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An electrochemical model for the leaching kinetics of gold ore in cyanide solutions

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effect on the redox potential, the relevant impurities probably formed a complex with cyanide.

It is now difficult to predict exactly which species are involved in setting the redox potential. Experiment A3 showed that the redox potential decreased as the copper concentration increased. On the one hand the addition of copper reduced the cyanide concentration. However, the change in the cyanide concentration was so small that it couldn't account for the change in the redox potential. It is not clear from the literature, at this stage, why such a large reduction in the redox potential was observed when copper was added to the solution.

8 CONCLUSIONS AND RECOMMENDATIONS

In this chapter a summary is given of all the conclusions made in this project. Recommendations are also made for further study in this field.

8.1 Conclusions

1. From the design procedures used in gold plant design, it seems as if a lack of understanding of the processes involved still exists. The need for some accurate knowledge of the processes and mechanisms involved in the leach process was specifically identified.

2. From the literature study it became clear that the effects of various variables on the dissolution rate of pure gold are thoroughly documented. Unfortunately most researchers do not present broadly based mathematical models. Furthermore, very little information is available on the dissolution of gold from a gold bearing ores.

3. The leaching rate expressions given in the literature for the leaching of gold from gold ore, are all empirical or semi-empirical, and can therefore not be used for general design or predictive purposes.

4. The redox potential measurements with a Pt electrode are relatively easy to reproduce. The potential measurements with the gold and the gold-silver electrodes are far less reproducible.

5. From the effect that the oxygen and cyanide concentrations had on the leaching rate, it was concluded that in the leach experiments, the reaction was controlled by a combination of the diffusion rates of both the oxygen and the cyanide. Because the addition of thallium did not have a substantial accelerating effect on the leaching rate, it was concluded that the gold surface was not passivated in the leach experiments.

6. It was concluded that the potentials, measured with the gold and the gold-silver electrodes, did not give a true account of the surface

potential of the gold in the ore. This conclusion also signifies that the measured gold surface potential was not related to the leaching rate and, therefore, these potential measurements could not be used in the rate expression.

7. There is no theoretical basis on which the solution redox potential can be taken as an approximation for the gold surface potential. However, it was found that the leaching kinetics could be modelled very accurately by using this potential in a rate expression of the same form as an electrochemical rate expression, i.e.

$$\text{rate} = -k_1\left([Au]_s - [Au]_s^{\infty}\right)\exp\left(k_2 E_{redox}\right) \quad \ldots[30]$$

8. The two constants seemed to be related which means that they compensated for each other when the expression was fitted to the experimental data.

9. The explanation for the solution redox potential turned out to be very complex. From the experimental data it was concluded that the potential that was measured, was most probably a mixed potential between the reduction of oxygen and the oxidation of some impurities present in the solution. It was further concluded that these impurities were leached from the solids during the experiments and that they probably formed complexes with the cyanide ions in the solution.

8.2 Recommendations

1. The possibility of the leaching kinetics of gold ore being modelled with an electrochemical rate expression, cannot be ruled out on the basis of this project. It is recommended that a gold or a gold--silver electrode is designed, which will give more reproducible results and which will give a true account of the surface potential of the gold in the ore.

2. It might be worth doing some more redox potential measurements in artificial solutions. By investigating the effects of metal ions, other than copper, on the redox potential, it might be possible to give a better explanation of the redox potential. Only after it has

become known precisely which ions in solution, set the measured redox potential, one will be able to explain the significance of this potential in the modelling of the leaching kinetics of gold ore.

3. Valuable knowledge might also be gained from a more extensive analysis of the solid fraction of the pulp at various stages of the leach. This will give an indication of the rate at which other minerals dissolve from the ore. It will also show where the refractory gold is situated.

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Appendix A

The raw experimental data

Run 1.

Vaal Reef pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 20 °C
NaCN added: 7.31 g
Airated for ½ hr before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
5	10.88	-146	1.625
17	10.91	-132	2.400
30	10.91	-125	3.000
45	10.90	-120	3.525
60	10.88	-115	3.800
90	10.87	-111	4.025
120	10.88	-108	4.300
180	10.88	-98	4.500
300	10.88	-95	4.850
360	10.87	-92	4.850

Run 2.

