SUPPLEMENTARY MATERIAL FOR

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Optimized Bioleaching Pre-treatment of UG-2 PGM Flotation Concentrate Using Design of Experiments

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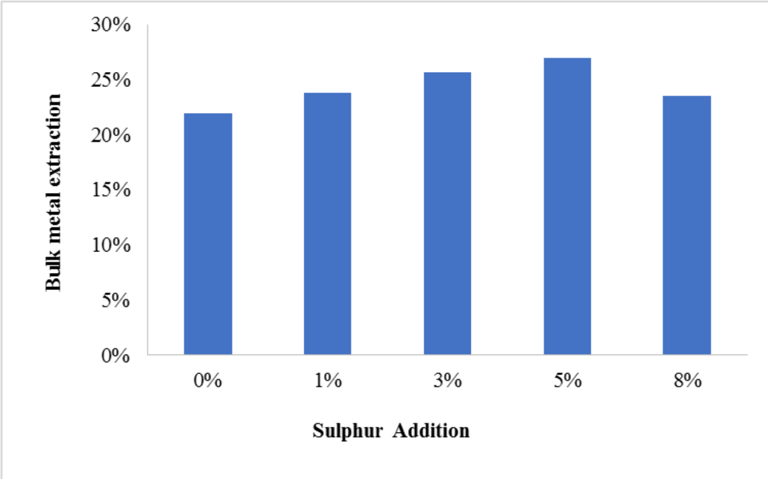

