

PLASMA SMELTING OF UNCONVENTIONAL ORES AND MINE RESIDUES FOR THE RECOVERY OF PRECIOUS METALS

T. P. Johnson¹ and A. Vathavooran²

¹Tetronics International
Marston Gate
South Marston Park, Swindon, Wiltshire, UK SN3 4DE

²Tetra Tech
Unit 2, Apple Walk, Kembrey Park, Swindon, UK SN2 8BL

ABSTRACT

Conventional mining operations can produce a wide range of wastes containing gold and other precious metals but which are less suitable for processing by traditional methods. There are also types of ore that do not fit easily into a traditional processing flowsheet, e.g. because the refractory nature of their mineralogy or the combination of valuable metals is less suitable for traditional processes. Nevertheless, these potential sources of valuable metals remain unexploited resources that have attracted growing interest in the metals and mining industries over recent years. The challenge is therefore to develop and use alternative processing methods that have the flexibility of operation to cope with a wide variety of material types and tonnages, whilst providing high recoveries for valuable metals. Tetronics' DC plasma smelting technology achieves industry-leading recovery rates for precious metals from a wide range of input materials and initial precious metal concentrations, whilst generating an inert slag-based material as a by-product (even when starting from a hazardous waste input material), approved within the EU for use in construction applications. This paper describes how this technology can be used as a key part of an overall process for the recovery of precious metals from these interesting materials.

KEYWORDS

Plasma, DC plasma smelting, refractory ores, recovery rate

INTRODUCTION

The extraction of gold from its ores by various forms of cyanide leaching has been practised by the mining industry for over a century (Minerals Council of Australia, 2005) and it remains the primary extraction method in a wide range of mining operations. The ability of cyanide to extract gold efficiently and quickly from lower grade ores without extensive additional processing, coupled with well-known methods to recycle the cyanide for re-use within the process mean it is often both the most economically preferable and environmentally acceptable method for recovering gold. As a result, 88% of all gold produced from mines in the USA in 2014 was recovered via leaching of open heaps or dumps (UGGS, 2016). Nevertheless, there are occasions where certain combinations of mineralogy and other circumstances reduce the effectiveness of cyanidation techniques, so that ever more elaborate additional processing steps are required, with inevitable increases in operating costs (Swash, 1988). In these circumstances, which are likely to be more common in future as ore qualities diminish, other methods of extraction may offer better alternatives. Whilst much less commonly used for Au extraction at present, pyrometallurgical methods are amongst the longest-established of these alternative approaches and merit serious consideration in such cases.

Pyrometallurgical methods have been used for many years for the extraction and recovery of precious metals (PM) from both primary (Jones, 2002; Jones, 2005; Sanchez, 2004) and secondary sources (Kim, 2009; Saternus & Fornalczyk, 2013). They also form a fundamental part of fire assay, which remains the oldest and most reliable method for analysis of gold and other precious metals from a wide variety of gold-bearing materials (Blyth, 2004). This paper seeks to outline one such method, DC plasma arc smelting, and the circumstances in which it represents a viable alternative to more conventional approaches.

DC PLASMA ARC TECHNOLOGY

Tetronics' DC plasma arc technology has been used for the commercial recovery of platinum group metals (PGM) from automotive and industrial catalysts for over 30 years. The unique combination of design and operational benefits of the technology during this period has ensured that industry-leading technical recovery rates have been demonstrated for a wide range of PM and PGM at both a pilot and full commercial scale. These recovery rates are typically around 98% for all major PM and PGM in pilot-scale trials using spent catalyst materials, which then rise to around 99% recovery at a full commercial scale as a result of greater equipment and operational optimisation. More recently, the technology has been applied commercially to the recovery of PM/PGM from printed circuit boards (Johnson, Deegan & Wise, 2012).

Consequently, Tetronics' DC Plasma Arc technology is one of the key pyrometallurgical solutions available for the recovery of PM and PGM from unconventional and refractory ores as a result of several key features, including its ability to operate with a wide range of feed materials, tight control of smelting conditions and minimal losses of dust to the exhaust gases as a result of low furnace gas flows. The high furnace temperatures and the ability to vary the reaction conditions of the process also allow the operator to separate the elements in the charge into gaseous, slag and metal fractions. This in turn maximises the value derived from the waste and minimises the secondary waste, whilst achieving low ultimate emissions to air and water. The small footprint of a typical plant also makes it relatively simple for a plasma system to be retrofitted into an existing facility close the source of the raw material.

