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SIMULATION AND SELECTION OF A PROTECTION TYPES IN THE DESIGN STAGE OF SHIPS AND OFFSHORE STRUCTURES

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Summary

The requirements of the rules and regulations of the Classification Societies are based on the assumption that during the construction and operation of ships the hull corrosion protection measures are implemented according to the standards and other regulatory documents currently in force. For the purposes of designing the ship hull structures, the load components for different corrosion protection types have been obtained in the paper. There have been collected the data on the relationship between the corrosion protection weight load and the ship displacement, which enables to select the lowest corrosion protection type by weight. Technical and economic parameters of corrosion protection of ship hull structures have been analyzed. To achieve the objective of the paper a cumulative simplified approach of economic feasibility of selecting the corrosion protection type for ship hull structures has been employed. It has been determined that a total cost of protection from stress-corrosion fractures decreases for the ships with a displacement of more than 6000 [t] in the case of usage of the impressed current cathodic protection instead of the sacrificial anode cathodic one. The results of the investigation can be used by shipbuilders at the ship design stage, which enables to make a correct selection of a corrosion protection type and decreases its total cost.

Key words: *weight load; corrosion protection; ship; cost; capital expenses; operating expenses*

1. Introduction

The corrosion control is the most important objective of the shipbuilding. A large quantity of sea-going ships and offshore structures is wrecked due to stress-corrosion fractures. The severity of this problem increases since a growth rate of corrosion losses exceeds growth rates of metal production. The metal loss is not determinative in this connection. A real economic damage consists of the cost of the lost equipment, expenses on its repair and renovation, losses from the operation down time and etc.; for example, the explosion of the Deepwater Horizon oil rig caused billions of dollars in costs. In case the integrity of tanks of sea-going ships and tanks containing oil, gas hydrates or other raw materials for energy resources is damaged, a threat of contamination to the environment is posed. The contamination of a water surface with oil products does a great deal of harm to the ecosystem. The oil spilled on the water surface quickly begins to spread over, its heavy fractions settle down on the seabed, contaminating both the coastal area and beds of water bodies.

The rules of the Classification Societies (Russian Maritime Register of Shipping [1, 2], Det Norske Veritas [3], DNV GL AS [4], NACE International [5]) envisage an obligatory protection of sea-going ships from corrosion. The electrochemical corrosion protection is one of the most promising corrosion protection methods [6]. The essence of the method is to reduce the speed of the electrochemical metal corrosion during the contact with an extracting electrode being an anode relative to hull structures of ships and offshore structures (sacrificial anode cathodic protection) or during the polarization of hull structures of ships and offshore structures from a DC power supply source (impressed current cathodic protection) [7].

The issues of corrosion protection are still very relevant. Many scientists deal with similar problems, but the problem is not solved comprehensively. An aspect is made only on individual components of the problem. Let's highlight some of the well-known publications of scientists who dealt with corrosion problems. We structure the components of their research and dynamics. The physical aspects of processes in sea water with hull structures are considered by [8]. The development of fatigue cracks in sea water was studied in [9]. Fatigue and crack resistance of structural materials in sea water were studied in [10]. The corrosion loss coefficients depending on the location of the hull structure element were substantiated based on the method proposed in [11]. The importance of corrosion-mechanical damage when choosing a protection system is confirmed by the studies described above. The cost estimate for the replacement of the ship's hull structural elements subjected to random non-uniform corrosion degradation is studied by [12]. The results of this study indicate the need for an economic justification when choosing a protection system against corrosion-mechanical destruction. Paragraphs “3.2 Mass load of the ship's hull acting on the current cathodic protection” and “4. Discussion" of this article are fulfilled on the basis of constituent elements of a new system of ships impressed current cathodic protection from corrosion developed by [13], [14]. However, the issue of the corrosion protection type influence on the ship's mass load and the economic effect of the applied protection has not been studied before. The proposed method is universal for ships carrying various types of cargo and offshore structures. In this article, the authors use a combined simplified approach to the economic feasibility of choosing the type of corrosion protection for hull structures of ships. They will assess the total cost of protection against corrosion damage for vessels with a displacement of more than 6000 [t] in the case of using impressed current cathodic protection instead of sacrificial anode cathodic protection. The research can be used by shipbuilders at the design stage of the vessel, which allows you to choose the right type of corrosion protection and reduce its total cost.

2. Materials and Methods

When an electrochemical corrosion protection system of the underwater hull part (with sacrificial nodes or impressed current) is installed on the ship, it is provided as a rule to install a collector-and-brush-assembly unit designed to be connected to the corrosion protection system of a propeller shaft assembly and at the same time to exclude the contact corrosion. The collector-and-brush-assembly unit consists of a split ring installed on the propeller shaft, a brush holder with copper-graphite brushes, a wire cup brush and a bracket for securing brush holders.

The sacrificial anode cathodic protection is provided by metal sacrificial anodes having a greater electronegative potential than steel and connected with the hull either directly or by means of intermediate electrical resistances that are designed to limit developing currents to the values necessary for protection without excessively using the sacrificial anodes. The sacrificial anode has a more negative potential and is an anode, it releases positive ions into a solution and dissolves. Excess electrons flow into the ship hull or the substructure of an offshore structure having a higher electrode potential. The ship (the substructure of the offshore structure) is a cathode and is not destroyed, with the electrons from it being released into the external medium. A principle of operation of the sacrificial anode cathodic protection is shown in Figure 1 [8].

