

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

6  
7  
8 4 K. Zakowski<sup>a</sup>, P. Iglinski<sup>b\*</sup>, J. Orlikowski<sup>a</sup>, K. Darowicki<sup>a</sup>, K. Domanska<sup>b</sup>

9  
10 5 <sup>a</sup> Gdansk University of Technology, Faculty of Chemistry, Department of Electrochemistry,  
11  
12 6 Corrosion and Materials Engineering, 11/12 Gabriela Narutowicza Street, 80-233 Gdansk,  
13  
14 7 Poland

15  
16  
17 8 *E-mail address:* krzysztof.zakowski@pg.edu.pl, juliusz.orlikowski@pg.edu.pl,  
18  
19 9 kazimierz.darowicki@pg.edu.pl

20  
21  
22 10 <sup>b</sup> LOTOS Petrobaltic S.A., Stary Dwor 9 Street, 80-758 Gdansk, Poland

23  
24 11 *E-mail address:* piotr.iglinski@lotospetrobaltic.pl, kinga.domanska@lotospetrobaltic.pl

25  
26  
27 12 \* Corresponding author, *E-mail address:* piotr.iglinski@lotospetrobaltic.pl  
28  
29  
30 13

31  
32 **14 ABSTRACT**

33  
34 15 The modernization of cathodic protection system of the Baltic Beta platform legs is described.  
35  
36 16 It was that the sacrificial anodes cone-shaped groups were to be placed on the seabed at a  
37  
38 17 depth of 80 meters. The measurements results of cathodic protection effectiveness during its  
39  
40 18 ten-years operation are presented. The effectiveness was assessed based on the potential value  
41  
42 19 along the entire length of the legs from the sea surface to the seabed. The gained experience  
43  
44 20 indicates that use of sacrificial anode systems mounted on the seabed can be an effective form  
45  
46 21 of cathodic protection of offshore platforms legs. It is basically the only means of  
47  
48 22 anticorrosion protection in case of a platform not able to leave its location for renovation  
49  
50 23 works in a shipyard.  
51  
52  
53  
54  
55  
56  
57  
58

