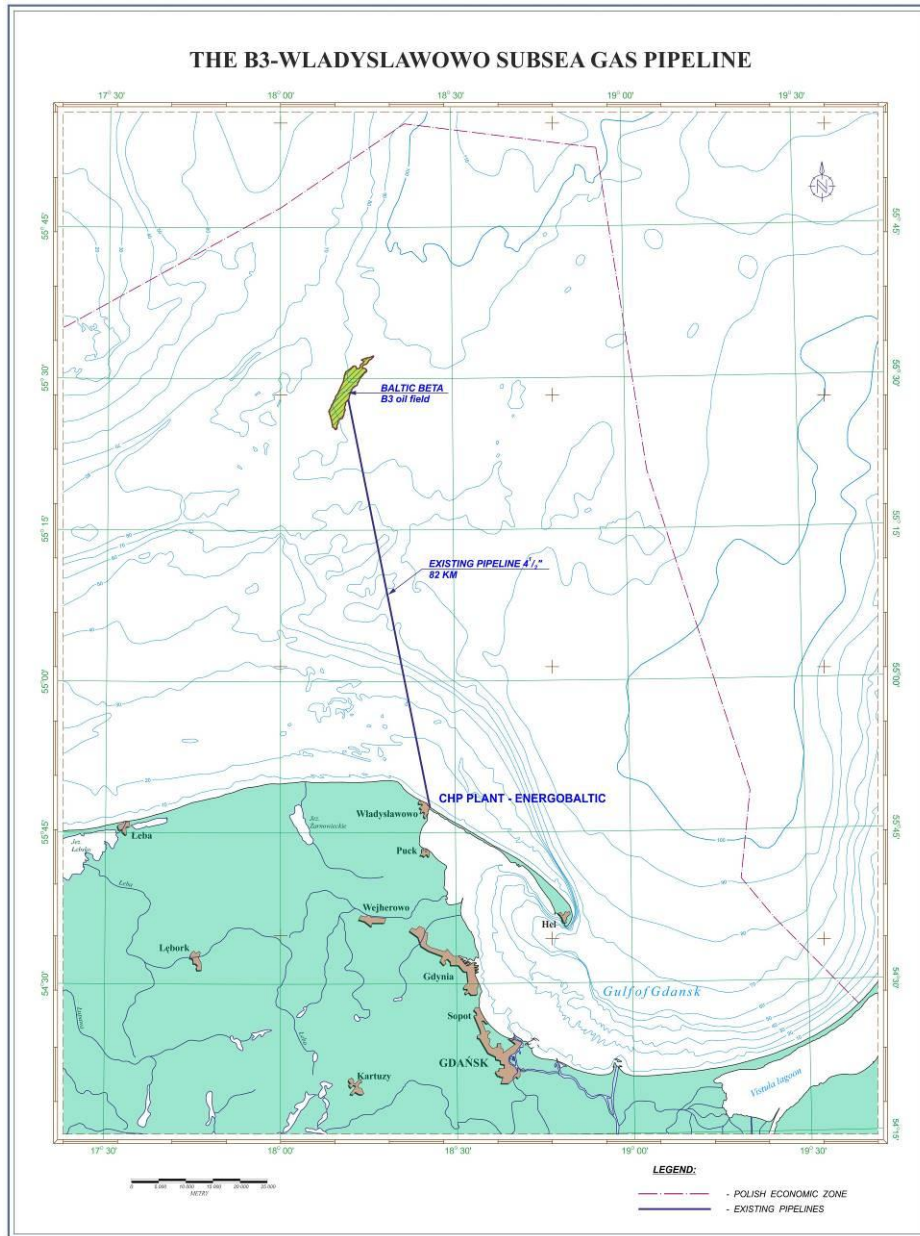


Fig. 2. Main deck arrangement of Baltic Beta with the indication of all five main systems.

After the process of drying and compressing, the so called dense phase gas, which is a suspension of hydrocarbons in dry gas, is transferred by the underwater pipeline to the gas separation station in the heat power plant in Wladyslawowo (Map. 1). The gas pipeline is 82.5 km long and its diameter is 115 mm (4 ½ "). The pressure of the gas transferred by it reaches 13 MPa.



