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APPLICATION OF SACRIFICIAL ANODES AND CORROSION SENSORS IN AIRCRAFT FUSELAGE STRUCTURES

The article presents a scientific justification and a novel structural solution for the application of a system of sacrificial anodes and sacrificial corrosion sensor for corrosion protection of the fuselage bottom of a transport-category aircraft. Replaceable elements operating as anodes in the condensate environment accumulating in the underfloor area of the fuselage are used as sacrificial anodes. Periodically replaceable elements of the drain valve are employed as sacrificial corrosion sensor. The sacrificial anodes and sensors are manufactured from a material that, in a condensate environment and in electrical contact with the fuselage skin structure, forms a galvanic couple in which the more active element acts as a source of electrons and positively charged ions, resulting in its degradation while preserving the integrity of the primary structural elements

Key words: *aircraft, corrosion, bilge area, Airworthiness standards, drain valve, cathodic protection, sacrificial anode.*

Introduction. The problem of aircraft corrosion is a major focus for aircraft manufacturers, operators, and aviation regulators due to its impact on aviation safety and the enormous costs associated with addressing this issue. Approximately one quarter of failures of the primary structural elements of an aircraft result from various types of corrosion damage [1]. Direct costs in the U.S. aviation industry associated with corrosion amounted to USD 2.2 billion in 2002 [2].

Corrosion, Stress-Corrosion cracking, Corrosion Fatigue of aircraft metal structures have led to catastrophic consequences [3-5]. Airworthiness standards state (CS 25.609) that each structural element must be adequately protected against damage or loss of strength due to corrosion [6].

The solution to the problem of corrosion protection is addressed by the Corrosion Prevention and Control Program (CPCP) issued by the Federal Aviation Administration, FAA Order 8300.12b; European Union Aviation Safety Agency (EASA), which represents a system for ensuring the continued airworthiness of aircraft through the prevention, detection, and mitigation of damage.

The intensity of corrosion damage depends on many factors, including operating conditions, protection methods, and compliance with periodic maintenance requirements, design solutions, and others.

This article presents a scientifically substantiated comprehensive design solution aimed at preventing an unacceptable level of corrosion in one of the most corrosion-sensitive areas of the aircraft structure - the underfloor fuselage area, where corrosion is most frequently observed due to the accumulation of condensate.

Corrosion of the aircraft bilge area. Statistics on corrosion damage indicate that the aircraft skin in the underfloor (bilge) area is one of the most corrosion-susceptible zones of the airframe structure. According to Advisory Circular AC 43-4B issued by the U.S. Department of Transportation, Federal Aviation Administration, the bilge is a natural sump or collection area for waste hydraulic fluids, water, dirt, loose fasteners, drill chips, and other debris. Residual oil frequently masks small quantities of water that

settle at the bottom, creating a hidden potential corrosion cell. With the exception of water-displacing corrosion-preventive compounds, keeping bilge areas free from extraneous materials, including water and oil, provides the most effective protection against corrosion. A vacuum cleaner and clean wiping cloths are practical tools for cleaning such areas. The fuselage bilge is also a zone where condensate accumulation commonly occurs.

By its nature, corrosion of aircraft structures is predominantly galvanic**.** This type of corrosion requires the presence of an anode**,** which tends to corrode, a cathode**,** which has a lower tendency to corrode, electrical contact between them, and an electrolyte**,** i.e. a conductive liquid. In the present case, the electrolyte is the condensate that accumulates in the underfloor area of the fuselage. Elimination of any one of these conditions will prevent the corrosion process.

The composition of the condensate that accumulates within an aircraft structure has a significant influence on its damaging effect. The results of a study on the corrosive activity of fuselage condensate in passenger aircraft are presented in the referenced work [7]. The density of the condensate varies from 0.994 to 1.011 g/cm ^{3} and the acidity from pH 6.5 to pH 8.8. Results of the chemical analysis of the subfloor condensate are shown in the table 1. The salt composition of the condensate was found to be: 600 mg/liter sodium chloride; 250 mg/liter ammonium chloride; 320 mg/liter anhydrous sodium sulfate; 350 mg/liter potassium sulfate; 1150 mg/liter condensate of ST-2 liquid.

