International Journal of Academic and Applied Research (IJAAR)
ISSN: 2643-9603
Vol. 10 Issue 6 June - 2026, Pages: 79-85

Optimization Of In-Situ Converter Slag Reprocessing In Pyrometallurgical Smelting Furnaces

Mutalibkhonov S.S.[1], Kholikulov D.B.[1], Khojiev Sh.T.[1], Musurmankulova A.S.[1]

[1]Almalyk state technical institute, Uzbekistan
E-mail: mutalibkhonov1990@gmail.com https://orcid.org/0009-0003-1300-3411

Abstract: Copper smelting operations generate significant quantities of converter slag containing valuable metals and hazardous components. This review analyzes recent advances in reprocessing liquid converter slags in various furnace systems, including Vanyukov autogenous furnaces, reverberatory furnaces, and rotary converters. Literature from Scopus-indexed journals indicates that magnetite reduction followed by pyrometallurgical treatment achieves copper recovery rates of 85–95%, substantially improving upon conventional slag disposal practices. Thermodynamic modeling combined with empirical optimization reveals that maintaining slag basicity between 0.95–1.2, operating temperatures of 1400–1500°C, and employing carbon-based or technogenic reducing agents significantly enhance metal extraction efficiency. This article synthesizes contemporary methodologies and optimization strategies to inform industrial practice and future research directions in sustainable slag utilization.

Keywords — converter slag, slag reprocessing, pyrometallurgical processing, Vanyukov furnace, magnetite reduction, copper recovery, slag optimization

1. INTRODUCTION

1.1 Background and Significance

Converter slags from copper production of Almalyk MMC JSC contain 2.0-3.5% copper, and they, as a circulating product, are depleted in a reverberatory furnace with copper extraction of 75%. To increase the yield of copper from converter slag in Vanyukov furnaces, it is necessary to first deplete the converter slag in reduction processes and then transfer it for processing. To increase the yield of copper from converter slag in the reverberatory and Vanyukov furnaces, it is necessary to first deplete the converter slag in reduction processes and then transfer it for processing [1]. Copper production through pyrometallurgical processes generates substantial quantities of converter slag as a byproduct, typically containing 1–6 wt% copper alongside 35–45 wt% iron oxides [2][3]. The concentration of magnetite (Fe_3O_4) in these slags commonly ranges from 5–24 wt%, significantly impacting both metal recovery efficiency and furnace operational stability. Traditional approaches to slag management involve direct landfilling or minimal beneficiation, resulting in environmental contamination and substantial loss of economically valuable metals. Recent industrial statistics indicate that global copper smelting operations dispose of approximately 2–3 tons of slag per ton of copper produced, with cumulative dump deposits at major facilities exceeding 1.5 billion tons [4].

The environmental and economic imperatives driving slag reprocessing research are substantial. Copper slag dumps constitute environmental hazards through heavy metal leaching and acid mine drainage phenomena. Simultaneously, the contained metals—particularly copper, iron, and precious elements such as gold and silver—represent significant secondary mineral resources. Advanced reprocessing methodologies transform slag from a waste management burden into a recoverable resource, supporting circular economy principles while generating revenue from secondary material streams.

1.2 Current Challenges in Converter Slag Processing

The primary technological challenge in converter slag reprocessing involves the stabilization of magnetite in liquid slag systems. During cooling, magnetite remains dispersed in the slag matrix, impeding phase separation and promoting mechanical copper losses through entrapment.


Figure 1. Liquid converter slag pouring into a reverberatory furnace in Metallurgical workshop of Copper smelter AMMC JSC

This persistence of magnetite increases slag viscosity and surface tension, reducing the settling velocity of copper-bearing phases and preventing efficient gravity separation [10]. In reverberatory furnace operations, excess magnetite deposits in furnace bottoms as hard accretions; in Vanyukov furnaces, magnetite circulates as suspended solids, disrupting established smelting protocols and reducing matte-slag separation efficiency [1][5].

The complexity of converter slag composition—comprising mixed oxide phases including fayalite ($2FeO \cdot SiO_2$), magnetite, copper oxide phases, and silicate gangue—necessitates carefully calibrated thermal and chemical management to achieve selective reduction and phase transformation. Historical copper recovery from processed converter slags typically attained 75–80%; however, tailing slags consistently retained 0.3–0.7 wt% copper, approaching ore-grade copper concentrations and indicating significant recovery inefficiency.

