Supplementary material

Selective removal of arsenic and antimony from Pb-Ag sulfide concentrates by alkaline leaching: Thermodynamic and kinetic studies

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Table 1S. Reactions of PbS and Ag_2S with sodium hypochlorite. Data obtained from HSC database.

Reaction	ΔG^0, kcal/mol	
	25°C	60°C
$PbS + 4ClO^-_{(aq)} = PbCl_3^-{}_{(aq)} + SO_4^{2-}{}_{(aq)} + Cl^-_{(aq)}$	-253.689	-254.113
$PbS + 4ClO^-_{(aq)} = PbSO_4 + 4Cl^-_{(aq)}$	-262.044	-263.023
$Ag_2S + 4ClO^-_{(aq)} = 2AgCl_2^-{}_{(aq)} + SO_4^{2-}{}_{(aq)}$	-236.682	-237.611
$Ag_2S + 4ClO^-_{(aq)} = 2Ag^+_{(aq)} + SO_4^{2-}{}_{(aq)} + 4Cl^-_{(aq)}$	-222.209	-222.759
$Ag_2S + 4ClO^-_{(aq)} = Ag_2SO_4 + 4Cl^-_{(aq)}$	-229.187	-230.164

Table 2S. Reactions of PbS, Ag_2S, FeS_2, As_2S_3, and Sb_2S_3 with sodium hypochlorite in an alkaline medium. Data obtained from HSC database.

Reaction	ΔG^0, kcal/mol	
	25°C	60°C
$PbS + 4ClO^-_{(aq)} + 3OH^-_{(aq)} = HPbO_2^-{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 4Cl^-_{(aq)} + H_2O$	-270.551	-271.850
$PbS + 4ClO^-_{(aq)} + 2OH^-_{(aq)} = PbO + SO_4^{2-}{}_{(aq)} + 4Cl^-_{(aq)} + H_2O$	-272.212	-273.454
$Ag_2S + 4ClO^-_{(aq)} + 4OH^-_{(aq)} = 2AgO^-_{(aq)} + SO_4^{2-}{}_{(aq)} + 4Cl^-_{(aq)} + 2H_2O$	-232.933	-234.912
$Ag_2S + 4ClO^-_{(aq)} + 2OH^-_{(aq)} = 2AgOH_{(aq)} + SO_4^{2-}{}_{(aq)} + 4Cl^-_{(aq)}$	-227.729	-228.482
$FeS_2 + 7ClO^-_{(aq)} + 2OH^-_{(aq)} = Fe^{2+}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 7Cl^-_{(aq)} + H_2O$	-479.862	-480.324
$FeS_2 + 7ClO^-_{(aq)} + 4OH^-_{(aq)} = Fe(OH)_2 + 2SO_4^{2-}{}_{(aq)} + 7Cl^-_{(aq)} + H_2O$	-500.381	-502.815
$2FeS_2 + 15ClO^-_{(aq)} + 2OH^-_{(aq)} = 2Fe^{3+}_{(aq)} + 4SO_4^{2-}{}_{(aq)} + 15Cl^-_{(aq)} + H_2O$	-965.398	-962.617
$2FeS_2 + 15ClO^-_{(aq)} + 8OH^-_{(aq)} = 2Fe(OH)_3 + 4SO_4^{2-}{}_{(aq)} + 15Cl^-_{(aq)} + H_2O$	-1068.907	-1073.581
$FeS_2 + 7.5ClO^-_{(aq)} + 5OH^-_{(aq)} = FeO_2^-{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 7.5Cl^-_{(aq)} + 2.5H_2O$	-534.221	-537.282
$As_2S_3 + 14ClO^-_{(aq)} + 12OH^-_{(aq)} = 2AsO_4^{3-}{}_{(aq)} + 3SO_4^{2-}{}_{(aq)} + 14Cl^-_{(aq)} + 6H_2O$	-1028.524	-1031.233
$As_2S_3 + 3Ag_2S + 26ClO^-_{(aq)} + 12OH^-_{(aq)} = 2Ag_3AsO_4 + 6SO_4^{2-}{}_{(aq)} + 26Cl^-_{(aq)} + 6H_2O$	-1756.591	-1765.087
$As_2S_3 + 2FeS_2 + 29ClO^-_{(aq)} + 14OH^-_{(aq)} = 2FeAsO_4 + 7SO_4^{2-}{}_{(aq)} + 29Cl^-_{(aq)} + 7H_2O$	-2045.076	-2055.667
$Sb_2S_3 + 14ClO^-_{(aq)} + 12OH^-_{(aq)} + 6Na^+ = 2Na_3SbO_{4(aq)} + 3SO_4^{2-}{}_{(aq)} + 14Cl^-_{(aq)} + 6H_2O$	-960.156	-966.463
$Sb_2S_3 + 14ClO^-_{(aq)} + 6OH^-_{(aq)} = Sb_2O_5 + 3SO_4^{2-}{}_{(aq)} + 14Cl^-_{(aq)} + 3H_2O$	-950.808	-954.865
$Sb_2S_3 + 12ClO^-_{(aq)} + 6OH^-_{(aq)} = Sb_2O_3 + 3SO_4^{2-}{}_{(aq)} + 12Cl^-_{(aq)} + 3H_2O$	-852.208	-856.062
$Sb_2S_3 + 12ClO^-_{(aq)} + 8OH^-_{(aq)} = 2SbO_2^-{}_{(aq)} + 3SO_4^{2-}{}_{(aq)} + 12Cl^-_{(aq)} + 4H_2O$	-848.280	-850.559

