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Sustainable Mining – Decommissioning and Mine Closure Processes

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ABSTRACT
Mining, a pivotal societal contributor, furnishes crucial resources for diverse industries. However, mining operations exert significant environmental impact, necessitating subsequent environmental repair and rehabilitation. The importance of addressing both environmental and social implications in mine closure planning is escalating.

Under legal mandates, mining companies must formulate thorough closure plans, specifying the site's final condition, required measures, anticipated expenses, and financial assurances for effective closure execution. Accurately estimating closure costs, though challenging, is crucial to secure sufficient funding for rehabilitation.

In Brazil, mining site closures often diverge from initial plans, with closure efforts mistaken for rehabilitation. Responding to this, regulatory bodies are fortifying requirements for new projects, enhancing mine closure laws by mandating a comprehensive Mine Closure Plan (MCP) covering decommissioning, rehabilitation, and post-closure activities.

Recognizing, evaluating, and addressing mining site risks in a standardized manner is imperative. This includes ensuring the stability of the mining area in biological, physical, and chemical aspects, averting unintended emissions, and tackling issues like acid drainage. Groundwater geochemistry, particularly concerning mine acid drainage, assumes a vital role. Closure of underground mines involves flooding and continual water level monitoring, while open-pit mines necessitate efforts to repurpose the area for new economic or social activities.

Adhering to standardized criteria is essential to effectively manage the environmental and social impact of mining activities. By prioritizing comprehensive closure planning and adherence to environmental and social considerations, the mining industry can strive to minimize its environmental footprint and champion responsible post-mining practices for a sustainable future.

Keywords: Mine closure, Environmental factors, Financial Viability, Brazilian Mine Legislation

Introduction

Mining plays a crucial role in sustaining society's way of life and is expected to continue existing in the foreseeable future. As socioeconomic growth advances, there is a corresponding increase in the consumption of mineral resources. Development, quality of life, and the consumption of mineral goods are interconnected.

However, mining is widely recognized as having a significant environmental impact. While it generates wealth, it also gives rise to substantial issues in its surrounding areas. Mining

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operations rely on deposits with finite reserves, which can only be exploited for a limited period. Nonetheless, the effects of mining activities often endure long after their cessation [1].

The long-term socio-environmental consequences following the conclusion of mining activities have been a topic of intense discussion over the past decade.

Current Situation and Trends on Mine Closure - International Perspective
In addition to legal obligations, there is a growing recognition of the significance of environmental restoration during mine closure. This includes taking socio-environmental factors into account, such as the impact of mining on local communities and the restoration of natural habitats. A notable trend is the adoption of innovative and sustainable approaches to mine closure, such as resource reuse and the utilization of long- term monitoring technologies. Successful mine closure is seen as contingent upon collaboration between companies, governments, and local communities [2].

When a company seeks to relinquish a mining title for an area where mineral extraction or prospecting has taken place, the company bears the responsibility of reclaiming the site before government authorities grant the release. In most countries, companies are legally required to submit a closure plan to the regulatory authority, ensuring that satisfactory rehabilitation occurs. This plan must be submitted prior to commencing any work on the site.

Increasingly, regulatory authorities demand that closure plans outline the envisioned final state of the site, the sequence of necessary actions, estimated costs, and the establishment of financial sureties. The primary objective of site rehabilitation is to mitigate pollution risks, restore the land and landscape for appropriate use, enhance the aesthetics of the area, and prevent future degradation. The extent and expense of final site rehabilitation can be reduced if the recovery process begins as early as possible, even while mining activities are ongoing, aligning the restoration and exploration rates. However, this ideal scenario is not always achievable, and most rehabilitation typically occurs after work on the site has concluded [3].

Even with the best intentions, accurately forecasting closure costs is exceedingly challenging, with approximation being the most realistic expectation. While the temptation may exist to overestimate costs to prevent a shortfall in funds, this should not be done at the expense of the industry's financial viability.

Financial Feasibility
The World Bank's Environment, Health, and Safety Guidelines for Mining (2007), implemented by the International Finance Corporation (IFC), emphasize the need to incorporate closure and post-closure costs into the business's viability during the design phase. This is considered a fundamental requirement to ensure adequate funding for closure expenses. The objective is to guarantee that there are ample funds available to cover site rehabilitation, post-closure monitoring, and maintenance at any point during the project's lifespan, including early or temporary closure. These funds should be established through a cash provision or a financial guarantee system.