Table 1

Ionic Composition of the Fuselage Condensate [7]

Components of the condensate	Content, mg/liter		
	min	Max	avg.
Sodium cations	52	2430	341
Potassium cations	31	663	157
Ammonium cations	10	285	85
Chloride anions	94	3820	585
Sulfate anions	108	938	412
ST-2 concentrate	0	20000	1150

To remove the electrolyte, fuselage condensate drain valves (bilge valves) are used. These valves are opened on the ground**,** allowing the accumulated electrolyte (condensate) to be drained from the internal volumes of the fuselage, and closed in flight in order to maintain cabin pressurization. Bilge valves open automatically by means of a spring-loaded mechanism that responds to the pressure differential. However, the use of such valves, as shown by the results of structural inspections during maintenance and repair, does not sufficiently solve the problem of condensate accumulation. It is well known that the presence of dirt and mechanical particles can lead to clogging of the valve orifices and to the accumulation of condensate, which acts as an electrolyte required for galvanic corrosion**.**

Application of Sacrificial anodes for the bilge area protection against corrosion. By influencing the interaction between the anode and the cathode and imparting cathodic properties to a specific structural element, the corrosion (destruction) process can be prevented. This type of protection is known as cathodic protection**.**

At present, two types of cathodic protection are used: a) Impressed current cathodic protection, which employs an external source of direct current; b) Galvanic, or

sacrificial anode, protection, in which no external power source is required and the protective current is generated due to the potential difference between the anode and the cathode.

Cathodic protection was first developed by Sir Humphrey Davy in 1824 as a means of controlling corrosion on British naval ships [8]. The sacrificial anode made of metal which has more negative potential releasing positive ions into a solution. Electrons flow to the structure having a higher electrode potential. The protected structure is a cathode and is not destroyed, with the electrons from it being released into the external medium. The process is described by scheme shown in Figure 1.

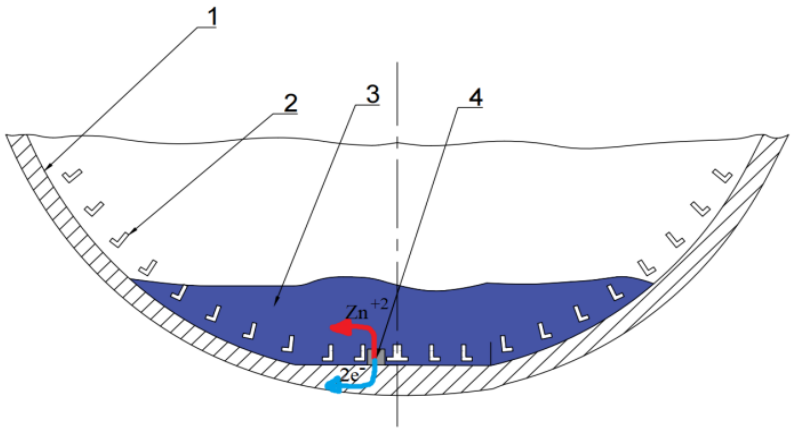


Fig.1. Proposed diagram of the sacrificial anode operation in the aircraft bilge area: 1 - skin; 2 - stringers; 3 - electrolyte; 4- sacrificial anode (Zn)

The use of sacrificial anodes for protecting aircraft structures is known in aviation; however, it is limited to external surfaces that are in direct contact with water, for example amphibian aircraft floats, their water-rudder installations, and landing-gear wheel wells [9].

The use of sacrificial anodes is widespread across various industries; therefore, anodes for different applications are currently manufactured on an industrial scale. Examples of commercially manufactured sacrificial anodes are shown in Figure 2 [10]; the geometry of typical sacrificial anodes allows one to conclude that they can be installed on structural elements of transport-category aircraft.



Flush anode for welding or bolting. A variety of sizes available in Zn and Al alloy.

Body bolted anode design for flush mounting. A variety of sizes in Zn and Al alloy.

Grip bracket set for flush anodes. Designed for easy replacement.

Fig.2. Most common anode models [10]

The selection of materials for the sacrificial anode is based on information provided by the Galvanic Series [11], in which metals are arranged according to their electrode potentials (Figure 3). The greater the difference between the electrode potentials of the metals, the higher their tendency to form galvanic couples.



Fig.3. Galvanic series [11]

For skin panels made of aluminum alloy, sacrificial anodes can be elements manufactured from magnesium or zinc. Magnesium is more active and therefore readily donates electrons. However, part of its mass is lost due to self-dissolution, which reduces its effectiveness. Zinc is less active, but its overall effectiveness in the given environment is higher [12].

An important aspect of using sacrificial anodes is their integration into the aircraft structure. The attachment must be designed in such a way as to avoid holes that would weaken the primary structural elements (PSE). This principle can be implemented by using clamp-type fastening elements.

The required mass of a sacrificial anode can be found using the conventional cathodic protection design approach based on Faraday's law, expressed as [13,14]:

$$M = I\,t/C\eta,$$

where: I – is the protection current, t – is the service time, C – is the electrochemical capacity of the anode material, η – is the utilization factor.

The following initial data are adopted for preliminary consideration:
- Protected area, $S=1m^2$;
- Specific protective current, $I = 0{,}001\ A/m^2$;
- Service duration, t = 1year = 8760 hours
- Electrochemical capacity of zinc, $C_{Zn} = 780$ A x hour x $kg^{-1} = 2{,}8 \times 10^6$ C x kg^{-1};
- η – is the utilization factor = 0,9.

