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Geochemical Controls on Critical Metal Sequestration in Passive AMD Remediation Systems

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Acid mine drainage (AMD) is a major environmental issue associated with coal and metal mining that contaminates thousands of kilometers of streams. Passive AMD treatment systems use natural geochemical and microbial processes to remove metals and generate precipitates enriched in critical metals [1, 2], with some systems producing ore-grade levels [3].

This study presents preliminary results of field experiments at two passive treatment systems in western Pennsylvania that treat high-Al (12–34 ppm) and/or high-Mn (~10 ppm) AMD using limestone. Reaction chambers were installed to evaluate how critical minerals behave with different media and in biotic and abiotic conditions. Nylon mesh bags containing plastic balls (serving as inert controls) or limestone, with or without the Mn mineral H^+-birnessite, were installed. Mesh pore sizes were 0.2 or 50 µm, to block or allow microbial infiltration, respectively. Media were collected at three different times over 12 months while AMD was sampled at influent, effluent, and intermediate locations.

Results confirm that pH is the primary control on sequential metal precipitation; Fe and Al precipitated from pH 4 to 7, and was fully removed by pH 7, while Mn precipitated at pH >6. Flow rates, retention times, metal concentrations, and microbial activity also influenced metal mobility and enrichment. The resulting Mn minerals were disproportionately enriched in Co, Ni, Zn, and REE, while Al-rich solids were enriched in REE. Mn enrichment was greatest in biotic chambers containing H^+-birnessite, underscoring the role of microbial Mn oxidation and preexisting hydrous Mn oxides.

Geochemical modeling reproduced most observed trends but did not fully capture microbially mediated Mn oxidation. Mn-rich precipitates accumulated Co at ore-grade levels (0.2–1%), Mn at low-grade ore levels (15–30%), and REE concentrations of 600–1,200 µg/g, comparable to ion-adsorbed clays. These findings demonstrate the potential of AMD to generate secondary critical metal resources and the importance of Mn oxides (either added or formed *in situ*) to sequester critical metal resources.

[1]Hedin et al. 2024, Chemosphere 346, 140475; [2] Boothe-Lordon et al. 2025, ACS Omega 42577 [3] Hedin et al. 2019, Int J. Coal Geol. 208:54