Fig. S-1: Metal extraction as a function of sulphur addition

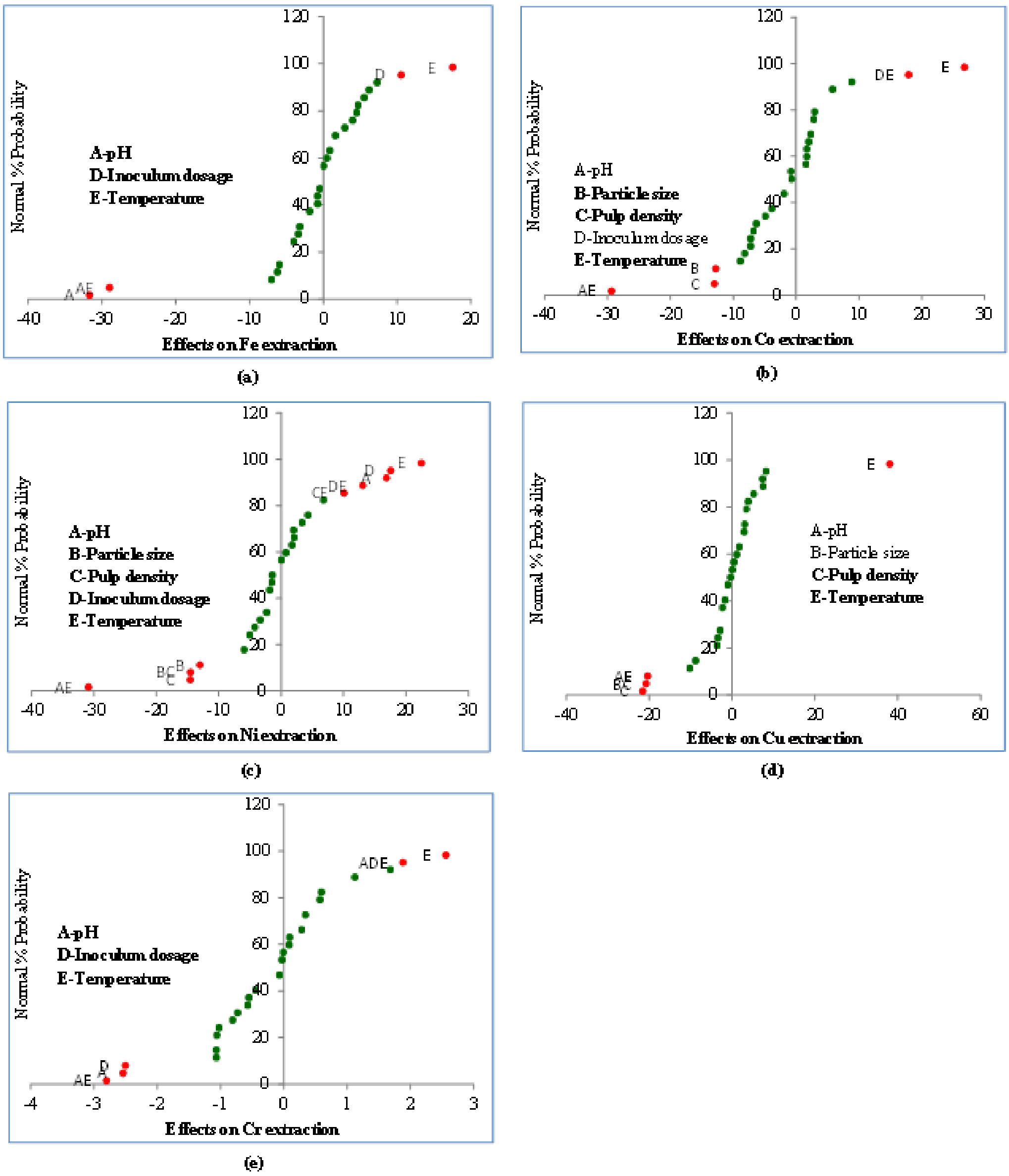

Fig. S-2 (a-e)): Normal probability plot of effects for Co, Cr, Cu, Fe and Ni extraction

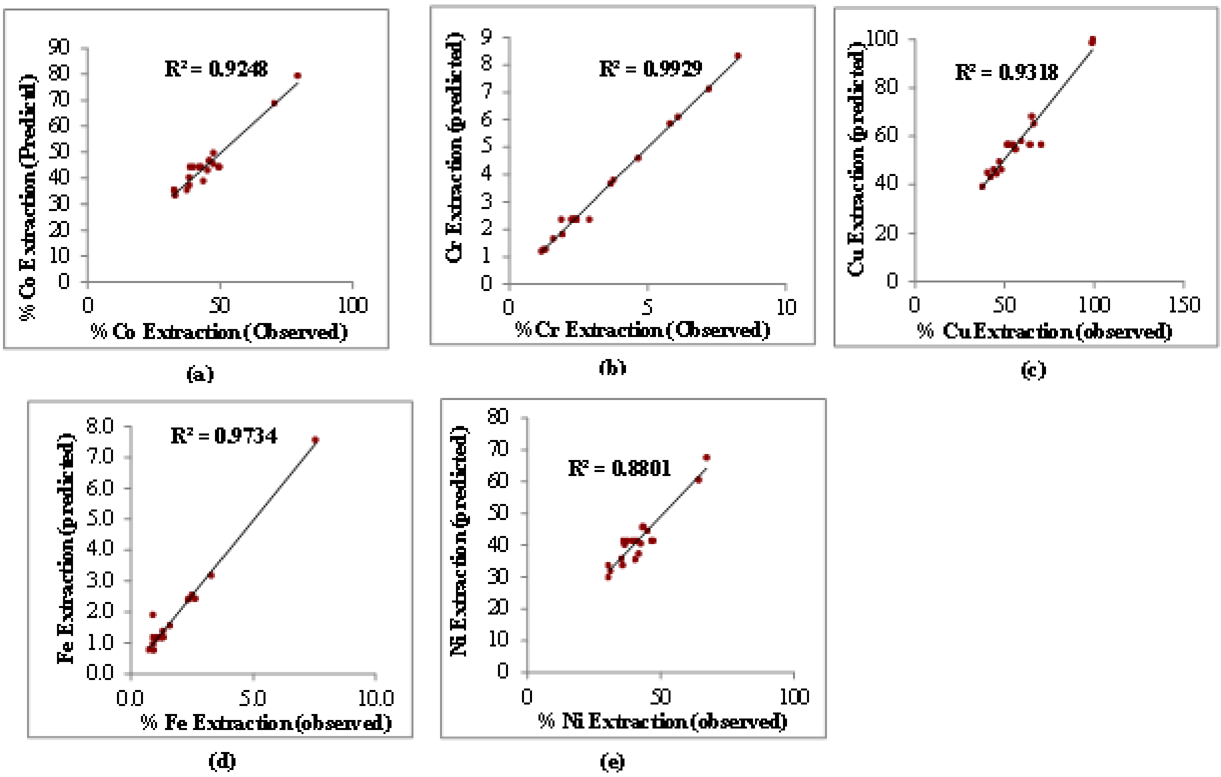

Fig. S-3: (a-e)): Relationship between experimental (observed) and predicted base metal extraction.