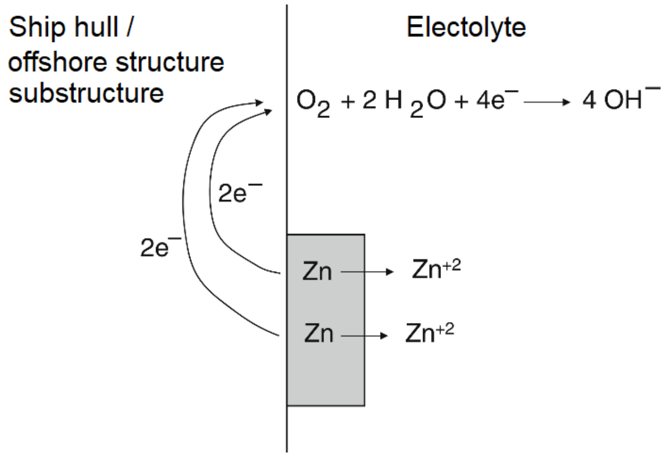

Fig. 1 A diagram of the sacrificial anode cathodic protection operation

In the case of the sacrificial anode cathodic protection system of the steel hull, a metal with a lower electric potential than steel (zinc, magnesium, aluminum and their alloys) is selected as a sacrificial anode. An electric contact is made between the sacrificial anode and the hull metal and a galvanic couple is formed. The sacrificial anodes are used for local and general corrosion protection of hulls, ballast tanks and compartments and can be placed singly or in groups [15, 16].

The general sacrificial anode cathodic protection of the underwater part of the hull is installed in way of bilge strakes along the ship hull and in way of fore and aft parts – at the level of the propeller shaft. Such a protection is the simplest way of corrosion prevention among the other known efficient ones. Installation and renovation of the sacrificial anode cathodic protection does not cause any difficulties both during the construction of ships and their repair. In principle, a service life of any duration can be assigned to it, depending on the quantity of the sacrificial anodes. The sacrificial anode cathodic protection can be provided practically in all sea basins by changing the material and typical dimensions of the sacrificial anodes [17].

A mechanism of electrochemical metal corrosion protection by means of a sacrificial anode is that while electric current is flowing through a border of the metal being protected with a corrosion medium, the surface of such a metal is cathodically polarized, its potential decreases and this can result in the almost full cessation of cathodic disbondment. On the surface of the sacrificial anode the anodic process occurs, which gradually leads to its dissolution (Figure 2). Therefore, the sacrificial anode shall be periodically renovated every 3–4 years [18]. The parameters of the sacrificial anodes as well as the rules and standards for designing the sacrificial anode cathodic protection of the ship hulls are governed by regulatory documents [19].

Fig. 2 A sacrificial anode at the beginning of the operation (left) and at the end of its service life (right) [20]

But in the case of the stress-corrosion fractures of hull structures of ships and offshore structures the sacrificial anode cathodic protection cannot fully resist this type of corrosion damages [10, 21, 22]. The cathodic polarization is an active method of protecting metal from failures. It enables to use the potential and protection current at the widest intervals. It also can adjust protection parameters including this in an automatic mode. The efficacy of the cathodic polarization, as opposed to the coatings, does not depend on the operation time. It can use on its own or in combination with other protection techniques: coatings, reinforcement and etc. The essence of the impressed current cathodic protection is to reduce the speed of electrochemical metal corrosion during the polarization of hull structures of ships and offshore structures from a DC power source. The ship is connected to a negative terminal of the DC power source and the anode is connected to a positive terminal (Figure 3).

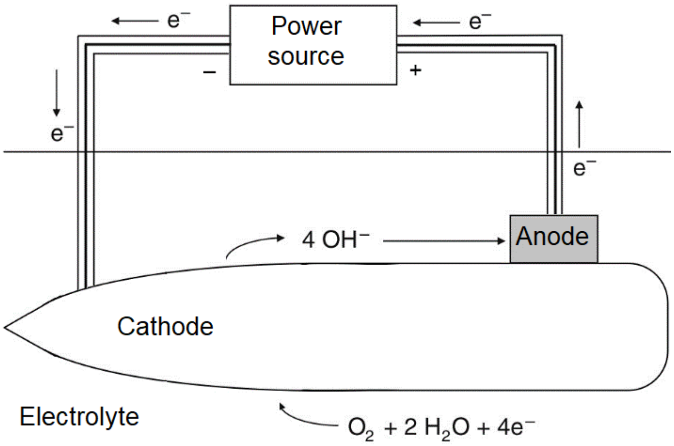

Fig. 3 A diagram of impressed current cathodic protection operation [8]

The ship hull surface is polarized at the constant current density. Corrosion products accumulate in sea water or cathode deposit on the surface, which leads to the change of the surface resistance. The potential displaces accordingly in a negative direction, oxygen ionization occurs at small potentials and, when the potential displaces further to a negative direction, an electrode process mechanism changes and hydrogen release occurs which leads to metal hydrogenation and further embrittlement, which shall not be allowed.

The impressed current cathodic protection systems consist of the following main components: anodes with anode screens, power supply sources with measuring and control equipment, reference electrodes, power cables for connecting anodes and cables for connecting reference electrodes and others as well as a control switchboard of the impressed current cathodic protection system. The impressed current cathodic protection system also includes gland seals and protective boxes at locations of current input to anodes through the hull shell plating and at locations of reference electrode installation [23].

In most cases the impressed current cathodic protection does not need to be replaced within the whole service life of the offshore facility and ensures the optimum hull protection under different operation conditions and with varying degree of wear of paint coating [13], provides the complete suppression of corrosion of base material of shell plating and hull weld joints, irrespective of the types of the used welding materials and welding conditions, and enables to reduce the shell plating roughness and to increase the interdocking period of operation of hull structures of ships and offshore facilities and, with regard to new offshore facilities being designed, to decrease the weight at the expense of excluding the enlarged thickness of structures by a value of corrosive wear and applying low-alloyed high-strength steels [14]. The possibility of finding out automatically the electric potential on the hull surface and, accordingly, increasing or decreasing the anode output current is the most important characteristic of the systems in question. Owing to it, the constant optimum protection level is provided on the ship. The electric potential is traced by reference electrodes. One of the innovative products of Cathelco [24] is represented by anodes to be replaced by a diver on the outer surface of the hull. They have been developed for floating, production, storage and offloading (FPSO) systems and ships having prolonged periods between entries to a dry dock. This is provided by means of an installed “sleeve”, which achieves by resinifying the anode during its manufacturing and replaces common electric wiring. The company has also developed a watertight system of a sealing cap and a seal ring that ensures power supply [24].

