



**RenoCell** ...

*for*  
***Precious Metals Recovery***

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***Renovare International, Inc.***

851 W. Midway, Suite 104C • Alameda, CA 94501 (USA)  
TEL (925) 945-7576 • FAX (925) 945-0131

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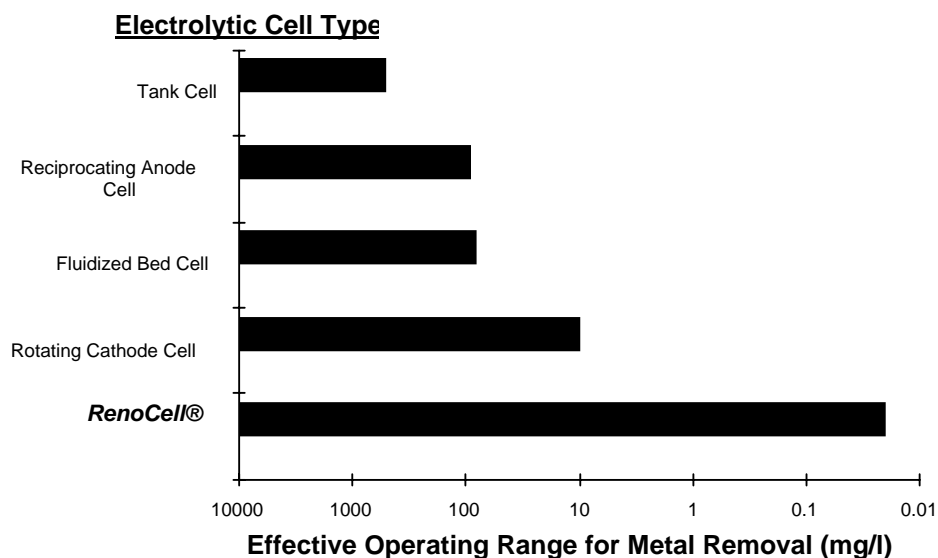
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## 1.0 INTRODUCTION

Electrodeposition on a cathode in an electrolytic cell is a well-established process for removal of metals, including precious metals, from aqueous streams including process liquors, metal leach solutions, and effluent waste waters. At low metal ion concentrations (<100 mg/l), the rate of removal and deposition is often limited by the rate of metal ion diffusion to the cathode surface from the bulk solution. Once metal ions arrive at the cathode surface, electrodeposition involves an electron transfer from the electrode surface to the ion until the ion is reduced to zero valance and is thereby deposited on the cathode surface as solid metal and becomes part of a solid polycrystalline metal structure. With conventional electrolytic cell designs these depositions scale-up in a 2-dimensional manner. This 2-dimensional deposition is the basis of plate-and-frame and rotating cathode cells and has resulted in operating concentration limits of tens or hundreds of mg/L. To enhance the electrodeposition process from dilute solutions, the available approaches of interest and greatest potential involve: (1) improved mass transfer (arrival rate of the reactant metal) through agitation or other means of increased turbulence promotion; and (2) maximizing the electrode surface area. The RenoCell® patented design provides this desired performance enhancement by utilizing a very high surface area 3-dimensional cathode and enhanced mass transfer capability through the use of novel flow paths that assure the maximum surface area is available to metal ions for efficient deposition.

The use of RenoCell as a heavy metal extraction and recovery device has been demonstrated for a wide range of heavy and precious metal ions from aqueous solutions. It has proven capable of achieving sub-part per million final concentrations of platable heavy metals. This extends the capability of electrolytic cell technology by at least two orders of magnitude lower compared to other electrolytic cell types (see Figure 1). In addition, RenoCell is more energy efficient by a factor of 3 to 5 than a rotating cathode, and by a factor of 10 or more than a fluidized bed or reticulated cathode electrolytic cell at low metal ion concentration.

**Figure 1**  
**Dependence of Cell Design on Concentration of Metal Ion in the Feed**



XR11-7028/ED#2

In the RenoCell, metals are plated into and onto porous cathodes mounted in easily removable cartridges. Metal laden cathodes can be quickly removed and replaced with fresh cathodes rendering the cell ready for re-use in just a matter of minutes. The metals can then be removed for re-use by re-dissolution, for example, into acid, or recovered pyrometallurgically by addition to a suitable melt.

Design of a RenoCell-based system application is dependent on the process stream conditions, on concentrations and identities of all constituents, flow rates, pH, temperatures and suspended solids. Where necessary, filters, tanks, pumps, and instrumentation and control mechanisms can be supplied by Renovare or a RenoCell reseller to meet specific application requirements.

The RenoCell technology is currently being utilized in over 25 installations in the US, UK and Asia for the removal and or recovery of silver, gold, platinum, palladium, copper, tin, lead, cadmium and other metals from a variety of plating, etch, leach and drag-out process, rinse and waste streams.