Vaal Reef pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 20 °C
NaCN added: 7.31 g
Airated for ½ hr before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
3	10.45	-170	1.368
13	10.67	-141	2.213
20	10.75	-137	2.783
30	10.74	-132	3.302
45	10.75	-125	3.797
60	10.78	-124	4.104
90	10.89	-119	4.599
120	10.92	-114	4.811
180	10.72	-113	5.187

Run 3.

Vaal Reef pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 19 °C
NaCN added: 7.31 g
Airated for 45 min before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
2	10.86	-153	0.873
13	10.90	-135	2.217
23	10.93	-126	2.783
45	11.21	-118	3.774
60	11.22	-117	3.962
90	11.20	-114	4.339
120	11.23	-112	4.627
180	11.19	-109	4.906
240	11.23	-101	5.189
300	11.21	-	5.307

Run 4.

Vaal Reef pulp
Volume of pulp: 15 liters
Sparging medium: O_2
Temperature: 20 °C
NaCN added: 7.31 g
Airated for 30 min before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
0	10.66	-	0.000
1	10.81	-119	-
2	10.84	-110	2.063
3	10.85	-105	-
5	10.85	-101	-
7	10.86	-99	3.228
10	10.86	-96	-
13	10.89	-92	3.762
15	10.91	-91	-
20	10.93	-90	4.053
25	11.03	-88	-
30	11.18	-87	4.369
45	11.24	-84	4.515
60	11.25	-81	4.903
90	11.26	-85	4.903
120	11.27	-84	4.976
200	11.30	-82	5.000
250	11.32	-87	5.243
300	10.95	-85	5.243

Run 5.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: O_2
Temperature: 20 °C
NaCN added: 7.31 g
Airated for 30 min before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
0	11.20	-	0.000
1	11.47	-97	-
2	11.55	-93	5.944
3	11.56	-93	-
5	11.56	-89	-
7	11.58	-89	-
10	11.59	-89	12.908
13	11.62	-82	-
15	11.61	-86	14.617
20	11.65	-83	-
25	11.65	-83	15.306
30	11.66	-83	15.306
47	11.84	-84	15.510
60	11.83	-83	15.561
90	11.83	-80	15.944
120	11.82	-83	16.020
180	11.81	-82	16.122
240	11.75	-83	16.122

Run 6.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: O_2
Temperature: 19 °C
NaCN added: 7.32 g
Airated for 30 min before NaCN addition

Time (min)	pH	E_h (mV)	[Au] (ppm)
0	11.36	-	0.300
1	11.40	-115	3.125
2	11.44	-112	-
3	11.45	-111	-
5	11.46	-108	-
7	11.49	-107	-
8	11.52	-104	11.750
15	11.55	-103	-
18	11.57	-104	14.275
30	11.54	-100	-
39	11.55	-102	15.175
45	11.56	-100	15.175
60	11.57	-101	15.175
90	11.62	-101	15.300
120	11.67	-100	14.675
180	11.71	-99	14.500
240	11.68	-95	15.675
300	11.61	-95	15.675
360	11.50	-97	15.675

Run 7.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 20 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time (min)	pH	E_h (mV)	$[Au]_l$ (ppm)	$[Au]_s$ (g/t)
0	11.25	-	0.200	-
2	11.34	-138	1.200	-
3	11.36	-136	-	-
5	11.37	-135	-	-
7	11.39	-132	3.525	-
10	11.42	-130	-	-
15	11.43	-131	6.750	-
20	11.45	-125	-	-
30	11.44	-121	10.800	-
45	11.42	-120	12.650	-
60	11.39	-116	13.700	-
90	11.30	-117	14.950	-
120	11.21	-114	15.250	-
180	10.99	-114	15.250	-
240	10.55	-112	15.500	-
300	10.39	-110	15.575	-
22h	10.39	-101	17.425	0.25

Run 8.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 15 °C
NaCN added: 2.25 g
Airated for 45 min before NaCN addition