3. Results

The requirements for determining dimensions of hull members of ships and offshore structures of the Rules for the Classification and Construction of Sea-Going Ships in Part II "Hull" [1] and the Rules for the Classification, Construction and Equipment of Floating Drilling Units and Offshore Fixed Platforms [2] of Russian Maritime Register of Shipping are based on the assumption that during their construction and operation the measures for hull corrosion protection are implemented according to the standards and other regulatory documents currently in force. The protection measures for hull structures of ships and offshore structures are determined at the design stage. The first stage of the ship design is to determine the displacement based on the load makeup. The displacement of a ship is a crucial characteristic of her dimensions which is on top of hierarchy of the design values and tightly connected with the load makeup influencing many other ship characteristics. The load makeup includes constant weights to which, in particular, weights of devices and electrical equipment refer. Industry standard of the Russian Federation OST5R.0206–2002 "Weight loads of civil and service ships" establishes a typical ship weight load breakdown to components and corresponding codes for carrying out design calculations as well as calculations on determination of ship displacements [25].

The elements composition of the sacrificial anode cathodic protection of ship hulls is described in international [16] and domestic [26] sources. This protection as a load component (Table 1) is included in the ship weight load makeup under code 01050111.

Table 1 Corrosion protection as part of ship weight load makeup

Load component code					Load component description
Section	Group	Subgroup	Item	Subitem	
01	05	01	11		Sacrificial anodes and their fastening
01	05	01			Coatings, hull cementing, sacrificial anodes
01	05				Coatings, paintwork
01					Hull
05	03	09	##		Electrical devices of different purpose
05	03				Lighting networks, power supply networks
05					Power supply system, ship internal communications and control

The elements composition of the impressed current cathodic protection of the ship hull is described in international [19, 24] and domestic [27] sources. According to the note [25], sacrificial anodes, anodes, reference electrodes, screens for protecting hull components are taken into account in the given load component. Hence, the impressed current cathodic protection of the ship hull is partly included in the ship weight load makeup under code 01050111 (reference electrodes, anode assemblies, anode screens and collector-and-brush-assembly unit). The load component "Electrical devices of different purpose" takes into account the sacrificial anode cathodic protection system and, consequently, the impressed current cathodic protection of ship hulls, namely, power supply sources, distribution switchboards, power and control cables is included in the ship weight load makeup as a load component (Table 1) under code 050309##; where the last two signs ## are represented by a digital code depending on the quantity of electrical devices of different purpose. The quantity of components depends on the principal ship dimensions shown in Table 2.

Table 2 Principal ship dimensions

	Harbour tug *RB-389*	Hydrographic survey ship *Donuzlav*	Floating repair ship *PM-139*	Oil carrier *Balt Flot 11*	Ro-ro/general-cargo/container ship *Adler*	Refrigerator ship *Bosfor Vostochnyy*
Displacement [t]	417	2 499	5 540	9 483	11 819	16 600
Length [m]	25.40	82.50	121.70	136.29	120.24	142.00
Breadth [m]	9.30	13.50	17.00	16.86	20.00	22.20
Draft [m]	3.30	4.00	4.63	4.20	6.65	9.60
Depth [m]	4.70	8.00	9.50	6.00	11.50	13.60
Block coefficient	0.522	0.547	0.564	0.959	0.721	0.535

The influence of selection of corrosion protection type on the weight load has been assessed for the following ships: oil carrier *Balt Flot 11* (Figure 4, a), ro-ro/general-cargo/container ship *Adler* (Figure 4, b), refrigerator ship *Bosfor Vostochnyy* (Figure 4, c), harbour tug *RB-389* (Figure 4, d), hydrographic survey ship *Donuzlav* (Figure 4, e) and floating repair ship *PM-138* (Figure 4, f).

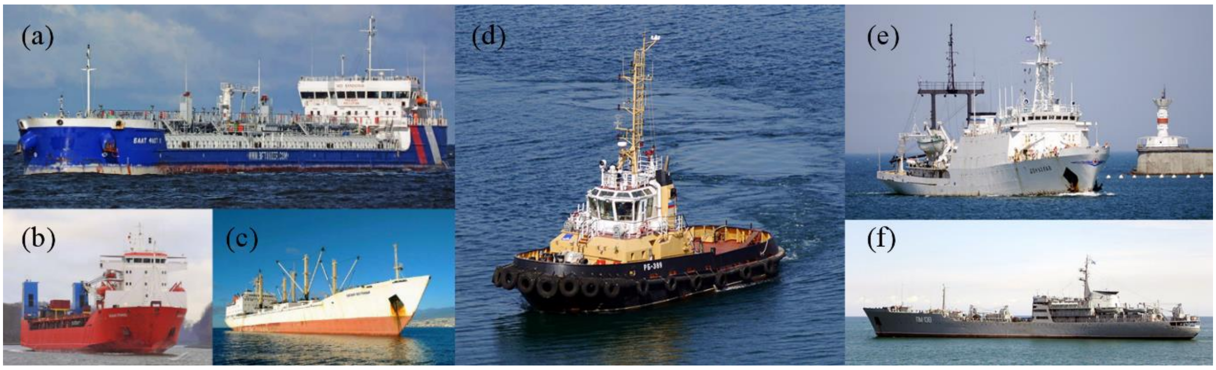

Fig. 4 Ships in question

Compare different corrosion protection types as part of the weight loads of the abovementioned ships.

