

Carbon Re-Adsorption of Gold from Eluate as an Alternative to Gold Electrowinning

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Abstract: A number of metallurgical techniques have been adopted for the recovery of gold from eluate solution in the mining industry, such as electrowinning and zinc cementation techniques. Electrowinning process is facilitated via the application of current (electricity) to recover gold from eluate. A partial operating cost estimate of electrowinning in gold recovery asserts that 73% of the cost is attributed to electricity used at the electrowinning stage. One of the business improvement approaches towards reducing operating cost is finding ways to cut down electricity cost. This paper assessed the possibility of economically recovering gold from eluate using carbon re-adsorption technique. This process, contrary to the conventional electrowinning, is devoid of stimulators such as direct current (electricity) in respect of recovering gold from eluate. After using fresh carbon to re-adsorb gold from the eluate, ashing the loaded carbon, and smelting the ash, the partial operating cost for recovering gold was estimated to be \$10,580, with fresh carbon cost accounting for more than 50%. The cost of using electrowinning technique was, however, \$3,260. The estimated net revenues from the sales of gold using the carbon re-adsorption and electrowinning techniques were \$1,711,527 and \$1,638,951 respectively, with the difference stemming from corresponding purities of 92.9 % and 88.59% respectively. A total of \$ 72,576 weekly increase in revenue, about 4.24% profit margin was realised from the carbon re-adsorption process. This paper shows promising results, which sets the platform for further investigation into decreasing the cost of re-adsorption by using less expensive carbon-base materials.

Keywords: Gold recovery; Eluate; Carbon re-adsorption; Electrowinning; Smelting; Ashing

1. Introduction

Recovery of gold from pregnant solution is a much sensitive aspect of operations in the gold processing industries, most especially in the 21st century. Most of the present-day mining industries are treating large volumes of low-grade ore to meet their annual gold production target, and hence, fast and highly efficient techniques of recovering gold from pregnant solution at a profitable cost in a safe and healthy environment is the pursuit of present-day industries.

Over the years, Merrill-Crowe and electrowinning processes have extensively been used both on large- and small-scale for the reduction of silver and gold from cyanide solutions.^[1-1] The process involves clarification of the metal bearing solution, deaeration, zinc dust addition, precious metal precipitation and filtration of precipitate.^[1-7] According to Walton, the concentration of suspended solids in a clarified solution should be 1ppm or less.^[16] The deaeration process prior to zinc addition decreases zinc consumption and enhances the gold reduction processes.^[6-9] These techniques have proven to increase recoveries at a safe and economical cost to some extent. Makoba stated that MINTEK researchers proposed zinc cementation approach as an alternative to electrowinning for direct carbon treatment of carbon eluate.^[9] Mooiman and Aktas further added that the process chemistry of Merrill-Crowe approach is

simple and can be applied directly to concentrated solutions produced by the elution of silver and gold.^[2-11]

However, since the advent of concentration technologies based on activated carbon, electrowinning process has been extensively used to recover gold and silver from very high and more concentrated solutions generated by the activated carbon elution process to produce higher grade doré.^[11] Electrowinning process provides superior advantages over the Merrill-Crowe process; apart from its compact equipment setup, few process steps and reduced operational cost, electrolytic solution can be recycled for the next batch of elution process as reagents added do not impede solution reuse. Secondly, it is a highly selective process that enhances bullion purity.^[5]

Considering the, above-mentioned process technological approach in precious metal recovery from solution, fine zinc dust and direct current (DC current) are respectively used by the Merrill-Crowe approach and electrowinning process as stimulators to catalyse the precipitation/displacement of gold from solution prior to smelting. Unlike the electrowinning process of gold recovery, the zinc cementation approach of gold recovery has not received much industrial application due to its complex set-up, single solution use and complex process of recovery. The question now is, can there be

another process approach to recover gold from eluate at a profitable return without the application of any stimulator?

With the electrowinning process, one major cost component is electricity. With the current power (electricity) ration and erratic supply, few industries have resolved to self-owned power generating plant for uninterrupted power supply during production. This has increased the production cost of such mines. Fast growing mines have resolved to best business improvement practices aiming at cutting down power (electricity) cost in their operation. This has opened up another page for researchers to find alternative mode of recovering gold from eluate at a fast, efficient, effective, environmentally friendly means and most importantly, at a high profit return. Granulated activated carbon (GAC) in the CIL/CIP application, is used to adsorb and concentrate gold from low grade solution followed by elution. This paper thus hypothesises that activated carbon adsorption will be a better alternative to electrowinning as a method of recovering gold from eluate. The loaded activated carbon will be ashed and gold, obtained by smelting.

2. Experimental Section

2.1. Materials Used

A miniature elution column and eluate holding tank was set up using cleaned plastic 'Voltic' bottles (1.5 L, 750 mL and 500 mL) and a 24-L gallon. The eluate solution and fresh carbon used in this experiment were collected from the operations of Golden Star Wassa Limited which is currently running a Zadra elution system. The hot eluate collected from the field was cooled to room temperature before being used in the experiment. An intravenous infusion set was employed for dispensing eluate solution used in the experiment. The effluents from the experimental setup were collected in a 20 mL glass tubes for gold analysis via an Atomic Absorption Spectroscopy (AAS).

2.2. Materials Characterization

Carbon properties that have the potential of influencing the performance of activated carbon were diagnosed; absolute adsorptivity, carbon size fractions and attrition rate. These parameters were pre-examined before running the test with the choice carbon.