59 **25 Keywords:**  
60  
61  
62  
63  
64  
65

26 Gas and oil production rig

27 Sea platform

28 Corrosion

29 Cathodic protection

30 Sacrificial anode

31

## 32 **1. Introduction**

33

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

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75

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

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52

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

106

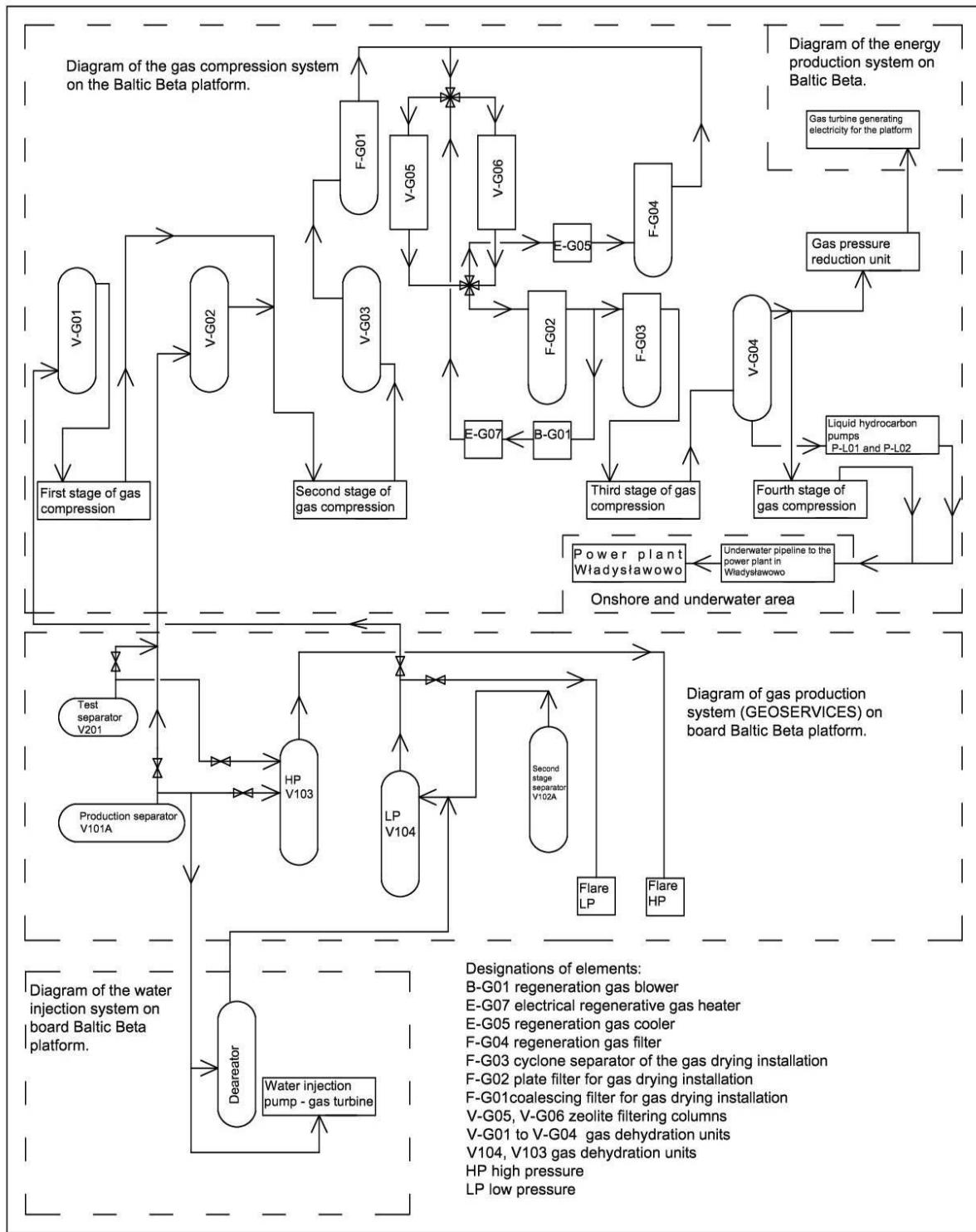
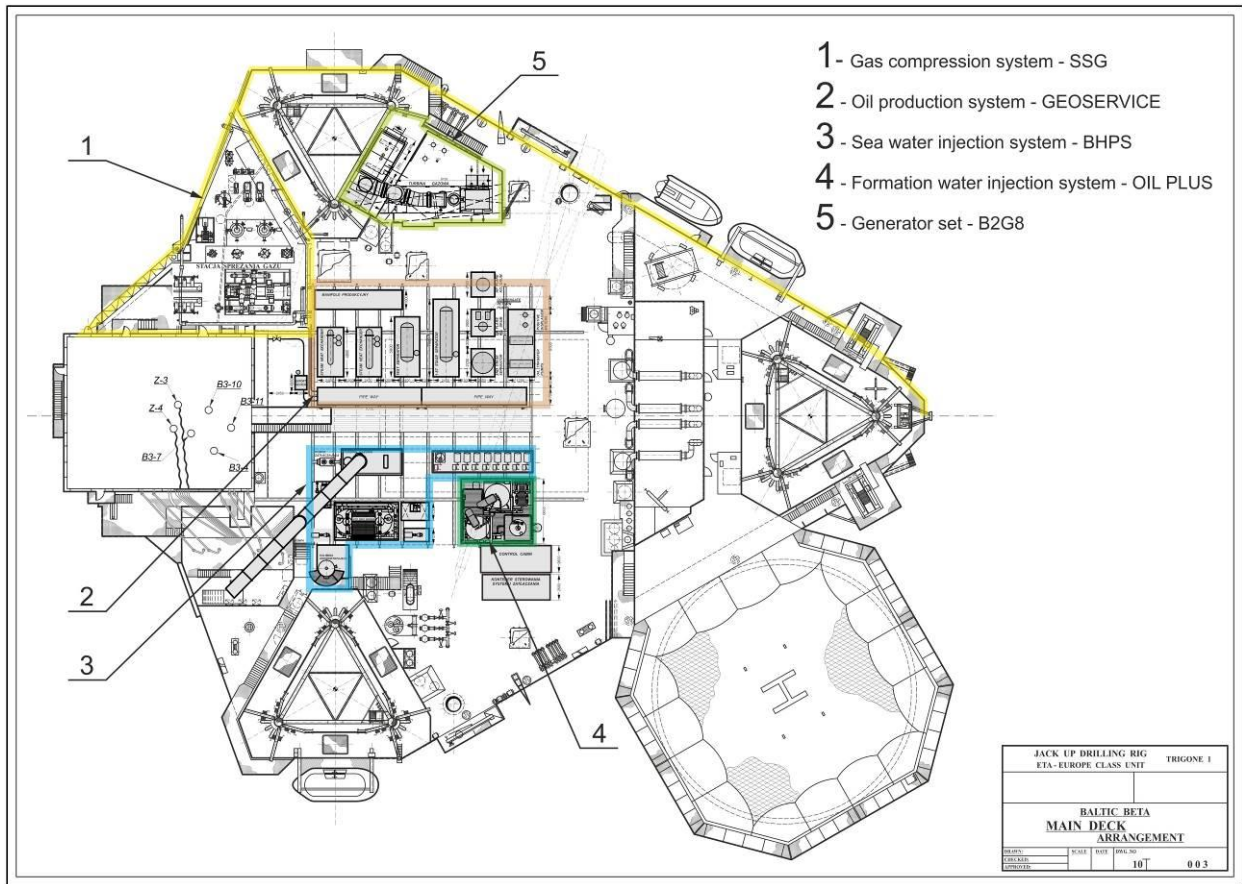