3.1 Weight load of ship hull sacrificial anode cathodic protection

The sacrificial anode cathodic protection has been adopted as corrosion protection while designing the harbour tug *RB-389*, floating repair ship *PM-138*, hydrographic survey ship *Donuzlav*, oil carrier *Balt Flot 11*, ro-ro ship *Adler* and refrigerator ship *Bosfor Vostochnyy*. When the underwater part of the hull is protected, the quantity of sacrificial anodes (Figure 5) is determined depending on the ship displacement and regulated accordingly international [16] and domestic [26] sources: the sacrificial anodes are installed in way of bilge strakes along the ship hull and in way of fore and aft parts – at the level of the propeller shaft.

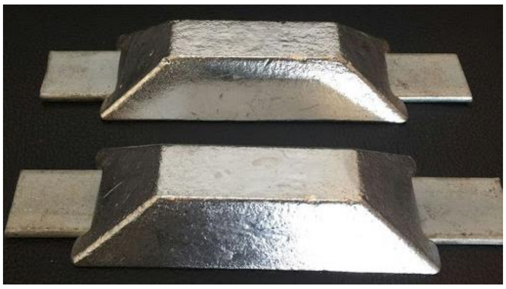

Fig. 5 Sacrificial anodes

A detailed description of the weight load of the sacrificial anode cathodic corrosion protection for the ships in question is set out in Table 3.

Table 3 shows the following standard sizes of sacrificial anodes: P-KOA-10 – short-circuited single aluminum sacrificial anode with a nominal weight of 10 [kg]; P-KKA-13 – short-circuited aluminum end sacrificial anode with a nominal weight of 13 [kg]; P-KOZ-10 – short-circuited single zinc sacrificial anode with a nominal weight of 10 [kg]; P-KLA-15 – short-circuited linear aluminum sacrificial anode with a nominal weight of 15 [kg].

Thus, the sacrificial anode cathodic protection weight is equal to: 280 [kg] for the harbour tug *RB-389*, 722 [kg] for the hydrographic survey ship *Donuzlav*, 1817 [kg] for the floating repair ship *PM-138*, 2170 [kg] for oil carrier *Balt Flot 11*, 2754 [kg] for the ro-ro ship *Adler* and 3630 [kg] for refrigerator ship *Bosfor Vostochnyy*.

Table 3 Weight load of ship hull sacrificial anode cathodic protection

RB-389				
Name of components	Sacrificial anode P-KOA-10	Plate 15.0		
Quantity [pcs]	24.000	72.000		
Weight of component [kg]	10.000	0.520		
Total weight [kg]	**280.000**			
Donuzlav				
Name of components	Sacrificial anode P-KKA-13	Sacrificial anode P-KOZ-10	Half-pipe 100x10	Plug 50x100
Quantity [pcs]	32.000	18.000	32.000	64.000
Weight of component [kg]	13.000	10.000	3.300	0.310
Total weight [kg]	**722.000**			
PM-138				
Name of components	Sacrificial anode P-KKA-13	Sacrificial anode P-KLA-15	Half-pipe 100x10	Plug s10
Quantity [pcs]	56.000	64.000	32.000	64.000
Weight of component [kg]	13.000	15.000	3.300	0.310
Total weight [kg]	**1 817.000**			
Balt Flot 11				
Name of components	Sacrificial anode P-KKA-13	Sacrificial anode P-KLA-15	Half-pipe 100x10	Plug s10
Quantity [pcs]	28.000	112.000	32.000	64.000
Weight of component [kg]	13.000	15.000	3.300	0.310
Total weight [kg]	**2 170.000**			
Adler				
Name of components	Sacrificial anode P-KKA-13	Sacrificial anode P-KLA-15	Half-pipe 100x10	Plug s10
Quantity [pcs]	36.000	144.000	32.000	64.000
Weight of component [kg]	13.000	15.000	3.300	0.310
Total weight [kg]	**2 754.000**			
Bosfor Vostochnyy				
Name of components	Sacrificial anode P-KKA-13	Sacrificial anode P-KLA-15	Half-pipe 100x10	Plug s10
Quantity [pcs]	48.000	192.000	32.000	64.000
Weight of component [kg]	13.000	15.000	3.300	0.310
Total weight [kg]	**3 630.000**			

3.2 Weight load of ship hull impressed current cathodic protection

Consider how the weight load will change during the usage of the impressed current cathodic protection instead of the sacrificial anode cathodic one. The quantity of the impressed current cathodic protection components is determined depending on the principal ship dimensions (Table 2) and ship hull wetted surface area (Table 4). The ship hull wetted surface area is calculated according to the Mumford equation:

$$S_w = L \cdot (1.7 \cdot T + \delta \cdot B), \tag{1}$$

where L – the ship length [m]; T – the draft [m]; δ – the block coefficient; B – the breadth [m].

Table 4 Wetted surface area of the ship hulls

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Wetted surface area [m^2]	266	1 171	2 125	3 176	3 093	4 004

The impressed current cathodic protection system of the ship hulls includes power supply sources, anode assemblies, anode screens, reference electrodes, collector-and-brush-assembly unit, distribution switchboards, power and control cables.

According to the requirements, static rectifiers of TPTS3-200-24 type (DC silicon rectifiers with digital indication of monitored parameters) having a service life of 25 years and approved by Russian Maritime Register of Shipping should be used as power supply sources in the impressed current cathodic protection system. The rectifier is designed as a metal cabinet [13].

It is recommended to use platinum-columbium anodes of AU-1M type with a texture platinum coating on a columbium substrate (Figure 6).

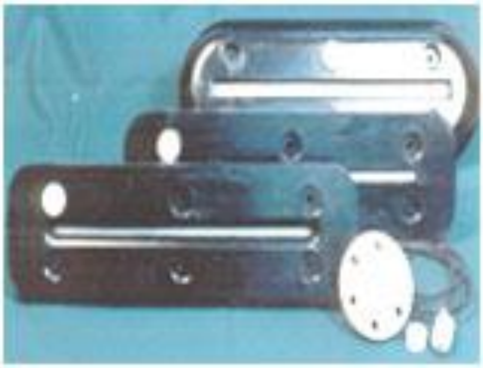

Fig. 6 Platinum-columbium anodes for the impressed current cathodic protection system [28]

The weight load of the impressed current cathodic protection for the harbour tug *RB-389*, the floating repair ship *PM-138*, the hydrographic survey ship *Donuzlav*, the oil carrier *Balt Flot 11*, the ro-ro ship *Adler* and the refrigerator ship *Bosfor Vostochnyy* is set out in Table 5.