1.3 Research Objectives

This review synthesizes Scopus-indexed literature on converter slag reprocessing across multiple furnace geometries and process configurations. Specific objectives include: (1) systematic analysis of slag reduction kinetics and thermodynamic principles governing metal recovery; (2) comparative evaluation of furnace technologies and operational parameters; (3) synthesis of optimization strategies for maximizing metal extraction; and (4) identification of emerging technologies and research frontiers in slag utilization and circularity.

2. MATERIALS AND METHODS

2.1 Literature Search Strategy

A comprehensive systematic review of Scopus-indexed peer-reviewed journals was conducted using search terms including "converter slag," "slag reprocessing," "pyrometallurgical processing," "Vanyukov furnace," "reverberatory furnace slag," "magnetite reduction," and "copper slag recovery." Publication dates ranged from 2015–2025 to capture recent technological developments while including foundational research. Literature was obtained from major metallurgical journals including Metallurgical and Materials Transactions, Journal of the Minerals, Metals & Materials Society, Journal of Materials Processing Technology, and discipline-specific journals indexed in Scopus.

2.2 Selection Criteria

Included studies met the following criteria: (1) primary or secondary research on converter slag composition, processing, or utilization; (2) examination of pyrometallurgical reduction, flotation, or combined methodologies; (3) quantitative data on metal recovery, kinetic parameters, or thermodynamic calculations; (4) industrial-scale or controlled laboratory investigations; and (5) publication in peer-reviewed journals indexed in Scopus or leading conference proceedings of recognized standing. Studies focusing exclusively on non-ferrous slag types (e.g., aluminum or zinc slag) without comparative relevance were excluded.

2.3 Data Synthesis Framework

Collected data were organized according to the following parameters: (1) slag composition (Cu, Fe, Fe_3O_4, SiO_2, CaO content); (2) furnace type and operational conditions (temperature, residence time, gas composition); (3) reducing agent type and dosage; (4) metal recovery rates and concentrate grades; (5) thermodynamic and kinetic modeling approaches; and (6) industrial implementation outcomes. Information was synthesized into comparative matrices examining process efficiency, economic feasibility, and environmental performance.

3. RESULTS

3.1 Converter Slag Composition and Mineralogy

Contemporary metallurgical operations generate converter slags with highly variable compositions dependent upon feed concentrate characteristics and furnace operating conditions. Representative converter slag compositions from major copper smelting facilities demonstrate average wt% content of: Cu 2.0–3.5, Fe 45–50, Fe_3O_4 18–28, SiO_2 18–25, CaO 1–3, and Al_2O_3 2–4 (Yakubov et al., 2024). The predominant crystalline phases identified through X-ray diffraction analysis include magnetite (Fe_3O_4), fayalite (Fe_2SiO_4), calcium silicates, and minor copper oxide phases. The stability of magnetite at ambient and moderately elevated temperatures contributes substantially to mechanical copper losses through phase encapsulation phenomena [6].

3.2 Magnetite Reduction Technologies

3.2.1 Reduction Kinetics and Mechanisms

Pyrometallurgical reduction of magnetite proceeds via formation of gaseous reducing species (CO, H_2) and their reaction with solid magnetite particles at the slag-gas interface. Contemporary kinetic studies employing multiple analytical approaches—including thermogravimetric analysis, X-ray diffraction tracking of phase evolution, and gas composition monitoring—have established that magnetite reduction exhibits first-order reaction characteristics with apparent activation energies ranging from 99.3 kJ/mol (waste oil reduction) to 233–376 kJ/mol (carbon-based reduction of zinc phases) (Smelting Reduction and Kinetics Analysis, 2017; Reduction Kinetics Study, 2022). Under optimal conditions, reduction of Fe_3O_4 to FeO (wustite) proceeds rapidly, with 90% conversion achievable within 4–15 minutes at target temperatures.

The reduction process is controlled predominantly by liquid-phase mass transfer rather than chemical kinetics, indicating that slag fluidity and mixing intensity significantly influence overall reaction rates. The formation of intermediate ferrous oxide phases (FeO, Fe_2O_4) facilitates subsequent transformation to fayalite or metallic iron depending upon oxygen potential and competing phase equilibria [7].