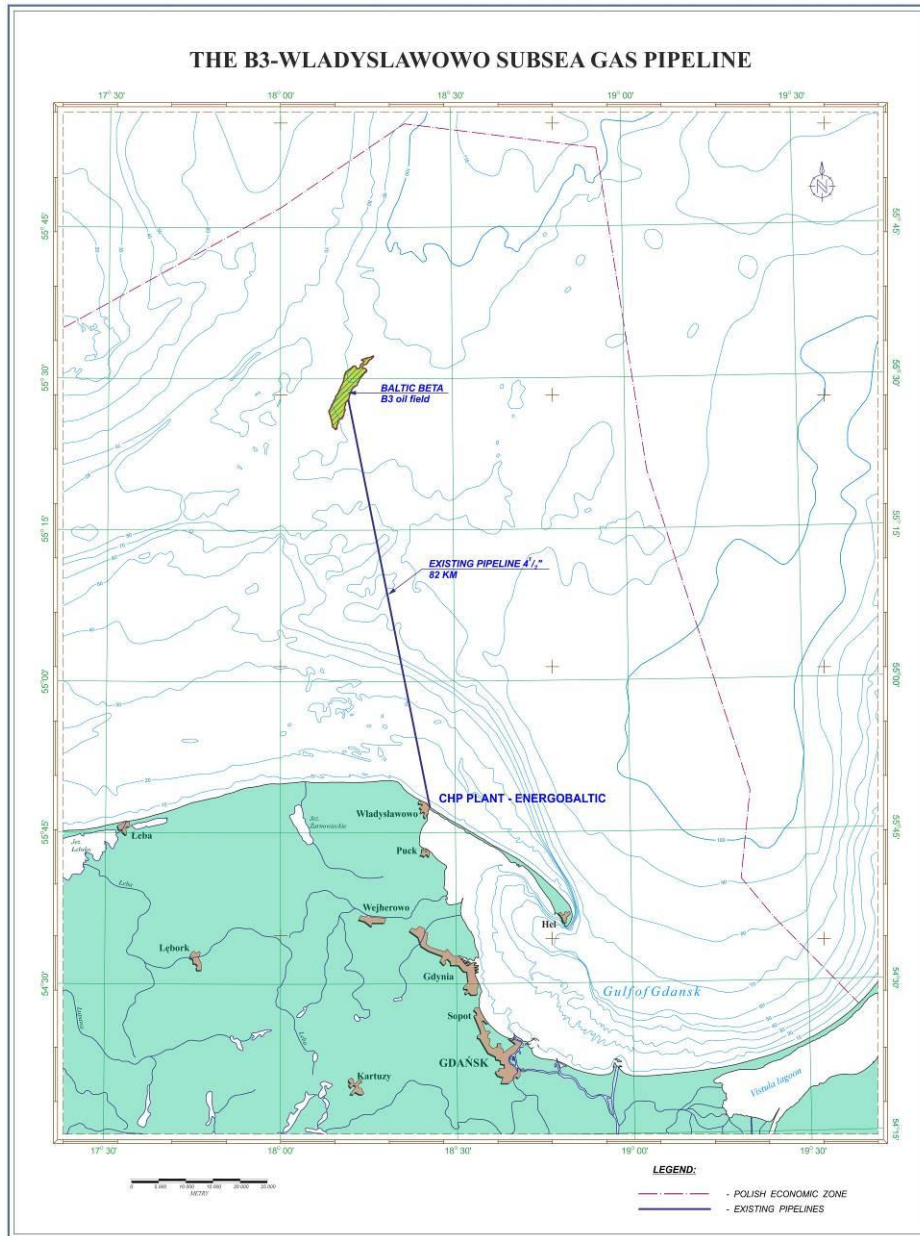
Fig. 1. Block diagram of the gas processing systems on board Baltic Beta.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
107  
108



**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 1/2 "). 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.

### 134 1.2 Modernization of the cathodic protection system

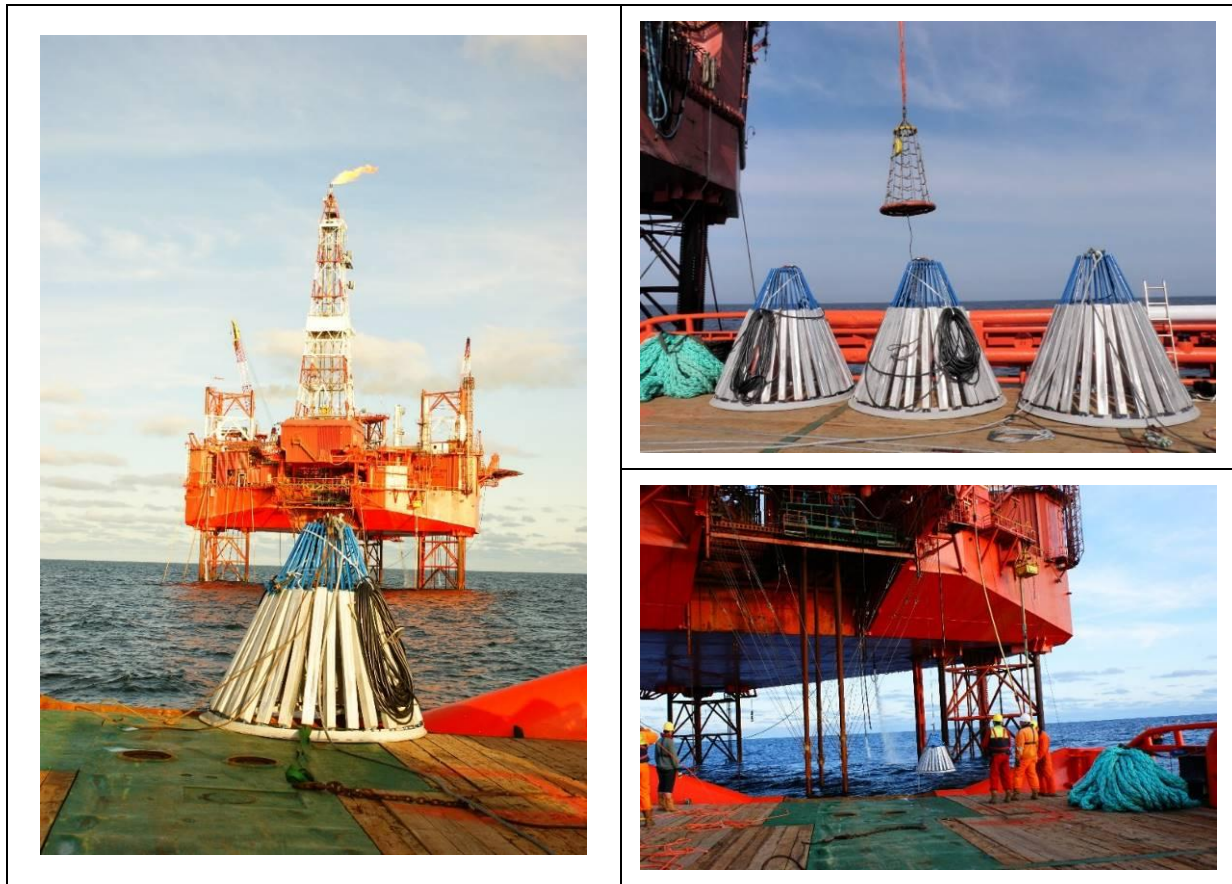
135  
136 In 2008 there began work on a modernization project for the cathodic protection of the  
137 legs. According to the standard DNVGL-RP-B401:2017 "Cathodic protection design",  
138 cathodic protection current density for bare steel in seawater is a function of depth and  
139 climatic region (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/m<sup>2</sup> in depth  
142 0-30 meters, and 80 mA/m<sup>2</sup> 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  
1  
2 150 requires protection is approximately 1800 m<sup>2</sup>. In accordance with the design calculations  
3  
4 151 connected with the coating breakdown factor, the demand for cathodic protection current for  
5  
6  
7 152 each leg of Baltic Beta platform totaled about 50 A.  
8