Process & Plant Description

In a typical DC plasma metals recovery plant (see Figure 1), the input material is conditioned as required, e.g. crushed, dried, concentrated, calcined, etc., and then blended with various additions, including fluxes (typically calcia and/or silica) to adjust the melting point and viscosity of the slag. In the case of PM/PGM recovery, where the target metals are present in low concentrations in the input material, a source of a collector metal such as iron (usually added as a mixture of magnetite and coke) or copper is also blended with the other feed materials. The charge materials are then fed into the furnace via one or more feed ports in the furnace roof.

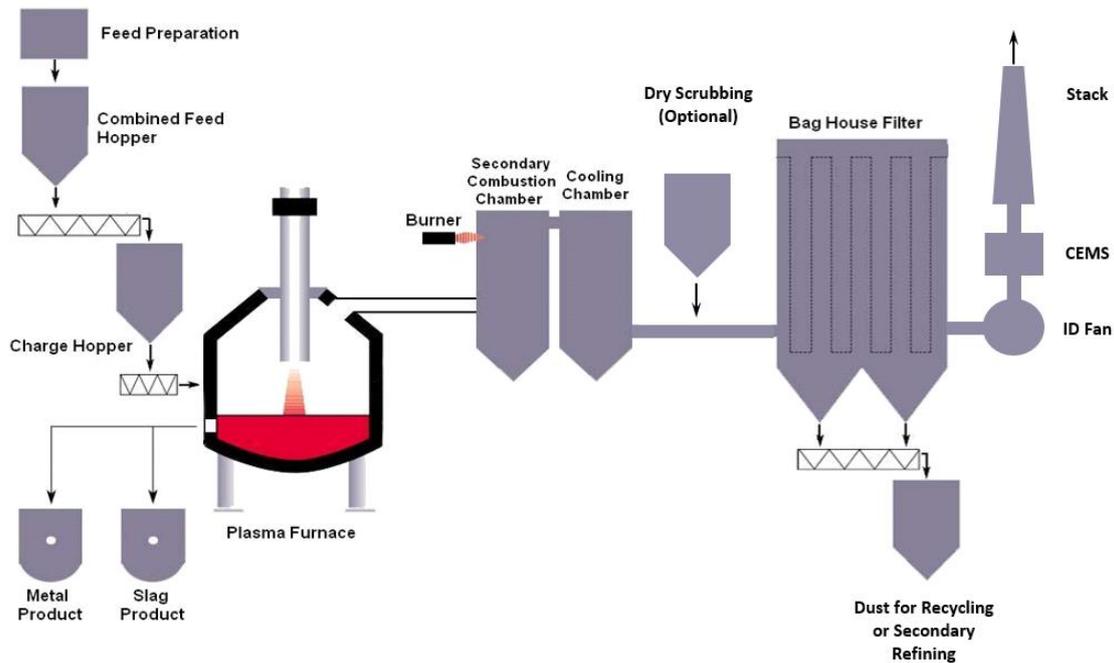


Figure 1. Schematic process flow diagram for a typical DC plasma smelting plant

The plasma furnace consists of a refractory lined steel vessel, which is water cooled in the roof and upper shell areas, and with either a graphite electrode or a water cooled plasma torch as the plasma device, which is inserted through the furnace roof. The molten bath forms the anode of the circuit and the plasma device acts as the cathode. The plasma arc attaches onto the surface of a molten bath of slag, which floats on a layer of liquid metal in the bottom of the plasma furnace, both of which are typically at a temperature of 1300°C to 1600°C. The charge material feed falls onto the molten slag bath, which causes the moisture and volatile species to vaporize and be drawn off into the gas cleaning system.

The non-volatile components in the input blend melt to form layers of slag and metal that separate very effectively as a result of density differences and very quiescent conditions in the bath. The collector metal droplets percolate through the slag to form the collector metal layer at the base of the furnace. These liquid metal droplets are able to dissolve both small droplets of lower melting point metals (such as Au and Ag) and small particles of solid metals (such as Pt, Pd, Rh and other higher melting point PGM), thereby ‘sweeping up’ valuable metals and ensuring high recovery rates for both PM and PGM. The solubility of Au in slags is very low, especially under the reducing conditions usually occurring under smelting conditions (Boriso, Palme & Spettel, 1993) and consequently very low residual levels of PM are attainable by this method. In addition to the recovery of valuable metals, the slag product of the process, known as Plasmarok[®], can be sold for use as an aggregate, owing to its inertness, low leachability and engineering properties.