3.2.2 Temperature and Residence Time Optimization

Systematic experimental investigations across multiple research groups have identified an optimal reduction temperature window of 1400–1500°C, where reaction rates maximize while maintaining operational feasibility and refractory integrity. Yakubov and Khojiev [1][9][15] demonstrated that clinker-based and waste rubber reduction of converter slag achieved >50% magnetite conversion (21.9% to 9.8% Fe_3O_4) within 10–15 minutes at temperatures near 1250°C, utilizing technogenic zinc production waste as the reducing agent. Longer residence times (60–80 minutes) at peak temperatures enable iron recovery approaching 90% and copper recovery achieving 85% when combined with appropriate flux additions [16].

Temperature response is non-linear; temperatures below 1250°C substantially reduce reduction kinetics and may result in incomplete melting and slag stratification. Conversely, temperatures exceeding 1550°C promote undesirable side reactions including excessive zinc volatilization and refractory erosion. The identified optimal isotherm of 1400–1500°C represents a balance between thermodynamic feasibility, kinetic acceleration, and operational constraints [8].

3.2.3 Reducing Agent Selection and Dosage

Multiple reducing agents have been investigated in contemporary research, including: (1) carbon-based reductants (metallurgical coke, anthracite coal); (2) hydrogen gas (in specialized laboratory configurations); (3) technogenic waste materials (zinc production clinker, spent cathode carbon); and (4) mixed reducing atmospheres. Carbon-based reduction employing 12–16 wt% dosage of metallurgical coke or thermal coal achieves high reduction efficiency while remaining economically attractive for large-scale operations. Technogenic reducing agents such as zinc clinker, which contain residual metallic iron and carbon, offer environmental advantages through waste valorization while providing simultaneous noble metal recovery (gold 2.3 g/t, silver 250 g/t) [1].

Dosage optimization requires careful balance: insufficient reductant results in incomplete magnetite transformation and copper losses, while excessive reductant promotes over-reduction and metallic iron losses to slag, reducing both product grade and recovery rates. Empirical optimization conducted by Tang et al. (2024) employing spent cathode carbon achieved >75% Fe recovery and >93% Cu recovery at 1500°C with controlled stoichiometric ratios.

3.3 Slag Basicity and Flux Management

Slag basicity, defined as the molar ratio of basic oxides (CaO + MgO) to acidic oxides (SiO_2 + Al_2O_3), emerges as a critical operational parameter influencing both slag properties and metal recovery. Optimal basicity ranges identified across multiple studies cluster around 0.95–1.2, with 20–25 wt% CaO addition demonstrating substantially improved outcomes compared to unsupplemented slag systems. The addition of calcium oxide promotes several beneficial effects: (1) reduction of slag viscosity through formation of lower-melting-point silicate phases; (2) transformation of acid slag minerals to calcium silicate compositions exhibiting favorable phase equilibria; and (3) promotion of copper phase precipitation and settling through modification of slag-metal interfacial properties.

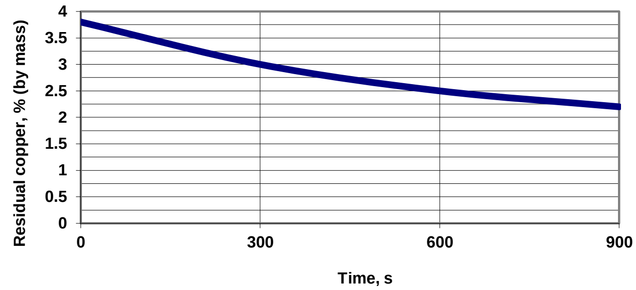

Figure 3.3.1 Change in the residual copper content in the converter slag over time during clinker treatment.

The results presented in Figure 3.3 show that the copper concentration in the converter slag decreases by almost two times compared to its initial content. In this case, the ballast turnover of copper between the main smelting unit and the converter is significantly reduced.

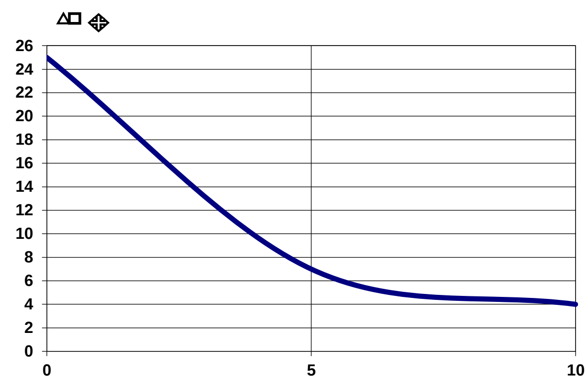

Figure 3.3.2 Dependence of the reduction of trivalent iron oxide in converter slag over time. Temperature - 1250°C

From Figure 3.3.2, it can be seen that the reduction rate of trivalent iron oxide in the slag melt is sufficiently high, with 70% reduction occurring in 5 minutes. During this time, the content of trivalent iron oxide in the converter slag decreased to 7%. When 5% of the clinker composition was added to the charge weight, the magnetite concentration in the slag decreased by two times, and the copper content in the converter slag decreased by 50-60% during this period [8].