9 153 The existing sacrificial anodes welded to the legs of the platform in 1995 turned out to  
10  
11  
12 154 be used up in about 50%, which has been confirmed by a visual inspection of an underwater  
13  
14 155 vehicle (so-called ROV – remotely operated vehicle). As an additional source of cathodic  
15  
16 156 protection current, sacrificial anodes groups were designed in the form of cone-shaped baskets  
17  
18  
19 157 (see Phot.1-3), two for each leg, which were to be placed on the seabed at the distance of  
20  
21 158 about dozen meters from the legs (Zakowski, 2011). The anode groups were electrically  
22  
23  
24 159 connected to the legs with a cable. It was assumed that the anode systems should provide  
25  
26 160 protection current for the next 10 years, therefore each group contains 30 aluminum anodes,  
27  
28  
29 161 1.5 meters long and 45 kg each.  
30

31 162 Works related to mounting and connecting the anode groups were implemented in  
32  
33  
34 163 September 2009. The task of placing the anode groups on the seabed required a cooperation  
35  
36 164 of tugboats, rig cranes and divers. The total time for assembly of the anode groups as well as  
37  
38  
39 165 start-up of the installation was about one week. Photographs taken during the works in 2009  
40  
41 166 are included herein as Photos 1–3.  
42  
43  
44 167  
45  
46 168  
47  
48  
49  
50  
51





1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29 169  
30  
31 **Photos 1–3.** *The anode groups system installed during the modernization of cathodic*  
32 *protection system of the Baltic Beta sea platform.*  
33  
34 171

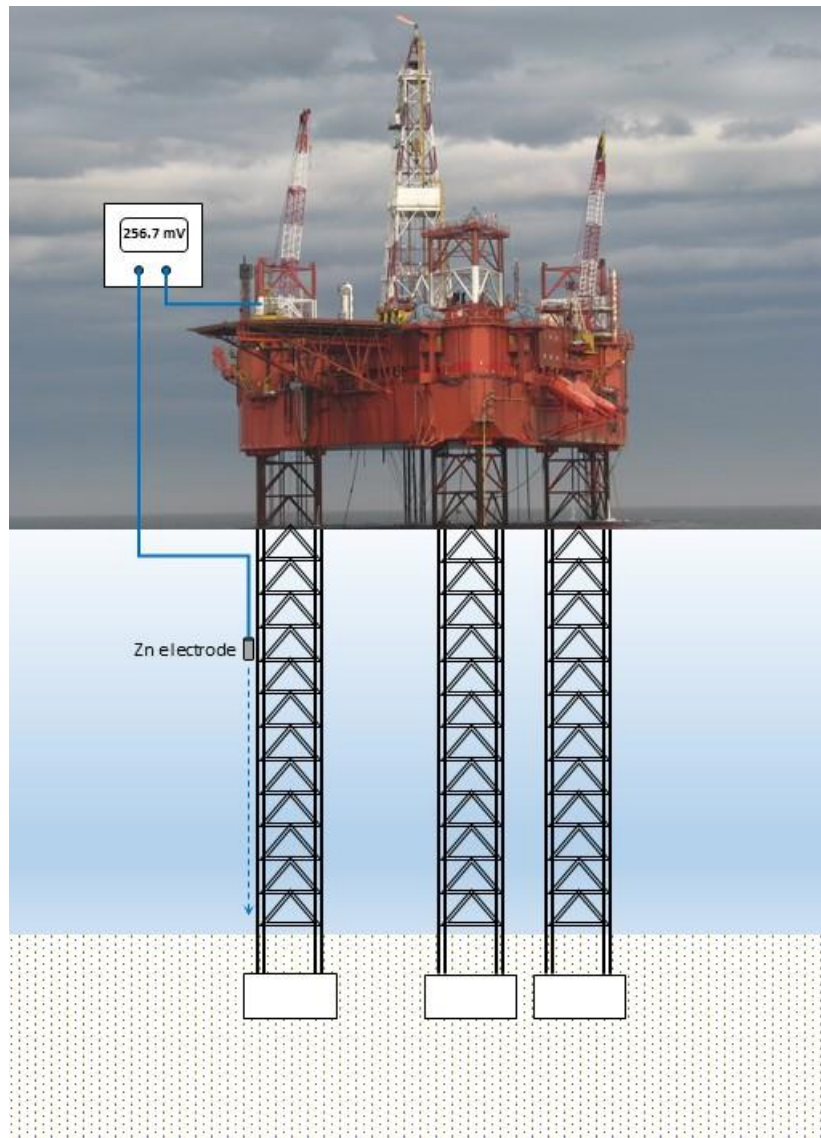
35  
36 172  
37  
38  
39 173 **2. Methodology for assessing the effectiveness of the modernized cathodic protection**  
40 **system**  
41 174  
42  
43  
44 175