Table 3S. Reactions of PbS, Ag_2S, FeS_2, As_2S_3, and Sb_2S_3 with sodium hypochlorite in acid medium. Data obtained from HSC database.

Reaction	ΔG^0, kcal/mol	
	25°C	60°C
$PbS + 8ClO^-_{(aq)} + 5H^+_{(aq)} = HPbO_2^-_{(aq)} + SO_4^{2-}_{(aq)} + 4Cl_{2(g)} + 2H_2O$	-279.849	-285.969
$PbS + 8ClO^-_{(aq)} + 6H^+_{(aq)} = PbO + SO_4^{2-}_{(aq)} + 4Cl_{2(g)} + 3H_2O$	-300.595	-307.426
$PbS + 5ClO^-_{(aq)} + 2H^+_{(aq)} = PbCl_3^-_{(aq)} + SO_4^{2-}_{(aq)} + Cl_{2(g)} + H_2O$	-270.328	-272.532
$Ag_2S + 8ClO^-_{(aq)} + 4H^+_{(aq)} = 2AgO^-_{(aq)} + SO_4^{2-}_{(aq)} + 4Cl_{2(g)} + 2H_2O$	-223.144	-229.178
$Ag_2S + 8ClO^-_{(aq)} + 6H^+_{(aq)} = 2AgOH_{(aq)} + SO_4^{2-}_{(aq)} + 4Cl_{2(g)} + 2H_2O$	-256.112	-262.454
$FeS_2 + 14ClO^-_{(aq)} + 12H^+_{(aq)} = Fe^{2+}_{(aq)} + 2SO_4^{2-}_{(aq)} + 7Cl_{2(g)} + 6H_2O$	-558.161	-569.554
$FeS_2 + 15ClO^-_{(aq)} + 14H^+_{(aq)} = Fe^{3+}_{(aq)} + 2SO_4^{2-}_{(aq)} + 7.5Cl_{2(g)} + 7H_2O$	-588.403	-599.601
$FeS_2 + 15ClO^-_{(aq)} + 10H^+_{(aq)} = FeO_2^-_{(aq)} + 2SO_4^{2-}_{(aq)} + 7.5Cl_{2(g)} + 5H_2O$	-563.582	-576.164
$As_2S_3 + 28ClO^-_{(aq)} + 16H^+_{(aq)} = 2AsO_4^{3-}_{(aq)} + 3SO_4^{2-}_{(aq)} + 14Cl_{2(g)} + 8H_2O$	-1032.435	-1050.872
$As_2S_3 + 28ClO^-_{(aq)} + 22H^+_{(aq)} = 2H_3AsO_{4(aq)} + 3SO_4^{2-}_{(aq)} + 14Cl_{2(g)} + 8H_2O$	-1088.729	-1113.485
$As_2S_3 + 3Ag_2S + 52ClO^-_{(aq)} + 40H^+_{(aq)} = 2Ag_3AsO_4 + 6SO_4^{2-}_{(aq)} + 26Cl_{2(g)} + 20H_2O$	-1960.167	-2005.758
$As_2S_3 + 2FeS_2 + 58ClO^-_{(aq)} + 44H^+_{(aq)} = 2FeAsO_4 + 7SO_4^{2-}_{(aq)} + 29Cl_{2(g)} + 22H_2O$	-2260.396	-2311.891
$Sb_2S_3 + 28ClO^-_{(aq)} + 22H^+_{(aq)} = Sb_2O_5 + 3SO_4^{2-}_{(aq)} + 14Cl_{2(g)} + 11H_2O$	-1069.235	-1093.621
$Sb_2S_3 + 24ClO^-_{(aq)} + 18H^+_{(aq)} = Sb_2O_3 + 3SO_4^{2-}_{(aq)} + 12Cl_{2(g)} + 9H_2O$	-937.358	-957.978
$Sb_2S_3 + 24ClO^-_{(aq)} + 16H^+_{(aq)} = 2SbO_2^-_{(aq)} + 3SO_4^{2-}_{(aq)} + 12Cl_{2(g)} + 8H_2O$	-895.258	-912.769

Table 4S. Reactions of PbS, Ag_2S, FeS_2, As_2S_3, and Sb_2S_3 with hydrogen peroxide in an alkaline medium Data obtained from HSC database.