The exhaust gases pass into a secondary combustion chamber to oxidize species such as organic compounds and volatile metals, before being cooled to <200°C using either air or water injection, in order to prevent reformation of dioxins and furans. The cooled gas is then filtered to remove particulates, which are collected in the filter for disposal, sale, refining or recycling back in the plasma furnace, depending on their composition. The removal of acid gases can be accomplished by dry or wet scrubbing, depending on the application. The pressure inside the plasma furnace is carefully controlled to be just below atmospheric pressure by means of a variable speed, induced-draught fan, which prevents significant ingress of air or egress of process gases. The exhaust gas is analysed for permitting purposes using a continuous emissions monitoring system (CEMS), and then vented to atmosphere.

METHODS FOR EXTRACTION OF GOLD

Gold ores that are less amenable to traditional extraction methods are classified as 'refractory'. Whilst 'free milling' ores typically have recovery levels above 95%, refractory ores have recovery levels significantly below this, with some only achieving 50% to 60% recovery (Vaughan, 2004). Many refractory ores can be subjected to further processing to improve the cyanidation-based recovery rate, but often at greater expense.

Refractory behaviour in gold ores includes those ores in which the gold is less accessible physically, typically because the gold particles are extremely fine and locked inside a protective layer of material. This type of ore is characterised typically by sulphide-based mineralogy (e.g. pyrite or arsenopyrite-based ores) or by fine gold particles that are trapped inside a silica-based mineral. In these cases, roasting and/or fine grinding of the ore is required to expose the fine particles to the leaching solutions. A second major cause of refractory behaviour is as a result of the nature of the gangue in the ore and typically either contains other metals such as copper, nickel and zinc that react with the leaching solutions (leach-robbing), thus increasing cyanide consumption and creating greater environmental issues, or else are carbonaceous and complex ores that reabsorb the soluble gold (preg-robbing). Those ores that display multiple causes of refractory behaviour are regarded as 'double-refractory' (Vaughan, 2004). In addition, it should be noted the use of cyanidation-based extraction in the PGM industry is not as widespread as for gold and silver, at least partly because of the slower reaction kinetics and the higher temperatures and pressures required to achieve the highest levels of recovery (Desmond, 1991). Therefore, whilst it is possible to use cyanidation for ores containing PGM alongside Au, the presence of PGM increases the challenges of recovering maximum value from the ore.

It is with these ores, where the recovery rates decrease and the costs of extraction increase using traditional extraction methods, that other extraction methods can become a more attractive option.

Recovery of PM & PGM using DC Plasma Smelting

Typical results for the smelting of a variety of precious metal-containing materials are shown in Table 1. As these data show, DC plasma smelting consistently achieves high levels of recovery of all precious and platinum group metals, with essentially no differences between the recovery rates of different elements and regardless of the input composition. Even when applied to Re and Ru, which can form volatile oxides, the process achieves the same high levels of recovery as with other precious and platinum group metals by operating under reducing conditions. The high levels of metal recovery are also generally achieved whilst maintaining a significant degree of concentration from the input material to the output alloy, thereby enabling the operator to minimise downstream refining costs.

This insensitivity of recovery efficiency to specific metals provides DC plasma smelting with a key advantage and is one of the main reasons for its flexibility to process a wide range of feed materials. This is in contrast to a cyanidation-based approach, where the presence of PGM elements alongside gold and silver is likely to lead to increased difficulties with extracting maximum value from the ore. It is probable, therefore, that pyrometallurgical techniques such as DC plasma smelting will be especially useful for ores that contain precious and platinum group metals in combination. Note that whilst DC plasma smelting is suitable for S-containing materials, the elevated levels of S present in the concentrates of many double refractory ores makes it advisable to roast the concentrate prior to smelting in many cases.

It is also worth noting that these results in Table 1 are taken from materials with widely differing bulk compositions from 100% alumina to alumina-silica and alumina-silica-magnesia based materials. This illustrates the ability of DC plasma smelting to: (a) produce a sufficiently fluid slag to allow the efficient recovery of valuable metals, and (b) to create ideal conditions for good slag/metal separation, regardless of the bulk composition or mineralogy of the base material. Consequently, it seems likely that DC plasma smelting will be applicable where the precious metals are released more effectively by melting of the ore than by other non-melting methods.