*The information given below may be taken as a general guide. However, before any plant design is contemplated, the user should determine the exact operating performance under proposed conditions of use by testing of actual feed solution with focus on pH, temperature and inlet concentration.*

## 2.0 EXPERIENCE AND EXPERTISE

RenoCell, evolved from on-going development work in the late 1980s and early 1990s, is a major extension of electrolytic cell technology both in terms of effective treatment range and reduced life cycle costs. Field tests and trials initiated in the UK in 1993 and 1994 demonstrated excellent results that have allowed this advanced cell design to leave the laboratory and pilot scale, and enter the industrial world with over 40 applications. The technology has been successfully demonstrated on the following metals in a variety of matrices:

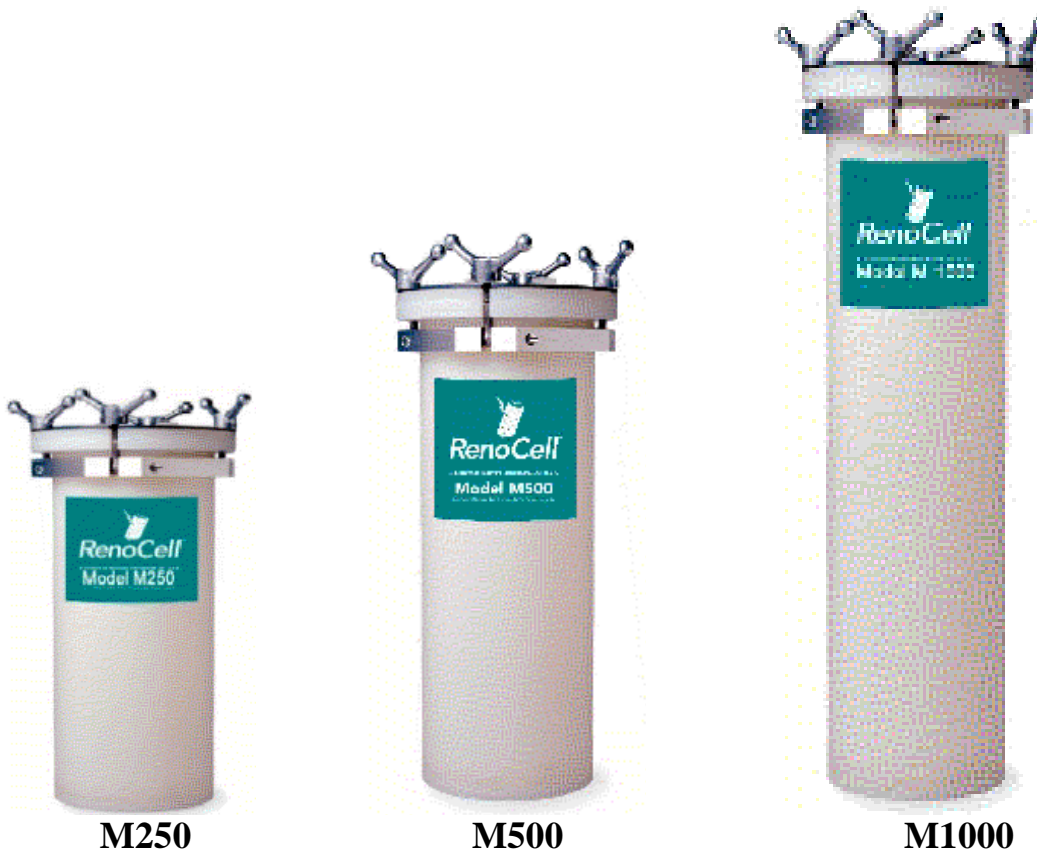
Cadmium	Cobalt	Copper	Gold
Indium	Iridium	Iron	Lead
Mercury	Nickel	Osmium	Palladium
Platinum	Rhodium	Ruthenium	Silver
Tantalum	Tellurium	Tin	Zinc

Other metals being investigated include arsenic, antimony, polonium, molybdenum and tungsten which are recovered as alloys with other platable metals. While no metal electrodeposition occurs with chromium, manganese and titanium, these metals can be electrolytically recovered as oxide or hydroxide precipitates at the RenoCell cathode. If a metal is electrolytically depositable, it probably is recoverable by RenoCell technology but would require testing to identify the operating conditions.

RenoCell-based systems use this advanced electrolytic cell technology to meet ever more stringent process control, waste minimization and waste treatment specifications. This patented technology has been tested on a wide range of metal-bearing process and effluent waste streams,

and demonstrated, as shown in Table 1, a processing capability extending effective removal of heavy and precious metals into the parts per billion (ppb) or  $\mu\text{g/L}$  range. Table 2 summarizes test results for several metals in various electrolytes.