Time (min)	pH	E_h (mV)	$[Au]_l$ (ppm)	$[Au]_s$ (g/t)
0	11.01	-	0.133	11.1
2	11.05	-166	-	-
3	11.05	-163	1.000	-
5	11.05	-157	-	-
8	11.05	-156	2.911	-
13	11.05	-151	4.667	-
20	11.05	-148	6.378	5.98
30	11.04	-143	8.111	4.31
45	11.03	-139	10.067	-
60	11.01	-137	11.133	1.84
90	10.98	-133	12.400	-
120	10.95	-133	12.600	0.70
180	10.89	-130	13.000	0.59
240	10.84	-127	13.556	0.69
300	10.81	-126	13.444	-
470	10.73	-114	13.889	-
24h	10.28	-83	14.511	0.29

Run 9.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 19 °C
NaCN added: 1.125 g
Airated for 45 min before NaCN addition

Time (min)	pH	E_h (mV)	$[Au]_l$ (ppm)	$[Au]_s$ (g/t)
0	10.98	-	0.125	10.8
3	11.04	-146	1.050	-
5	11.02	-141	-	-
10	11.02	-134	2.700	-
20	11.00	-128	5.750	-
30	10.99	-124	7.750	-
45	10.96	-122	9.875	3.33
70	10.90	-120	12.000	1.91
90	10.87	-119	12.500	-
120	10.89	-116	13.125	0.98
180	10.81	-110	13.625	0.69
240	10.75	-112	13.750	0.57
300	10.70	-112	13.550	0.49
360	10.65	-110	13.950	-
24h	9.99	-34	14.950	0.48

Run 10.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time (min)	E_{Pt} (mV)	E_{Au} (mV)	$[Au]_l$ (ppm)	$[Au]_s$ (g/l)
0	-	-	0.168	11.5
2	-118	-	-	-
2.5	-	-360	-	-
6	-130	-	4.899	9.15
8	-	-367	-	-
10	-148	-	-	-
11.5	-	-373	-	-
14	-	-374	-	-
15	-146	-	9.628	5.75
20	-	-380	-	-
21.5	-141	-383	-	-
30	-140	-387	14.696	2.86
32	-	-392	-	-
48	-134	-	17.635	2.04
60	-133	-	18.919	-
62	-	-394	-	-
90	-130	-393	20.027	0.85
120	-129	-396	21.115	0.53
180	-125	-410	21.453	0.45
240	-123	-414	21.622	0.40
300	-116	-430	21.622	0.37
∞	-105	-373	23.311	0.27

Run 11.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time (min)	E_{Pt} (mV)	E_{Au} (mV)	$[Au]_l$ (ppm)	$[Au]_s$ (g/t)
0	-	-	0.168	11.3
2	-163	-	-	-
2.5	-	-395	-	-
3	-	-	2.432	7.63
4	-	-388	-	-
5.5	-158	-	-	-
8	-154	-	-	-
9	-	-380	-	-
11	-	-379	-	-
12	-149	-	-	-
16.5	-	-	10.743	5.16
20	-144	-	-	-
21	-	-391	-	-
30	-	-404	15.372	3.39
31	-139	-	-	-
44	-136	-	-	-
45	-	-410	17.973	1.96
60	-	-411	19.459	1.43
90	-130	-412	20.946	0.84
120	-129	-418	21.284	0.61
180	-128	-428	21.959	0.49
240	-126.5	-446	22.297	0.42
300	-126	-464	22.297	0.36
390	-123.5	-464	22.297	0.35
∞	-	-	23.243	0.36

Run 12.