45  
46 176 Following modernization of the cathodic protection system, its effectiveness was  
47  
48 177 assessed periodically based on measurements of the platform legs potential (Zakowski, 2011).  
49  
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  
1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000

182 the accuracy of 0.1 mV using a digital recorder.

183 The reference electrode was made of high purity zinc (99.99% of weight). It was made  
184 in the shape of a cylinder with a diameter of 2.5 cm and a height of 5 cm. The cable  
185 connection to the electrode was isolated against water ingress by a resin. The side surface of  
186 the cylinder and the cable connection were secured with a heat-shrinkable polyethylene tube  
187 with adhesive in such a way that only the base of the zinc cylinder had contact with the  
188 electrolyte (sea water). Before the measurements, the potential of the zinc electrode was  
189 checked versus a saturated calomel electrode (SCE). The value of the potential of the zinc  
190 electrode versus SCE in 1 % NaCl solution was equal to  $-1020 \pm 5$  mV. Before measuring the  
191 potential of the Baltic Beta platform legs, the zinc reference electrode was immersed in  
192 seawater for 30 minutes to stabilize the electrode potential.



**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

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
193  
37  
38  
194  
39  
40  
41  
195  
42  
43  
196  
44  
45  
197  
46  
47  
198  
48  
49  
199  
50  
51  
200  
201  
202  
MOST WIEDZY  
Pobrano z mostwiedzy.pl

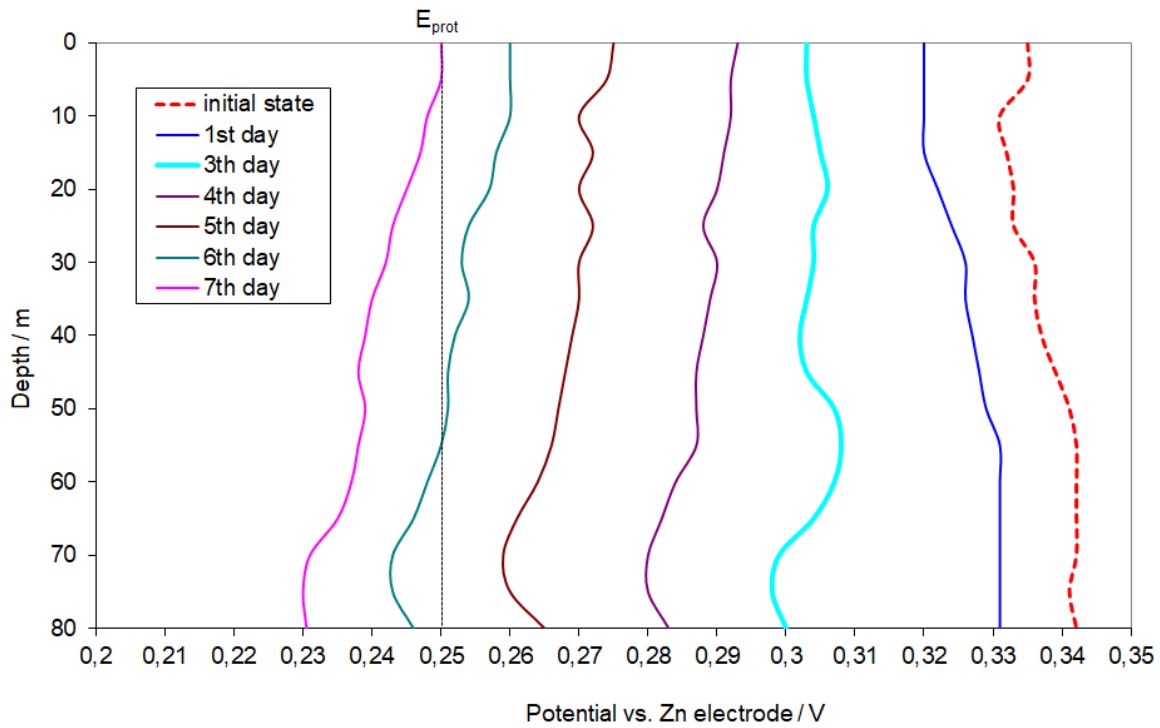
203 metallic structures") indicate that the linear corrosion rate of the structure polarized to the  
204 protective potential is less than 0.01 mm/year – a wall thickness of the structure is reduced  
205 annually by 0.01 mm. Potential in the range between 0.25 V and 0.40 V versus Zn electrode  
206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