A reliable financial institution must provide an acceptable financial guarantee. It is essential to review mine closure requirements on an annual basis and adjust closure financing agreements accordingly to accommodate any changes [4].

Current Situation
At present, few mines have been closed according to some scheduled plans. Closure actions are still confused only with acts to rehabilitate disturbed areas. Experience is still rarely shared with industry professionals and the knowledge acquired still lacks a systematic approach. We recall that mining texts published twenty years ago rarely mentioned “decommissioning” or closure as stages or milestones in the life of a mine.

When an ending occurs due to the depletion of the deposit, it is easier to foresee the end, but it is quite common for closure to occur due to market and economic reasons, without prior planning or prior communication, which makes it difficult for government control.

The global trend is for mining regulatory institutions to impose increasing requirements on companies to start a new mining project, ruled to the existence of a plan that minimizes the impacts when a stoppage occurs. Countries, where mining is more developed, tend to pass laws that make new licensing conditional on the existence of insurance for the liabilities generated. In Chile, a South American country, since 2012, there has been legislation for large mines to maintain insurance to guarantee regularization or indemnify liabilities at the end of the operation.

The objective is to prevent, when a mine is ended due to depletion, for legal or economic reasons, employees without termination, debts with suppliers, environmental liabilities, and legal proceedings that drag on for many years. There are cases of mining companies (legal entities), which, before closing the mine, pass on obligations to third parties, without financial capacity or resort to other artifices, which make it difficult to hold them accountable and indemnify the liabilities left. The burden ends up being shared with society.

There are many examples of this situation in Brazil. A recent example is the case of “Mina do Verdinho” in the Region of Criciuma, in Santa Catarina, a large underground coal mine, which operated for more than thirty years and ceased activities in 2015. The situation caused a strong commotion: The owner simply abandoned the site with large environmental and social liabilities. Legislation in Brazil - Mine Closure Plan.

The mining act in Brazil is centenary and the legislation has been improved, showing the growing concern about the abandonment of areas degraded by mining. Since 2001, the DNPM and its subsidiary National Mining Agency have issued regulations to modernize legislation on the subject. The resolution of the National Mining Agency ANM 68 of April 20, 2021, is the most recent in which the Mine Closure Plan (PFM) was instituted.

The plan consists of a procedures sequence for the decommissioning of the mine area after the mining activity ended. It involves the removal of temporary support structures for mining and processing operations, the physical and chemical stabilization of excavation and their monitoring, as well as such as the qualification of the area for a new mineral use or other future use [5].

The enforcement of the plan, once approved, should start, as far as possible, as soon as possible with the mine still in operation.

The PFM must Include Among other Documentation

The conceptual decommissioning of the development with information on the rehabilitation actions already carried out, monitoring, and planned maintenance with a physical-financial schedule of pre-closure, closure, and post-closure actions. Description of gradual closure actions that will be carried out during mine operation (progressive closure).

It should also include an assessment of the risks arising from the closure, ways to mitigate damage and guidelines for adapting the area to the intended use in the future.

The PFM containing mining dams must also include the decommissioning plan for these dams or other technical solutions. If it is not possible to decommission the dam, the PFM requires its monitoring, in accordance with the applicable legislation.

In case of closure before reserve exhaustion: There must be a technical-economic justification with a declaration of the remaining mineral resources and reserves.

The PFM must be updated every 5 (five) years or in the "Economic Use Plan" (PAE) updates. In addition, in the event of an early closing decision, before the reserve is exhausted, communication must be given at least 2 (two) years in advance. The ANM resolution determines that the latest update of the PFM must be communicated to the ANM at least two (2) years in advance of the date scheduled for the closure of the mine.

Mine Closure Steps

Decommissioning corresponds to the operations necessary to guarantee the deactivation of the mine, aiming to return the site to other uses by the community.

Closure and rehabilitation of the area, where the impacts caused to the environment are repaired. It involves the stabilization of structures built during the life of the mine that cannot be removed, such as open pit excavations, underground mine galleries, dams, tailings, and sterile material deposits that should not present risk situations when the area is deactivated.