Thus, the impressed current cathodic protection weight is equal to: 374.65 [kg] for the harbour tug *RB-389*, 832.55 [kg] for the hydrographic survey ship *Donuzlav*, 1338.4 [kg] for the floating repair ship *PM-138*, 1181.75 [kg] for the oil carrier *Balt Flot 11*, 1314.35 [kg] for the ro-ro ship *Adler* and 1869.2 [kg] for the refrigerator ship *Bosfor Vostochnyy*.

Table 5 Weight load of ship hull impressed current cathodic protection

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Quantity of anode assemblies [pcs]	6	12	18	12	14	16
Weight of AU-1M anodes [kg]	7.9	7.9	7.9	7.9	7.9	7.9
Quantity of reference electrodes [pcs]	2	4	6	4	4	4
Weight of ESKHP-SS reference electrodes [kg]	3.2	3.2	3.2	3.2	3.2	3.2
Quantity of silicon rectifiers	1	2	3	2	2	3
Weight of TPTS3-200-24 silicon rectifiers [kg]	300.000	300.000	300.000	300.000	300.000	300.000
Distribution switchboards, power and control cables, collector-and-brush-assembly unit	20.850	124.950	277.000	474.150	590.950	830.000
Weight of impressed current cathodic protection [kg]	374.650	832.550	1 338.400	1 181.750	1 314.350	1 869.200

3.3 Assessment of influence of corrosion protection type selection on the ship weight load

The weight load of a sacrificial anode and impressed current cathodic corrosion protection significantly differ, which is shown by a 3D column chart in Figure 7. However, not for all ships the weight of the impressed current cathodic protection is lower than the weight of the sacrificial anode cathodic one.

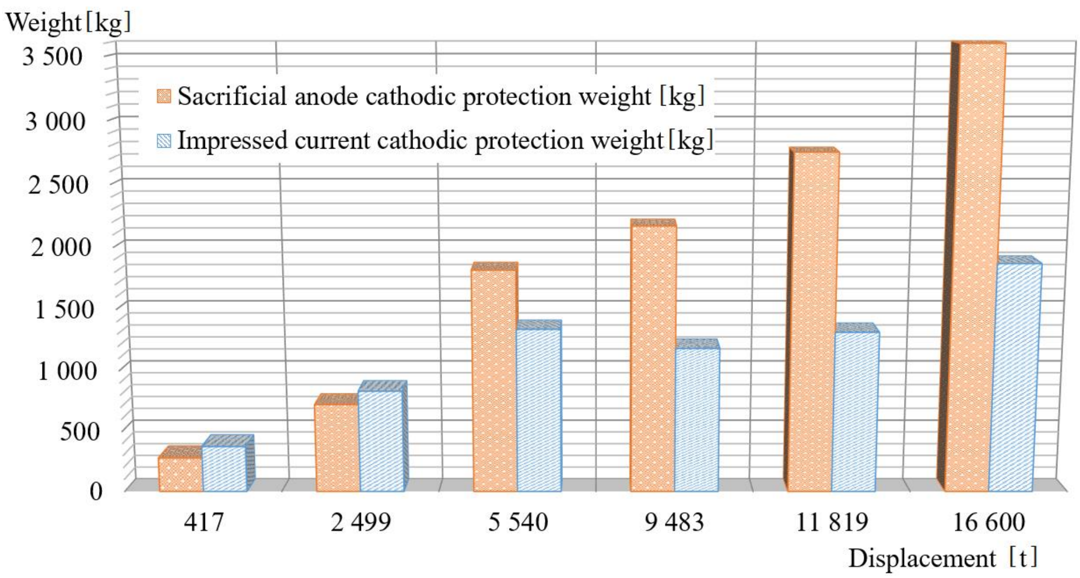

Fig. 7 Corrosion protection weight as part of the weight load

The relationship between the difference of the sacrificial anode cathodic protection and impressed current cathodic protection weight load and the displacement is shown in Figure 8.

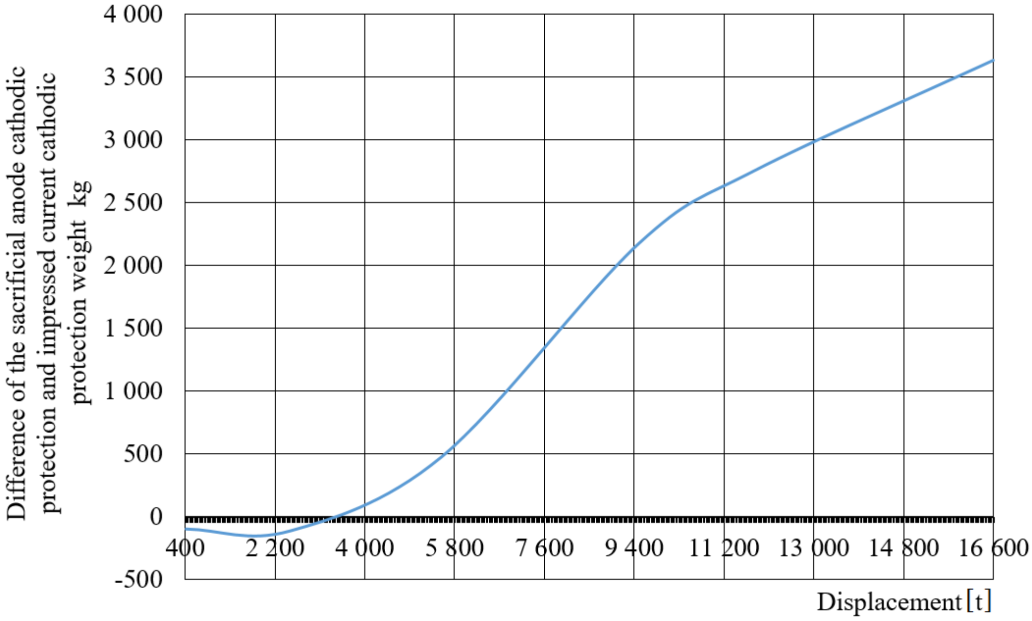

Fig. 8 Influence of corrosion protection type selection on the ship weight load

Thus, in terms of corrosion protection weight reduction, it is appropriate to consider the use of the impressed current cathodic protection system instead the sacrificial anode cathodic one for the ships with a displacement of more than 3400 [t].