Table 1. Recovery rates for DC plasma smelting by element

	Feed (ppm)	Collector Metal (ppm)	Slag (ppm)	Recovery Rate (%)
Pt	716	6,000	12.9	98.0%
Pt	1,194	16,997	15.3	98.7%
Pt	4,167	9,911	25.8	98.7%
Pd	1,003	13,537	9.1	99.1%
Pd	3,406	13,500	14.1	99.5%
Pd	8,498	19,444	48.9	98.9%
Rh	217	3,439	2.3	98.9%
Rh	1,175	2,233	3.1	99.5%
Re	2,240	9,220	10.6	98.8%
Ru	2,240	11,500	15.7	98.3%
Ru	16,410	56,820	95.0	99.7%
Au	214	680	0.2	99.9%
Au	109	773	4.9	99.5%
Ag	251	1,403	12.5	99.5%
Ag	36,639	68,773	172.9	99.7%

Recovery of Precious Metals Using Conventional Processes

One typical conventional process for the recovery of precious metals from refractory ores is summarised in this paper with the intention of setting up a baseline for cost comparison against the DC Plasma smelting. This conventional approach normally involves milling and concentration (e.g. flotation), followed by oxidation of the concentrate product and cyanidation. The precious metals are dissolved into cyanide and recovered into activated carbon during the Carbon in Leach (CIL) process. The carbon will then be pressure stripped with a hot caustic solution to re-dissolve the precious metals into a high-grade pregnant solution, which will then be treated by conventional electrowinning and smelting, in order to produce gold doré bars. The CIL tailings will be discharged after the destruction of cyanide below acceptable levels (Nicholson & Oti-Atakorah, 1993; Altman & McTavish, 2002).

The oxidation can be achieved by one of the main commercially available technologies (e.g. Roasting, Pressure Oxidation, BIOX, Albion Process). Each oxidation method has its merits and limitations but the optimal process for a project will be selected based on the analysis of metallurgical test work results and engineering trade-off studies. In this paper, roasting has been selected as the oxidation method in order to be consistent with the first stages of the DC plasma smelting approach.

OPERATING REQUIREMENTS & COSTS

As laid out above, in circumstances where the costs and recovery efficiencies of conventional extraction techniques are less favourable, alternative methods of extraction may be able to offer a better overall solution. Ultimately, however, the choice to use one technique over another will be based on a balance between the operating costs versus the recovery of metal value that can be achieved. The following information seeks to provide an illustration of these factors for an extraction route based on DC plasma smelting and the more conventional process route outlined above, consisting of CIL followed by Pressure Zadra elution, electrowinning and refining and Inco/SO₂ method of Cyanide destruction.

For the purposes of this illustration, a number of assumptions have been made in order to provide a basis for the process modelling exercise. These assumptions include the following:

- The ore being processed is double refractory in nature and has a sulphur and carbon content that requires it to be roasted as part of a conventional processing route.
- The head grade of the ore is 10 g Au per tonne.

- The concentration and roasting steps lead to a 10-fold reduction in mass and achieve an overall 90% recovery of Au to the concentrate, giving 90 g Au per tonne in the concentrate.
- The production rate of ore is 1000 t per day, i.e. c.330,000 tpa.
- The roasted ore concentrate has a composition as shown in Table 2.
- The DC plasma smelting process route is as shown in Figure 2.

Based on these assumptions, the operating requirements and main process outputs for the DC smelting process and the conventional CIL process are shown in Table 3 and Table 4 respectively.

A number of assumptions have been made in order to provide a basis for the process modelling exercise. These assumptions include the following:

- Unit costs have been based on typical values found in a North American context, including:
 - Electricity: \$ 0.06 per kWh
 - Labour: \$ 25 per man hour
 - Burnt lime: \$100 per tonne
 - Sodium Cyanide: \$ 2,800 per tonne
 - Sodium Metabisulphite: \$ 450 per tonne
 - Copper Sulphate: \$ 2,600 per tonne
 - Sodium Hydroxide: \$ 880 per tonne
 - Hydrochloric acid: \$ 0.37 per litre
 - Activated Carbon: \$ 2,170 per tonne
 - Smelting Fluxes: \$ 2,000 per tonne
 - Diesel: \$ 0.60 per litre.
- Gold metal price: \$1245 per oz Au; \$40.03 per g Au.
- The consumptions of reagents for the CIL process are based on typical values from similar projects.