Renovare has commercialized three industrial RenoCell product models: the “half-meter” (0.5 m) Model 500; the “one-meter” (1.0 m) Model 1000; and the “quarter-meter” (0.25 m) Model 250, typically used for gold and other high value metals to minimize lockup. The RenoCell is constructed of materials suitable for the metal recovery applications and appropriate for years of industrial operations in both acid and alkaline electrolytes. In most applications, the anode is a DSA (dimensionally stable anode) of iridium oxide/tantalum oxide coated titanium with titanium current connectors, and the cathode current feeder is also titanium. The body of the cell, end caps and couplings are polypropylene with titanium hardware. Alternative materials of construction are available.



**Table 1**  
**RenoCell Testing & Operational Experience (Partial List)**

Cadmium cyanide; sulfate

Chromium sulfate; Acid Chromium; Chromating liquors [oxidation Cr<sup>3</sup> → Cr<sup>6</sup>]  
Cr-containing dye effluent  
Cr-containing tanning solution

Cobalt sulfate

Electroless Copper  
Copper pickling baths  
Copper cyanide; fluoborate; sulfate; pyrophosphate; sulfuric acid/peroxide microetch  
Cu/ Scotch whisky

Cyanide destruction

Fe, Ni, Zn  
Fe pickle solution

Lead fluoborate

Mercury  
Mercury from 50% sodium hydroxide  
Mercury from 30% lithium chloride

Nickel  
Nickel chloride; sulfate  
Ni, Cr  
Electroless Nickel  
Nickel, Vanadium  
Ni, Fe

PCB Strip Solutions  
PCB Etch Solutions

Pt, Pd, Te, Ir, Ru, Au, Rh

Pd, Pt from refinery wastes

Silver cyanide, nitrate  
Silver--[photo] fixer; bleach-fix

Tin, Tin-lead  
Tin sulfate

Zinc cyanide; sulfate  
Zn-Fe pickle solution

<b>Table 2 Typical Testing and Operating Experience</b>				
<b>Effluent</b>	<b>Metal</b>	<b>Concentration</b>		<b>Removal Efficiency (%)</b>
		<b>Initial (mg/L)</b>	<b>Final (mg/L)</b>	
Acid sulfate rinse	Cu	910	0.02	99.99+
	Cu	98.2	0.22	99.78
Cyanide plating rinse	Cu	105	0.34	99.68
Fluoborate plating rinse	Cu	115	0.3	99.74
Electroless Cu rinse	Cu	82	0.8	99.02
Micro etch bath rinse	Cu	44	0.11	99.75
Cyanide plating rinse	Ag	740	0.34	99.95
Cyanide static dragout	Cd	107	0.34	99.68
Acid sulfate rinse	Cd	978	0.37	99.96
Acid sulfate rinse	Zn	77.5	0.23	99.70
Acid sulfate rinse	Sn	93.2	0.5	99.46
Fluoborate plating rinse	Pb	85	0.32	99.62
Watt's bath rinse	Ni	105	0.5	99.52
Acid sulfate rinse	Cr(III)	124	1	99.19
Cyanide liquor	Au	380	<0.1	99.97
Acidic liquors	Pt/Pd	24/110	1/0.01	95.83/99.99
Acidic liquors	Pt	2000	0.5	99.98
Acidic liquors	Pd	500	<0.5	99.90
Groundwater (acidic)	Hg	6.3	0.036	99.43

### 3.0 SILVER EXPERIENCE

#### 3.1 Silver Cyanide Waste

The recovery of silver from cyanide rinse baths was demonstrated with final concentrations of less than 1 mg/L readily attainable, although the current efficiencies were relatively low depending on the cyanide concentration.

The results were obtained with a low background cyanide electrolyte concentration and therefore a high cell voltage was observed. Because of the combination of high voltage and high current, the electrolyte increased in temperature to around 60°C. In spite of this, the silver was effectively removed from solution. In spite of the higher concentration of the complexing cyanide ion, the silver recovery was effective to less than 1 mg/L.

### 3.2 Photographic Silver Recovery

Silver bearing waste solutions from photographic applications were processed. These results demonstrated the highly efficient recovery of Ag to around 1 mg/L in an undivided RenoCell in the cases of incoming fixer and wash fix. In the cases of developer and bleach fix, silver could not be recovered below 50 mg/L using an undivided cell. However, use of a divided RenoCell was effective in silver removal from these sources down to ~1 mg/L for the bleach fix solution. The presence of iron appears to be the principal factor creating these difficulties. Ferric ion can be regenerated continuously at the anode in an undivided cell, followed by the reduction of the ferric ion to ferrous ion at the cathode in preference to silver deposition after silver has reached a relatively low level and depending on how much iron is in solution.

The following tabulation was prepared based upon the on-going test program of the RenoCell divided cell for the silver bleach-fix agent.