4. Discussion

To assess the economic efficiency of the impressed current cathodic protection usage, compare the cost of the sacrificial anode cathodic protection and impressed current cathodic protection of the ship hulls.

The cost of the sacrificial anode cathodic protection (Table 6) is calculated based on its weight. For the purposes of taking into account the time factor, the total cost of sacrificial anode replacement every 4 years has been calculated using a currency unit correction method according to the compound interest formula. The compound interest is a percentage for each regular period which is calculated on an initial basis in a sum with the previously calculated interest [29, 30].

The value of the currency unit for a future moment of time is the product of the value of the currency unit for a current (present) moment of time and the compound interest factor corresponding to a recalculation period, depending on the replacement period (year) of the sacrificial anode cathodic protection from its initial installation [27].

The calculation of the total cost of sacrificial anode replacement for the ships in question over 35 years using the refrigerator ship *Bosfor Vostochnyy* as an example is set out in Table 7.

Table 6 Sacrificial anode cathodic protection cost for the ship hulls

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Weight of sacrificial anode cathodic protection [kg]	280	722	1 817	2 170	2 754	3 630
Cost of 1 kg [€]	3.24	3.24	3.24	3.24	3.24	3.24
Cost of sacrificial anodes [€]	907	2 339	5 887	7 031	8 923	11 761
Cost of sacrificial anode cathodic protection installation (replacement – every 4 years) [€]	30	62	148	172	221	295
Cost of sacrificial anode cathodic protection (capital expenses) [€]	937	2401	6035	7203	9144	12056
Material costs on sacrificial anode cathodic protection over 35 years [€]	22 082	116 064	291 743	348 225	442 078	582 859

Table 7 Sacrificial anode replacement cost calculation for the refrigerator ship

Period, year of operation	4	8	12	16	20	24	28	32
Compound interest factor corresponding to recalculation period	1.40	1.95	2.72	3.80	5.30	7.40	10.34	14.43
Cost for a future moment of time [€]	16832	23499	32807	45803	63945	89274	124636	174006
Total cost over 35 years [€]	570 803							

Table 8 Sacrificial anode replacement cost

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Total cost over 35 years [€]	21 145	113 663	285 708	341 022	432 934	570 803

The cost of the impressed current cathodic protection of the ship hulls is calculated as a sum of costs of all components (Table 9).

Table 9 Impressed current cathodic protection cost for the ship hulls

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Quantity of anode assemblies [pcs]	6	12	18	12	14	16
Anodes of AU-1M type [€]	8700	17400	26100	17400	20300	23200
Quantity of reference electrodes [pcs]	2	4	6	4	4	4
Reference electrodes ESKHP-SS [€]	600	1200	1800	1200	1200	1200
Quantity of silicon rectifiers	1	2	3	2	2	3
Silicon rectifiers TPTS3-200-24 [€]	3500	7000	10500	7000	7000	10500
Distribution switchboards, power and control cables, collector-and-brush-assembly unit [€]	1536	3072	4608	3072	3420	4188
Impressed current cathodic protection cost (capital expenses) [€]	14336	28672	43008	28672	31920	39088
Impressed current cathodic protection cost (annual operation costs) [€]	89	394	715	1068	1041	1347
Material costs on impressed current cathodic protection over 35 years [€]	33 917	114 910	199 588	262 658	259 817	267 654

The analysis of the performed calculations has shown that the capital expenses (Figure 9) in the impressed current cathodic protection system is greater than ones in the sacrificial anode cathodic protection system: ≈ 15.3 times for the harbour tug *RB-389*, ≈ 11.9 times for the hydrograhic survey ship *Donuzlav*, ≈ 7.1 times for the floating repair ship *PM-138*, ≈ 4.0 times for the oil carrier *Balt Flot 11*, ≈ 3.5 times for the container ship *Adler*, ≈ 3.2 times for the refrigerator ship *Bosfor Vostochnyy*.