Kloof pulp
Volume of pulp: 15 litre
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)	$[Au]_l$(ppm)	$[Au]_s$(g/t)
0	-	-	-	0.168	11.4
2	-	-358	-	-	-
3	-	-	-441	-	-
4	-	-	-450	-	-
5	-131	-	-	3.784	7.97
7	-	-365	-	-	-
8	-	-	-460	-	-
9	-130	-	-	-	-
10	-	-367	-	-	-
11	-	-	-458	-	-
13	-	-	-460	-	-
14	-	-376	-	-	-
15	-125	-	-	-	-
19	-	-388	-	-	-
20	-	-	-460	12.331	4.78
28	-120	-	-	-	-
29	-	-405	-	-	-
30	-	-	-460	-	-
33	-	-	-	-	-
38	-	-	-460	-	-
39	-	-408	-	-	-
40	-	-	-	17.365	2.27
45	-119	-408	-	-	-
46	-	-	-457	-	-
58	-	-	-458	-	-
59	-	-457	-	-	-
60	-116	-	-	19.932	1.53
90	-117	-408	-466	21.284	0.92
120	-116.5	-405	-490	21.993	0.70
170	-120	-420	-535	22.635	0.55
240	-120	-443	-532	23.986	0.44
300	-122	-452	-528	24.324	0.44
340	-120	-460	-519	-	-
360	-120	-555	-519	25.507	0.45
∞	-	-	-	26.689	0.29

Run 13.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)	$[Au]_l$(ppm)	$[Au]_s$(g/t)
0	-	-	-		11.3
2	-	-381	-		-
3	-	-	-425		-
4	-	-	-430		-
5	-119	-	-		6.79
10	-	-400	-		-
15	-	-	-473		-
18	-	-380	-		-
21	-	-	-		3.99
25	-	-	-480		-
25.5	-	-413	-		-
26	-108	-	-		-
39	-	-	-510		-
40	-	-442	-		2.29
43	-108	-	-		-
56	-	-	-485		-
57	-	-423	-		-
60	-104	-	-		1.50
90	-101	-413	-515		0.90
120	-95	-403	-551		0.65
180	-96	-415	-535		0.43
245	-89	-550	-515		0.44
300	-95	-552	-505		0.39
360	-86	-545	-505		-
∞	-	-	-		0.29

Run 14.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)	$[Au]_l$(ppm)	$[Au]_s$(g/t)
0	-	-	-		
2	-	-375	-		
3	-	-	-446		
4	-108	-	-		
5	-	-342	-		
7	-	-	-450		
9	-104.5	-	-		
10	-	-345	-		
11	-	-	-450		
17	-91	-	-		
18	-	-365	-		
19	-	-	-445		
20	-	-370	-		
24	-89	-	-		
25	-	-380	-		
26	-	-	-440		
40	-83	-	-		
41	-	-386	-		
42	-	-	-432		
45	-	-	-		
60	-80	-390	-435		
90	-79	-390	-460		
120	-77	-400	-500		
180	-75	-465	-548		
240	-134	-465	-548		
300	-132	-478	-555		
310	-132	-580	-555		
360	-128	-580	-536		
390	-130.5	-600	-550		
∞	-	-	-		

Run 15.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-	-337	-467
5	-	-410	-525
7	-	-425	-525
10	-	-446	-521
15	-	-461	-513
20	-	-465	-505
25	-	-455	-488
30	-	-435	-465
40	-	-423	-447
50	-	-425	-445
60	-	-428	-440
70	-	-447	-440
80	-	-533	-440
90	-	-542	-437
100	-	-540	-435
110	-	-540	-437
120	-	-538	-435
130	-	-538	-435
140	-	-535	-435
150	-	-530	-445
160	-	-530	-460
170	-	-530	-472
180	-	-530	-485
240	-	-525	-481
300	-	-520	-478
360	-	-510	-470

Run 16.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-	-512	-518
5	-	-486	-528
7	-	-472	-535
10	-	-457	-530
15	-	-455	-526
20	-	-457	-522
25	-	-455	-521
30	-	-453	-522
40	-	-425	-470
50	-	-427	-470
60	-	-433	-485
70	-	-452	-500
80	-	-525	-528
90	-	-557	-522
100	-	-555	-520
110	-	-550	-518
120	-	-550	-512
130	-	-550	-512
140	-	-548	-510
150	-	-545	-510
160	-	-543	-510
170	-	-542	-510
180	-	-542	-508
240	-	-535	-500
300	-	-525	-490
330	-	-520	-488