Map. 1. Map indicating the route of the gas pipeline on the seabed from the platform to the CHP plant onshore.

The production process in the heat power plant is divided into two stages. At the first stage, the heavy hydrocarbons fractions are separated from the gas supplied from the rig, in result of which the liquid propane – butane gas (LPG), natural gas condensate (KGN) and dry gas are obtained. At the second stage the dry gas is used for the production of heat and electrical energy.

125 The work of an oil and gas production rig is continuous by nature, which means that
126 the platform cannot leave the position where it had been originally founded. During
127 exploitation of the reservoir, the platform remains connected to underwater production and
128 water injection wells. In connection to the above, the renovated in the early nineties system of
129 sacrificial anodes welded to the legs and renewal of the rig legs paint coating were the only
130 applied means of the protection of the legs against corrosion.

131 To sum up, in 2019 the Baltic Beta platform will have ended 42 years of active
132 operation, 25 of which are continuous work on the Baltic B3 gas and oil field.

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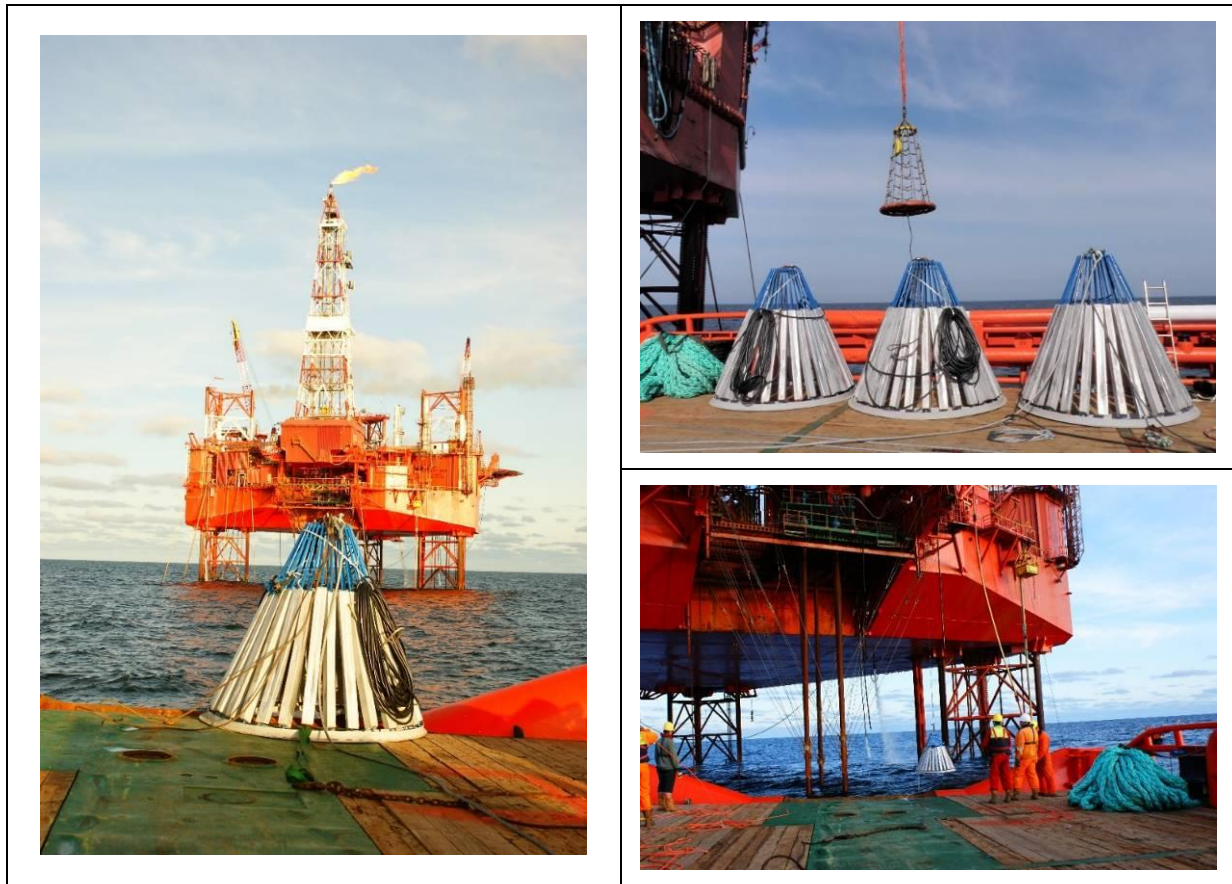
134 1.2 *Modernization of the cathodic protection system*