It also involves the removal of support structures, such as civil infrastructure, treatment plants, overburden yards; water and energy distribution systems, among others, which must be demobilized.

The closure of the mine ends the decommissioning and rehabilitation activities of the impacted areas, marking the beginning of the monitoring and maintenance phase of the measures that were implemented.

Monitoring and maintenance are represented by systematic actions to control subsequent impacts that may occur in the environment, after the end of mining activities and rehabilitation of the area. It is about monitoring and correcting the effects on the environment that may still occur after the end of mining or rehabilitation activities.

Post-Closure corresponds to the final part of the process, for the release of the area. Mining owners must submit a final report to the ANM, proving that the closure works were completed correctly and in accordance with the presented Mine Closure Plan. Only after the approval of the final PFM implementation report can the waiver of the mining title be ratified [6-8].

It should also be noted that the approval of the final report on the implementation of the PFM by the ANM does not imply the release of obligations provided for in other legislation in force.

The identification Process of the Risks Presented by Each Mine Site Installation

Each mine site is different and risk management is unique and particular. The aim should be to ensure adequate protection of people's life, health and safety, and the environment. Also, a long-term view must be considered as some facilities or structures will remain in place forever. Figure 1 shows facilities typically found in mining areas where risks must be identified, assessed, and mitigated.

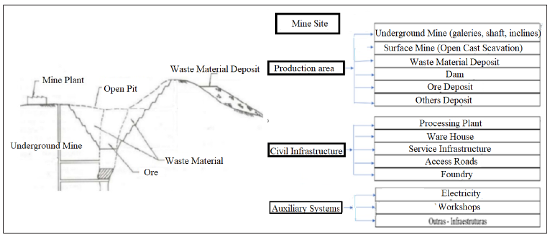

Figure 1: Typical arrangement found on a mining site. Source: Own

The initial step of the process involves identifying the structures present on the site and assessing the associated risks. Various methods can be employed for this purpose, including qualitative, quantitative, or a combination of both (semi-quantitative) approaches.

Among these methods, the semi-quantitative approach utilizing a matrix is the most employed. The criteria used in the risk matrix should be standardized, proposed, and mutually agreed upon by the mining company and the regulatory body (such as ANM or the environmental authority).

The risk matrix enables the classification of risks based on two key factors: the probability of occurrence and the severity of the consequences. This classification serves as a basis for planning and implementing necessary mitigation actions.

Biological, Physical, and Chemical Stability of the Mining Area

The remaining mining area must have its chemical, biological and physical stability assured.

The stabilization of the biological environment refers to the process of reoccupation of fauna and flora in areas that were degraded, with a return to a self-sustaining condition. Physical stability refers to containing erosion processes and the risk of mass movements because of mining activities, which can make surfaces unstable and can cause erosion and landslides on slopes in open pit mines. In underground mines, it basically refers to controlling landslides and subsidence due to pillar rupture.

Another important action is to prevent fugitive emissions comprised of dust and other contaminants in the air and water from mining pits and tailings deposits. Emissions can contaminate neighboring areas and the drainage of the downstream region, which can extend far beyond the mining site [9-11].

In mining, a major contributing factor to chemical instability is acid drainage. For this to occur, there must be ores, overburden, or sulfide tailings, which in contact with oxygen and water oxidize, generating sulfuric acid and, consequently, leaching of the metals contained in the rock.

Groundwater Geochemistry

Groundwater is usually known as the water that occurs in the geological environment located below the surface of the land. The composition of these waters can be variable, some are alkaline, others acidic, and they can be rich in aluminum, iron, or other metals or even be clean, with few metals and neutral ph. Therefore, each groundwater or mine water has a particular geochemical signature, derived from the interaction of various processes along the flow path of these waters.

Water interacts with the rock it percolates, generating geochemical processes that tend to result in the consumption of dissolved O2 and CO2, pH elevation and production of alkalinity, and release of base cations. Also, mixing of water from different aquifers may occur, e.g., mixing with saline water formations or mixing with saline surface water, or of the deep aquifer with the surface aquifer.