Test No.	Ag In (mg/L)	Ag Out (mg/L)	Current Density (A/m <sup>2</sup> )	RenoCell Type	Comments
1	1100	30	200	undivided	The 30 mg/L level is the <u>best</u> results which alternative technologies have been able to reach.
2	1100	0.8	---	divided	The 0.8 mg/L level exceeds the requirement of 1 mg/L Ag; test were initiated to determine if lower levels could be attained.
3	1010	0.14	---	divided	If the level could be reduced below 1 mg/L then it might be possible to suggest to the regulator that the lower concentration should be required as best available technology.
4	1080	0.21	---	divided	

## 4.0 PRECIOUS METAL EXPERIENCE

### 4.1 Platinum and Palladium

#### 1997 Testing of Pt and Pd Solutions

Actual platinum and palladium diammine liquor solutions were tested with a divided RenoCell.

The divided cell is utilized in a number of applications typically involving metals in multiple oxidation states where it is desirable to separate the anolyte and catholyte within the RenoCell. If not utilized, it is possible that the oxidized species generated at the anode will reach the cathode and then be reduced, leading to loss of current efficiency, or in some cases to a redissolution of the desired metal deposition. In other cases it is necessary to isolate the anions from the anode to minimize the formation of noxious or toxic gases such as chlorine or HCl. Generally a cation-selective membrane is utilized to allow only innocuous cations to reach the cathode from the anolyte.

<b>Characteristics</b>	<b>Test 1 Pd Solution</b>	<b>Test 2 Pt Solution</b>
<b>Pt</b> Starting Conc., mg/l Ending Conc., mg/l	50 10	2000 0.5
<b>Pd</b> Starting Conc., mg/l Ending Conc., mg/l	300-500 <0.5	50 <1
<b>pH</b>	1-4	0-2

In both of these tests, two liters of solution were processed at a current density of 300 A/m<sup>2</sup> and 2 lpm flow rates through a 0.015 m<sup>2</sup> lab test unit. In Test 1 the Pd concentration was reduced from about 500 mg/l to about 10 mg/l in 15 minutes while the Pt was reduced from 50 mg/l to 10 mg/l. After 30 minutes, the Pd concentration had been reduced to <0.5 mg/l while the Pt was at 10 mg/l at the current and voltage conditions chosen for Pd removal.

In Test 2 the Pt concentration was reduced from about 2000 mg/l to about 800 mg/l in 15 minutes while the Pd was reduced to <1 mg/l. After 30 minutes the Pt concentration had been reduced to <50 mg/l while the Pd was at <1 mg/l. The Pt was 15 mg/l after 45 minutes, 2 mg/l after 60 minutes, and <0.5 mg/l after 120 minutes. These were limited tests that confirmed the application of RenoCell. The test program was expanded to pilot system testing and process optimization that resulted in Pd and Pt being removed to non-detect levels.

### 1994-95 Testing of Pt Group Solutions

These tests were performed with early prototypes of the RenoCell technology. The early testing was performed at very low current density. At low current density [100 A/m<sup>2</sup>], redissolution and other factors impact electrodeposition. The results are not representative of expected performance with optimized conditions and higher current densities. Even so, the results did confirm electrodeposition of Pd, Pt, Rh, Ni and Au from very dilute solutions.

These results were very promising even though no attempt was made to optimize pH, current density or treatment flow rate. The exact composition of the process solutions was undisclosed but an upper and lower limit for metal concentrations was determined. The test protocol is summarized and the results reproduced below.

### Concentrated Pt Effluent

After a period of equilibration, an aliquot was removed, and current equivalent to 200 A/m<sup>2</sup> was passed that resulted in a maximum cell voltage of 3.3V. Aliquots were removed at intervals for analysis by ICP Emission Spectroscopy.

In some instances, namely iridium, ruthenium, and palladium, the relevant analytical standard was not available and in these cases, analyses were completed on the basis of comparison with the starting solution. The other measurements were made against aqueous standards, i.e., there

was no matrix matching. It should also be noted that the liquor contained a high proportion of solids. These did not have any effect on the solution pumping but may account for the unexpectedly low analysis for platinum that may have been precipitated as the ammoniacal complex.

<b>Concentration (mg/L)</b>							
<b><u>Time (min.)</u></b>	<b><u>Pt</u></b>	<b><u>Ir</u></b>	<b><u>Ru</u></b>	<b><u>Cu</u></b>	<b><u>Pd</u></b>	<b><u>Rh</u></b>	<b><u>Au</u></b>
0	6.3	100	100	0.2	100	4.5	1.3
15	5.1	92	100	0.2	84	3.9	1.4
30	4.9	94	100	0.17	71	3.6	1.3
60	3.4	86	95	0.14	40	2.2	1.3
120	1.0	39	17	0.02	0	0.5	0.4

#### Dilute Pt Effluent

The dilute effluent was treated in exactly the same way as the concentrated solution.