2.2.1. Carbon Size Analysis

The bulk activated carbon sample used in this study was obtained from Golden Star Wassa Limited processing plant. The bulk plant carbon sample was riffle split into three (3) representative parts.

Table 1. Activated Carbon Particle Size Distribution

Sample	Mass of Carbon(g)	+2mm (g)	+1.7m (g)	+1mm (g)	+850um (g)
1	204.7	83.7	85.8	35.1	0.1
2	203.4	77.2	99.1	27.1	0
3	209	59.6	110.3	39	0.1
Average	205.7	73.5	98.4	33.7	0.1
Percentile (%)		35.73	47.84	16.38	0.05

Table 2. Absolute Adsorptivity of Chemquest Activated Carbon

sample	standard	Residual gold	% Gold Adsorbed
1	9.95	5.45	45.22
2	9.95	5.4	45.73
3	9.95	5.65	43.22
Average	9.95	5.5	44.72

Particle size distribution (PSD) studies of the split were carried out with the following nest of sieves; 2 mm, 1.7 mm, 1 mm and 0.85 mm stacked on the AS 200 Retsch sieve shaker under dry condition. The percentage size distribution is shown in the Table 1.

2.2.2. Absolute Adsorptivity

Absolute adsorptivity defines the total adsorption of an adsorbate (dissolved gold) by an adsorbent (activated carbon) in a defined period of time. The absolute adsorptivity of the Chemquest activated carbon was analysed to confirm factory value which is between 45% - 50%. For the absolute adsorptivity test experiment, 1 g carbon sample obtained from a 15 g riffle split bulk sample was weighed into three different sample bottles (1.2 L) after pre-conditioning process (wetting to degas carbon and drying).

To produce a 10-ppm gold chloride working solution for the three carbon samples, 3 litres of demineralized water (pH adjusted to 10.8 with NaOH) was conditioned with 60 mL of stock gold chloride solution, NaCN (0.76 g) and CaCl (1.36 g). A litre of the working solution was poured into the 1.2 L sample bottle containing the carbon sample to be analysed. The samples were corked and rolled on a bench roller at a rate of 111 revolutions per minutes (rev/min) for 1 hour. 30 mL of the solution was decanted into cleaned test tubes for residual gold in solution analysis via an Atomic Absorption Spectrometer machine. The absolute adsorptivity result is shown in Table 2.

2.3. Gold Adsorption from Eluate unto Carbon Experimental Setup

Fresh Chemquest activated carbon (125 g, 250 g, 500 g and 1000 g) were stacked in an inverted plastic bottles of various sizes; 500, 750, 1500, 4500 mL respectively.

The concentrated eluate solution (32 ppm head) was dispensed under gravity from the 24-L eluate holding tank via the intravenous infusion kits onto the respective carbon setup. The eluate solution trickled down through the respective carbon bed at a regulated flow rate of 6 litres per hour. The effluent was collected as tailings for residual gold analysis via the Atomic Absorption Spectrometer machine. For standardisation purposes, the setup was said to be at its saturated point when its effluent gold reading was in the range of 1 ppm -1.6 ppm. The respective volume of eluate passed before saturation, and the concentration of effluent at saturation were noted.

2.3.1. Loaded Carbon Analysis

The respective loaded carbon (LC) samples were thoroughly washed with raw water to remove any residual caustic traces on them. Carbon losses were avoided during the washing process. The samples were dried in an electrical oven at a temperature of 130 °C

Table 3. Optimal Equilibrium Loading Point of Varied Carbon Masses

Experimental set-up	Initial Eluate Concentration (mg/l)	Mass of activated carbon (g)	Volume of eluate dispensed before equilibrium (L)	Average effluent concentration (mg/l)
1	35	125	31.46	1.55
2	35	250	120.12	1.47
3	35	500	216.65	1.08
4	35	1000	501.71	1.36

and cooled at room temperature. The respective loaded carbons were split to a working mass (15 g) with a riffle splitter. Samples weighing 1 g were taken in quadruplicate into a porcelain boat and ashed in a muffle furnace at 650 °C for 3 hours until the carbon turned greyish, indicating complete ashing. The ashed samples were carefully transferred into a 150 mL beaker and digested in a 30 mL aqua regia solution on a hot plate. After digestion, the mixture was transferred into a 250 mL volumetric flask and topped up with deionized water to the 250 mL mark. The respective solutions were analyzed for gold via the Atomic Absorption Spectrometer machine.

2.3.2. Base Metal Analysis

The concentration of base metal types and their respective concentration levels that could be present on the loaded carbon and possibly report in the bullion was investigated. In this analysis, the 1 kg loaded carbon was riffle split to 50 g. A gram was picked for the base metal analysis. The 1 g carbon was ashed at a temperature of 850 °C for 1 hour until all carbon was reduced to ashes. The ashed sample was cooled and digested in an aqua regia. The digested residue was poured into a 250 mL volumetric flask and topped up with deionized water to the 250th mark. The flask was thoroughly shaken for homogeneity and submitted for the dissolved metals analysis via Inductively Coupled Plasma Optical Emission Spectrometry machine.

2.4. Gold Bullion Recovery Process

Out of the 1 kg loaded carbon sample, 850 g was ashed to obtain 50 g of ash. The ashed sample was leached with 20 g/L Ca(OCl)₂ and HCl (1%) for two (2) hours. The leached slurry was filtered to obtain gold chloride solution residue. Sodium Metabisulfite was added to the solution to precipitate the gold from solution. The precipitate was dried at controlled temperature to obtain gold powder. The gold powder was smelted to obtain bullion of weight, 1.145 g.