Then the mass of zinc sacrificial anode:

$$m = 8{,}76 / 780 \times 0{,}9$$

$$m = 0{,}0125 \text{ kg}.$$

Taking into account the uncertainties of operating conditions (uneven moisture, contamination, anode aging), and a safety factor is usually applied in practice:

$$m_{real} = (1{,}5 – 2{,}0)\, m = 20\text{-}25 \text{ (g)} = 0{,}020 - 0{,}025 \text{ (kg)}$$

The density of pure zinc is: $\rho \approx 7.14$ g/cm³ (or 7140 kg/m³).

At a density of 7.14 g/cm³, the volume of an anode with a mass of 25 g is: 25 g / 7.14 g/cm³ = 3.5 cm³. Assuming that the surface area exceeds 1 m², the anode volume should be increased proportionally.

Sacrificial Anode-Indicator Integrated into the Drain Valve. When sacrificial anodes are used to protect the fuselage bilge area from corrosion, it becomes important to monitor not only the condition of the structure but also the condition of the sacrificial anodes themselves, which gradually dissolve as a result of the corresponding galvanic reaction.

Below, the possibility of integrating a corrosion sensor into the design of a drain valve is considered. Figure 4 shows the location of the drain valves in accordance with the layout presented in the patent [15].



Fig. 4. Location of drainage valves in the belly of a transport-category aircraft [15]

It is typical to place drain valves at intervals of 2–3 meters along the length of the fuselage. Figure 5 shows the design of a drain valve of a modern transport-category aircraft as viewed from the inner surface of the bilge area [16].



Fig.5. Fuselage drain valve [16]

The drain valve automatically drains moisture that collected in an aircraft's belly. The valves are located on the aircraft's fuselage bottom and use pressure differentials to open when the aircraft is on the ground and close when the cabin is pressurized in flight. Valves use a spring mechanism that is biased to be open on the ground. At altitude, the pressure difference creates a force that overcomes this bias and closes the valve.

The use of drainage valves is regulated by airworthiness standards, for example according to the CS 25.609 - Protection of structure: Each part of the structure must be suitably protected against deterioration or loss of strength in service due to any cause, including weathering, corrosion, abrasion, and have provisions for ventilation and drainage where necessary for protection.

When sacrificial anodes are used, the task of monitoring their consumption (dissolution) arises. This task can be addressed by integrating additional sacrificial elements into the valve structure (Figure 6). Design of the proposed valve comprises typical elements of the drainage valve, as for example it is described in the patent of Gorges et al. [15].

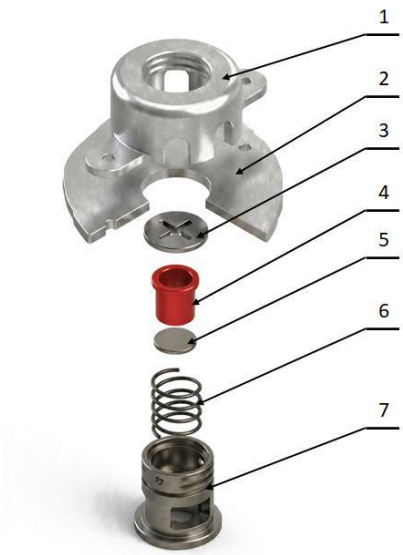


Fig.6. Integration of the sacrificial anode component into the drainage valve: Drain valve assembly; 1 - retainer; 2 - fuselage skin; 3- valve stem; 4 - retainer (sacrificial anode); 5 - blanking disc ; 6 - return spring; 7 - sacrificial anode; 8 - valve housing.

The drainage valve operates as a normally open, pressure-responsive device integrated into the fuselage structure (2), enabling continuous removal of accumulated condensate under depressurized conditions. Its functional principle follows the piston-type configuration. A spring-biased movable element ensures automatic switching between open and sealed states depending on the pressure differential across the fuselage wall.

In the presented configuration, the valve housing (8) contains a valve stem (3) that is axially movable and biased by the return spring (6) toward the open position. Under ground conditions or when the cabin is depressurized, the spring force dominates, maintaining the valve in an open state. This allows water to pass through the drainage path without obstruction. The retainer (1), fixed to the fuselage skin (2), provides structural support and alignment of the internal components. A key difference of this design is the use of a metallic retainer (4) that functions as a sacrificial anode. This element is intentionally made from a material with lower electrochemical potential relative to surrounding structural components, thereby preferentially undergoing corrosion. The blanking disc (5) is rigidly attached to this retainer and manufactured

from the same material as the valve housing (8), ensuring compatibility with the sealing interface. During flight, when cabin pressure increases relative to the external environment, the pressure differential acts on the valve stem (3), overcoming the preload of the return spring (6). As a result, the valve transitions into the closed position, and the blanking disc (5) contributes to sealing the drainage opening, preventing air leakage and maintaining pressurization efficiency. This behavior is consistent with the piston-like reciprocating mechanism described in the referenced patent, where the valve member is driven against a seat by differential pressure.