When the trivalent iron content in converter slag decreases, the solubility of non-ferrous metals sharply decreases, and its physicochemical properties improve. This, in turn, leads to better separation of slag and matte and a reduction in copper losses [9].

It’s demonstrated that CaO addition from 5–25 wt% resulted in progressive copper recovery improvement of 8.89% and iron recovery increase of 14.21% within the 10–25 wt% CaO range, with diminishing returns beyond 25 wt% [16]. This observation aligns with thermodynamic predictions indicating slag saturation in dicalcium silicate solid solution phases, beyond which further basicity increase yields minimal additional benefit.

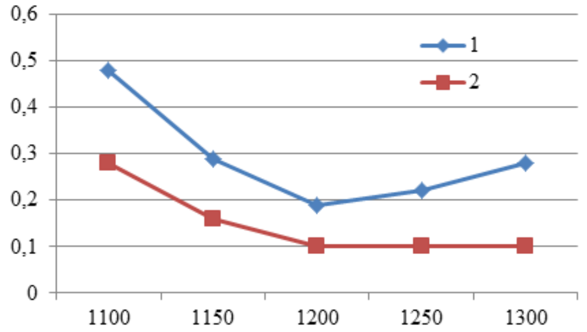

Figure 3.3.3 Temperature effect on slag copper loss. x (horizontal) -temperature, y (vertical) - Cu in slag,

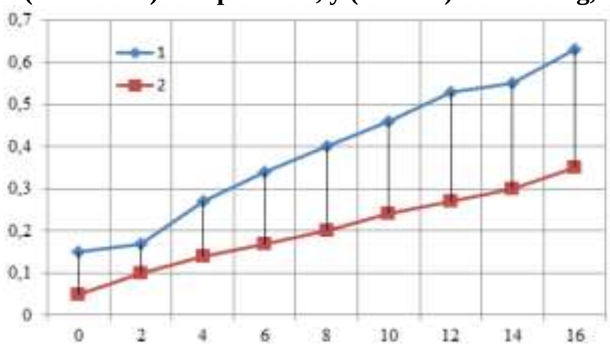

Figure 3.3.4 Influence of magnetite on slag copper losses: 1-total losses; 2 - losses in dissolved form. x(horizontal)-magnetite quantity in slag, %, y(vertical)-Cu in slag, %

$$CuO + C = Cu + CO\uparrow \quad (1)$$
$$Cu_2O + C = 2Cu + CO\uparrow \quad (2)$$
$$3Fe_2O_3 + C = 2Fe_3O_4 + CO\uparrow \quad (3)$$
$$Fe_3O_4 + C = 3FeO + CO\uparrow \quad (4)$$
$$FeO + C = Fe + CO\uparrow \quad (5)$$

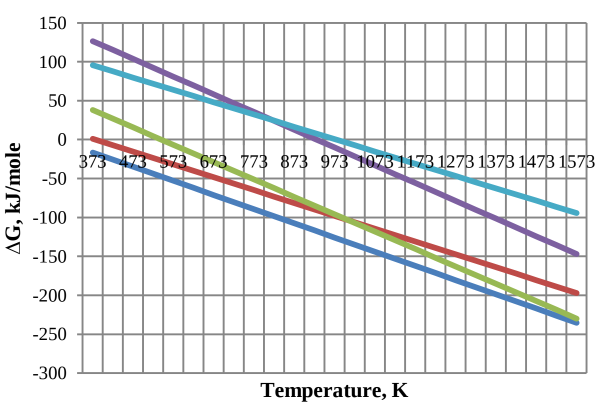

Figure 3.3.5 - General Ellingham diagram of all carbothermic reactions occurring in the slag-carbon system. Reaction lines:
1-react, 2-react, 3-react, 4-react, 5-react