To further investigate the concentration of base metals that has reported in the bullion, 0.06 g of the bullion was dissolved in aqua regia (45 mL of HCl and 15 mL of HNO₃). 20 mL of the resulting solution was diluted to 100 mL and submitted for dissolved metal (32 element test) analysis via Inductively Coupled Plasma Optical Emission Spectrometry.

3. Results and Discussions

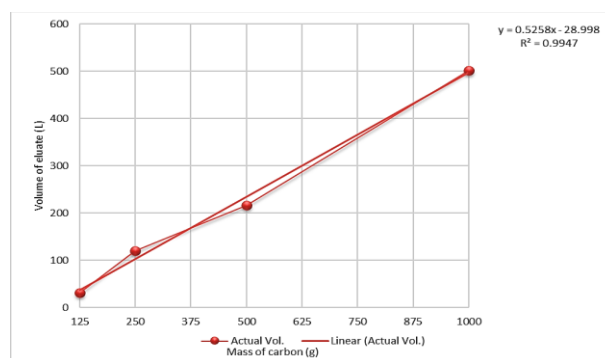
This study hypothesized that activated carbon adsorption would be a better alternative to electrowinning as a method of recovering gold from eluate. The loaded activated carbon would be ashed and gold obtained by smelting. The results and discussions from the experimental investigations are presented in the following sections.

3.1. Carbon Equilibrium Loading Point

The equilibrium loading point of activated carbon defines the maximum loading capacity of the activated carbon. Industrial investigation has proved that for a pure gold solution condition, activated carbon loading of > 1000 g/t could be realised.^[13] Based on this finding, it is emphatic that with a known carbon mass, gold in an eluate can be re-concentrated from solution into a much higher concentration on carbon. However, due to the economic consideration of this process, an optimum amount of activated carbon is required to guarantee a lower operational cost. To ascertain this position, four (4) carbon setup at varied mass concentrations were investigated to establish the optimum equilibrium loading point of these carbons. The carbon set-ups were all subjected to the same test operating conditions. The respective volume of eluate passed before saturation, and the concentration of effluent at saturation are presented in Table.3.

As indicated in Table 3, 501.71 L of the pregnant eluate was dispensed unto the 1000 g activated carbon setup before attaining equilibrium. The 500 g activated carbon also received a total eluate volume of 216.65 L before reaching equilibrium. The 250 g and 125 g carbon set-ups received 120.12 L and 31.46 L respectively of the eluate before attaining pore equilibrium. For the purpose of this work, the effluent concentration indicating the attainment of equilibrium was pegged between 1.00 - 1.60 mg/L. Fig.1 depicts the respective volume of eluate dispensed unto the corresponding carbon setup to bring it to saturation or equilibrium.

Fig. 1 shows a close to linear correlation for the four-carbon setup (0.125 kg, 0.25 kg, 0.5 kg and 1.0 kg carbon). McDougall and Hancock stated that when gold loading equilibrium is attained between the carbon and the adsorbate, a further increase of the adsorbent (activated carbon) will alter the equilibrium point which indicates more pore space available to receive eluate unto the activated carbon.^[10] This validates the linear increase in eluate volume at increased carbon mass. Under ideal situation for an assumed batch adsorption system, adsorbate will have a high initial adsorption rate followed by slow approach to equilibrium point. This

**Fig. 1.** Eluate Volume Dispensed as a function of Carbon Mass

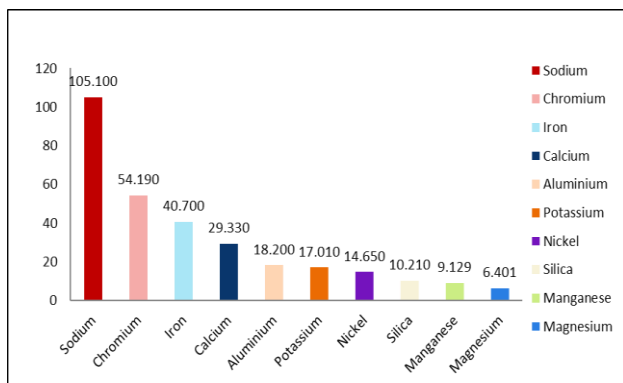


Fig. 2. Top Ten Base Metal on Loaded Carbon

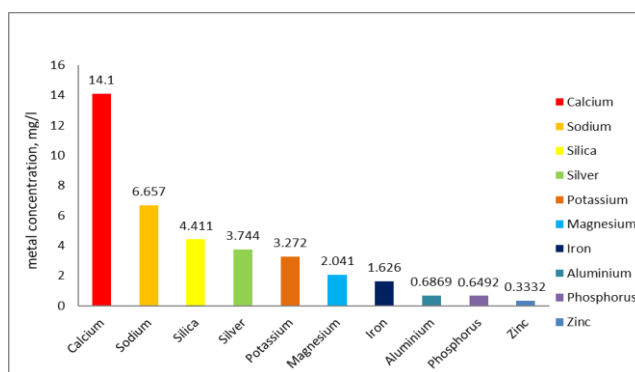


Fig. 3. Top Ten Base Metals on Bullion

Table 4. Loaded Carbon Assay Result in g/t of Gold

Set up	Mass of Carbon (g)	Volume of Eluate dispensed	Experimental Results - Summary				
			Sample(a) g/t	Sample(b) g/t	Sample (c) g/t	Sample (d) g/t	Average g/t
1	125g	31	6098	6691	6469	6600	6465
2	250g	120	12311	12437	12492	12489	12432
3	500g	217	10967	11008	10820	10998	10948
4	1000g	502	12428	12257	12220	12012	12229

phenomenon allows more gold from eluate to be adsorbed prior to equilibrium. This postulate was confirmed at the early stages of the experiment where effluent of the experimental setup analysed consistently recorded zero ppm (0 ppm) indicating high adsorption rate. As the system approached equilibrium, the effluent readings recorded some amount of gold.