The sacrificial function introduces an additional monitoring feature. In the event of progressive corrosion and eventual degradation of the retainer (4), its structural integrity is lost. As a result, the blanking disc (5) is no longer supported and falls down. It closes the drainage opening. This can be easily noticed during ground inspection. Under normal conditions, the return spring (6) keeps the valve open. If the opening appears closed, it indicates a failure of the sacrificial retainer. Such a deviation from the expected open state provides a clear visual indication of retainer failure and signals the need for maintenance and replacement of the sacrificial anode component.

Thus, the proposed valve design makes it possible to inspect the condition of the sacrificial anodes without performing complex access procedures to the internal surfaces of the skin in the bilge (underfloor) area. The use of removable auxiliary sacrificial elements integrated into the structure allows their condition to be assessed and, on this basis, conclusions to be drawn regarding the condition of the sacrificial anodes mounted on the inner surface of the skin.

The inspection procedure for the indicator anodes consists of visual examination and assessment of their mass loss due to corrosion. This approach is consistent with the well-established practice of using corrosion coupon sensors to monitor material degradation. The inspection interval should be determined based on operational experience for a specific aircraft type operating under particular climatic conditions, as well as on data regarding the rate of corrosion damage. However, it is advisable to align the inspection frequency with the established maintenance schedule.

The following routine inspections are carried out: A-Check (every 400–600 flight hours), which involves a general visual inspection of the area for signs of corrosion or fluid accumulation that may indicate blocked drains, and C-Check (every 18–24 months), which consists of a detailed inspection. It is during these “heavy” maintenance checks that the valves are typically function-tested, cleaned of contaminants, and inspected for blockages (the so-called Drain Path Check).

In addition, inspections must be performed in accordance with applicable Service Bulletins (SBs) or Airworthiness Directives (ADs)**,** which may require more frequent checks in cases where significant fuselage corrosion due to water stagnation has been identified, when the aircraft is operated in high-humidity environments, or when there have been instances of debris accumulation leading to valve blockage.

Given the exploratory nature of the proposed solution, it is necessary to conduct a series of studies to establish a correlation between the condition of the proposed regular cathodic protection of the Principle Structural Elements (PSE) in the bilge area and the level of degradation of the indicator anodes.

Conclusions. The proposed methodology for improving the aircraft corrosion protection system and the corresponding design solutions enable the comprehensive application of the cathodic protection concept using sacrificial anodes. Installation of sacrificial anodes inside the aircraft fuselage makes it possible to slow down the development of galvanic corrosion of the primary structural elements of the fuselage in the condensate accumulation area, which is identified as one of the most corrosion-sensitive zones of the structure.

Modification of the drain valve by integrating its design with a sacrificial corrosion sensor allows monitoring of the depletion level (remaining service life) of the sacrificial anodes that protect the fuselage skin from corrosion.

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ЗАСТОСУВАННЯ ЖЕРТВЕНИХ АНОДІВ І СЕНСОРІВ КОРОЗІЇ В КОНСТРУКЦІЇ ФЮЗЕЛЯЖУ ЛІТАКА

Корозія авіаційних конструкцій є одним із основних факторів, що впливають на несучу здатність конструкцій, їх надійність та довговічність. Однією із найбільш чутливих зон конструкції літака, є його днище, яке є зоною накопичення конденсату та інших рідин у випадках недостатньо ефективної дренажної системи. У статті наведено наукове обґрунтування та запропоновано нове конструктивне рішення щодо застосування системи жертвенних анодів і жертвенного сенсора корозії для захисту від корозії нижньої частини фюзеляжу транспортного літака.

В якості жертвенних анодів використовуються змінні елементи, що працюють в умовах конденсату, який накопичується в підпідлоговій зоні фюзеляжу. В якості жертвенного сенсору корозії застосовуються елементи дренажного клапана, що підлягають періодичній заміні.

Жертвенні аноди та сенсори виготовляються з матеріалу, який у середовищі конденсату та за наявності електричного контакту з обшивкою фюзеляжу утворює гальванічну пару. У такій парі більш активний елемент виступає джерелом електронів і позитивно заряджених іонів, унаслідок чого він зазнає руйнування (корозії), тоді як цілісність основних елементів конструкції зберігається.

Ключові слова: повітряне судно, корозія, днище фюзеляжу, Норми льотної придатності, катодний захист, жертвенний анод.

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