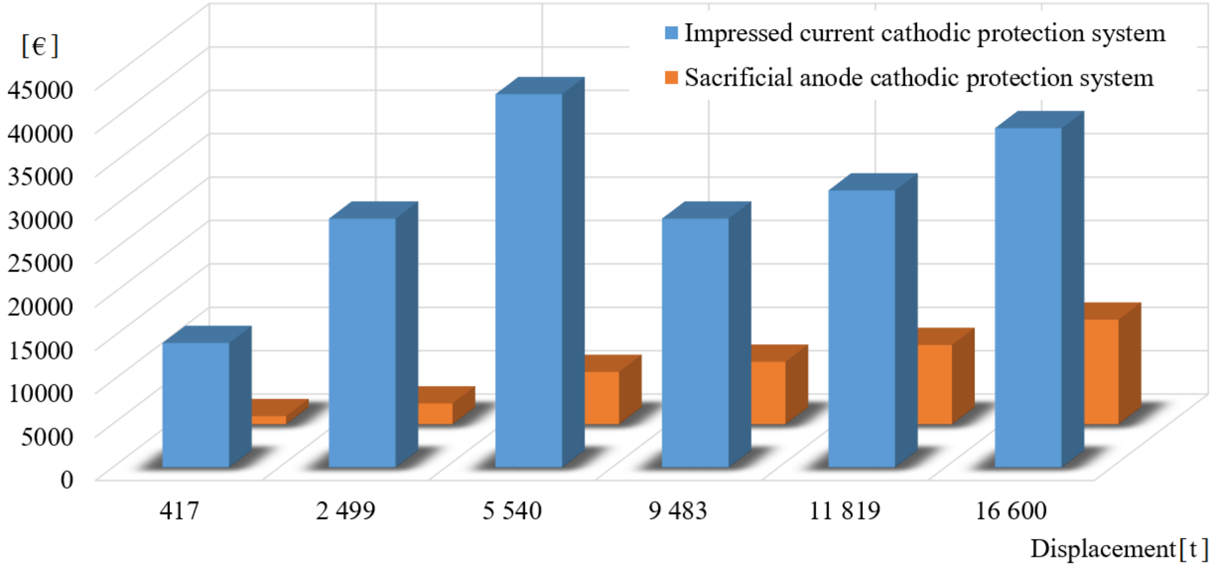

Fig. 9 Capital expenses on corrosion protection

Thus, the relationship between the decrease of difference in the initial cost of corrosion protection and the increase of ship displacement is established [16,31].

The operation costs on the impressed current cathodic protection system are calculated depending on the necessary protective current density, rated voltage and wetted surface area. First, the power to be consumed by the impressed current cathodic protection is calculated as per Equation (2):

$$N_{cp} = I_{cp} \cdot U \ \text{[kW]}, \tag{2}$$

where $I_{cp} = S_w \cdot i$ – the impressed current cathodic protection current [A], S_w – the wetted surface area of the ship hull [m^2], i – the density of current of the impressed current cathodic protection [A/m^2], U – the rated voltage [V].

The quantity of fuel oil necessary for the impressed current cathodic protection operation:

$$Q_f = q_f \cdot N_{cp} \cdot t \ \text{[t]}, \tag{3}$$

where q_f = 0.2 · 10^{-3} [t/kW · h] – the specific fuel oil consumption, t – the time for calculating the fuel weight per day is taken as 24 [h].

Fuel oil costs per year:

$$C_f = S \cdot Q_f \ \text{[€]}, \tag{4}$$

where S – the fuel oil cost.

The calculation is performed in tabular form (Table 10).

For the purposes of taking into account the time factor, the total cost of operation costs of the impressed current cathodic protection (Table 11) for each year has been calculated using a currency unit correction method according to the compound interest formula which is similar to the total cost of sacrificial anode replacement.

Table 10 Cost of operation expenses on ship hull impressed current cathodic protection

	RB-389	*Donuzlav*	*PM-138*	*Balt Flot 11*	*Adler*	*Bosfor Vostochnyy*
Protective current density [A/m^2]	0.02	0.02	0.02	0.02	0.02	0.02
Wetted ship surface area [m^2]	265.776	1 170.512	2 125.261	3 175.898	3 093.258	4 004.432
Required protective current [A]	5.316	23.410	42.505	63.518	61.865	80.089
Rated voltage [V]	24.000	24.000	24.000	24.000	24.000	24.000
Power [kW]	0.128	0.562	1.020	1.524	1.485	1.922
Specific fuel oil consumption [t/kW h]	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Fuel oil weight per day [t]	0.001	0.003	0.005	0.007	0.007	0.009
Fuel oil cost per year [€]	89.40	393.74	714.90	1068.32	1040.52	1347.03

Table 11 Annual operation costs based on the example of the refrigerator ship

Period, year of operation	2	3	4	5	…	33	34	35
Compound interest factor corresponding to he recalculation period	1.18	1.28	1.40	1.52	…	15.69	17.05	18.54
Cost for a future moment of time [€]	1 592	1 336	1 453	1 579	…	16 324	17 744	19 288
Total cost over 35 years	227 219							

Over the whole operation period the material costs (Figure 10) on the impressed current cathodic protection system is less than ones on the sacrificial anode cathodic protection system: ≈ 1.5 times for floating repair ship *PM-138,* ≈ 1.3 times for oil carrier *Balt Flot 11*, ≈ 1.7 times for container ship *Adler*, ≈ 2.2 times for refrigerator ship *Bosfor Vostochnyy*. However, the material costs for harbour tug *RB-389* and hydrographic survey ship *Donuzlav* over the whole operation period are practically equal in the case of usage of both the sacrificial anode cathodic protection and impressed current cathodic protection.