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136 In 2008 there began work on a modernization project for the cathodic protection of the
137 legs. According to the standard DNVGL-RP-B401:2017 "Cathodic protection design",
138 cathodic protection current density for bare steel in seawater is a function of depth and
139 climatic region (based on surface water temperature). The platform works in a temperate
140 climatic region (water temperature 7-12 °C). Recommended in the standard DNVGL-RP-
141 B401 design current densities needed for the protection of bare steel are 100 mA/m² in depth
142 0-30 meters, and 80 mA/m² in depth 30-100 meters. Cathodic protection current demand is
143 lower when the structure is paint coated, therefore the design calculations of the current
144 densities take into account the thickness and age (wear) of the paint coating. This describes
145 the coating breakdown factor. The design current density is calculated by multiplying the
146 current density for bare steel by this factor. If the factor is equal to zero, then coating is
147 considered to provide full insulation, and if factor is equal to 1, coating has no protective
148 properties and the design current density is the same as for bare steel.

149 The submerged surface area of each of the three legs of the Baltic Beta platform that
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2 150 requires protection is approximately 1800 m². In accordance with the design calculations
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4 151 connected with the coating breakdown factor, the demand for cathodic protection current for
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7 152 each leg of Baltic Beta platform totaled about 50 A.
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9 153 The existing sacrificial anodes welded to the legs of the platform in 1995 turned out to
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11 154 be used up in about 50%, which has been confirmed by a visual inspection of an underwater
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13 155 vehicle (so-called ROV – remotely operated vehicle). As an additional source of cathodic
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15 156 protection current, sacrificial anodes groups were designed in the form of cone-shaped baskets
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17 157 (see Phot.1-3), two for each leg, which were to be placed on the seabed at the distance of
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19 158 about dozen meters from the legs (Zakowski, 2011). The anode groups were electrically
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21 159 connected to the legs with a cable. It was assumed that the anode systems should provide
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23 160 protection current for the next 10 years, therefore each group contains 30 aluminum anodes,
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25 161 1.5 meters long and 45 kg each.
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31 162 Works related to mounting and connecting the anode groups were implemented in
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33 163 September 2009. The task of placing the anode groups on the seabed required a cooperation
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35 164 of tugboats, rig cranes and divers. The total time for assembly of the anode groups as well as
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37 165 start-up of the installation was about one week. Photographs taken during the works in 2009
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39 166 are included herein as Photos 1–3.
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31 **Photos 1–3.** *The anode groups system installed during the modernization of cathodic*
32 *protection system of the Baltic Beta sea platform.*
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39 173 **2. Methodology for assessing the effectiveness of the modernized cathodic protection**
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46 176 Following modernization of the cathodic protection system, its effectiveness was
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48 177 assessed periodically based on measurements of the platform legs potential (Zakowski, 2011).
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50 178 The measurements were conducted in a way allowing to obtain the potential profiles of each
51 179 leg over its entire height. The potentials were measured versus the zinc/seawater reference
180 180 electrode, which was lowered on a measuring line along the entire length of the leg from the