### 209 **3. Results and discussion**

#### 211 *3.1. Effect obtained after installation of the new anode systems*

213 The potential profiles of the leg on the bow of the rig, measured during the assembly  
214 of subsequent anode systems in 2009 are shown in Fig. 4. Before assembling the anode  
215 groups, the average value of the potential along the entire length of the leg was approximately  
216 0.34 V versus Zn reference electrode (initial state – red dashed line in Fig. 4). A gradual  
217 increase in the size of cathodic polarization (i.e. gradual decreasing the value of the potential)  
218 on the subsequent days can be observed, which is associated with assembly of each new  
219 anode group. The potential change in relation to the potential from before assembly of the  
220 systems (the initial state) was about 100 mV in the lower leg, and about 80 mV in the upper  
221 part – see pink line in Fig. 4 (7<sup>th</sup> day). The potential of the lower part of the leg was 0.23 V  
222 and potential of the upper part of the leg was 0.25 V. The lower cathodic polarity of the upper  
223 part results from the greater distance from the anode group. It is visible in Fig. 4 that  
224 polarization to the protective potential, i.e. below 0.25 V, occurred along the entire length of  
225 the leg. So, the effect of effective corrosion protection was obtained.

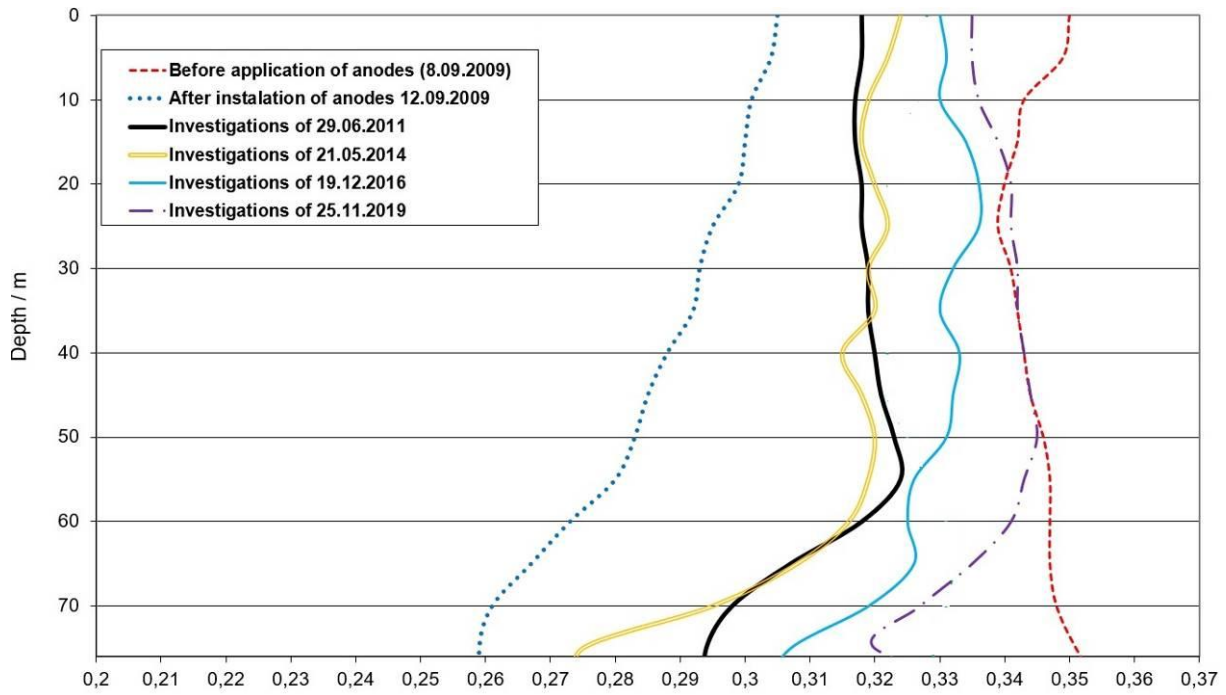




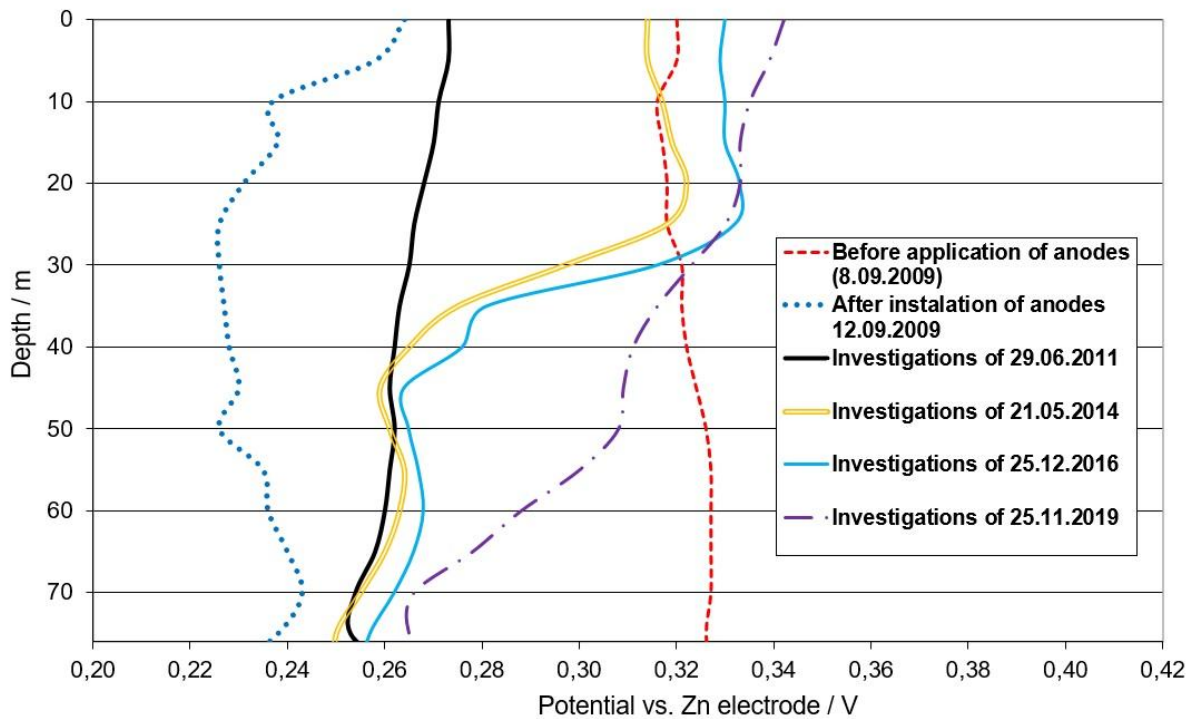
**Fig. 4.** An example of the potential profile of the platform leg during assembly and start-up of the installation.

### 3.2. Effect obtained during ten-year operation

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



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



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

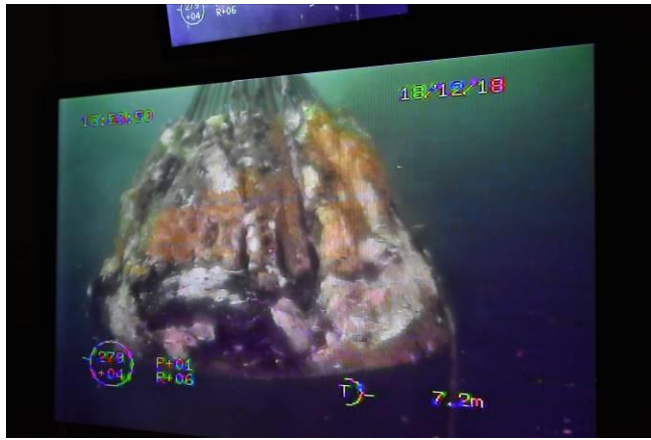


243 In both figures the red dotted line shows the potential distribution over the entire  