The high carbon bed mass also presented the setup with much longer contact time and restricted solution flow. The 0.125 kg setup attained an early equilibrium point and is justified by its small carbon pore volume available relative to the other setups. The fast eluate percolation through the small carbon bed mass also contributed to the early pseudo-equilibrium condition. Burnett in her dissertation referenced this occurrence as a total equilibrium regime a carbon can attain. She reiterated that gold cyanide complex ($\text{Au}(\text{CN})_2^-$) is initially adsorbed in the macropores and mesopores resulting in pseudo-equilibrium within 4 to 48 hours.^[4] However, when adequate contact time is allowed, the gold cyanide complex adsorb slowly, diffusing into the network of micropores until a true equilibrium regime is attained. Other literatures have also affirmed that the total equilibrium period for carbon adsorption could exceed that of the pseudo-equilibrium regime by a factor of 10.^[8]

3.2. Characterisation of Loaded Carbon from Eluate Re-Adsorption

To envisage the types of base metals and their respective concentration levels that were adsorbed onto carbon, a 32-element test was carried out on the 1.0 kg loaded carbon. Apart from arsenic and cadmium which were below detection limit, the other elements under review recorded significant values. To make analysis easy, the top 10 elements were singled out for discussion. Fig.2 shows the top ten (10) base metals that reported on the activated carbon. Sodium was the highest (105.1 mg/L) element to be adsorbed. The next element was chromium (54.19 mg/L) followed by iron (40.7 mg/L) and calcium (29.33 mg/L). Aluminium, potassium, nickel and silicon

respectively recorded 18 mg/L, 17.01 mg/L, 14.65 mg/L and 10.21 mg/L. The last two (2) were magnesium and manganese which were in the 9.13 mg/L and 6.401 mg/L respectively.

Most of the base metals that reported on the loaded carbon are in the period 3, 4 and group 3 through to 13 of the periodic charts. They are mostly alkali metals, alkaline earth metals, post transition and transitional metals. The high sodium content is likely to originate from the caustic (NaOH) used in the stripping process. Alkaline earth metals such as calcium (Ca^+) and magnesium (Mg^+) are noted for their contribution to the enhancement of gold loading on carbon.^[3-7] Chromium is not found as a free metal but in ores mostly in the form of chromite (FeCr_2O_4). In the leach circuit, it is oxidized to produce free iron (Fe^+) and chromium (III) oxide (Cr_2O_3).

Although copper level is low relative to the top 10 elements under review, it is worth noting that its presence does affect the loading capacity of noble metals.^[14] To a greater effect, bullion fineness is compromised when copper is co-deposited with gold at a significant rate.^[15]

3.3. Gold Loadings on Carbon Used in Eluate Re-Adsorption

To envisage the loading capacity of the respective carbon under review, approximately 2 g carbon from each set-up was sampled and ashed, and the ash analysed for gold aqua regia digestion. The results are displayed in Table 4.

From Table 4, the 125 g carbon set-up yielded an average loading value of 6,465 g/t while the 500 g carbon setup produced an average carbon loading value of 10,948 g/t. The 250 g and the 1000 g carbons on the average produced carbon loadings of 12,432 g/t and 12,229 g/t respectively. The values obtained are in agreement with those obtained by John Rogan, who stated that the maximum loading capacity of activated carbon is approximately 12,000 g/t.^[13]

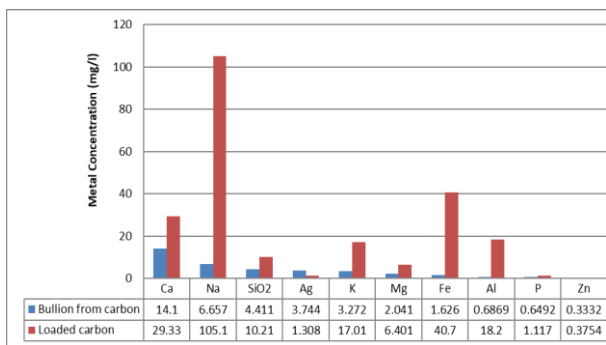


Fig. 4. Residual Base Metal Concentrations on Bullion Compared with Initial Levels on Loaded Carbon

3.4. Characterization of Bullion Gold from Eluate Re-Adsorption Test

A 32 elements test was carried out on the bullion obtained from carbon used for the eluate re-adsorption test to quantify the levels of base metals reporting in the bullion.

The top ten (10) base metals that reported in the bullion are presented in Fig. 3. From the categorisation, calcium was the highest element (14.1 mg/L) among the top ten (10) base metals under review. Sodium came second at 6.657 mg/L. Silica, silver, potassium, magnesium and iron, were in the concentrations of 4.411 mg/L, 3.744 mg/L, 3.272 mg/L, 2.041 mg/L and 1.626 mg/L respectively. Aluminium (0.687 mg/L), phosphorous (0.649 mg/L) and zinc (0.333 mg/L) were the least concentration among the top 10. Chromium which showed up at 54.19 mg/L on the loaded carbon was reduced to 0.0139 mg/L (99.9% reduction) in the bullion.