Table S-1: Procedures for fire assay and acid digestion [57, 58]

Fire Assay
• **Weighing sample** 10-30 grams of sample is weighed. • **Fluxing and fusion of the sample.** Fluxing reagents and some silver are added to the crucible. If a sample contains sulphides, arsenides, antimonides and tellurides, a roasting pre-treatment at 700˚C for 20 minutes may be required before fluxing. The weighed sample is poured into the crucible and the charge is thoroughly mixed. The mixed charge is placed into a furnace at a temperature of 1900 ˚F (1038˚C) – 2000˚F (1093˚C). As the mixture heats up, the PbO of the charge is reduced to lead by the carbon or sulphides of the charge. The sample minerals fuse and the shots of lead then take up the freed gold and silver from the surrounding particles of the ore. This produces an alloy of lead and the precious metals. At the same temperature, the borax of the charge begins to melt and forms fusible compounds with some of the bases of the flux. The fusion usually takes 45 minutes at a temperature of 1950˚F (1066 ˚C) to 2000˚F (1093˚C). Lead oxide and silica combine and from this point the slag begins to form rapidly. The slag remains viscous until the ore particles are thoroughly decomposed and every particle of gold and silver has been taken up by the suspended molten lead. The slag becomes thoroughly fluid, and the lead falls through the slag and collects at the bottom of the crucible. The molten mixture is poured into a metal conical mould where the Pb alloy collects beneath the slag as a small cone. • **Separation of the slag from the button.** When the slag is cooled, the lead button is separated from the slag by hammering the slag off the button. The lead button should be bright, and it is separated from the slag easily. The Pb buttons is between 15 to 35 grams. • **Cupellation.** Empty cupels are placed in the furnace for 10 minutes in order to expel all the moisture and organic matter. The pounded lead buttons are placed into the cupel in the furnace and the lead is oxidized to PbO, which is absorbed into the cupel. The objective of cupellation is the conversion of Pb and other base metals such as Cu that are in the lead button into oxides. The furnace vent and door are closed for 5 minutes to make sure that all the buttons have opened up. The door is opened slightly to admit a supply of air to promote oxidation of the lead. The air oxidizes the Pb to PbO, 98.5% soaks into the porous surface of the cupel and about 1.5% volatilizes. Cupellation is continued for 35 – 40 minutes. The oxidation proceeds at a rate of about 1 g of lead per minute so 30 gram buttons should take about 30 minutes for all the lead to be oxidized. The Au, Ag and the other precious metals do not oxidize under cupellation conditions and are left as a small bead in the bottom of the cupel. The gold and silver bead is separated from the lead. • **Parting** Parting is the process of dissolving the Ag in the bead from the cupellation to leave the Au behind for weighing or to be read on the AAS. The bead is weighed before parting using sensitive micro-balances. The following solutions are used in the parting process: Nitric Acid (HNO_3) – Dissolves Ag and Pt group metals and leaves the gold behind. Sulphuric Acid (H_2SO_4) – dissolves Ag, leaves the Pt group metals and gold behind. Hydrochloric acid (HCl) – In the AAS finish, HCl is added after the Ag is dissolved to form aqua regia (3:1 HCl to HNO_3). Aqua regia dissolves the gold Ammonia (NH_4OH) – used to dissolve any possible silver chloride which may have precipitated out. The idea of parting is to prevent the gold from breaking up into small particles. The gold that remains in one piece is much easier to handle. • **Weighing finish/Instrumental finish** After parting, the Au left behind is weighed or dissolved in aqua regia to be read using AAS.
Acid Digestion

Lab Method 3050:1T

5mL of 1:1 nitric acid is added to 1-2g of solid sample measured into a digestion tube. The sample is heated in a block at 90-95°C for 15 minutes. 2.5mL of concentrated nitric acid is added, and sample is refluxed for 30 minutes. The sample is then cooled and 2.5mL of concentrated nitric acid is added again. The sample is refluxed for an additional 30 minutes. 0.5mL of 30% hydrogen peroxide is added to the cooled sample, and the sample is re-heated in the block until the sample no longer is effervescing. 1.0mL of hydrogen peroxide is added to the sample three more times and the sample is heated in the block between each aliquot addition of 30% hydrogen

Peroxide. 5mL of concentrated Hydrochloric acid is added, and the sample is heated on the block for 15 minutes. After cooling, the sample is diluted up to 50mL with deionized water. If the sample should go to dryness, the sample must be re-prepared. All solid samples require filtration due to insoluble silicates and the formation of precipitates during digestion.