From the graph shown in Fig. 3, it can be seen that, taking into account endothermic reactions, the probability of bustite recovery corresponds to a temperature of 1150 oC (1423 K). At this temperature, the probability of the flow of other chemical reactions is very high. When slag from a laboratory furnace at a temperature of 1200-1240 °C is poured into a crucible, it collides with pieces of automobile tire waste (pre-filled) inside the crucible, and [10] oxidation-reduction chemical reactions occur in the system. In the temperature range of 1000 - 1240 °C, the hydrocarbons present in the rubber part of unusable tire waste decompose with the formation of carbon, hydrogen, and sulfur:

(C4H6S0,25) n → 4nC + 3nH2 + 0.25nS (6)

Knowledge of the various properties of the oxidation process of these substances is of particular importance. When most polymers burn, the flame temperature reaches 1500-1700°C. This is significantly higher than the corresponding value for common materials such as wood and brown coal.

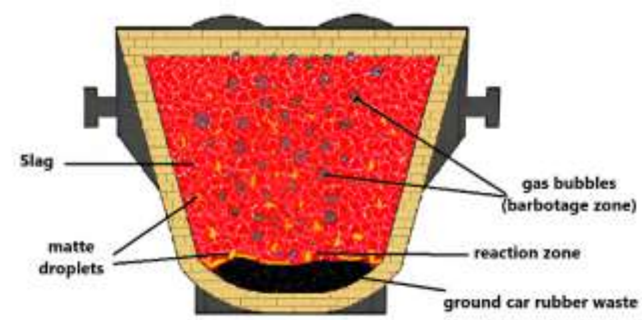

Figure 3.3.5 - Copper slag processing using car tire waste

The phase separation is clearly shown schematically in Fig. 6. In the process of coalescence, small matte droplets merge with each other and form large matte droplets with a large radius. An increase in the radius of the Stein drop accelerates their deposition in the lower phase [6][7].

3.4 Furnace Type Comparison: Vanyukov, Reverberatory, and Rotary Converters

3.4.1 Vanyukov Autogenous Furnace Performance

The Vanyukov furnace—a two-zone bath smelting reactor designed for autogenous processing of sulfide concentrates—has recently been adapted for integrated converter slag reprocessing. Industrial trials conducted at Almalyk MMC JSC demonstrated successful incorporation of pre-reduced converter slag into the concentrate charge without disruption to established smelting parameters. The key technological innovation involves preliminary magnetite reduction in a separate converter unit followed by introduction of reduced slag into the main Vanyukov furnace melt.

Results from December 2022 industrial trials operating the Vanyukov furnace of Almalyk Copper Smelter in continuous mode while processing recovered converter slag demonstrated copper content in waste slag of 0.58–0.72 wt%, equivalent to standard operating performance without slag addition and representing substantial reduction from initial converter slag copper content of 2.2–3.5 wt%. The exothermic oxidation of metallic iron and carbon within clinker provided thermal compensation for endothermic reduction reactions, maintaining process energy balance despite cold slag introduction .

3.4.2 Reverberatory Furnace Operations

Reverberatory furnaces traditionally employed for secondary copper production have long been utilized for converter slag treatment. The indirect heating mechanism and large surface area characterizing reverberatory furnace geometry facilitate extended residence times (2–8 hours) enabling comprehensive metal recovery. Contemporary slow-cooling protocols applied to reverberatory-processed slag—involving controlled cooling to 850°C at rates of 2°C/min—promote copper phase coagulation and growth, increasing average matte particle diameter from ~1 μm to 18–72 μm, substantially improving subsequent flotation recovery.

Dimitrijevic et al. (2016) documented achievement of flotation concentrate grades of 20 wt% copper with recovery efficiency of 86–89% following optimized slow-cooling and flotation protocols applied to reverberatory furnace slag. The extended residence time in reverberatory furnaces permits more complete reduction of copper oxide phases and enhanced phase separation compared to rapid processing in autogenous furnaces, though at the cost of reduced throughput and increased fuel consumption.

3.4.3 Rotary Converter and Specialized Furnace Designs

Emerging specialized furnace designs including top-blown rotary converters (TBRC), rotary furnaces, and innovative slag settling-cleaning furnace configurations developed by technology providers such as SMS Group demonstrate enhanced operational flexibility for diverse slag compositions. These furnaces enable processing of contaminated or variable-composition materials while maintaining precise temperature control and residence time management. The rotational mechanism facilitates enhanced mixing, promotes homogeneous slag composition, and enables efficient separation of distinct liquid phases through enhanced settling conditions.