Reaction	ΔG^0, kcal/mol	
	25°C	60°C
$PbS + 4H_2O_{2(aq)} + 3OH^-_{(aq)} = HPbO_2^-_{(aq)} + SO_4^{2-}_{(aq)} + 5H_2O$	-278.387	-276.795
$PbS + 4H_2O_{2(aq)} + 2OH^-_{(aq)} = PbO + SO_4^{2-}_{(aq)} + 5H_2O$	-280.047	-278.399
$PbS + 4H_2O_{2(aq)} = PbSO_4 + 4H_2O$	-269.879	-267.968
$Ag_2S + 4H_2O_{2(aq)} + 4OH^-_{(aq)} = 2AgO^-_{(aq)} + SO_4^{2-}_{(aq)} + 6H_2O$	-240.768	-239.856
$Ag_2S + 4H_2O_{2(aq)} + 2OH^-_{(aq)} = 2AgOH_{(aq)} + SO_4^{2-}_{(aq)} + 4H_2O$	-235.564	-233.426
$Ag_2S + 4H_2O_{2(aq)} = 2Ag^+_{(aq)} + SO_4^{2-}_{(aq)} + 4H_2O$	-230.045	-227.703
$Ag_2S + 4H_2O_{2(aq)} = Ag_2SO_4 + 4H_2O$	-237.022	-235.109
$FeS_2 + 7H_2O_2(a) + 4OH^-_{(aq)} = Fe(OH)_2 + 2SO_4^{2-}_{(aq)} + 8H_2O$	-514.093	-511.468
$FeS_2 + 7.5H_2O_2(a) + 4OH^-_{(aq)} = Fe(OH)_3 + 2SO_4^{2-}_{(aq)} + 8H_2O$	-549.145	-546.062
$FeS_2 + 7.5H_2O_2(a) + 5OH^-_{(aq)} = FeO_2^-_{(aq)} + 2SO_4^{2-}_{(aq)} + 10H_2O$	-548.912	-546.554
$FeS_2 + 7H_2O_2(a) + 2OH^-_{(aq)} = Fe^{2+}_{(aq)} + 2SO_4^{2-}_{(aq)} + 8H_2O$	-493.574	-488.977
$FeS_2 + 7.5H_2O_2(a) + OH^-_{(aq)} = Fe^{3+}_{(aq)} + 2SO_4^{2-}_{(aq)} + 8H_2O$	-497.390	-490.580
$As_2S_3 + 14H_2O_{2(aq)} + 12OH^-_{(aq)} = 2AsO_4^{3-}_{(aq)} + 3SO_4^{2-}_{(aq)} + 20H_2O$	-1055.948	-1048.540
$As_2S_3 + 3Ag_2S + 26H_2O_{2(aq)} + 12OH^-_{(aq)} = 2Ag_3AsO_4 + 6SO_4^{2-}_{(aq)} + 32H_2O$	-1807.521	-1797.227
$As_2S_3 + 2FeS_2 + 29H_2O_{2(aq)} + 14OH^-_{(aq)} = 2FeAsO_4 + 7SO_4^{2-}_{(aq)} + 36H_2O$	-2101.882	-2091.516
$Sb_2S_3 + 14H_2O_{2(aq)} + 12OH^-_{(aq)} + 6Na^+ = 2Na_3SbO_{4(aq)} + 3\ SO_4^{2-}_{(aq)} + 20H_2O$	-987.580	-983.769
$Sb_2S_3 + 14H_2O_{2(aq)} + 6OH^-_{(aq)} = Sb_2O_5 + 3SO_4^{2-}_{(aq)} + 17H_2O$	-978.232	-972.172

$Sb_2S_3 + 12H_2O_{2(aq)} + 6OH^-_{(aq)} = Sb_2O_3 + 3SO_4^{2-}{}_{(aq)} + 15H_2O$	-875.714	-870.896
$Sb_2S_3 + 12H_2O_{2(aq)} + 8OH^-_{(aq)} = 2SbO_2^-{}_{(aq)} + 3SO_4^{2-}{}_{(aq)} + 16H_2O$	-871.786	-865.393

Table 5S. Reactions of Pb and Ag species with sulfide or hydroxide ions. Data obtained from HSC database.

Reaction	**ΔG^0, kcal/mol**	
	25°C	60°C
$HPbO_2^-{}_{(aq)} + S^{2-}{}_{(aq)} + H_2O = PbS + 3OH^-_{(aq)}$	-18.719	-18.138
$PbSO_4 + 3OH^-_{(aq)} = HPbO_2^-{}_{(aq)} + SO_4^{2-}{}_{(aq)} + H_2O$	-8.507	-8.827
$2AgO^-_{(aq)} + S^{2-}{}_{(aq)} + 2H_2O = Ag_2S + 4OH^-_{(aq)}$	-56.337	-53.925
$2AgOH_{(aq)} + S^{2-}{}_{(aq)} = Ag_2S + 2OH^-_{(aq)}$	-61.541	-61.549