Table 2. Composition of roasted ore concentrate assumed for cost and process modelling

Species	wt%
Moisture	2.5%
C	0.44%
S	5.0%
Na ₂ O	1.7%
MgO	2.9%
Al ₂ O ₃	13.2%
SiO ₂	59.8%
P ₂ O ₅	0.21%
K ₂ O	1.6%
CaO	2.1%
Fe ₂ O ₃	7.6%
As	0.003%
Au	0.0090%

Table 3. Main operating requirements and process outputs for DC plasma smelting of gold concentrate

Inputs	Unit	Qty per tonne concentrate
Electricity (plasma)	kWh	1,179
Electricity (auxiliary)	kWh	70
Nitrogen (plasma gas, purges)	Nm ³	6.0
Graphite (plasma electrode)	kg	2.4
Burnt lime (flux)	kg	296
Copper (collector metal)	kg	50
Natural gas (combustion chamber, metal ladle, etc.)	kWh	80
Labour (3 per shift, 1 manager)	man.hour	0.9
Hydrated lime (acid gas scrubbing)	kg	148

Outputs	Unit	Qty per tonne concentrate
Collector metal (c.1760 ppm Au)	kg	50
Slag (c.1.5 ppm Au)	kg	798
Emissions to air (stack gases)	Nm ³	3,500
Water cooling losses from furnace	kW	3,139

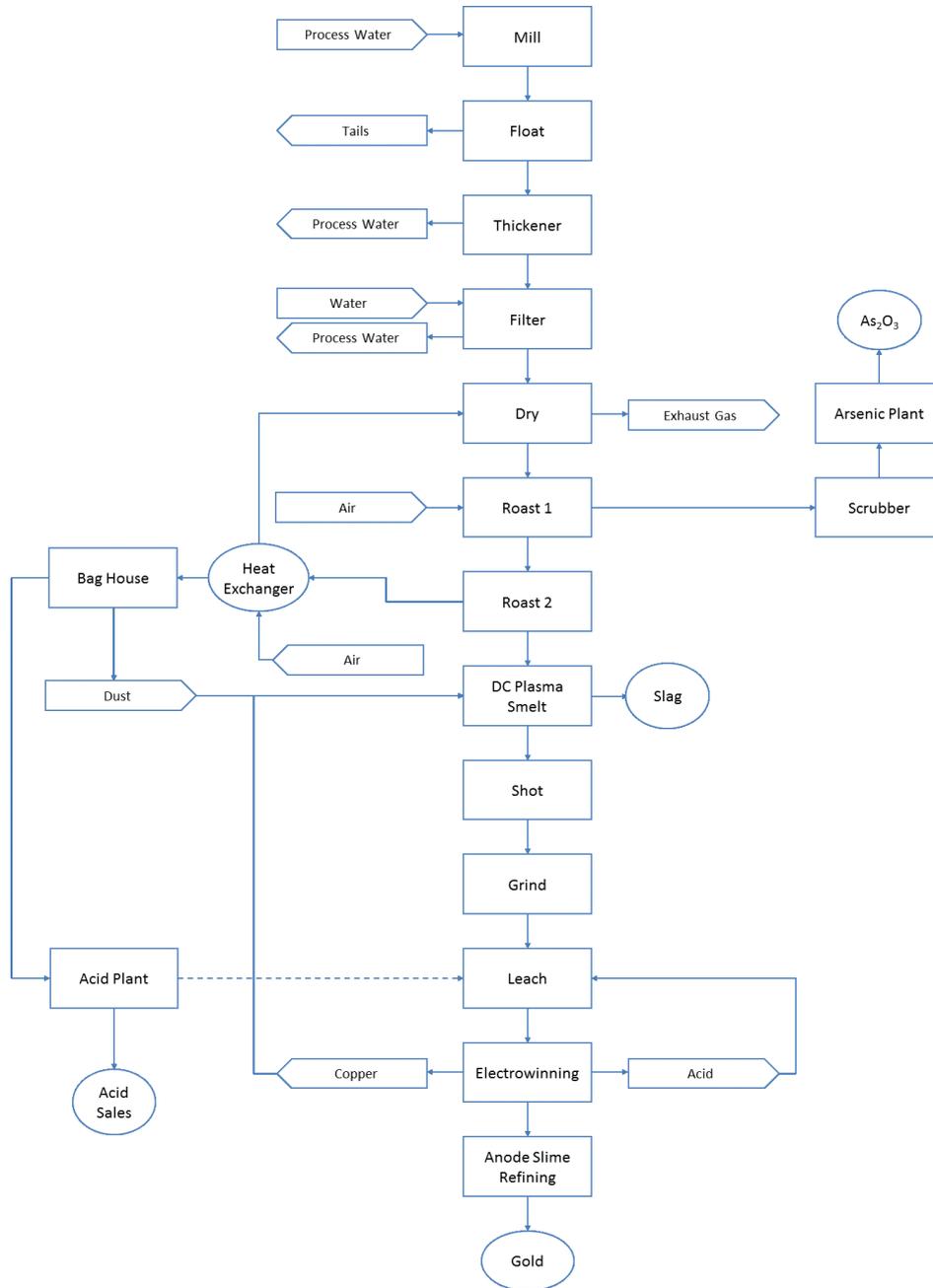


Figure 2. Block flow diagram of roast and DC plasma smelting process route

Based on these assumptions, the operating costs and Au yield for the DC smelting process and the conventional CIL process are shown in Table 5 and Table 6 respectively.