<b>Concentration (mg/L)</b>							
<b><u>Time (min.)</u></b>	<b><u>Pt</u></b>	<b><u>Ir</u></b>	<b><u>Ru</u></b>	<b><u>Cu</u></b>	<b><u>Pd</u></b>	<b><u>Rh</u></b>	<b><u>Au</u></b>
0	3.0	100	100	0.3	100	3.2	0.35
15	2.4	100	100	0.2	81	2.1	0.35
30	1.3	83	0	0	33	1.1	0.27
60	1.2	83	0	0	33	1.1	0.27
90	1.2	83	0	0.01	28	0.8	0.13
120	1.2	82	0	0.03	28	0.8	0.04

#### Other Tests

##### Test 1

This aqueous solution of PdCl<sub>2</sub> nominally contained 100 mg/L Pd and 50 mg/L of Cu in an acidic matrix. The test was run with a divided RenoCell configuration because of the presence of chlorides. An anolyte of ~0.3M Na<sub>2</sub>SO<sub>4</sub> was used. The actual metal concentration processed was:

Pd            85 mg/L (mg/L)  
Cu            130 mg/L (mg/L)

The bench scale system set point operating conditions were:

Volume - catholyte (PdCl <sub>2</sub> solution)	4000 ml
Volume - anolyte ( Na <sub>2</sub> SO <sub>4</sub> )	3000 ml

Flow rate - catholyte	6 Lpm
Flow rate - anolyte	4 Lpm
Temperature	15 C
pH	3.47
Current	7.5 A
Current density	300 A/m <sup>2</sup>
Voltage	5 V

At test initiation, the cell was operated at a constant current of 7.5 A. The voltage was allowed to fluctuate and started at 5 V before decreasing after 5 minutes to 4.1 V. Samples were taken at 15 minutes and 30 minutes. The RenoCell reduced both the Pd and Cu concentration in a very short time (probably less than 5 minutes) since the metal concentrations were at detection limits for both the 15 and 30 minute samples. This was confirmed by visual observation that the test solution was decolorized within 10 minutes.

Concentration (mg/L)			
Time (min.)	Pd	Cu	pH
0	86	130	3.47
15	<0.1	<0.01	3.7
30	<0.1	<0.01	

Since we do not know the actual time or current used before reaching detection limits, no estimate of current efficiency is possible.

## Test 2

This aqueous solution of PdCl<sub>2</sub> nominally contained 100 mg/L Pd and 50 mg/L of Cu in an alkaline organic matrix with pH of 10 - 11. The test was run with a divided cell configuration because of the presence of chlorides. An anolyte of ~0.3M Na<sub>2</sub>SO<sub>4</sub> was used. The actual concentration was:

Pd	100 mg/L (mg/L)
Cu	0.62 mg/L (mg/L)

The system set point operating conditions were:

Volume - catholyte (PdCl <sub>2</sub> solution)	4000 ml
Volume - anolyte ( Na <sub>2</sub> SO <sub>4</sub> )	3000 ml
Flow rate - catholyte	6 Lpm
Flow rate - anolyte	4 Lpm
Temperature	20 C
pH	10 - 11
Current	7.5 A
Current density	300 A/m <sup>2</sup>

Voltage

3.65 V

The test was initiated and the cell operated at a constant current of 7.5 A. The voltage was allowed to fluctuate at about 3.6 V. Samples were taken at 15 minutes and 30 minutes. The RenoCell reduced both the Pd and Cu concentration in a very short time since the concentrations were at detection limits for both 15 and 30 minutes samples. This was confirmed by visual observation of solution decolorization within 10 minutes.

<b>Concentration (mg/L)</b>		
<b><u>Time</u></b> <b><u>(min.)</u></b>	<b><u>Pd</u></b>	<b><u>Cu</u></b>
0	100	0.62
15	<0.1	<0.01
30	<0.1	<0.01

Since we do not know the actual time or current used before reaching detection limits, no estimate of current efficiency is possible.

### Test 3

This test was a repeat of Test 1— aqueous solution of PdCl<sub>2</sub> in an acidic matrix. The test was run with a divided RenoCell configuration with an anolyte of ~0.3M Na<sub>2</sub>SO<sub>4</sub>. The actual concentration processed was:

Pd	85 mg/L (mg/L)
Cu	130 mg/L (mg/L)

The bench scale system set point operating conditions were:

Volume - catholyte (PdCl <sub>2</sub> solution)	4000 ml
Volume - anolyte ( Na <sub>2</sub> SO <sub>4</sub> )	3000 ml
Flow rate - catholyte	6 Lpm
Flow rate - anolyte	4 Lpm
Temperature	15 C
pH	3.5
Current	7.5 A
Current density	300 A/m <sup>2</sup>
Voltage	3.2 V

When the test was initiated, the cell was operated at a constant current of 7.5 A. The voltage was allowed to fluctuate and started at 3.2 V before increasing after 10 minutes to 3.7 V. Samples were taken at 5, 10, 15 and 30 minutes. The RenoCell reduced both the Pd and Cu concentration in a very short time (between 5 and 10 minutes) since the concentrations were at detection limits for both metals in the 15 minute sample.