181 sea surface to the seabed, as schematically shown in Figure 3. The results were recorded with
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2 182 the accuracy of 0.1 mV using a digital recorder.
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4 183 The reference electrode was made of high purity zinc (99.99% of weight). It was made
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7 184 in the shape of a cylinder with a diameter of 2.5 cm and a height of 5 cm. The cable
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10 185 connection to the electrode was isolated against water ingress by a resin. The side surface of
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12 186 the cylinder and the cable connection were secured with a heat-shrinkable polyethylene tube
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14 187 with adhesive in such a way that only the base of the zinc cylinder had contact with the
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17 188 electrolyte (sea water). Before the measurements, the potential of the zinc electrode was
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19 189 checked versus a saturated calomel electrode (SCE). The value of the potential of the zinc
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22 190 electrode versus SCE in 1 % NaCl solution was equal to -1020 ± 5 mV. Before measuring the
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24 191 potential of the Baltic Beta platform legs, the zinc reference electrode was immersed in
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27 192 seawater for 30 minutes to stabilize the electrode potential.
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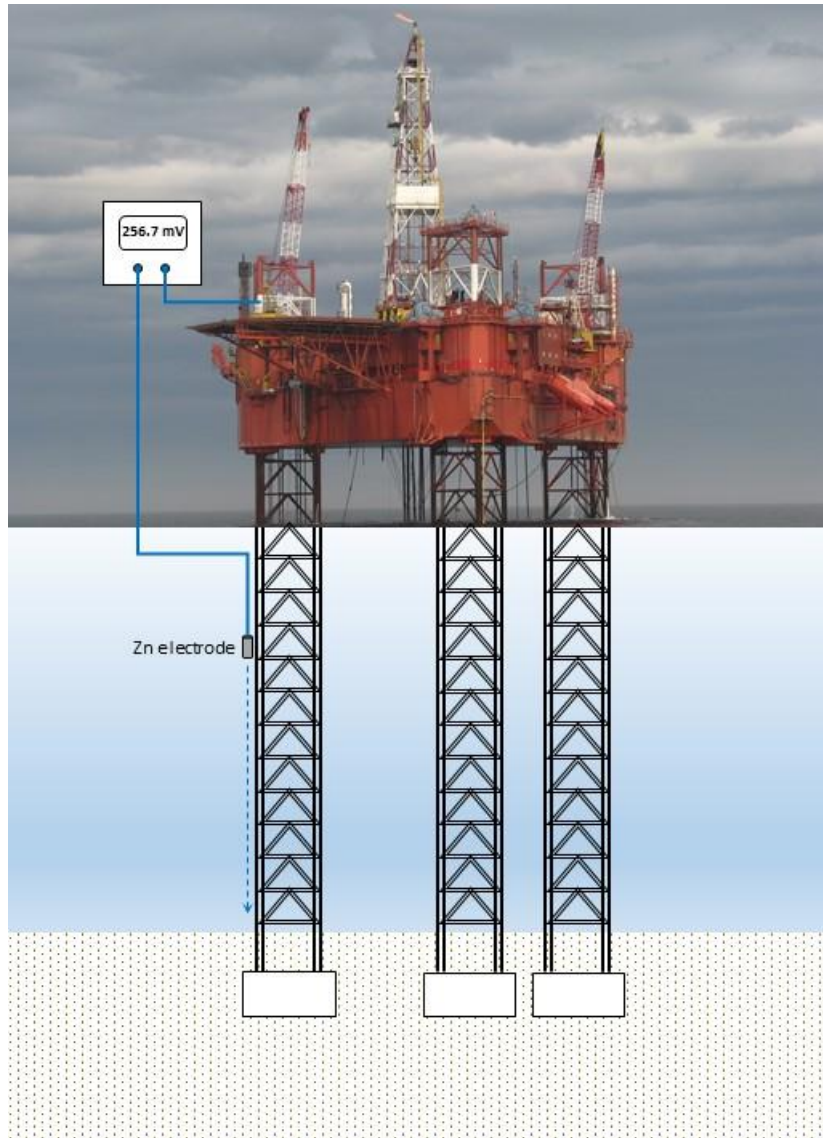


Fig. 3. A way to measure the potential profile of the platform leg.

Typical values of the potential of steel corroding in seawater are approximately +0.50 V versus the zinc reference electrode. A more electropositive potential indicates occurrence of intense corrosion of steel structures on the high seas. According to the standard EN 12473:2014-04 "General principles of cathodic protection in sea water", the protection potential of steel structures is between +0.25 V and -0.05 V vs. Zn electrode (so called full cathodic protection). Recognized engineering practice and some standards (e.g. EN 12954:2019-12 "General principles of cathodic protection of buried or immersed onshore