Table S-2: PGE Assay of UG2 PGM concentrate

element	Pt	Pd	Rh	Au
ppm	119	72.1	23.2	2.18

* The PGE results are an average of duplicate assays

Table S-3*:* Bulk modal analysis of UG2 PGM flotation concentrate

legend	mineral group	phase	chemical formula	abundance (wt %)
	Pyroxene	Enstatite/Ferrosilite	$(MgFe)SiO_3$	33.1
		Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	8.7
	Amphibole	Hornblende	$(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$	4.1
	Feldspar	Anorthite	$CaAl_2Si_2O_8$	0.8
	Serpentine	Lizardite	$Mg_3Si_2O_5(OH)_4$	11.5
	Mica	Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$	13.0
	Chlorite	Clinochlore	$(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$	3.0
	Talc	Talc	$Mg_3Si_4O_{10}(OH)_2$	16.7
	Chromite	Chromite	$FeCr_2O_4$	4.2
	Pentlandite	Pentlandite	$(Fe,Ni)_9S_8$	2.8
	Chalcopyrite	Chalcopyrite	$CuFeS_2$	1.3
	Pyrite	Pyrite	FeS_2	0.9
			Total	**100.0**

Table S-4*:* Base metal sulphide analysis

base metal sulphides		
phase	**chemical formula**	**mass %**
pentlandite	$(Fe,Ni)_9S_8$	41.3
millerite	NiS	1.0
chalcopyrite	$CuFeS_2$	25.7
pyrrhotite	$Fe_{(1-x)}S$	19.5
pyrite	FeS_2	12.2
Other base metal sulphides*	-	0.3
	Total	**100.0**

* Other base metal sulphides include sphalerite, galena, and chalcocite

Table S-5*:* UG2 BMS grain size distribution

BMS grain distributions (*)			
	fine (<20um)	med (20-50um)	coarse (>50um)
BMS Distribution	58.5%	26.2%	15.3.0%

* BMS distributions - these values are for BMS-containing particles only and not representative of the whole sample

Table S-6: Free surface area liberation

	Mineral				
Liberation Classes	Pentlandite	Millerite	Chalcopyrite	Pyrrhotite	Pyrite
Locked	7.8	25.9	11.6	12.3	18.1
Low middlings	8.1	12.6	6.6	8.4	9.2
High middlings	22.4	24.3	12.8	35.5	23.7
Liberated	13.7	15.7	7.5	19.3	11.5
Very Liberated	20.9	9.8	14.9	16.2	22.1
Completely Liberated	27.2	11.8	46.6	8.2	15.5

Table S-7: Discrete area % liberation

	Mineral				
Liberation Classes	Pentlandite	Millerite	Chalcopyrite	Pyrrhotite	Pyrite
Locked	6.7	16.0	11.2	10.5	17.7
Low middlings	6.6	16.3	6.1	7.3	9.2
High middlings	15.8	12.6	9.3	19.5	13.1
Liberated	11.1	23.1	5.4	14.4	11.7
Very Liberated	34.2	20.5	24.4	40.7	35.3
Completely Liberated	25.7	11.5	43.6	7.6	13.0

Table S-8: Base metal sulphide mineral association

	Mineral association					
Minerals	**pentlandite**	**millerite**	**chalcopyrite**	**pyrrhotite**	**pyrite**	**other base metal sulphides**
free surface	56.4	35.8	55.7	47.0	33.1	20.9
pentlandite	0.0	16.2	7.0	11.0	18.2	8.0
millerite	0.6	0.0	0.1	0.0	1.0	2.3
chalcopyrite	5.6	1.8	0.0	5.2	11.7	7.5
pyrrhotite	7.4	0.0	4.4	0.0	18.9	0.9
pyrite	18.4	31.2	14.8	28.2	0.0	29.4
other base metal sulphides	0.2	1.5	0.2	0.0	0.6	0.0
pyroxene	1.9	0.7	1.8	2.6	2.5	1.2
feldspar	2.8	5.8	8.1	1.9	4.9	2.0
quartz	2.2	3.4	2.7	1.2	3.4	11.2
olivine	0.0	0.0	0.0	0.0	0.0	0.0
talc	1.6	0.6	1.9	0.8	1.4	0.5
serpentine	0.0	0.0	0.0	0.0	0.0	0.0
chlorite	1.3	1.8	1.2	0.5	2.1	0.8
mica	0.1	0.0	0.1	0.0	0.2	0.0
amphibole	0.4	0.2	0.7	0.3	0.5	0.2
other silicates	0.1	0.0	0.4	0.2	0.3	0.3
chromite	0.1	0.0	0.2	0.0	0.3	0.1
Fe oxides	0.1	0.0	0.1	0.3	0.2	0.0
other oxides	0.0	0.0	0.1	0.0	0.1	8.9
calcite	0.1	0.0	0.1	0.0	0.1	0.1
other	0.8	0.9	0.4	0.7	0.4	5.5
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table S-9: UG-2 PGM species

