minerals

MDPI

*Article*

# Cathodic Protection System of the Spiral Classifier at the KGHM Polska Miedź S.A. Ore Concentration Plant—Case Study of Commissioning and Control of Operating Parameters

**Marcin Czekajlo [1,*] and Krzysztof Zakowski [2]**

[1] KGHM Polska Miedź S.A. Ore Concentration Plant, 1 Kopalniana Street, 59-101 Polkowice, Poland
[2] Department of Electrochemistry, Corrosion and Materials Engineering, Faculty of Chemistry, Gdansk University of Technology, 11/12 Gabriela Narutowicza Street, 80-233 Gdansk, Poland
* Correspondence: marcin.czekajlo@kghm.com

**Abstract:** The project involved designing, constructing and commissioning a cathodic protection system for a selected spiral classifier operating at the KGHM Polska Miedź S.A. Ore Concentration Plant (O/ZWR). The authors developed a concept and assumptions regarding the corrosion protection of a large industrial device using a cathodic protection system with an external power source. Pre-project studies included conducting a trial polarization of one of the 28 classifiers operating at O/ZWR. The obtained results enabled the determination of the protective current demand required and the selection of a target polarization device, ensuring the flow of current with an intensity that guarantees that the required corrosion protection level will be achieved. The ultimately installed cathodic protection system consisted of an external cathodic protection current source with maximum output parameters of 50V/20A, a power supply system and a polarization anode system. Elements for monitoring corrosion occurring during system operation were installed, which employed reference electrodes of zinc (Zn) and silver chloride (Ag/AgCl) to measure the potential of the structure under cathodic protection. Furthermore, resistive corrosion sensors were installed to measure the steel corrosion rate under polarization conditions, making it possible to assess the effectiveness of the protection. The system will also be equipped with a prototype system for remote monitoring of the operation of the protection system, enabling online observation and analysis of settings and temporary indicators influencing the ongoing corrosion processes.

**Keywords:** erosion corrosion; spiral classifier; gravity classification; cathodic protection system; advanced control; optimization



**Citation:** Czekajlo, M.; Zakowski, K. Cathodic Protection System of the Spiral Classifier at the KGHM Polska Miedź S.A. Ore Concentration Plant—Case Study of Commissioning and Control of Operating Parameters. *Minerals* **2022**, *12*, 1132. https://doi.org/10.3390/min12091132