Run 17.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 18 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-	-510	-528
5	-	-495	-528
7	-	-480	-525
10	-	-450	-498
15	-	-435	-480
20	-102	-432	-475
25	-	-432	-467
30	-101	-428	-458
40	-98	-425	-450
50	-	-432	-445
60	-90	-460	-445
70	-	-540	-455
80	-82	-542	-470
90	-	-542	-489
100	-77	-537	-488
110	-	-530	-485
120	-69	-525	-480
130	-	-520	-478
140	-	-520	-477
150	-	-517	-475
160	-	-515	-470
170	-	-515	-472
180	-65	-517	-470
240	-80	-525	-482
300	-107	-520	-478
360	-76	-500	-410

Run 18.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-160	-542	-545
5	-153	-518	-540
7	-148	-505	-540
10	-144	-495	-535
15	-110	-452	-497
20	-96	-440	-480
25	-90	-435	-468
30	-89	-425	-457
40	-83	-416	-448
50	-83	-410	-439
60	-78	-405	-430
70	-	-407	-437
80	-72	-420	-452
90	-66	-515	-486
100	-	-530	-489
110	-	-530	-489
120	-65	-522	-490
130	-	-525	-490
140	-	-523	-487
150	-	-520	-485
160	-	-522	-483
170	-	-521	-480
180	-64	-518	-480
240	-63	-511	-473
300	-64	-505	-467
360	-	-510	-470

Run 19.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-113	-485	-485
5	-102	-460	-485
7	-97	-445	-482
10	-91	-432	-476
15	-86	-425	-468
20	-82	-415	-459
25	-79	-412	-450
30	-76	-408	-442
40	-73	-395	-430
50	-71	-395	-423
60	-70	-400	-420
70	-	-408	-425
80	-	-403	-425
90	-67	-428	-428
100	-	-475	-423
110	-	-528	-425
120	-65	-532	-425
130	-	-530	-430
140	-	-528	-428
150	-	-525	-425
160	-	-524	-426
170	-	-527	-425
180	-65	-523	-423
240	-64	-520	-420
300	-64	-513	-410

Run 20.

Kloof pulp
Volume of pulp: 15 liters
Sparging medium: N_2
Temperature: 17 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)
2	-206	-640	-605
5	-215	-635	-535
7	-244	-690	-660
10	-237	-689	-645
15	-232	-685	-625
20	-	-685	-615
25	-230	-667	-605
30	-203	-640	-574
40	-189	-627	-560
50	-	-620	-555
60	-189	-612	-550
70	-	-592	-540
80	-	-588	-535
90	-175	-588	-535
100	-	-582	-530
110	-	-575	-527
120	-169	-560	-515

Run 21.

Kloof pulp with liquid fraction replaced with distilled water
Volume of pulp: 15 liters
Sparging medium: air
Temperature: 20 °C
NaCN added: 4.50 g
Airated for 45 min before NaCN addition

Time(min)	E_{Pt}(mV)	E_{Au}(mV)	E_{Au-Ag}(mV)	[CN]mmol/l	$[Au]_s$(g/t)
0	-	-	-	0.00	11.1
1	-	-390	-	-	-
2	-	-	-455	-	-
3	-123	-	-	-	-
4	-	-396	-	-	-
5	-	-	-465	9.746	7.12
10	-118	-	-	-	-
12	-	-440	-	-	-
14	-	-	-465	-	-
15	-	-	-485	-	-
16	-149	-468	-	-	-
20	-151	-475	-500	-	-
25	-151	-	-	9.092	4.46
28	-	-475	-	-	-
29	-	-	-500	-	-
35	-	-500	-500	-	-
40	-145	-	-	8.595	2.72
45	-	-520	-	-	-
54	-	-	-475	-	-
59	-	-558	-	-	-
60	-109	-	-	8.257	1.58
75	-100	-550	-500	-	-
90	-98	-545	-500	7.625	1.15
120	-92	-535	-500	7.129	0.67
180	-91	-515	-480	6.204	0.46
220	-86	-515	-478	5.595	0.57
300	-79	-500	-455	4.557	0.47
360	-133	-545	-490	3.858	0.54
390	-137	-525	-450	-	-
∞	-	-	-	-	0.40

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