Fig. 4 compares the level of base metal elements on the loaded carbon to its corresponding residue on the bullion after the loaded carbon ashing and smelting process. All the base metal elements in reference recorded a significant drop in concentration as shown in Fig. 4. Significantly among them was sodium and iron which dropped from 105.1 mg/L to 6.657 mg/L and 40.7 mg/L to 1.26 mg/L respectively. The residual change for the zinc metal was marginal compared to that of the other base metal elements. Silver content in the bullion however increased in level compared with its initial level on the loaded carbon. The application of the Sodium Metabisulfite selectively precipitate predominantly gold and to some extent silver leaving behind most of the other base metal still in solution. This could be the reason for the increased silver content in bullion and the reduction in concentration of the other base metals.

3.5. Comparative Analysis of Bullions Produced from Electrowinning and Experimental Carbon

Table 5 reviews the key economic base metal elements and their respective concentration in the two (2) forms of bullion under study. 'Wassa bullion' is Golden Star Wassa Limited (GSWL) bullion produced via the conventional electrowinning and smelting process whereas the experimental bullion was produced via a loaded carbon ashing and smelting technique. The gold purity level and base metal

Table 5. Rand Refinery Bullion Assay Report

Bullion	Au	Ag	Cu	Fe	Pb	Zn	Ni	Bi
Electrowinning (%)	88.59	7.61	3.745	0.189	0.121	0.049	0.123	0
Experimental (%)	92.9	4.35	0.366	1.889	0.07	0.271	0.042	0

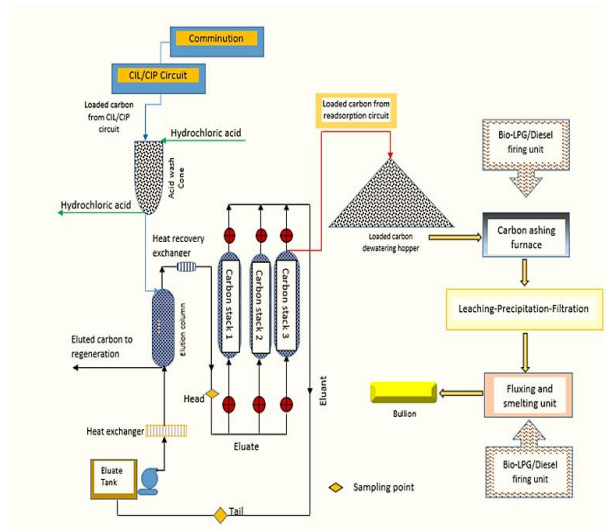


Fig. 5. Proposed Flow Sheet for Gold in Eluate Re-adsorption Circuit

levels in Wassa bullion (electrowinning bullion) as reported by Rand Refinery (RR) over the experimental period (week 22-50/2016) were averaged and compared to the bullion assay result from the ashed carbon (experimental bullion). The Results are shown in Table 5.

The electrowinning bullion indicated high level of silver (7.61%) and copper (3.75%) relative to that of the experimental bullion which recorded 4.35% silver and 0.37% copper. However, the iron (1.89%) content for the experimental bullion turned out to be higher relative to the level of iron (0.189%) in the electrowinning bullion. The high iron content in the loaded carbon ash and bullion could be attributed to an externally introduced contaminant (iron) from the metal plate receptacle used in the ashing and smelting process. In place of a loco boat (crucibles), a metal plate receptacle was used in the ashing and smelting process and this might have introduced some level of iron contaminants into the loaded carbon ash and bullion influencing the qualities. The gold content for the electrowinning bullion and the experimental bullion were 88.59% and 92.9% respectively.

The different levels of the base metals in the bullions present different economic benefit interpretation. From Table 5 the experimental bullion compared with the electrowinning bullion displays low levels of base metals. Bullion with less base metal comes with less refinery charges.^[12] This makes the carbon ashing and smelting technique a more profitable process. This is justified by the less base metals reporting in the final bullion indicating less refinery charges. The gold purity level for the experimental bullion was higher than the electrowinning bullion by 4.3%

3.6. Proposed Carbon Re-adsorption Circuit Flow Sheet for Recovering Gold from Eluate

A newly proposed carbon re-adsorption circuit for recovering gold from eluate is presented in Fig.5. Comparative to the Zadra and AARL electrowinning approach of gold recovery, the carbon re-adsorption

Table 6. Partial Operating Cost of a Gold Electrowinning Circuit for a Week Operation

Items	Amount (\$)	Cost description
Steel wool cathode	61	Cost of steel wool used on the cathode
Electrowinning	2390	Electricity cost for gold deposition per 8 hour elution (AARL)
Calcination	204	Electricity cost for calcination for 24 hours
Fluxing	358	Total reagents cost
Smelting	246	Average fuel cost for four smelt
Total	3260	