Academic Editors: Josep Oliva and Carlos Hoffmann Sampaio

Received: 27 July 2022
Accepted: 2 September 2022
Published: 6 September 2022



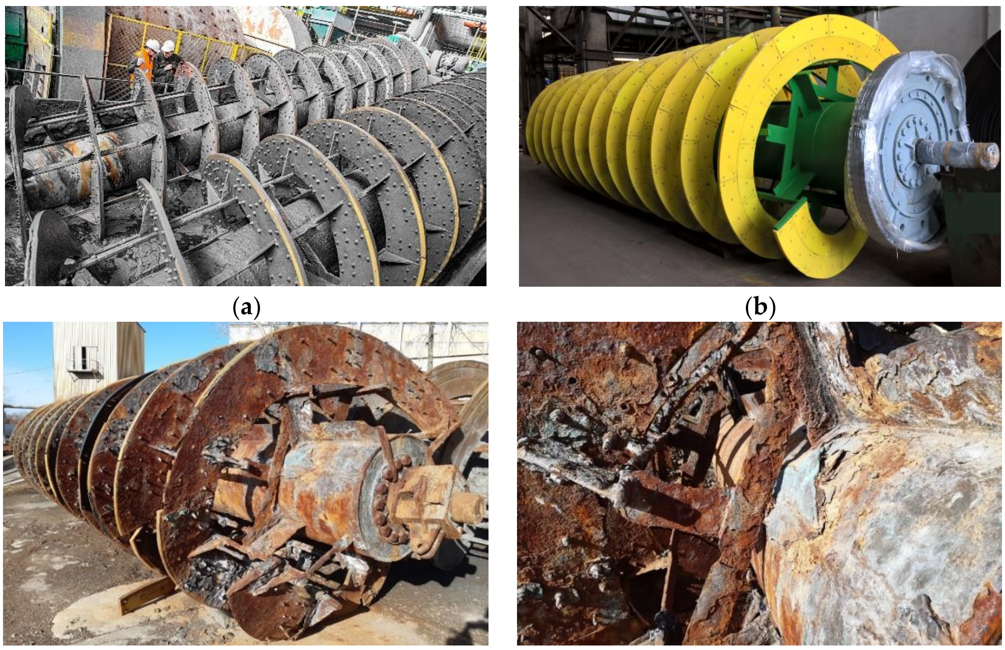
## 1. Introduction

KGHM Polska Miedź S.A. is one of the world leaders in copper and silver production. As a modern and global company, KGHM Polska Miedź S.A. conducts mining and processing activities on three continents, namely, Europe, as well as North and South Americas [1]. In addition to copper deposits reaching 40 million tonnes of pure metal, the company owns other valuable raw materials, broadly used in different industry sectors. These include gold, molybdenum, rhenium, and lead [2]. Owing to constantly improved manufacturing processes and extensive R&D (research and development) activities, it is possible to continue mining and processing operations targeted at obtaining final products, the largest share of which corresponds to metallic copper with a minimum raw material content of 99.99%.

The Division of Ore Enrichment Plants (O/ZWR) is crucial among the many production divisions comprising the process line. It consists of three production areas: Lubin, Polkowice and Rudna. The main goal of O/ZWR is to maximize metal output and produce concentrates meeting the quality parameters required by steel mills, while maintaining the lowest possible costs and minimizing the impact on the natural environment. This task is implemented through a series of subsequent processes. The first stage is to prepare (i.e., break up) the output, which contains 1.5% copper on average, and prepare it for grinding and classification. The amount of processed output oscillates around 32 million tonnes of wet weight. The appropriately prepared grains are then subjected to floatation [3], leading to the production of copper concentrate with an average copper content of 23%. The produced concentrate ultimately undergoes drainage, filtration, and drying processes, before being sent to steel mills. Meanwhile, the generated waste, which makes up 94% of the processed material, is sent to the "Żelazny Most" Mining Waste Treatment Facility [4].

The implemented system solutions make it possible to effectively utilize natural resources, including the copper deposits and water employed as part of the technological process, while also optimizing the use of the energy required for the operation of the many machines and devices involved in the production line. Achieving nearly 90% recovery of valuable metals requires high availability rates to maintained for the machines and equipment, as well as the processing and technological systems. One of the main causes behind their reduced effectiveness is operation under conditions of strong erosion corrosion [5].

One key device that is exposed to corrosion and erosion processes is the spiral classifier. This is a large-sized device used to segregate feed grains in terms of their size and weight in an aqueous medium [6]. O/ZWR has 29 parallel grinding and classifying systems, which include primary and secondary grinding mills, as well as spiral classifiers. Their size is determined by means of coil diameter, which falls in the range of 2400–2600 mm, with a length of up to 13,000 mm. In total, there are 86 mills and 29 classifiers operating at O/ZWR. Each of the classifiers is fitted with two spirals, totalling 58 units. Every classifier shutdown is associated with processing section downtime, i.e., of the primary grinding mill, classifier, and secondary grinding mill. A shutdown leads to certain hindrances in conducting the concentration process and leads to the reduced operational effectiveness of the plant (Figure 1). The most common cause of classifier shutdown is the need to regenerate both the inside of the classifier tank and the spiral therein [7].



(**a**) (**b**) (**c**) (**d**)

**Figure 1.** View of an operating classifier (**a**), and a new (**b**) and used (**c**,**d**) spiral.

The operating environment of the classifier is very demanding, due to the presence of highly saline process water and crushed rock [8], 95% of the grains of which are smaller than 1 mm. The 2021 data originating from the chloride and sulphate monitoring system created for the purposes of KGHM Polska Miedź S.A. indicate the presence of chloride ions ($Cl^-$) at a level of 36.05 g/dm$^3$, while the concentration of sulphate ions reaching the Polkowice area is 1.81 g/dm$^3$.