1  
2 244 length of the legs in 2009 before applying new anodes. You can see that old, worn anodes  
3  
4 245 welded to the legs (in accordance with the original protection scheme developed for the  
5  
6  
7 246 structure) did not provide enough current to polarize the legs to the potential of full cathodic  
8  
9  
10 247 protection. The value of the potential over the entire length of the leg located on the left side  
11  
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  
13  
14 249 right side of the stern was 0.32 - 0.33 V versus Zn electrode (see Fig. 6).

16  
17 250 After installation of a new anode systems in 2009, the potential of the left leg  
18  
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.  
20  
21  
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,  
25  
26 254 which progressed with dissolution of the anode material and degradation of the protective  
27  
28  
29 255 coating over the years. At present, in November 2019, the system causes polarity of the left  
30  
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  
32  
33  
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  
35  
36 258 of 40 m, and 0.34 V at the sea surface (see Fig. 6). Thus, an effect of partial cathodic  
37  
38  
39 259 protection of the legs is now obtained.

40  
41 260 At the seabed, the potential of the leg located on the left side of the stern is more  
42  
43 261 negative (0.32 V – Fig. 5 investigation in November 2019) than the leg on the right side of the  
44  
45  
46 262 stern (0.26 V – Fig. 6). This is due to the presence of bare, non-insulated steel casing pipes for  
47  
48  
49 263 the oil and gas extraction system (risers). These pipes capture the cathodic protection current  
50  
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**

290  
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.