Distribution of PGM types			
PGM	PGM Vol %	# PGM grains	average ECD (um)
	100.0	**184**	
PtRhCuS	8.6	48	2.3
RuS	7.1	21	4.0
PtS	19.6	54	3.9
PtPdS	47.1	30	7.5
PdBiTe	0.2	4	1.5
PtBiTe	0.1	2	1.4
PdPb	0.4	3	2.8
PdAs	0.1	1	3.0
PtFe	2.1	10	3.0
PtAsS	0.2	3	1.9
PtPdPb	0.3	1	4.4
PtPdBiTe	0.0	1	1.2
PtPdAs	0.1	2	1.9
PtAs	13.6	1	30.9
PdSb	0.4	2	3.7
PdS	0.2	1	3.8

Table S-10: UG-2 PGM grain size distribution

PGM grain distributions (*)			
	fine (<20um)	med (20-50um)	coarse (>50um)
PGM distribution	23.9%	76.1%	0.0%

* PGM distributions - these values are for PGM-containing particles only and not representative of the whole sample

Table S-11: UG-2 PGM grain mode of occurrence

PGM grain mode of occurrence				
	Liberation characteristic	PGM Vol%	#PGM grains	# PGM grains <3μm ECD
L	Liberated PGMs	50.1	17	4
SL	PGMs associated with liberated BMS (Base Metal Sulphides)	33.6	112	65
SG	PGMs associated with BMS locked in silicate or oxide gangue particles			
AG	PGMs attached to silicate or oxide gangue particles	4.4	8	2
SAG	PGMs associated with BMS attached to silicate or oxide gangue particles	10.2	39	23
G	PGMs locked within silicate or oxide gangue particles	1.6	8	2
		100	184	96

Table S-12: Observed values for Co, Cr, Cu, Fe and Ni extraction.

Factor Levels						% Metal Extraction (Observed)				
Coded			Actual							
pH	Pulp Density	Inoculum Dosage	pH	Pulp Density	Inoculum Dosage	Co	Cr	Cu	Fe	Ni
-1	-1	-1	1.4	8	9	62.2	5.0	62.9	16.3	68.6
+1	-1	-1	1.6	8	9	64.6	4.5	66.0	11.0	71.4
-1	+1	-1	1.4	15	9	51.5	3.4	56.7	9.7	58.5
+1	+1	-1	1.6	15	9	65.0	3.3	78.4	7.2	71.7
-1	-1	+1	1.4	8	20	56.8	4.4	51.4	14.1	62.3
+1	-1	+1	1.6	8	20	59.8	3.9	59.3	11.1	64.8
-1	+1	+1	1.4	15	20	63.9	4.2	62.5	12.8	68.2
+1	+1	+1	1.6	15	20	45.8	2.4	53.5	6.2	51.1
-1.682	0	0	1.3	12	15	90.8	7.8	92.8	27.4	99
+1.682	0	0	1.7	12	15	73.3	2.8	99.0	8.1	84.8
0	-1.682	0	1.5	5	15	66.7	5.2	61.9	15.4	74.7
0	+1.682	0	1.5	18	15	38.1	2.4	41.6	6.9	42.9
0	0	-1.682	1.5	12	5	60.6	4.4	62.5	14.3	67.7
0	0	+1.682	1.5	12	24	54.9	4.4	52.9	11.4	62.9
0	0	0	1.5	12	15	60.9	3.5	66.2	8.9	68.7
0	0	0	1.5	12	15	64.4	4.2	68.7	11.1	70.2
0	0	0	1.5	12	15	55.9	4.0	56.3	11.6	59.5
0	0	0	1.5	12	15	60.6	3.8	68.0	8.5	69.7

0	0	0	1.5	12	15	58.5	3.7	58.4	10.4	65.3
0	0	0	1.5	12	15	79.3	5.4	84.6	14.0	87.7