3.5 Thermodynamic Modeling and Phase Equilibria

Contemporary thermodynamic optimization studies employing FactSage software and Calphad methodology have established predictive databases for complex copper smelting and converting slag systems. Hidayat and Jak (2012) developed comprehensive thermodynamic optimization for the Cu_2O-Al_2O_3-CaO-FeO-Fe_2O_3-MgO-SiO_2-S system, enabling prediction of phase diagrams, element partitioning between slag and metal phases, and activity coefficients across wide composition and temperature ranges [9][11].

Phase equilibria calculations indicate that at target reduction temperatures (1400–1500°C), magnetite preferentially transforms to fayalite (Fe_2SiO_4) under controlled oxygen potential conditions, achieving approximately 10–12 wt% Fe_3O_4 residual content—a threshold below which magnetite precipitation upon cooling remains minimal. Thermodynamic predictions of copper partition coefficients between slag and metal phases suggest that achieving copper content below 0.5 wt% in final slag requires rigorous control of oxygen potential to ensure preferential copper reduction to metal phase [12].

3.6 Integrated Processing Strategies: Multi-Stage Approaches

Recent advances emphasize integrated multi-stage processing combining complementary technologies. A representative two-stage methodology involves: (1) pyrometallurgical reduction of converter slag to reduce magnetite and concentrate copper in metal phase; followed by (2) integration of reduced slag into autogenous smelting furnaces or alternative secondary processing [1][17] documented this approach, demonstrating copper reduction in waste slag from 2.2–3.5 wt% to 0.58–0.72 wt%, representing 80–95% copper recovery in the first processing stage alone[13].

Alternative integrated approaches combine pyrometallurgical reduction with subsequent hydrometallurgical extraction or flotation, achieving total copper recoveries exceeding 95% [15]. Tang et al. employed chlorination roasting of reduced slag followed by hydrometallurgical extraction, achieving comprehensive element recovery including copper, iron, and precious metals [14][16].

4. DISCUSSION

4.1 Comparative Technology Assessment

Analysis of diverse furnace technologies and processing methodologies reveals significant variation in technical performance and economic feasibility depending upon scale, feed characteristics, and desired product specifications. Vanyukov furnace integration offers the advantage of processing high-volume slag streams within existing autogenous smelting circuits, minimizing capital investment and operational complexity. Industrial implementation at Almalyk MMC demonstrates practical feasibility at production scale, though requires careful pre-reduction of converter slag to acceptable magnetite concentrations and coordination with existing concentrate processing.

Reverberatory furnace processing trades higher metal recovery rates (85–89% copper) and superior concentrate grades against lower throughput and higher fuel consumption. This approach remains optimal for processing lower-volume streams or where maximum metal recovery justifies operational costs. Emerging specialized furnace designs offer intermediate solutions combining enhanced flexibility with reasonable economic metrics.

4.2 Optimization of Slag Basicity and Phase Chemistry

The identified optimal slag basicity window (0.95–1.2) and target CaO content (20–25 wt%) provide empirical guidance for industrial operations. Mechanistic explanation derives from consideration of slag phase diagrams and component activities: calcium oxide reduction of silica activity promotes precipitation of calcium silicates as solid phases, removing silica from the liquid slag and thereby reducing slag viscosity and enhancing copper phase settling. Additionally, preferential dissolution of copper oxides in basic slag components over silicates facilitates copper enrichment in reduced metal phases.

Future optimization may benefit from systematic variation of additional fluxing agents including magnesium oxide, alumina, and fluorite, examining combined effects upon slag viscosity, thermal conductivity, and phase equilibria. Computational thermodynamic modeling may predict novel flux combinations achieving improved outcomes with reduced overall flux consumption.

4.3 Economic and Environmental Implications

Industrialization of converter slag reprocessing transforms substantial economic and environmental metrics. Economic analysis indicates that slag containing >1 wt% copper economically justifies pyrometallurgical recovery, with integrated recovery value (copper + iron + precious metals) commonly exceeding $40–80 USD per ton of slag processed at contemporary metal prices. Environmental benefits include elimination of slag landfilling, reduced mining pressure on primary ore reserves (equivalent to ore-grade copper concentrations), and prevention of heavy metal leaching and acid drainage phenomena.