The techniques currently employed to protect spiral classifiers against corrosion are focused on barrier protection made up of coating layers and protection in the form of abrasion-resistant linings [9] applied on the working surfaces of the spirals, which transport classified grains. There are several materials, in the form of both coating layers and plastic layers, that are able to protect parts of operating devices exposed to erosion corrosion. In the case of coating layers, the highest durability is exhibited by phenolic epoxy- and urea-based elastomer materials, as well as materials containing hard ceramic additives [10]. The lowest weight losses among a number of tested linings (in the original study presented in [11]) were exhibited by ultra-high molecular polyurethanes and polymer materials, including polyamides containing added molybdenum disulphide [12]. The application of a barrier coating and lining protection significantly limits the degradation process of a device, namely, the spiral classifier. However, it does not provide full corrosion protection due to the always-ongoing degradation of the coating, and for this reason, the first spiral classifier cathodic protection system at O/ZWR was launched in the Polkowice Area at the beginning of 2022. This is a scientific and process novelty on a global scale [13].

## 2. Materials and Methods

### *2.1. Concept of Spiral Classifier Cathodic Protection*

The direct adaptation of typical solutions for the cathodic protection of industrial facilities was not possible in the case of the implemented project. The classifier spirals are not constantly immersed in the electrolyte, which is an aqueous suspension of ground ore, but rather emerge periodically. The spirals perform approximately four rotations per minute. Meanwhile, the classic method of cathodic protection is applied to metal structures immersed in an electrolyte (water, ground), and surfaces emerging from the electrolyte are not protected by the cathodic protection current. An additional difficulty is the assembly of the elements of the protective installation inside the bathtub in which the spirals rotate, and the fact that metal contaminants (e.g., mining anchors) may get inside, which can result in damage to the polarizing anodes. In the future, it is planned to modify the shape of the bathtub in order to better protect the polarizing anodes.

Cathodic protection is one of the most efficient methods for protecting steel structures in electrolytic environments against corrosion [14]. It is an active electrochemical method, and enables protection against corrosion by lowering the potential of steel to a protected potential range, within which the metal is thermodynamically stable [15]. In such cases, the propagation of iron ions through the solution is stopped by halting the metal oxidation process. Subsequently, only reduction processes occur on the metal's surface. The reduction of the potential through cathodic polarization is achieved with the use of a protection current that flows from auxiliary anodes, through the electrolyte, and to the metal surface [16,17].

No literature reports on the application of cathodic protection for protecting spiral classifiers against corrosion were found. Since the inside of the classifier is a steel structure that is electrically continuous and filled with a highly conductive water suspension, it was assumed that it would be possible to obtain a uniform current and potential distribution on the surface of the element immersed in the feed inside a classifier tank subjected to cathodic protection.

Pre-project tests showed that the desired potential distribution could be achieved owing to the high electrolytic conductivity of the water suspension, the high polarization resistance of the metal structure, which was increased by the presence of an insulating coating, and an appropriate number and correct positioning of polarization anodes. Preparation of the classifier tank for anode installation is shown in Figure 2. The structural details of the anode and the arrangement method are not provided in this publication due to a patent application having been submitted for this process solution.


**Figure 2.** Preparation for anode installation: (**a**) view of the classifier with dismantled spiral; (**b**) view of the classifier with two dismantled spirals and feed removed from inside the tank.

### *2.2. Selection of Protection System Elements*

A trial cathodic polarization of the classifier was conducted during a shutdown of one of ten processing sections operating at the O/ZWR Polkowice Area. The first stage of the operation involved uniformly distributing polarization anodes and measuring the corrosion potential of the classifier elements prior to polarization (Figure 3). The measurements were conducted relative to a zinc reference electrode by immersing it in a water suspension directly at the surface of the tested element.

**Figure 3.** Spiral classifier potential measurements during the trial cathodic polarization.

In the course of cathodic polarization using a portable cathodic protection station employing a 5 A (Test 1) and 10 A (Test 2) current, it was observed that the trial cathodic protection system induced a desirable change of the classifier potential, proportional to the protection current intensity. The change in the potential was the highest in the area of the polarization anodes, where a full classifier cathodic protection value was achieved in Test 2, i.e., below +250 mV versus the zinc electrode (pursuant to the standard [18]). In places more remote from the anodes, where the cathodic polarization value is always lower, the change in the potential amounted to several tens of millivolts less. Therefore, the distribution of the target anodes was crucial to enabling the polarization of the steel structures of the classifier to the full level of protection.