<b>Concentration (mg/L)</b>		
<b><u>Time</u></b> <b><u>(min.)</u></b>	<b><u>Pd</u></b>	<b><u>Cu</u></b>
0	86	130
5	15	11
10	0.2	0.07
15	<0.1	<0.01
30	<0.1	<0.01

Based upon the samples taken at T = 5 min. and T = 10 min., the current efficiency for the Pd and Cu removal was calculated based upon other test data that indicated that the current efficiency for Pd would be at least 40%. The estimates for this test is:

<u>Time</u>		<u>Current Efficiency</u>
T = 10 min.	Pd	42%
	Cu	63%

#### Test 4

This aqueous solution of PdCl<sub>2</sub> nominally contained 100 mg/L Pd and 50 mg/L of Cu in an alkaline organic matrix with pH of 10 - 11. The test was run with a divided cell configuration because of the presence of chlorides. An anolyte of ~0.3M Na<sub>2</sub>SO<sub>4</sub> was used. The actual concentration was:

Pd	100 mg/L (mg/L)
Cu	0.62 mg/L (mg/L)

The system set point operating conditions were:

Volume - catholyte (PdCl <sub>2</sub> solution)	4000 ml
Volume - anolyte ( Na <sub>2</sub> SO <sub>4</sub> )	3000 ml
Flow rate - catholyte	6 Lpm
Flow rate - anolyte	4 Lpm
Temperature	20 C
pH	10 - 11
Current	7.5 A
Current density	300 A/m <sup>2</sup>
Voltage	5.2 V

When the test was initiated, the cell was operated at a constant current of 7.5 A. The voltage was allowed to fluctuate at about 5.2 V. Samples were taken at 15 minutes and 30 minutes. The RenoCell reduced both the Pd and Cu concentration in a very short time since the concentrations were at detection limits for both 15 and 30 minutes samples.

<b>Concentration (mg/L)</b>			
<b>Time (min.)</b>	<b>Pd</b>	<b>Cu</b>	<b>pH</b>
0	100	0.62	10
20	<0.5	<0.05	9
30	<0.5	<0.05	

No estimate of current efficiency was possible since actual time to reduce metal concentration is unknown.

## 4.2 Gold

Early experience with gold was limited to lab testing including the solutions identified above. The results of the additional Au tests performed are summarized below.

### South African Gold Tests

A number of dilute gold solutions were tested during a limited test program in late 1998 at a major South African gold mine operation. Typical results and conditions are given below.

All tests were on 2 liter samples and at 1 or 2 lpm flow rates, and 150 Amp/m<sup>2</sup> (1.8 Amps) or 225 Amp/m<sup>2</sup> (2.7 Amps) current density. While not needed, these tests were performed with a divided cell since other tests involved precious metals in highly acidic chloride matrices used a divided cell for testing.

The following tables present the results of the ten tests.

### Solution RC1

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (°C)</b>	<b>pH</b>
0	331	7.8	2.75	19	12.5
5.6	144	7.2	2.7	21	12.4
10	17.5	7.1	2.7	23	12.5
15	0.3	7.1	2.7	24	12.5
31	0.2	7.1	2.7	25	12.6
45	0.1	7.1	2.7	26	12.6

Overall current efficiency from 331 to 0.3 ppm is 39.9 % and from 331 to 0.1 ppm is 13.3%. The flow rate was 2 lpm. Current efficiency from 17.5 to 0.1 ppm over 35 min. was 0.9%

Solution RC1a (rerun of RC1)

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (°C)</b>
0	331.4	9.4	2.65	21
5	144.9	9.4	2.65	22
11	23	9.6	2.65	22
16	2.2	9.7	2.65	23
31	0.15	10.2	2.65	25
45	0.1	10.6	2.55	26

Overall current efficiency from 331 to 0.1 ppm is 19.8%. The flow rate was 2 lpm.

Solution RC2

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	381	6.8	2.6	23	10.7
5	295	6.95	2.6	24	10.9
10	156	6.95	2.6	24.5	11
15	2.8	7	2.6	25	11.1
30	0.15	7	2.6	26	11.3
45	0.1	7.15	2.6	27	11.5

Overall current efficiency from 381 to 0.1 ppm is 23.9%. The flow rate was 2 lpm.

Solution RC3

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	373	8.6	2.7	23	11.8
5	164	8.65	2.7	23.5	11.7
10	60	8.55	2.7	24	11.8
15	16	8.5	2.7	24.5	11.9
30	1.4	8.25	2.7	26	12.1
45	0.1	8.1	2.7	27	12.2

Overall current efficiency from 373 to 0.1 ppm is 15.0%. The flow rate was reduced to 1 lpm.

Solution RC4

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	297.5	7.6	2.7	21	11.6
5	96.9	7.3	2.7	21.5	11.7
10	23.7	7.2	2.7	22	11.8
15	9.5	7.2	2.7	23	12
30	0.9	7	2.7	24	12.2
45	0.7	6.8	2.7	25	12.3
60	0.3	6.7	2.7	26	12.4

Overall current efficiency from 297.5 to 0.9 ppm is 17.9%. The flow rate was 1 lpm.