The main reactions involving water and mineral phases underground are dissolution, ion exchange, acid-base, and redox reactions. Acid-base reactions are very important as they affect the most common rock-forming minerals like feldspars and carbonates. These reactions tend to consume CO2 and raise the pH, releasing alkalinity from bicarbonates and base cations. Frengstad & Banks (2000) indicate that in normal groundwater this type of reaction is dominant, resulting in neutral to slightly alkaline waters, dominated by base cations (Ca^{++}, Mg^{++}, Na^{+}) and bicarbonates.

In the groundwater environment, the content of oxidizable minerals (pyrite) in relation to the total mineral mass is small. Access by water and air to oxidizable species is normally low, and acid-base reactions (those that consume protons) dominate oxidation and redox reactions. Therefore, normal groundwater normally has a neutral to slightly alkaline pH, dominated by base and bicarbonate cations.

When a mine is excavated, a rapid circulation of oxygen and water is introduced deep into the geosphere and into zones that may have a high concentration of oxidizable minerals (sulfides), thus allowing oxidation reactions to dominate. Then comes one of the ways to produce acid mine drainage (AMD). This reaction can be represented by the oxidation of pyrite [12].

Mine water quality is very difficult to predict, as many variables can interfere. But, in general, it can be estimated that acidic and contaminated mine waters are characteristic of unsaturated sites, with rapid water output and oxygen availability. Places where there are oxidizable minerals exposed to ambient air being leached by surface waters, as in the case of open pit mines and deposits of mineral tailings. It also occurs in underground mining in some cases of uncontrolled surface infiltration. This consideration can be observed in coal mining (Figure 2).

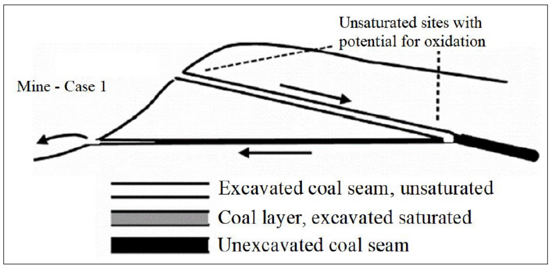

Figure 2: Situations of uncontrolled seepage from underground mines that influence the quality of mine water (Situation of formation of AMD).

Source: Project - Study for the evaluation of the Mine Closure Plan (Mina Verdinho Case)

Figure 3 shows a situation of AMD formation; aggressive water produced in unsaturated areas under drained excavation conditions. The upwelling that occurs in the topography tends to be acidic with contaminants produced by the oxidation of pyrite in coal seams in unsaturated areas.

Flooded coal mines with restricted oxygen access and slow water flow are often characterized by more neutral mine water (Figure 3).

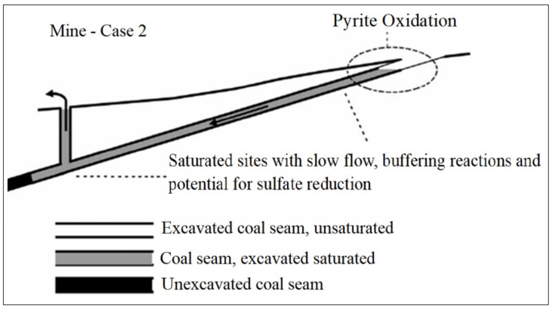

Figure 3: Mine waters with more neutral characteristics arise downstream when the conditions of saturation and slow water flow are met

Source: Project - Study for the evaluation of the Mine Closure Plan (Mina Verdinho Case).

Recommendations for Closure of Underground Mines

When it comes to the closure of an underground mine, the common approach is to allow the mine to flood. After the water level in the deep aquifer has stabilized, a balance is achieved, resulting in an improvement in the groundwater quality. To ensure a successful closure, the following measures are recommended:

- **Flooding the Mine:** Allow the mine to fill with water, as this facilitates the natural equilibrium of groundwater.

- **Installation of piezometers:** Install monitoring devices, such as piezometers, to track water levels in both deep and surface aquifers. Continual monitoring is essential.
- **Removal of Power Cables:** Remove the power cables that supplied electricity to the underground mine and seal the openings where these cables were routed.
- **Sealing of boreholes:** Identify and seal any remaining boreholes that have not yet been closed and are accessible.
- **Construction of Barriers:** Construct a concrete barrier around wells and inclined planes used for access to the underground area. This prevents the entry of air and ensures the safety of individuals and animals by preventing accidents due to unauthorized access.
- **Emergency Monitoring:** Maintain a system for monitoring and responding to any emergencies that may arise during the closure process. If there is a risk of contaminating other surface water sources, appropriate treatment measures should be implemented.