### *2.3. Cathodic Protection Station—Polarizer*

Based on the measurements performed during the trial cathodic protection of the spiral classifier and the low anode transition resistance owing to high feed conductivity, the authors installed a station with maximum output parameters of 20 A/50 V. The station consists of an MSOK-02 polarizer by Apator Elkomtech Poland, which is a DC source and an anode system (consisting of a dozen or so polarization anodes) fitted inside the classifier, with external cabling in the form of conduits routed to the cathodic protection station. The device is equipped with a control and measurement panel designed to conduct measurements related to changes in the station's operating parameter settings, and monitoring cathodic protection (Figure 4).


**Figure 4.** View of the MSOK-02 microprocessor cathodic protection station and its control panel.

A schematic diagram of the polarization system is shown in Figure 5.

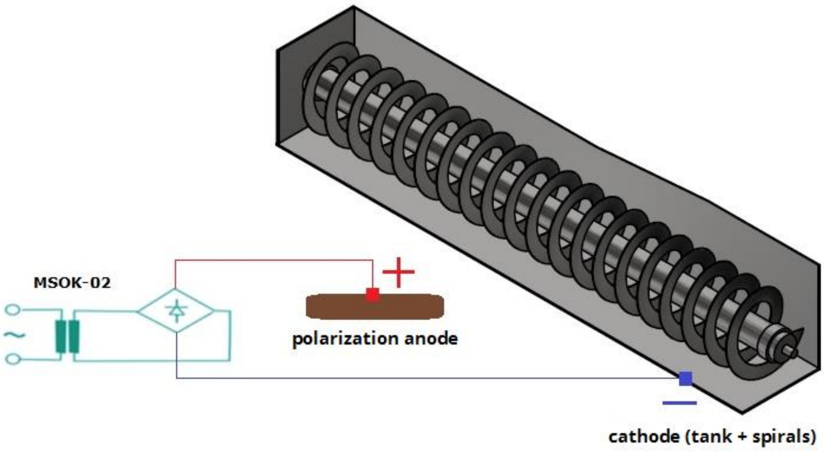



**Figure 5.** Simplified polarization system diagram—view of a single classifier spiral.

The polarizer cabinet, with dimensions of 850 × 1300 × 320 mm and made of a polymer material, was also equipped with a residual current device, a fuse switch, an overcurrent switch, a protection circuit overvoltage limiter, and a measuring circuit overvoltage limiter (Figure 6).

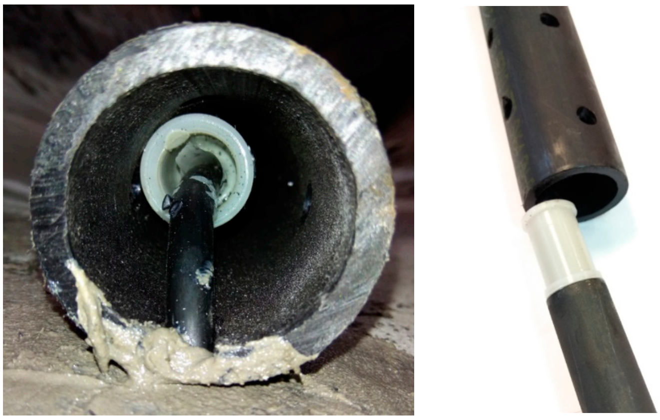
(**a**) (**b**) (**c**)

**Figure 6.** (**a**) Polarizer cabinet, (**b**) view of housing, (**c**) interior.

Cables from all of the cathodic protection system elements and the power supply system routed from a voltage switchgear located near the classifier were connected to the cabinet.

*2.4. Polarization Anodes*

All anodes were placed in a perforated thin-walled DN50 pipe made of ABS plastic. Polarization anodes made of durable titanium oxide coated with Ti/MMO (mixed metal oxide) noble metal oxides were selected based on the analysis conducted of the chemical composition of the aqueous electrolyte constituting the feed for the operation of the spiral classifier and the operation specifications of the device itself [19]. Details such as the number and dimensions of the anodes, as well as their location, are described in the patent application. The anodes were cabled from two sides, and cable–anode connections were covered with an epoxy resin-based sealing compound (Figure 7).



(**a**) (**b**)

**Figure 7.** (**a**) View of the Ti/MMO anode installed on the bottom of the classifier tank, (**b**) view of the anode tip and protective tube before installation.

*2.5. Other Cathodic Protection System Elements—Zinc Electrode*

The potential of a cathodically protected device structure can be conducted using appropriately selected reference electrodes installed within the protection system. In the highly saline water environment used during the classification process, this function can be performed by zinc or silver chloride electrodes.