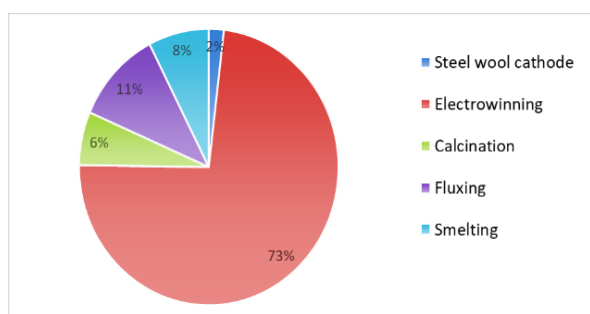
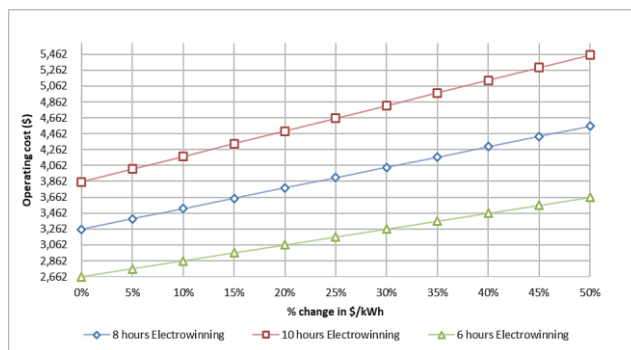
technique is devoid of an electrowinning cell. The electrowinning cell is replaced with columns of activated carbon to adsorb gold from eluate. This eliminates the cost of electricity for gold deposition which is the case for the electrowinning process. The loaded carbon is transferred into the loaded carbon dewatering hopper. The carbon is then dried and ashed in the furnace. The ashed residue is leached with HCl and $\text{Ca}(\text{ClO})_2$. The gold in the filtrate is precipitated with Sodium Metabisulfite. The precipitate could be smelted directly to produce gold bullion or dried to remove moisture before smelting. The chlorine gas from this process is collected under water to produce hydrochloric acid which can be recycled reducing the operating cost.

3.7. Economic Evaluation and Revenue Estimation

3.7.1. Economic Evaluation of the Electrowinning and Smelting Circuit

The process of gold recovery from eluate via the electrowinning (Zadra or AARL) techniques to produce final bullion is achieved through four (4) main stages. These process starts with electrowinning, calcination of steel wool cathode, fluxing of calcined product and smelting. The main operational cost components are the cathode replacement, power (electricity) for electrowinning, fluxing reagents and diesel fuel for smelting. Golden Star Wassa currently operates three electrowinning cells with three (3) rectifiers (power rating at 65 kVA per unit). The average electrowinning time for a single elution is 16 hours. Calcination is done in a 70-kW oven to calcine the steel wool. The fluxing reagents include borax, silica sand, sodium carbonate and sodium nitrates.

Table 6 gives a partial operating cost for a typical AARL electrowinning operation doing an average of 14 strips per week. The cost of steel wool, electrowinning or deposition cost, calcination cost,

**Fig. 6.** Partial Operating Cost Percentage Breakdown for Gold Electrowinning and Smelting Technique**Fig. 7.** Operating Cost Variation of Electrowinning and Smelting Process with Percent Increase in Electricity Cost (\$/kWh)

fluxing and smelting cost was estimated to be \$ 61, \$ 2,390, \$ 204, \$ 358 and \$ 246 respectively. Fig. 6 highlights the metal deposition stage (electrowinning process) as the major cost component 73% followed by the fluxing process 11%

The major cost component with the electrowinning and smelting technique is electricity which is mainly employed in the metal deposition process. This component makes up 73% of the operating cost. The energy (electricity) cost therefore becomes a sensitive cost item in this operation, i.e. an increase in the cost of energy (electricity) automatically increases the operational cost for gold recovery via the electrowinning technique. Fig.7 projects how operating cost for the electrowinning and smelting technique will vary over changes in electricity cost (\$/kWh) for a 6-hour, 8-hour and 10-hour elution periods.

3.7.2. Economic Evaluation of the Carbon Re-Adsorption Circuit

Unlike the electrowinning process which recovers gold from eluate unto its cathode (steel wool), the re-adsorption process is designed to recover gold from eluate unto a specified amount of carbon till saturation. The carbon is then ashed, leached, precipitated and smelted to obtain the bullion. This process technique considers four main process stages which include; gold adsorption, carbon ashing, leaching of carbon ash with hydrochloric acid and hypochlorite, precipitation of the gold from the leach solution with Sodium Metabisulfite and finally smelting.

The partial operating cost for 1 kg loaded carbon proportionally amounted to \$ 3,829. Considering the carbon re-adsorption technique, the two major cost components of this operation were the cost of carbon (78%) and cost of liquefied petroleum gas (LPG)

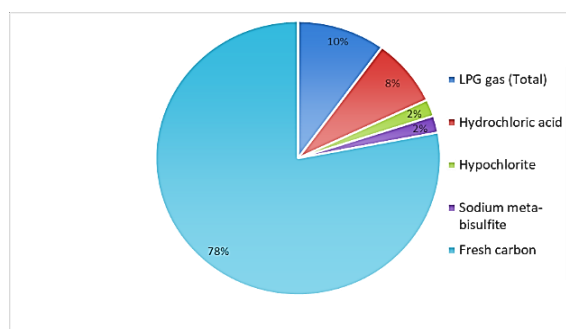
**Fig. 8.** Partial operating cost breakdown for carbon re-adsorption and smelting technique

Table 7. Activated Carbon Cost per Ton

Period	2013	2014	2015	2016	2017
	\$/ton	\$/ton	\$/ton	\$/ton	\$/ton
Q1	3707	3235	2996	2865	2788
Q2	3615	3032	2951	2788	2371
Q3	3235	3032	2931	2788	2376
Q4	3235	2967	2650	2788	2863
Average (\$)	3,448	3,067	2,882	2,807	2,600

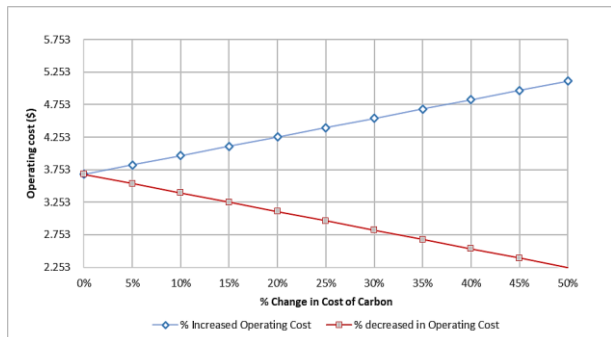


Fig. 9. Operating Cost Variations of the Carbon Re-adsorption Techniques with Percentage Changes in Carbon Cost