By implementing these recommendations, the closure of an underground mine can be conducted in a safe and environmentally responsible manner.

Surface Mines

Recommendations for Closure of Open Pit Mines

Throughout the lifespan of an open pit mine, the stability of the pit walls is a constant concern. Mining teams manage these geotechnical risks as part of normal operations. However, even after mining activities cease, stability risks persist as the pit slopes may deteriorate and experience progressive failure mechanisms. These long-term failures can impact existing mine infrastructure and any planned post-closure land use [13].

To ensure the environmental acceptability of open pit mines, a comprehensive stability study must be conducted, demonstrating both the chemical and physical stability of the site in the short and long term.

The terrain should be properly leveled and reshaped to blend harmoniously with the surrounding topography. Revegetation efforts should be undertaken unless the areas are located below the water table.

Various techniques can be employed for the future use of the remaining pit, such as using it for sterile material deposits, disposal of urban solid waste, creating artificial lakes for recreational purposes, or developing irrigation and water supply projects for rural and urban communities. However, careful planning is essential for the future utilization of the pit, considering factors such as the geological and geotechnical characteristics of the site, the climate, costs, and, most importantly, the needs of the local population.

In the state of Rio Grande do Sul, Brazil, there are successful examples of repurposing mining pits and decommissioned underground mines. One such example is the city of Butiá, where an old coal mine has been appropriately prepared and flooded to ensure water supply during dry seasons. Additionally, urban waste from the state capital of Porto Alegre and over 150 municipalities, after undergoing a recycling phase, is transported and deposited in mines located in the municipality of "Minas do Leão", 90 kilometers away. The landfill also includes a thermoelectric power plant that utilizes the gas generated from the landfill as fuel.

Another noteworthy example in Rio Grande do Sul is an underground restaurant located in the municipality of "Ametista do Sul", inside an underground mine. The development also features a museum park for tourist visitation [14].

By implementing these recommendations, the closure of open pit mines can result in sustainable and beneficial land use, ensuring the long-term stability of the site and meeting the needs of local communities.

Figure 4: Hotel and restaurant in the municipality of "Ametista do Sul/RS" – Use of deactivated mining galleries.

Source: https://www.booking.com/hotel/br/e-restaurante-belvedere-mina.pt-br.html?activeTab=photosGallery

Sterile and Tailings Deposits: Closure Measures

When dealing with the material left on the surface, such as tailings deposits and dams, two crucial factors need to be considered: physical stability conditions and the potential for generating acid drainage. In cases where instability is a concern, earthworks and slope reduction measures are recommended.

To minimize the generation of acid drainage, the deposits should be covered. The covering material should have a clayey composition to effectively isolate the waste, ensuring containment and confinement. The geotechnical characteristics of the cover material need to be determined to establish the appropriate thickness, placement method, and degree of compaction. This data will also facilitate slope stability analysis.

Some of the backfill material can be sourced from the demolition of mine offices, workshops, and service plants, which will generate material during their removal. Additionally, residual soil from the region with low permeability can be used as the remaining backfill material.

Alternatively, it is worth conducting a specific study to assess the economic feasibility of utilizing the tailings. This approach could generate resources to support environmental restoration activities on-site.

Complementary measures should also be implemented, such as drainage channels to effectively manage rainwater within the deposit area. These channels aim to minimize the residence time and infiltration of surface water on the deposits, thereby mitigating the risk of acid drainage generation and potential contamination of aquifers in the region.

By implementing these closure measures, the stability of sterile and tailings deposits can be ensured, reducing environmental risks and promoting the restoration of the affected area.

Final Considerations: Responsible Mining and Mine Closure

Mining has the potential to bring economic benefits, but it also carries significant socio- environmental impacts. It is crucial to approach mining with responsibility and sustainability to ensure that future generations can also benefit from the resources being extracted today.

Mining activities create jobs, generate income, and can contribute to regional development and economic growth, as seen in countries like Canada, Australia, and the United States. However, when mining is not conducted responsibly and with proper techniques, it can result in intense social and environmental impacts.