The zinc reference electrode acts as a control electrode in the constructed protection system. This means that its indications constitute a basis for the selection of the operating parameters of the polarization current source.

A zinc electrode was placed in a perforated thin-walled DN50 ABS plastic pipe and permanently fixed inside a spiral classifier tank (Figure 8).

**Figure 8.** View of a zinc electrode intended for installation within the protection system.

### 2.6. Other Cathodic Protection System Elements—Silver Chloride Electrode

A portable, silver chloride measuring electrode, together with its underwater adapter, was applied to measure the cathodic protection potential of the structure immersed in electrolyte. In the case of the system in question, it acts as a reference for the control (zinc) electrode. The potentials of the zinc electrode relative to the silver chloride electrode are measured in order to verify the correct operation of the zinc electrode. In this case, its potential versus the silver chloride electrode should reach a value of −1050 mV (±50 mV). An electrode produced by M.C.Miller, Sebastian, FL, USA was installed in the presented system (Figure 9).


**Figure 9.** A portable silver chloride Ag/AgCl/saltwater electrode intended for installation within the protection system.

### 2.7. Other Cathodic Protection System Elements—Corrosion Sensors

The corrosion rate of steel under cathodic polarization conditions can be measured using appropriately matched resistive corrosion sensors, which are shorted for this purpose using the cathodically protected structure in order to simulate its behaviour (Figure 10). The measured increments in resistance make it possible to determine the decrements in the metal due to corrosion over time. The resistive corrosimetry technique makes it possible to track changes in resistance over time, which ultimately enables the precise determination of ongoing corrosion processes [20].

(**a**) (**b**)

**Figure 10.** Corrosion sensor: (**a**) complete with a connecting cable, (**b**) view of a measuring element.

Two corrosion sensors of the types ER-5/1,0-FC-1 and ER-1/1-FR were installed inside the classifier tank (Figure 10). Each of them was placed in a perforated thin-walled DN50 pipe made of ABS plastic. In order to assess the effectiveness of the corrosion protection, the active part of the ER-1/1-FR sensor was galvanically connected to the classifier tank structure inside the polarizer cabinet (and was therefore subjected to cathodic protection), while the active part of the ER-5/1.0-FC-1 sensor remained unconnected to the structure in order to evaluate the changes taking place on its surface without cathodic protection.

### 2.8. Cathodic Protection Station Commissioning

The MSOK-2 device was started up in a galvano-static operation mode. The initial protection current value was set at 5.0 A, which was automatically maintained by the device during operation. Upon starting the system, the start-up and switch-off potential (potential without the IR component, measured immediately upon deactivation of the polarizing current) was measured versus the Zn electrode. The current was also measured individually for all anodes at a pre-set total polarization current. Furthermore, the authors measured the potential distribution along the protected structure versus the Ag/AgCl electrode. Two corrosion sensors were used to assess the effectiveness of the cathodic protection of the spiral classifier based on corrosion rate measurements. The aforementioned measurements were performed using two devices: a digital DT-987 Multimeter (CEM Test Instruments GmbH, Bremen, Germany) and an ATLAS 1001 COR (ATLAS-SOLLICH

Zakład Systemów Elektronicznych, Rębiechowo, Polska) resistive corrosion meter (Figure 11).

(**a**) (**b**) (**c**)

**Figure 11.** Meters fitted in the protection system: (**a**) multimeter for potential measurements, (**b**,**c**) ATLAS 1001 COR resistive corrosion meter with accessories.

## 3. Verification Measurements—Monitoring the Operational Effectiveness of Cathodic Protection

The designed spiral classifier cathodic protection system also includes a system for monitoring its operational effectiveness. The solutions applied therein make it possible to conduct a tangible assessment of the protection system's operation over a longer operation period. This is achieved by taking specialized corrosion measurements on the basis of the applied potential and/or the corrosion rate criteria.

The authors used an extensive control system consisting of:

- Measuring the potential of the cathodically polarized structure;
- Measuring the steel corrosion rate under conditions of cathodic protection using resistive corrosion sensors;
- Monitoring the station operating parameters in online mode (under development).