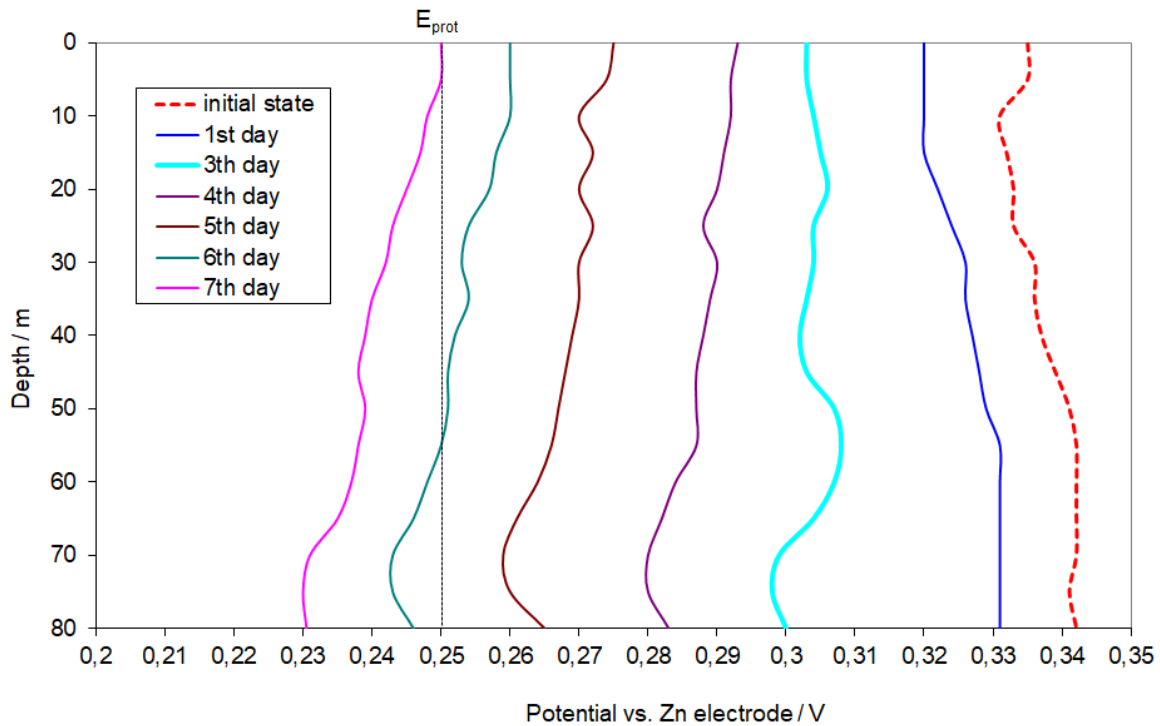
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metallic structures") indicate that the linear corrosion rate of the structure polarized to the protective potential is less than 0.01 mm/year – a wall thickness of the structure is reduced annually by 0.01 mm. Potential in the range between 0.25 V and 0.40 V versus Zn electrode indicates a partial cathodic protection of steel. In this state the corrosive processes are then limited, but not completely eliminated, and corrosion rate is greater than 0.01 mm/year.