Life cycle assessment comparisons demonstrate that pyrometallurgical slag reprocessing achieves 20–40% reduction in overall copper production greenhouse gas emissions compared to equivalent primary ore smelting, driven by energy recovery from exothermic reduction reactions and avoidance of mining-stage energy demands. Integration into existing smelting circuits minimizes infrastructure expansion and capitalizes upon established operational expertise.

4.4 Research Gaps and Future Directions

Despite significant progress, substantial research opportunities remain in converter slag optimization and utilization:

1. **Mechanistic Understanding of Magnetite Reduction**: While overall kinetic parameters are established, fundamental mechanisms of Fe_3O_4 reduction heterogeneity and particle-scale phenomena warrant deeper investigation through advanced microscopy and in-situ analytical techniques.
2. **Noble Metal Recovery Enhancement**: Systematic investigation of factors controlling gold and silver partition between slag, metal, and vapor phases could optimize precious metal recovery, particularly for technogenic waste streams from zinc production (containing 2–3.5 g/t Au, 160–250 g/t Ag).
3. **Slag Refractory Interactions**: Detailed characterization of slag-refractory corrosion and erosion mechanisms under variable slag composition and temperature profiles would inform furnace design and operational optimization.
4. **Real-Time Process Monitoring**: Development of advanced sensors and real-time feedback control systems could enable dynamic optimization of slag processing parameters, transitioning from static operating conditions to adaptive control regimes.
5. **Hybrid Processing Integration**: Investigation of synergistic combinations of pyrometallurgical, hydrometallurgical, and flotation processing stages could maximize metal recovery while minimizing waste streams.
6. **Scale-Up Challenges**: Current knowledge derives primarily from laboratory and pilot-scale experiments; systematic scale-up studies examining thousand-ton and multi-thousand-ton processing volumes would validate industrial feasibility and refine economic models.

4.5 Regional and Global Implementation Prospects

Current technological capabilities enable implementation of converter slag reprocessing at existing copper smelting operations worldwide. Regional opportunities vary based on local slag volumes, metal prices, environmental regulations, and existing furnace infrastructure. Regions with high slag accumulation (particularly Central Asia, Africa, and South America) represent priority implementation zones. Additionally, regions with stringent environmental legislation and high electricity costs creating incentive for integrated energy recovery present favorable conditions for technology adoption.

5. CONCLUSION

Contemporary research documents substantial advances in converter slag reprocessing through pyrometallurgical technologies, with Scopus-indexed literature establishing comprehensive understanding of fundamental processes and industrial implementation pathways. Key findings establish that magnetite reduction followed by appropriate furnace processing achieves copper recovery of 85–95%, substantially improving upon traditional slag disposal. Optimization of slag basicity (0.95–1.2), operating temperature (1400–1500°C), and reducing agent selection enables progressive improvement in metal extraction efficiency.

Integration of converter slag reprocessing into existing Vanyukov furnace operations demonstrates technical feasibility and economic viability, with industrial trials confirming achievement of waste slag copper content (0.58–0.72 wt%) equivalent to primary smelting performance. The emerging technological capability to transform converter slag from waste into a valuable secondary resource stream supports circular economy principles, reduces environmental burden, and provides economic value through metal recovery and avoided disposal costs.

Future research prioritizing mechanistic understanding, real-time process monitoring, and scale-up validation promises continued optimization and broader industrial implementation of slag reprocessing technologies. As global copper demand persists and primary ore grades decline, the development and implementation of comprehensive slag utilization strategies will remain critical for sustaining copper supply while minimizing environmental impact and resource consumption.

References

[1] Yakubov M.M., Yoqubov M.M., Kholikulov D.B., Maksudkhodjaeva M.S. (2023). Depletion of converter slags to waste in the Vanyukov furnace during pyrometallurgical copper production at JSC Almalyk MMC. Complex use of mineral resources. 331(4), 60-68. https://doi.org/10.31643/2024/6445.39

[2] Dosmukhamedov, N. K., Fedorov, A. N., & Yakubov, M. M. (2025). Distribution of Cu, Pb, Zn and As between products of two-stage reductive depletion of high-copper slags. *Non-Ferrous Metals, 7*, 30–35. • DOI:10.17580/tsm.2019.07.03

[3] Gabasiane, T. S., Danha, G., Mamvura, T. A., Mashifana, T., & Dzinomwa, G. (2021). Characterization of copper slag for beneficiation of iron and copper. *Heliyon*, *7*(4), e06757. https://doi.org/10.1016/j.heliyon.2021.e06757

[4] Bekhzod Gayratov, Bobur Gayratov, Labone L. Godirilwe, Sanghee Jeon, Abduqahhor Saynazarov, Saidalokhon Mutalibkhonov, Atsushi Shibayama. Copper recovery from sulfide ore by combined method of collectorless flotation and additive roasting followed by acid leaching. ChemEngineering – 2025. Volume 9. Issue 6. 117. https://doi.org/10.3390/chemengineering9060117.