Society is increasingly demanding more effective regulation of mining activities, including worker health and safety, as well as the mitigation of environmental impacts. The use of modern technologies enables more responsible, ecological, and safe mining practices.

Result

As a result of society's expectations, the environmental and socioeconomic consequences of mine closure have become subjects of study and stricter regulations worldwide, including in Brazil.

Discussion

The discussion around the establishment of a fund financed by mining companies themselves to address mine liabilities is gaining prominence. This is a complex issue that involves small, medium, and large mining operations with varying useful lives and economic capacities.

Mine closure should encompass a broader concept beyond project termination and environmental recovery of degraded areas. It should also include actions that ensure the environmental, economic, social, and cultural sustainability of surrounding communities.

Numerous propositions regarding the regulation of mine closure have been presented and discussed in congresses. There is a consensus that the closure plan, approved by regulatory bodies, should be developed well in advance to ensure its success. Closure plans and actions should commence as early as possible to disburse costs while the mine is still in operation.

Embracing the concept of "Open thinking about closing" can guide all stages of licensing and the activities of regulatory bodies, aiming to minimize costs and risks associated with mine closure.

Conclusion

In conclusion, the closure of mines that are reaching the depletion of reserves in the coming years will serve as a benchmark for the mining sector. How these closures are executed will impact the costs related to mine closure, society's perception of the mining industry, and the risks evaluated by investors.

References

1. Oil, Gas, and Mining Policy Division, Oil, Gas, Mining, and Chemicals Department, World Bank Group. Financial Surety: Guidelines for the Implementation of Financial Surety for Mine Closure. Meredith Sassoon. 2009. http://www.worldbank.org/ogmc (OR /oil OR /gas OR /mining).
2. International Finance Corporation/World Bank Group. Environmental, Health, and Safety Guidelines. IFC, 2007. www.ifc.org/ehsguidelines.
3. ANM RESOLUTION No. 68. Provides on the rules relating to the Mine Closure Plan - MFP. 2021.
4. Mining Regulations No. 20.4 and No. 20.5. DNPM Ordinance No. 237. 2001.
5. Project - Study for evaluation of Mine Closure Plan (Case Mina Verdinho). Agreement FEENG/UFRGS/ANM. 2019.
6. Zingano Andre Cezar, Koppe Jair Carlos, Gavronski Jorge Dariano, Cabral Roger Romao. Mine closure: the Mina Verdinho case. In: Brazilian Congress on Open Pit and Underground Mines. 2021.
7. Methodological Guide for Evaluating Riesgos for El Cierre de Faenas Mineras. Servicio Nacional de Geologia y Minería. SERNAGEOMIN. 2014. https://www.sernageomin.cl/-wp-content/uploads/2017/11/14.03.24-GuiadeEvaluacion-deRiesgosparaelCierreFaenasMineras.pdf
8. Guide to Evaluating EIAs for Mining Projects. World Alliance for Environmental Law (ELAW), Eugene OR 97403 by World Alliance for Environmental Law. 2010.
9. Banks, H. Geochemical processes controlling minewater pollution." Proceedings of the Groundwater Management in Mining Areas, Hungary. 2004. 17-42.
10. Frengstad, Banks. Evolution of high-pH Na-HCO3 groundwaters in anorthosites: silicate weathering or cation exchange In: Sililo et al. (eds). Groundwater: Past Achievements and future challenges, Proc. XXXII Congress of the Inter. Ass. of Hydrogeologists, Cape Town, Balkema. 2000. 493-498.
11. Johnstone A, Dennis I, McGeorge N. Groundwater stratification and impact on coal mine closure." North West University, South Africa. 2013. 6.
12. Younger PL, Banwart SA, Hedin, RS. Mine water: hydrology, pollution remediation. Kluwer, Dordrecht. 2002. 442.
13. Website Municipality of Ametista do Sul/RS. Available at: https://ametistadosul.rs.gov.br/
14. Rio Grande do Sul State Government Department Secretary for the Environment and Infrastructure. Mining in Rio Grande do Sul (E-book): Sectorial diagnosis and vision of the future: Porto Alegre/RS. 2022. 2