3. Results and discussion

3.1. Effect obtained after installation of the new anode systems

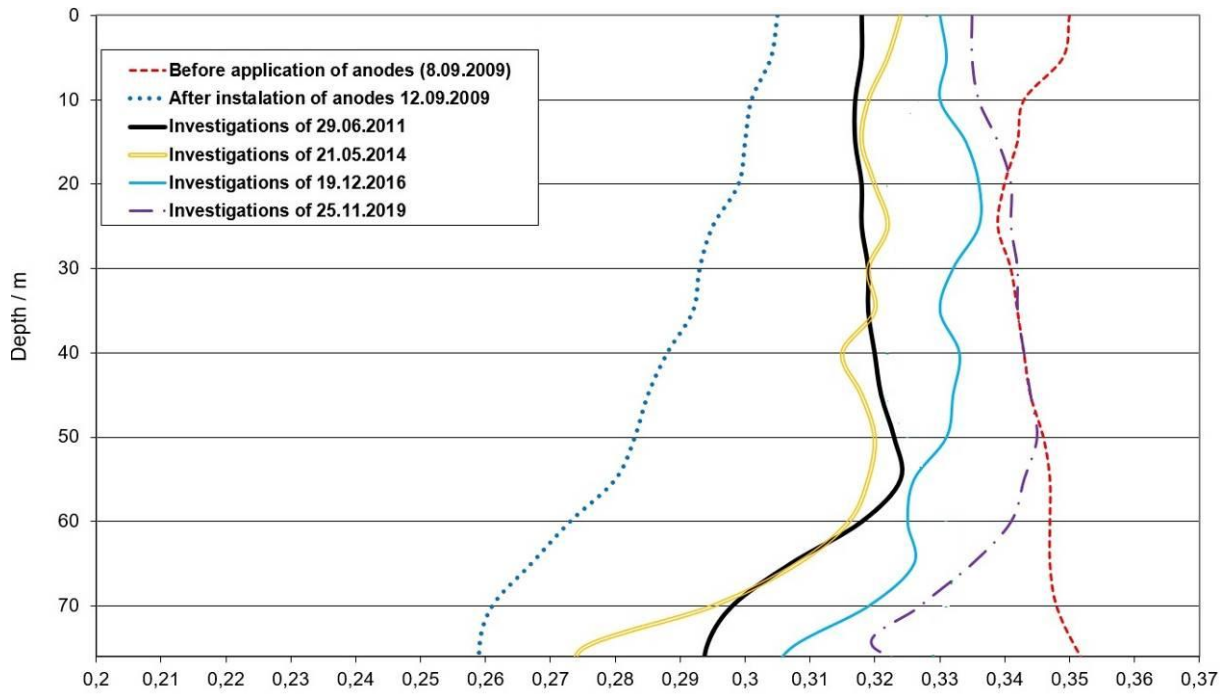
The potential profiles of the leg on the bow of the rig, measured during the assembly of subsequent anode systems in 2009 are shown in Fig. 4. Before assembling the anode groups, the average value of the potential along the entire length of the leg was approximately 0.34 V versus Zn reference electrode (initial state – red dashed line in Fig. 4). A gradual increase in the size of cathodic polarization (i.e. gradual decreasing the value of the potential) on the subsequent days can be observed, which is associated with assembly of each new anode group. The potential change in relation to the potential from before assembly of the systems (the initial state) was about 100 mV in the lower leg, and about 80 mV in the upper part – see pink line in Fig. 4 (7th day). The potential of the lower part of the leg was 0.23 V and potential of the upper part of the leg was 0.25 V. The lower cathodic polarity of the upper part results from the greater distance from the anode group. It is visible in Fig. 4 that polarization to the protective potential, i.e. below 0.25 V, occurred along the entire length of the leg. So, the effect of effective corrosion protection was obtained.



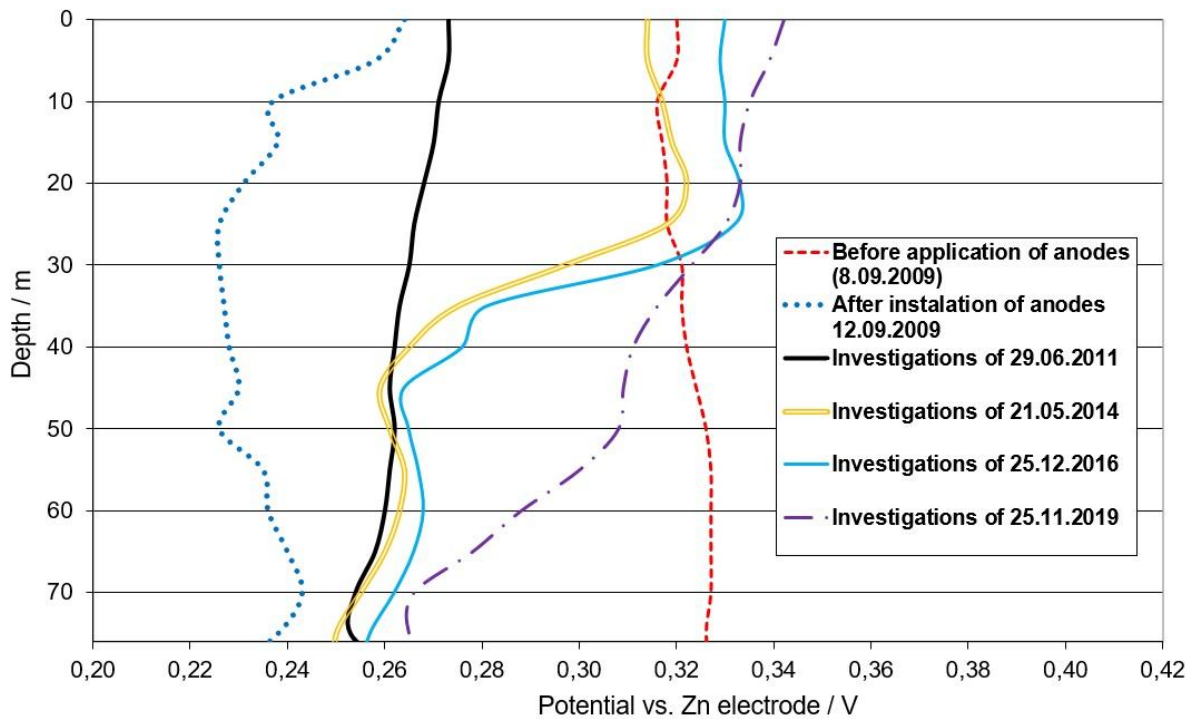
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228 **Fig. 4.** An example of the potential profile of the platform leg during assembly and start-up of
229 the installation.