The measurements described above are conducted at intervals of about one month. The requirement for the constructed anti-corrosion system is that is satisfies the cathodic protection criteria set out in EN 12499 [21] and EN 12954 [22], by polarizing the internal steel surface of the classifier tank and structural elements of the spiral to a protection potential of +250 mV versus the zinc electrode, and reducing the corrosion rate of the steel device surfaces immersed in the electrolyte to an assumed level of 0.05 mm/year, while reducing the corrosion rate of the steel surfaces of the device that are periodically immersed (i.e., the classifier band) to a level of 0.1 mm/year. Therefore, it is planned for the protection system to be in operation for a period of at least 10 years. Correct operation of the protection system, in line with the instructions and guidelines in the operation and maintenance manual, as well as performing periodic verification measurements, may ensure the full corrosion protection of a cathodically protected device. This simultaneously translates into longer service life and the reduction of the number of required repair interventions to a minimum.

The measured classifier potential distribution (Figure 12) and the operating parameters of the individual system elements (Figure 13) during the first 3 months of commissioning indicated that, in the case of a 5.0 A polarization current, it was impossible to achieve the polarization of the entire classifier surface to a full cathodic protection value. There were locations where the potential was several dozen mV more positive than 250 mV versus the zinc electrode, meaning that partial cathodic protection had been achieved [22]. Therefore, the polarization current intensity was increased to 7.5 A. On the basis of the measurements of potential distribution, it was found that the values in this case ranged from −50 mV to +250 mV throughout the entire classifier surface. Hence, the cathodic polarization was able to achieve the full cathodic protection value.

**Figure 12.** Verification measurements of the classifier spiral potential using a portable electrode.

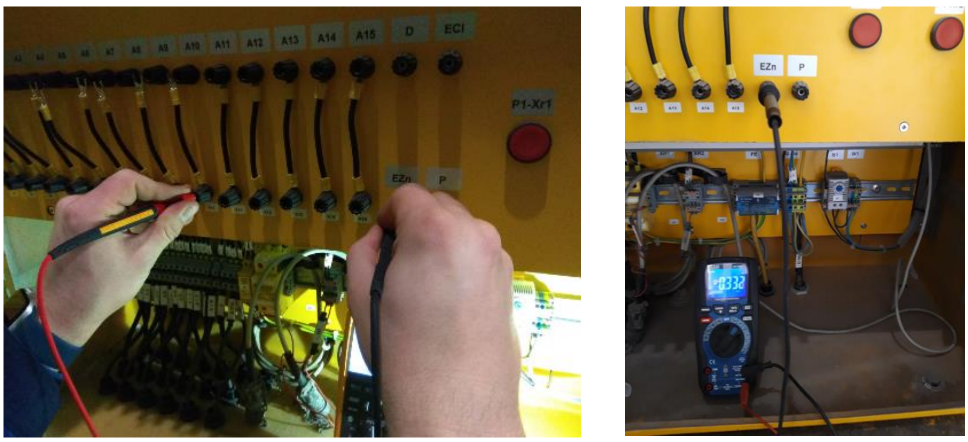



**Figure 13.** Measurement of the operating parameters of the protection installation element inside the polarizer cabinet.

Measurement data obtained using corrosion sensors indicate that the applied cathodic protection reduced the corrosion rate in the protected structure from a value of approximately 0.3 mm/year to 0.01 mm/year.

Furthermore, in order to assess the operational effectiveness of the electrochemical protection, the authors installed a 4-mm-thick steel reference plate with dimensions of 15 × 30 cm inside the classifier tank (Figure 14). This was galvanically connected to the classifier structure; therefore, it was subjected to cathodic protection. The plate, constantly immersed and in contact with the structure, undergoes periodic observation of the corrosion processes taking place on its surface, and thickness measurements are also performed.

An identical reference plate was also installed in a different spiral classifier that is not cathodically polarized. Both plates were compared in order to study the difference in the progression of corrosion failure mechanisms in order to determine their weight loss on the basis of the reduction in thickness. After 6 months, the thickness of the reference plates was measured. In the protected classifier, the average thickness loss of the plate (i.e., the averaged results of thickness measurements made in 10 places on the plate) was 0.008 mm, which after conversion gave a corrosion rate of 0.016 mm/year (Figure 15). This value was slightly greater than that obtained using the corrosion sensor (i.e., 0.01 mm/year), which was due to the feed having a greater erosive effect on the plate than on the mounted sensor. On the other hand, the average thickness loss of the reference plate placed in the unprotected classifier was 0.13 mm, which after conversion gave a value for the corrosion rate of 0.26 mm/year".