Solution RC5

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	364	7.9	2.7	22.5	10.5
5	131.8	8	2.7	23	10.8
10	57.2	8	2.7	23.5	11
15	12.6	8	2.7	24	11.2
30	1.7	7.9	2.7	25	11.4
45	0.7	7.8	2.7	26	11.6
60	0.36	7.8	2.7	27	11.8

Overall current efficiency from 364 to 0.7 ppm is 14.6%. The flow rate was 1 lpm.

Solution RC6

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	351.9	4.2	1.8	23	11.8
5	203.4	4.4	1.8	23.5	11.7
10	80	4.4	1.8	24	11.8
15	23.3	4.4	1.8	24.5	11.8
30	2.29	4.3	1.8	25	12
45	0.77	4.3	1.8	26	12
60	0.33	4.2	1.8	26.5	12.1

Overall current efficiency from 351.9 to 0.77 ppm is 21.2% and to 0.33 ppm is 15.9%. The flow rate was 1 lpm.

Solution RC7

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	334.7	5.6	2.7	22	12.5
5	96.2	5.7	2.7	23	12.4
10	9.65	5.7	2.7	23.5	12.4
15	1.58	5.7	2.7	24	12.4
30	0.87	5.7	2.7	24.5	12.4
45	0.72	5.8	2.7	25	12.4
60	0.56	5.8	2.7	25.5	12.4

Overall current efficiency from 334.7 to 0.87 ppm is 20.2% and to 0.56 ppm is 10.1%. The flow rate was increased to 2 lpm.

Solution RC8

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	359.9	4.7	2.7	23	12.7
5	126.9	4.8	2.7	23.5	12.6
10	12	4.9	2.7	24	12.6
15	1.92	4.9	2.7	24.5	12.6
30	0.87	4.8	2.7	25	12.6
45	0.76	4.7	2.7	25.5	12.5
60	0.71	4.7	2.7	26	12.5

Overall current efficiency from 359.9 to 0.87 ppm is 21.7% and to 0.71 ppm is 10.9%. The flow rate was 2 lpm.

Solution RC9

<b>Time (m)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Temp (C)</b>	<b>pH</b>
0	359.9	5	2.7	23	11.8
5	118.2	5.1	2.7	24	12.1
10	41.3	5.1	2.7	24.5	12.2
15	7.41	5	2.7	25	12.2
30	0.95	4.9	2.7	25.5	12.3
45	0.38	4.8	2.7	26	12.3
60	0.21	4.7	2.7	26.5	12.4

Overall current efficiency from 359.9 to 0.95 ppm is 21.7% and to 0.21 ppm is 10.9%. The flow rate was reduced to 1 lpm.

Viewed in their entirety, the results of the ten tests are remarkably consistent irrespective of variations in pH, flow rate, current density and solution conditions. Figure 1, attached, plots overall current efficiency vs. Au concentration for nine of the 10 runs. Overall current efficiencies at 2 lpm flowrate were consistently at or above 20% to below 1 ppm. Interestingly, current efficiencies are noticeably and consistently higher at the 2 lpm flowrate.

Thus, in all cases, the gold concentration in the eluate was reduced from ~350 mg/L Au to <1 mg/L Au in less than 45 minutes, and in most cases in less than 15 minutes. By comparison, the recycle time in the existing electrolytic cells was about 12 hours and the final gold concentration was about 16 mg/L Au. At face value, the improved performance is extremely good but clearly this would need to be corroborated on a larger scale. The gold plated on the carbon element was uniform on the outside and also on the inside surfaces of the carbon.

**Japanese Test**

This test involved the treatment of 11 L of a gold plating solution in two batches. The aqueous solution of Au/CN in an acidic matrix. The test was run with an undivided RenoCell configuration. The concentration processed was:

Au            480 mg/L (mg/L)  
CN            150 mg/L (mg/L)

The bench scale system set point operating conditions were:

Volume - catholyte (Au/CN solution)	5000 ml
Flow rate - catholyte	6 Lpm
Temperature	15 C
pH	5 - 6
Current	7.5 A
Current density	300 A/m <sup>2</sup>
Voltage	5.8 V

The test was initiated at a constant current of 7.5 A. The voltage was allowed to fluctuate and started at 5.8 V before decreasing after 10 minutes to 5.1 V and after 60 min. to 4.6 V. Samples were taken at 15 min. and every 10 min. thereafter for the first batch. The RenoCell reduced both the Au and CN concentration in a short time as indicated below.