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231 *3.2. Effect obtained during ten-year operation*

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233 Fig. 5 and Fig. 6 provide examples of potential profiles obtained for the legs located
234 on the platform stern over 10 years of the cathodic protection system's operation.



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237 **Fig. 5.** Potential profiles of the leg located on the left side of the stern, obtained during ten-
238 year operation of the cathodic protection system.



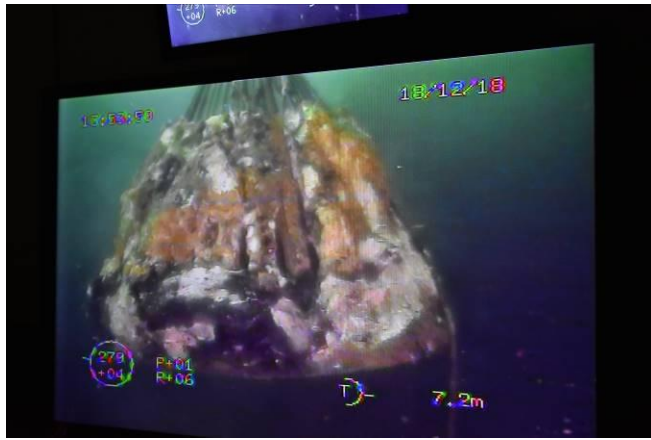
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241 **Fig. 6.** Potential profiles of the leg located on the right side of the stern, obtained during ten-
242 year operation of the cathodic protection system.

243 In both figures the red dotted line shows the potential distribution over the entire
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2 244 length of the legs in 2009 before applying new anodes. You can see that old, worn anodes
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4 245 welded to the legs (in accordance with the original protection scheme developed for the
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7 246 structure) did not provide enough current to polarize the legs to the potential of full cathodic
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10 247 protection. The value of the potential over the entire length of the leg located on the left side
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12 248 of the stern was in the range 0.34 - 0.35 V (see Fig. 5), and potential of the leg located on the
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14 249 right side of the stern was 0.32 - 0.33 V versus Zn electrode (see Fig. 6).

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17 250 After installation of a new anode systems in 2009, the potential of the left leg
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19 251 decreased to 0.26 V at the bottom, and up to 0.3 V at the sea surface (blue dotted line in Fig.
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22 252 5). The potential of the right leg was 0.24 V and 0.26 V, respectively (see Fig. 6).

23
24 253 In next years, there was a gradual deterioration in the cathodic polarization of the legs,
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26 254 which progressed with dissolution of the anode material and degradation of the protective
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29 255 coating over the years. At present, in November 2019, the system causes polarity of the left
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31 256 stern leg to the potential approx. 0.32 V at the seabed, 0.34 V at a depth of 40 m, and 0.33 V
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34 257 at the sea surface (see Fig. 5). For the right stern leg: 0.26 V by the seabed, 0.31 V at a depth
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36 258 of 40 m, and 0.34 V at the sea surface (see Fig. 6). Thus, an effect of partial cathodic
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39 259 protection of the legs is now obtained.