**Figure 14.** View of the reference plate installed inside the classifier tank.

**(a)** **(b)**

**Figure 15.** View of the reference plate installed inside the classifier tank: (**a**) plate with cathodic protection, (**b**) plate without cathodic protection.

In addition, due to the highly erosive nature of the classified rock material and the possible presence of foreign elements (mainly steel scrap), the system elements installed inside the tank undergo detailed inspections once every quarter. This involves identifying the condition of the anode (Figure 16) covers, electrodes and sensors, as well as the durability and continuity of the cable connections.

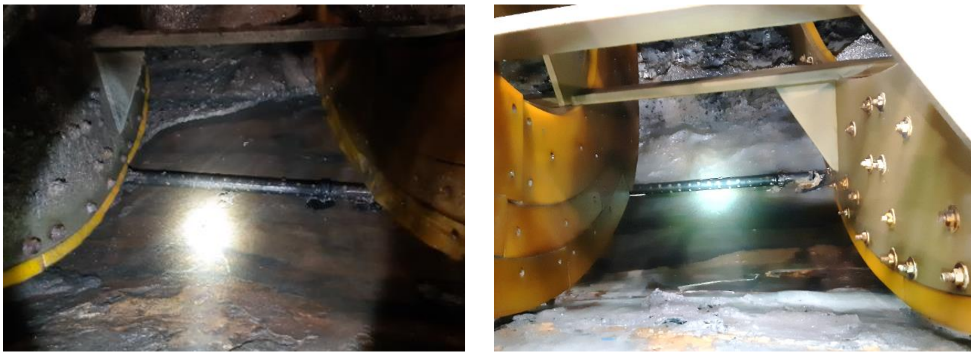


**Figure 16.** View of selected polarization anodes installed in a perforated ABS cover.

## 4. Conclusions

The implementation of an innovative spiral classifier cathodic protection technology under O/ZWR conditions went according to plan. Design guidelines were followed in terms of selecting the device and arranging the individual system elements. All installed protection system components were checked for correct operation. This included polarization anodes, reference electrodes and corrosion sensors. The next step was to commission the protection system. The authors simultaneously introduced internal procedures related to the operation of the cathodic protection system and ensuring its operational safety. An important part of the project was the determination of system operating parameters. In this case, the polarization current intensity amounted to 7.5 A. Despite the operating specificity of the device and the nature of the passing feed, the assumed effect of cathodic polarization with respect to full cathodic protection potential was achieved after the operating conditions of the protection system had stabilized. System commissioning entailed a stage of collecting and analysing data, in terms of both the correct operation of the protection station and the protection effects achieved. First, the corrosion rates of the structure, measured 6 months after the system was commissioned, indicated an average level of 0.01 mm/year. On the basis of the analysis of all of the work conducted and the effects achieved by the pilot cathodic protection of the spiral classifier system under O/ZWR conditions, the development of this technology is recommended, despite its unusual application conditions. It should be noted that designing or reconstructing the classifier circuits at O/ZWR requires modification of the construction of the classifier tanks to enable easier installation of polarization anodes and better mechanical protection during device operation.

**Author Contributions:** Conceptualization, methodology, formal analysis, and writing—original draft preparation, M.C.; investigation, M.C., K.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper originated as part of a Ph.D. thesis developed in the 'Implementation doctorate' programme, co-financed by funds from the Ministry of Science and Higher Education of the Republic of Poland and of KGHM Polska Miedź S.A. at the Department of Electrochemistry, Corrosion and Materials Engineering at the Gdansk University of Technology.

**Data Availability Statement:** Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Kuzba, B.; Pawlos, W.; Konieczny, A.; Krzeminska, M. Optimisation Platform for copper ore processing at the Division of Concentrator of KGHM Polska Miedz SA. In Proceedings of the E3S Web of Conferences, Paris, France, 12–14 September 2016; EDP Sciences: Les Ulis, France, 2016. [CrossRef]
2. Kaźmierczak, U.; Blachowski, J.; Górniak-Zimroz, J. Multi-criteria analysis of potential applications of waste from rock minerals mining. *Appl. Sci.* **2019**, *9*, 441. [CrossRef]
3. Bulatovic, S.M. *Handbook of Flotation Reagents*; Elsevier: Petersborough, ON, Canada, 2007; pp. 235–293. [CrossRef]