316  
317  
318  
319

320 **References**

- 1  
2 321  
3  
4  
5 322 Esaklul, K.A., Ahmed, T.M., 2009. Prevention of failures of high strength fasteners in use in  
6  
7 323 offshore and subsea applications. *Engineering Failure Analysis* 16 (4), 1195-1202.  
8  
9 324 Special Issue. <https://doi.org/10.1016/j.engfailanal.2008.07.012>  
10  
11 325 Hajjigholami M. et al., 2017. Modeling the Cathodic Protection System for a Marine Platform  
12  
13 326 Jacket. *Materials Performance* 56 (4), 34-38.  
14  
15  
16 327 Hartt, W.H., 2012. Cathodic protection of offshore structures-history and current status.  
17  
18 328 *Corrosion* 68 (12), 1063-1075. <https://doi.org/10.5006/0010-9312-68.12.1063>  
19  
20  
21 329 Hartt, W.H., Zhang, X., Chu, W., 2005. Issues associated with expiration of galvanic anodes  
22  
23 330 on marine structures. *Corrosion* 61 (11), 1035-1040. <https://doi.org/10.5006/1.3280619>  
24  
25  
26 331 Hong, M.S., Hwang, J.H., Kim, J.H., 2018. Optimization of the Cathodic Protection Design in  
27  
28 332 Consideration of the Temperature Variation for Offshore Structures. *Corrosion* 74 (1),  
29  
30 333 123-133. <https://doi.org/10.5006/2492>  
31  
32  
33 334 Jeffrey, R., Melchers, R.E., 2003. Bacteriological influence in the development of iron  
34  
35 335 sulphide species in marine immersion environments. *Corrosion Science* 45 (4), 693-714.  
36  
37 336 [https://doi.org/10.1016/S0010-938X\(02\)00147-6](https://doi.org/10.1016/S0010-938X(02)00147-6)  
38  
39  
40 337 Kiran, R, Teodoriu, C. et al., 2017. Identification and evaluation of well integrity and causes  
41  
42 338 of failure of well integrity barriers (A review). *Journal of Natural Gas Science and*  
43  
44 339 *Engineering* 45, 511-526. <https://doi.org/10.1016/j.jngse.2017.05.009>  
45  
46  
47 340 Larsen, K.R., 2019. Designing and Managing an Offshore Cathodic Protection System.  
48  
49 341 *Materials Performance* 58 (4), 26-30.  
50  
51  
342 Lemieux, E., Hartt, W.H., 2006. Galvanic anode current and structure current demand  
343  
344 determination methods for offshore structures. *Corrosion* 62 (2), 162-173.  
<https://doi.org/10.5006/1.3278261>

- 345 Liu, T., Cheng, Y.F., 2017. The influence of cathodic protection potential on the biofilm  
1  
2 346 formation and corrosion behaviour of an X70 steel pipeline in sulfate reducing bacteria  
3  
4 347 media. *Journal of Alloys and Compounds* 729, 180-188.  
5  
6 348 <https://doi.org/10.1016/j.jallcom.2017.09.181>  
7  
8  
9 349 Melchers, R.E., 2005. The effect of corrosion on the structural reliability of steel offshore  
10  
11 350 structures. *Corrosion Science* 47, 2391–2410.  
12  
13 351 <https://doi.org/10.1016/j.corsci.2005.04.004>  
14  
15  
16 352 Rossi, S., Deflorian, F., Fedrizzi, L. et al., 1998. Corrosion protection of offshore structures  
17  
18 353 for oil and gas extraction. *Metallurgia Italiana* 90 (2), 45-50.  
19  
20  
21 354 Szabo, S., Bakos, I., 2006a. Cathodic Protection with Sacrificial Anodes. *Corrosion Reviews*  
22  
23 355 24 (3-4), 231–280. <https://doi.org/10.1515/CORRREV.2006.24.3-4.231>  
24  
25  
26 356 Szabo, S., Bakos, I., 2006b. Impressed Current Cathodic Protection. *Corrosion Reviews* 24  
27  
28 357 (1-2), 39-62. <https://doi.org/10.1515/CORRREV.2006.24.1-2.39>  
29  
30  
31 358 Wu, S., Zhang, L. et al., 2018. A leakage diagnosis testing model for gas wells with sustained  
32  
33 359 casing pressure from offshore platform. *Journal of Natural Gas Science and Engineering*  
34  
35 360 55, 276-287. <https://doi.org/10.1016/j.jngse.2018.05.006>  
36  
37  
38 361 Yin, P., Liu, F. et al., 2019. Discussion on cathodic protection retrofit technical solution for a  
39  
40 362 jacket platform in the south china sea. *Corrosion and Protection* 40 (11), 856-860.  
41  
42 363 <https://doi.org/10.11973/fsyfh-201911014>  
43  
44  
45 364 Zakowski, K., 2011. Studying the effectiveness of a modernized cathodic protection system  
46  
47 365 for an offshore platform, *Anti-Corrosion Methods and Materials* 58 (4), 167-172.  
48  
49 366 <https://doi.org/10.1108/00035591111148876>  
50  
51  
52 367 Zakowski, K., Szocinski, M., Narozny, M., 2013. Study of the formation of calcareous  
53  
54 368 deposits on cathodically protected steel in Baltic sea water. *Anti-Corrosion Methods and*  
55  
56 369 *Materials* 60 (2), 95-99. <https://doi.org/10.1108/00035591311308065>

- 370 Zakowski, K., Narozny, M., 2014. Influence of water salinity on corrosion risk-the case of the  
1  
2 371 southern Baltic Sea coast. Environmental Monitoring and Assessment 186 (8), 4871-  
3  
4 372 4879. <https://doi.org/10.1007/s10661-014-3744-3>  
5  
6  
7 373 Zamanzade, M., Shahrabi, T., Yazdian, A., 2007. Improvement of corrosion protection  
8  
9 374 properties of calcareous deposits on carbon steel by pulse cathodic protection in  
10  
11 375 artificial sea water. Anti-Corrosion Methods and Materials 54 (2), 74-81.  
12  
13 376 <https://doi.org/10.1108/00035590710733566>  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51