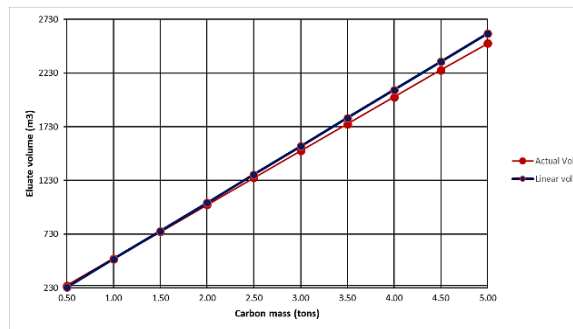


Fig. 10. Equilibrium Relationships between Eluate Volume and Carbon Weight.

(10%) as indicated in Fig. 8. It stands clear that major cost component for the carbon re-adsorption technique is 5% more than the major cost component projected by the electrowinning and smelting.

With all other cost parameters being constant, a change in the cost of activated carbon alters greatly the operating cost of the carbon re-adsorption technique. Table 7 shows how activated carbon cost per ton has varied over a period of time (2013-2017). The trend shows a decline trend in activated carbon cost over the study period with 7% average drop-in price rate. A continuous drop-in price rate will be an advantage to the re-adsorption techniques.

Fig. 9 highlights how the operating cost of the re-adsorption technique will vary with changes in carbon cost. Per the 7% drop in the cost of activated carbon annually, the operating cost is likely to drop extensively.

Table 8 shows an operation forecast for a simple AARL circuit. If the operation does an average of 14 strips per week at an eluate concentration of 32 mg/L, the gold forecast from this operation will be 44.352 kg. Per the production forecast, a total volume of 1,386 m³ of the 32-ppm eluate is sent for electrowinning to recover the estimated gold at the end of the week operation.

In modelling the carbon re-adsorption technique after the AARL gold recovery approach the same amount of eluate volume (1,386 m³) will be passed on a known mass of activated carbon. Per the eluate volume to carbon mass linear relation shown in Fig.10, approximately 2.763 tons of carbon would be required to recover the same amount of forecasted gold (44.352 kg) per the carbon re-adsorption approach.

Table 8. A Typical Industrial AARL Operation Forecast

7 days Operation Forecast for AARL Electrowinning Approach				
Pregnant solution Tank	Eluate concentration (mg/l)	Volume of Tank (m3)	Total volume of eluate passed on the 3EW cells	Gold recovered in a week (kg)
Tank 1	32	108	756	24.192
Tank 2	32	90	630	20.16
Total		198	1386	44.352

To comparatively estimate the partial operating cost of the two processing techniques under review, the cost for recovering gold from the 1,386 m³ volume of eluate via the electrowinning and smelting approach was estimated. An 8 hours or 10 hours electrowinning period with the AARL approach brings the partial operating cost of this process of gold recovery to \$ 3,260 and \$ 3,857 respectively.

Similarly, if the same eluate volume at 32 mg/L gold is to be recovered via the re-adsorption and smelting process technique with 2.763 tons of carbon, its partial operating cost comparatively will be around \$ 10,580. Comparing the two operating costs, the re-adsorption and smelting technique cost was 69.18% higher than the electrowinning and smelting technique. This wide variance is attributed to the high cost of activated carbon used in the re-adsorption process. An alternative carbon source which is highly active and economical could drop the operating cost of the re-adsorption process.

3.7.3. Revenue Estimation

The expected revenue returns on the sales of gold from each of the process technique was estimated taking into consideration the respective gold purity level realised from the gold fineness analysis. From Table 9, \$ 1,642,211 was realized from the sale of gold recovered via the electrowinning and smelting. Sales of gold from the ashing and smelting techniques yielded total revenue of \$ 1,722,107.

In order to make the best economic decision based on comparative cost analysis of the two process techniques, the net operating proceeds (NOP) for the two operations was estimated. Per the details in Table 10, the NOP from the ashing and smelting approach was \$ 1,711,527 as against \$ 1,638,951 for the 8 hours electrowinning and smelting approach. A net gain of \$ 72,576 was realized from the re-adsorption technique representing a total of 4.24% revenue gain. This makes the re-adsorption economically viable and a preferred alternative to the electrowinning and smelting technique.

Table 9. Gold Sales Revenue for Electrowinning Process and Re-adsorption Process

Revenue returns on sales of gold (44.352 kg)		
Item	Electrowinning process	Re-adsorption process
Gold recovered (kg)	44.352	44.352
\$/oz	1300	1300
Bullion purity (%)	88.59	92.9
Gold (oz)	1263	1325
Revenue(\$)	1,642,211	1,722,107

Table 10. Net Proceeds for the Electrowinning and Re-adsorption Technique

Item	AARL Electrowinning Approach			Re-adsorption Technique	
	6hr EW period	8hr EW period	10hr EW period	Actual Calculated	Linear calculated
Income (\$)	1,642,211	1,642,211	1,642,211	1,722,107	1,722,107
Expenditure (\$)	2,662	3,260	3,857	10,580	10,304
Revenue Returns (\$)	1,639,549	1,638,951	1,638,354	1,711,527	1,711,803

3.8. Environmental Challenge

Although the re-adsorption techniques delivered much higher revenue returns, their associated environmental challenges are worth considering. Apart from corrosion effects on structures and to some extent acid related injury that could be associated with this technique, smoke generation from the ashing of loaded carbon is recognised as an environmental concern worth considering. Carbon monoxide, carbon dioxide, nitrous oxides are common flue gasses that could be in release during the carbon ashing stage. The release of carbon dioxide and nitrous oxide into the environment are noted to have a significant global warming potential as greenhouse gases. However, with the advent of air pollution control techniques such as wet scrubber techniques and carbon offsetting techniques these flue gases emissions into the environment are totally eliminated or minimized.