[5] Dimitrijevic, M., Kamberovic, Z., Korac, M., Marinkovic, Z., & Raic, K. (2016). Recovery of copper from smelting slag by roasting and water leaching. *Metallurgical and Materials Transactions B, 52*(1), 409-421. http://dx.doi.org/10.5277/ppmp160134

[6] Khojiev Sh.T., Nuraliev O.U., Berdiyarov B.T., Matkarimov S.T., Akramov U, A. (2021). Some thermodynamic aspects of the reduction of magnetite in the presence of carbon. Universum, 3(84). 60-64. https://7universum.com/ru/tech/archive/item/11347

[7] Khojiev Sh.T., Mutalibxonov S.S., Askarova N.M., Turdiev A.B. (2024). Utilization of waste car tires as a reducing agent in the pyrometallurgical processing of converter slag: enhancing metal recovery and slag characteristics. "Current problems, innovative solutions and prospects of the chemical industry". Almalyk. – 2024y. 1-21 november. 286-287. https://www.researchgate.net

[8] Hidayat, T., & Jak, E. (2012). A thermodynamic optimization of copper-containing slag systems for copper smelting and converting processes. *Proceedings of the Seventh International Conference on Molten Slags, Fluxes and Salts,* 1-12. https://www.pyrometallurgy.co.za/MoltenSlags2012/W081.pdf

[9] Khojiakbar Sultonov., Shokrukh Khojiev., Saida'loxon Mutalibkhonov. Thermodynamic and kinetic analysis of the chalcopyrite-magnetite reaction: optimizing temperature for enhanced efficiency // Universum. Moscow. December 2023. P. – 37-39. https://7universum.com/ru/tech/archive/item/16580

[10] Li, B., Wang, Z., & Wang X. (2017). Smelting reduction and kinetics analysis of magnetic iron in converter slag. *Scientific Reports*, *7*, 2406. https://www.nature.com/articles/s41598-017-02696-y

[11] Khasanov U.A., Tolibov B.I., Sh.B.Karshibayev., Mutalibkhonov S.S., Khasanov A.S. (2018) Basic regularities of the thermogravitational method of slag aggregation // Republican Scientific and Technical Conference "Modern Problems and Prospects of Chemistry and Chemical-Metallurgical Production". 204.

[12] Mutalibkhonov S.S. Khojiyev Sh.T. Khudoymuratov SH.J. Riskulov D.D. Improved method of the fire refining of secondary copper-containing materials. Universum: technical sciences: electron scientific journal. May 2025. – № 5(134). – P. 10. – C. 48–54. https://doi:10.32743/UniTech.2025.134.5.20026

[13] Tang, X., Li, Y., & Zhang, H. (2024). Investigation of converter copper slag reduction using spent cathode carbon as a reductant. *Minerals*, *14*(3), 156.

[14] Khojiev Sh.T.., Kholikulov D.B., Mutalibkhonov S.S., Shaymanov I.I., Ma G. Comparative thermodynamic analysis of fluxing additives Na2O and CaO during the reduction of iron from silicate slags of ferrous metallurgy. Черные металлы. – 2025. – № 9. (1125) – C. 12-18. https://doi:10.17580/chm.2025.09.02

[15] Mutalibkhonov S. and et., el. Copper slags processing using NaOH. 89-th BGTU conference. 2025. 87-90. https://elib.belstu.by/handle/123456789/71811

[16] Weijun, H., et al. (2024). Reduction of copper smelting slag by carbon for smelting Cu-Fe alloy. *Alloys, 3(3) 164-177,* https://doi.org/10.3390/alloys3030010

[17] Živković Živan, Mitevska N, Mihajlović Ivan, Nikolić Đorđe (2009). The influence of converter slag magnetite on the scale formation during the smelting of copper concentrates in a reflective furnace Journal of Mining and Metallurgy, 45(1), 23-43. https://doi.org/10.2298/JMMB0901023Z