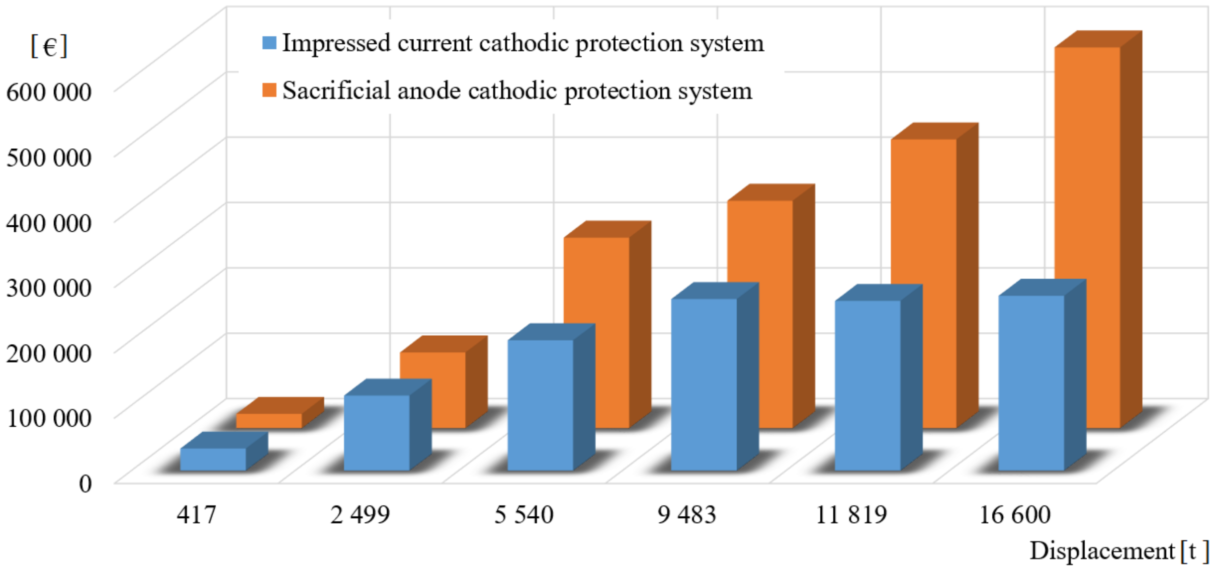

Fig. 10 Material costs for corrosion protection over 35 years

Thus, the relationship between the increase of difference in corrosion protection costs over the whole operation period and the increase of ship displacement is established [31]. The validity of the results is provided by the consistency with the data of other investigations.

The boundaries for feasibility of selecting one of the protection options are shown on reduced cost charts for various ships according to their service life. As can be seen from Figure 11, the total cost of the impressed current cathodic protection for the ships with a displacement of 417–2 499 [t] becomes less than one of the sacrificial anode cathodic protection after 30 years of operation; for the ships with a displacement of 5 540 [t] becomes less than one of the sacrificial anode cathodic protection after 18 years of operation; for the ships with a displacement of 9 483 [t] becomes less than one of the sacrificial anode cathodic protection after 12 years of operation; for the ships with a displacement of 11 819–16 600 [t] becomes less than one of the sacrificial anode cathodic protection before 8 years of operation.

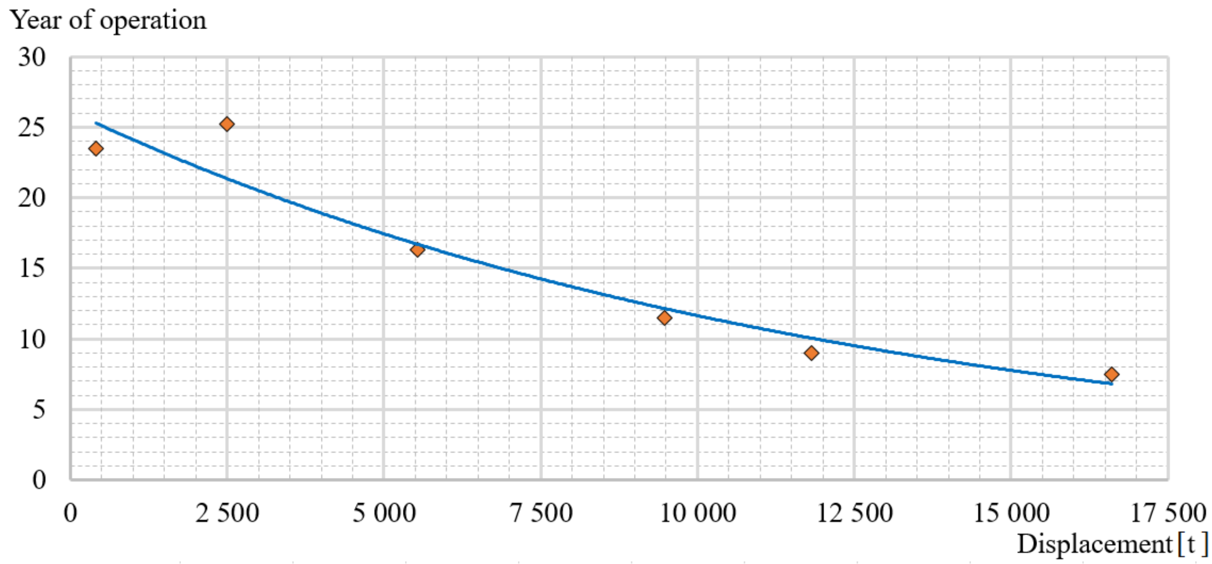

Fig. 11

Thus, it is economically feasible to use the impressed current cathodic protection system for the ships with a displacement of more than 6 000 [t]. Taking into account that the wetted surface area of the offshore structures significantly exceeds the given value for the ships with a displacement of 6 000 [t], it is recommended to use the impressed current cathodic protection for them on the basis of an economic benefit.

5. Conclusions

The performed analysis of the weight load being part of the load components under codes 01050111 and 050309## has shown that the decrease of corrosion protection weight load is observed for the ships with a displacement of more than 3 400 [t] in the case of usage of the impressed current cathodic protection instead of the sacrificial anode cathodic one. There has been identified the importance of assessing the weight loads of different corrosion protection types at initial design stages to determine the minimum corrosion protection type in terms of the weight.

In the course of the feasibility study it has been identified that the total cost of protection from stress-corrosion fractures decreases for the ships with a displacement of more than 6 000 [t] in the case of usage of the impressed current cathodic protection instead of the sacrificial anode cathodic one.

The feasibility study has also shown a benefit of using the sacrificial anode cathodic protection at the stage of capital expenses, however, when selecting a protection type it is necessary to take into account side effects from the usage of the impressed current cathodic protection at a potential of uncharged surface on the juvenile steel surface. The impressed current cathodic protection is significantly more cost-effective than the sacrificial anode cathodic one during the whole operation period, and the difference in the total cost of the impressed current cathodic protection and sacrificial anode cathodic protection increases with the ship displacement.

Prospects for further research: increasing the durability and reliability of ships and offshore structures by increasing the efficiency of their protection in the variable waterline region based on the improvement of the ships and offshore structures protecting method by cathodic polarization from local forms of corrosion-mechanical damage at the potential of an uncharged surface on the steel juvenile surface.

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