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41 260 At the seabed, the potential of the leg located on the left side of the stern is more
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44 261 negative (0.32 V – Fig. 5 investigation in November 2019) than the leg on the right side of the
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46 262 stern (0.26 V – Fig. 6). This is due to the presence of bare, non-insulated steel casing pipes for
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49 263 the oil and gas extraction system (risers). These pipes capture the cathodic protection current
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51 264 flowing from the sacrificial anodes, which results in less current flowing to the platform legs.
265 The result is less cathodic polarization, so the potential is more positive.



Photos 4–9. One of the cone-shaped anodes basket during a cleaning procedure carried out at sea. The upper three photos show the cone before hydro-cleaning, and the lower three photos show the cone after is cleaned.

270 Every time during potential measurements a close visual inspection of the anode
271 groups (cones) is carried out. These inspections indicated that all cones are working properly,
272 this is due to the fact that some products of aluminium alloy dissolution are overgrowing the
273 surface of the anodes. Such deposits can reduce the flow of protection current from the
274 anodes, this phenomenon is unwanted when it comes to corrosion protection. In order to
275 obtain the original operating parameters of the anodes, it is necessary to clean them of the
276 anode dissolution products. Due to their design, anode cones can be lifted and moved from the
277 seabed, this property has been useful several times before during their lifetime. This ability is
278 very useful and practical for any this type of objects when it comes to operating a platform at
279 sea. In 2018, a decision was made to recover the anodes cones for a cleaning operation.
280 Photos 4-9 show one of the cone during the cleaning process. Removing the overgrown
281 dissolution products was carried out by hydro-cleaning, all of the loose material was rinsed
282 off so that only the hard, unreacted protective alloy remained on the anodes. Information
283 gathered during each previous visual inspection, gave concerns about the amount of alloy left
284 on the anodes. After the cleaning process was finished it was clear that the amount of
285 protective alloy remaining on the anodes is about 50% of the original volume. After the
286 cleaning operation was completed, all of the cones were returned to their previous location on
287 the seabed.

288

289 **4. Conclusions**

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291 After installation of sacrificial anode groups placed on the seabed, providing
292 complementary protection, the cathodic protection conditions of the platform legs improved
293 significantly. The potential of legs near the seabed was higher than the full protection criterion
294 by approx. 0.01–0.02 V, while closer to the sea surface (at a considerable distance from the

295 anodes) protection conditions were weaker (at the level of 0.04 V above the criterion value).
296 During operation of the system, deterioration of protection conditions could be observed
297 resulting mainly from dissolution of sacrificial anodes and progressing degradation of
298 protective coatings.

299 The experience gained during the ten-year operation of the cathodic protection system
300 indicates that use of sacrificial anode systems mounted on the seabed can be an effective form
301 of cathodic protection of offshore platforms legs. It is basically the only means of protection
302 in case of a platform not able to leave its location for renovation works in a shipyard. The
303 obtained measurement results indicate that sacrificial anode systems located on the seabed can
304 polarize platform legs even over a length of 80 meters.

305 Dissolution of sacrificial anodes means that a periodic assembly of new anodes is
306 necessary. The more degraded the protective coating gets over time, the higher the demand
307 for cathodic protection current, which further accelerates wear of the anode material. The
308 sacrificial anode groups installed on the seabed, anticipated for 10 years of operation, have
309 worn out. Therefore, currently work is underway on the next same renewal of the cathodic
310 protection system of the Baltic Beta platform legs. On the basis of experience presented in
311 this publication, it is planned also to use additional anodes welded to the legs at a depth of 0-
312 10 meters. They will provide a better cathodic polarization effect of the upper part of the legs
313 to ensure polarization to the full cathodic protection potential.

314 Funding: This work was supported by the Ministry of Science and Higher Education of the
315 Republic of Poland in the 'Implementation doctorate' programme.

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