<b>Time (min.)</b>	<b>Au (mg/L)</b>	<b>Voltage (V)</b>	<b>Current Density (A/m<sup>2</sup>)</b>	<b>Temp (C)</b>	<b>CN- (mg/L)</b>
0	480	5.8	300	15	150
15	24	5.1	300	-	69
25	0.8	-	300	-	60
35	0.5	-	300	-	55
45	0.4	4.6	300	-	46

The treatment of the gold solution over the first 15 minutes was performed at a current efficiency of 49.6% from 480 to 24 ppm, and 3.8% over the next 10 minutes to below 1 ppm. The overall current efficiency was 31.3% from 480 to 0.8 mg/l in 25 min. The destruction of over two-thirds of the cyanide was also noted.

The second batch was run but no samples were taken since the purpose was to load the gold on the carbon cathode and then incinerate the carbon. The subsequent thermal processing proved successful and was complete after two hours of heating at 600 C.

### **PCB Gold Recovery**

This test was performed in late 1999 on the first drag-out tank on an actual PCB plating machine. The test was performed by directly connecting a RenoCell bench scale cell (RenoCell Model M100) to a 265 liter drag out tank. The Au concentration was 420 mg/L at the beginning of the test run. The unit was operated at 2 Lpm and 8 Amps (320 A/m<sup>2</sup>) for 20 hours. During this time additional Au was dragged in and out. At the completion of this 20 hour test, the Au concentration was 90 mg/L and 101.9 g of Au had been recovered. This included 87.45 g removed based on the beginning and ending concentrations, an estimated 26.2 g Au added by drag in, and 1.11 g of Au lost by drag out. This totals 112.54 g of Au by analysis of which 101.9 was on the cathode and 10.64 g of gold powder located in the bottom of the RenoCell.

The current density of 320 A/m<sup>2</sup> was high and resulted in a slightly powdery Au deposit a portion of which did not adhere to the cathode and was recovered in the bottom of the cell. Lower current density would result in improved Au deposits as demonstrated in other tests. A recent modification to the RenoCell may improve Au deposit morphology at higher current densities, reducing the accumulation of metal powder in the bottom of the cell.

After completion of the test, the cathode element was removed and pictures taken that showed a uniformly deposited Au layer on the carbon with some penetration of the carbon. A 28.7% overall current efficiency was achieved during this test.

It is interesting to note that gold recovery is critical to the PCB manufacturer since losses of Au from drag out is some 68 times greater than actual gold plated on the circuit boards! For a typical plating machine the daily drag out loss of gold has a value between \$250 and \$300.

## **5.0 SOUTH AFRICAN MIXED METAL TESTS**

Mixed precious metals and value metals were tested.

In all of these tests, two liters of solution were processed at a typical current density of 265 A/m<sup>2</sup> [2.1—>6.2A] and 2 lpm flow rates through a 0.015 m<sup>2</sup> RenoCell lab test unit. The pH was generally less than 1 [-1.39—>1.64] except for Run 16 and 17 that were alkaline. No attempt to optimize the conditions were made.

<b>Concentration, mg/l</b> <b>(Initial/Final)</b>								
<b>Test No.</b>	<b>Time min.</b>	<b>Pt</b>	<b>Pd</b>	<b>Rh</b>	<b>Ir</b>	<b>Ru</b>	<b>Cu</b>	<b>Ni</b>
1	100	21.1/0.93	111/0.01				102/0.02	
2	120	24.5/1.08	108/0.01				125/0.05	
3	120	60.4/66.1		166/140	28.9/24.2	5.12/8.16	1644/1558	24700/21000
4	180	66.5/59.4		157/140	24.9/25.6	0.25/0.35	1656/1456	24600/21800
5	90	54.7/46.1	5.49/3.02	128/94.4	21.2/21.3	0.14/0.17	1307/1133	19600/17000
6	100	66.1/66.8		165/139	32.8/24.7	0.32/0.43	1644/1432	24300/21500
7	1140		<.02/<.02	219/189	0.72/1.36	6.7/5.6	24K/7490	8490/7880
8	150		<.02/<.02	226/183	0.74/0.68	6.9/5.6	24.1K/12K	8520/7200
9	120	49.3/19.1	390/207				2080/1980	12400/11400
10	120	11.5/10.8	<0.5/<0.5	1.3/0.79			134/0.13	
11	180	62.8/23.9	77.3/<0.5	41.1/20.9	27.6/12	8.93/6.94		
12	30					25.7/22.9		
13	240	22.7/17.8	104/73				110/104	
14	240	21.8/0.85	109/0.01				114/0.1	
15	120	82.9/1.57	12.7/0.03				1.61/0.5	
16	120	29.6/18	0.07/0.06	0.37/0.19	6.06/4.38	0.92/0.42	3.7/0.7	0.18/<0.05
17	240	33.5/15.5	0.47/0.04	0.17/0.08	0.08/0.38	0.8/0.57	0.05/0.11	0.14/0.05
18	120	30.7/16.2	0.24/0.01				0.05/0.05	0.12/0.03

$K = 1,000$

**Figure 1**  
**South African Gold Recovery Tests**  
**Overall Current Efficiency vs. Concentration**