4. Pactwa, K.; Górniak-Zimroz, J. Copper ore post-flotation settling tanks in Poland: Socialacceptance or objection? *Environ. Dev. Sustain.* **2022**, *24*, 5003–5031. [CrossRef]
5. Lu, B.T. Statistical approaches for assessment of water corrosivity. *Corros. Eng. Sci. Technol.* **2011**, *46*, 651–656. [CrossRef]
6. Lan, X.; Gao, J.; Du, Y.; Guo, Z. A novel method of selectively enriching and separating rare earth elements from rare-earth concentrate under super gravity. *Miner. Eng.* **2019**, *133*, 27–34. [CrossRef]
7. Czekajło, M.; Zakowski, K. Increasing efficiency of technological process by limiting impact of corrosive environment on operation of spiral classifiers. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *427*, 012032. [CrossRef]
8. Torres, C.M.; Taboada, M.E.; Graber, T.A.; Herreros, O.O.; Ghorbani, Y.; Watling, H.R. The effect of seawater based media on copper dissolution from low-grade copper ore. *Miner. Eng.* **2015**, *71*, 139–145. [CrossRef]
9. Murzakov, M.; Petrovskiy, V.N. Receiving Wear-Resistance Coverings Additives of Nanoparticles of Refractory Metals at a Laser Cladding. *J. Phys. Conf. Ser.* **2016**, *691*, 012009. [CrossRef]
10. Biswas, S.; Satapathy, A. A comparative study on erosion characteristics of red mud filled bamboo–epoxy and glass–epoxy composites. *Mater. Des.* **2010**, *31*, 1752–1767. [CrossRef]
11. Czekajło, M.; Zakowski, K.; Krakowiak, S.; Kierepa, S. Analysis of the Possibility of Using New Types of Protective Coatings and Abrasion-Resistant Linings under the Operating Conditions of the Spiral Classifier at KGHM Polska Miedź S.A. Ore Concentration Plant. *Coatings* **2021**, *11*, 1138. [CrossRef]
12. Roy, S.; Deo, K.; Singh, K.A.; Lee, H.P.; Jaiswal, A.; Gaharwar, A.K. Nano-bio Interactions of 2D Molybdenum disulphide. *Adv. Drug Deliv. Rev.* **2022**, 114361. [CrossRef] [PubMed]
13. Czekajło, M.; Żakowski, K. Failures and a concept of corrosion protection system for spiral classifiers at KGHM Polska Miedź S.A. Ore Concentration Plant. *Eng. Fail. Anal.* **2019**. [CrossRef]
14. Hartt, W.H. Cathodic protection of offshore structures-history and current status. *Corros.* **2012**, *68*, 1063–1075. [CrossRef]
15. Revie, R.W.; Uhlig, H.H. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering*, 4th ed.; John Wiley & Sons: New York, NY, USA, 2008; ISBN 9780471732792. [CrossRef]
16. Szabo, S.; Bakos, I. Cathodic Protection with Sacrificial Anodes. *Corros. Rev.* **2006**, *24*, 231–280. [CrossRef]
17. Szabo, S.; Bakos, I. Impressed Current Cathodic Protection. *Corros. Rev.* **2006**, *24*, 39–62. [CrossRef]
18. European Standard EN 12473. *General Principles of Cathodic Protection in Seawater*; Comite Europeen de Normalisation: Bruxelles, Belgium, 2014.
19. Kroon, D.H.; Ernes, L.M. MMO-coated titanium anodes for cathodic protection. *Mater. Perform.* **2007**, *46*, 26–29.
20. Mintz, T.S.; Caseres, L.; Bocher, F.; Dante, J. Development of Corrosion Sensor Technology for Buried Piping. In Proceedings of the CORROSION 2015, Graz, Austria, 6–10 September 2015; NACE International: Houston, TX, USA, 2015.
21. European Standard EN 12499. *Internal Cathodic Protection of Metallic Structures*; Comite Europeen de Normalisation: Bruxelles, Belgium, 2003.
22. European Standard EN 12954. *General Principles of Cathodic Protection of Buried or Immersed Onshore Metallic Structures*; Comite Europeen de Normalisation: Bruxelles, Belgium, 2019.