4. Conclusions

This paper reports on investigation regarding the use of activated carbon in recovering gold from eluate as a process alternative to electrowinning. This task was attainable and concludes that recovering of gold from eluate via the carbon re-adsorption, ashing and smelting techniques is competitive to the electrowinning and smelting process. This conclusion was drawn after a pilot based experimental analysis at the laboratory which included investigating the optimum carrying capacity of activated carbon, determining the base metals levels on loaded carbon and bullion obtained from the carbon ash smelt and reviewing the operating cost analysis of the two processes approach. From the analysis carried out the following specific conclusions are deduced that on the average, the optimum carrying capacity of activated carbon was in the range of 12,229 g/t to 12,432 g/t.

The bullion analysis attests that the ashing and smelting techniques produce bullion with high fineness (92.9% gold) relative to the electrowinning and smelting technique which yielded 88.59%. Again, the base metals under review were in lower concentration in the experimental bullion relative to the electrowinning bullion, indicating a much higher returns on the sales of gold recovered via the ashing and smelting technique. The partial operating cost analysis for the carbon re-adsorption, ashing and smelting technique

was about \$ 10,580 and that of the electrowinning and smelting was \$ 3,260. Comparatively, carbon re-adsorption, ashing and smelting technique had an extra cost of \$ 7,320. In terms of revenue, the net operating proceeds (NOP) from the ashing and smelting approach was about \$ 1,711,527 and that of the electrowinning and smelting approach, \$ 1,638,951. A total of \$ 72,576 increase in revenue, representing about 4.24% profit margin was realised from the carbon re-adsorption process.

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Conflicts of Interest

The authors declare no conflict of interest.

References

- Angelov A.; Groudev S. Treatment of Gold Bearing Solution by Cementation with Metallic Zinc. *Mining and Mineral Processing*, 2002, **44-45**, 117-121. [\[Link\]](#)
- Aktas S. Rhodium recovery from Rhodium-containing Waste Rinsing Water via Cementation using Zinc Powder. *Hydrometallurgy*, 2011, **106**, 71-75. [\[CrossRef\]](#)
- Asiam E. K. Precious Mineral Beneficiation. UMaT, MSc. Lecture Notes.
- Burnett H. J. Equilibrium Shift of Gold Adsorption in a Batch Reactor, Cape Technikon, Unpublished MSc. Thesis Report. [\[Link\]](#)
- Cifuentes G.; Vargas C.; Simpson J.; Esteban R. Electrowinning of gold from cyanide solutions. *Santiago, Chile: Departamento de Ingenieria Metalurgica. Facultad de Ingenieria*. 2014. [\[Link\]](#)
- Guerra E. A Study of the Factors Affecting Copper Cementation of gold from Ammoniacal Thiosulphate Solution. UBC, Unpublished MSc. Thesis Report, 1997, 11.
- Hiskey J.B. Gold and silver extraction: the application of heap-leaching cyanidation. *Arizona Bureau of Geology and Mineral Technology Field Notes*, 1985, **15**, 1-5. [\[Link\]](#)
- Ibragimova P. I.; Grebennikov S. F.; Guryanov V. V.; Fedyukevich V. A.; Vorob'ev-Desyatovskii N.V. Effect of the Porous Structure of Activated Carbon on the Adsorption Kinetics of Gold (I) Cyanide Complex. *Russ. J. Phys. Chem. A*, 2014, **88**, 1037-1041. [\[CrossRef\]](#)
- Makoba M. Zinc Precipitation on Gold Recovery. 2013, 1-16. [\[Link\]](#)

- 10 MacDougall G.J.; Hancock R.D. Gold Complexes and Activated Carbon. *Gold Bulletin*, 1981, **14**, 141-151. [[CrossRef](#)]
- 11 Mooiman M.B.; Ewart I.; Robinson J. Electrowinning Precious Metals from Cyanide Solution Using EMEW Technology. In *Presentation at 142nd Annual Meeting of Society of Mining and Metallurgical Engineers, Denver, CO*. [[Link](#)]
- 12 Nehl F.H. Selective Electrowinning of Silver and Gold from Cyanide Process Solutions. 1993. [[Link](#)]
- 13 Rogans J. Activated Carbon in Gold Recovery. *Marketing Director Kemix (Pty) Ltd*. 2012. [[Link](#)]
- 14 Sceresini B.J. Sceresini Bruno Holding Pty Ltd, Forsayth NL, Forsayth (Gibson) Ltd and Reynolds Australia Metals Ltd, 1995. *Base metals recovery by adsorption of cyano complexes on activated carbon*. U.S. Patent 5,427,606. [[Link](#)]
- 15 Steyn J.; Sandenbergh R.F. A Study of the Influence of Copper on the Gold Electrowinning Process. *J. South. Afr. Inst. Min. Metall.*, 2004, **104**, 177-182. [[Link](#)]
- 16 Walton R. Zinc Cementation. *Developments in Mineral Processing*, 2005, **15**, 589-601. [[CrossRef](#)]



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