Table 4. Main operating requirements and process outputs for the conventional CIL process

Consumables	Unit	Qty per tonne of Concentrate
Cyanide - Leaching	kg	10
Lime - pH modification	kg	10
Sodium Metabisulphite	kg	6
Copper Sulphate	kg	4
Lime - CN Detoxification	kg	5
Cyanide - Stripping	kg	0.05
Sodium Hydroxide	kg	0.15
Hydrochloric Acid	litre	1.5
Activated Carbon	kg	0.3
Fluxes	kg	0.06
Diesel - Furnaces	litre	3.33
Electricity	kWh	24
Labour	man hour	0.32
Products	Unit	Qty per tonne of Concentrate
Gold Dore Bar (90% Au)	Oz	2.50

Table 5. Operating costs and Au yield for the DC smelting process

Item	Au Recovery through stage	Au Retained (g/tonne ore)	Costs (\$/t concentrate)	Costs (\$/oz Au produced)
Concentration & Roasting				
Concentration			60*	21
Roasting			50*	18
Sub-Total	90.0%	9.00	110	39
DC Plasma Smelting & Refining				
DC Plasma Smelting	99.0%	8.91	153	54
Refining	99.0%	8.82	13	4
Sub-Total			166	59
Overall				
Total			276	97

Table 6. Operating costs and Au yield for conventional CIL process

Item	Au Recovery through stage	Au Retained (g/t of ore)	Costs (\$/t concentrate)	Costs (\$/Oz Au produced)
Milling, Flotation & Roasting				
Milling & Flotation			60*	21
Roasting			50*	18
Sub- Total	90.0%	9.00	110	39
Carbon in Leach, Stripping & Refining				
Carbon in Leach	90.0%	8.10		
Stripping, Electrowinning & Refining	99.9%	8.09	58	20
Total			168	59

* Assumed order of magnitude cost for comparison purposes only

A summary of conceptual overall economic comparison of DC plasma smelting and conventional CIL process is shown in Table 7. Note that the higher capital cost of typical smelting equipment compared with conventional hydrometallurgical equipment has been reflected in a higher allowance for capital cost amortisation.

Table 7. Conceptual economic comparison

Description	Unit	DC Plasma	CIL	Difference Plasma - CIL
Gold head grade	g/t	10	10	-
Throughput of ore	t/y	330,000	330,000	-
Throughput of concentrate	t/y	33,000	33,000	-
Overall Recovery	%	88.2%	80.9%	7.3%
Gold Production	Oz/y	93,587	85,853	7,734
Revenue	Million \$/y	116.52	106.89	9.63
Operating Cost	Million \$/y	9.11	5.54	3.57
Capital Cost Amortization	Million \$/y	1.50	0.30	1.20
Overall Value Realized	Million \$/y	105.90	101.04	4.86

The operating cost and Au yield illustrations shown in Table 5 and Table 6 and the summary presented in Table 7 show that the operating cost and capital cost of the DC plasma smelting-based route is higher than that of the more conventional processing route. However, the data in Table 7 indicate the DC plasma smelting route has the potential to recover an extra 7,734 Oz of extra gold each year and that this extra value recovered more than makes up for the increased costs in this case. Consequently, it results in a higher overall margin of Au value over operating costs for the DC plasma smelting route and thus to significantly higher annual revenues, amounting to approximately \$4.86 million extra revenue per year.

The overall balance of costs and revenues is highly dependent of course on the working assumptions behind the model. The operating cost of the DC plasma smelting solution is especially dependent on the cost of power, with just under half the operating cost in the modelling exercise above being in the form of electricity. It is likely, therefore, that the DC plasma smelting option will be more favoured in locations where electrical power is relatively cheap.

It should be noted that smelting costs are directly related to the mass of concentrate being treated and thus a higher precious metal content in the concentrate will lead to a lower operating cost per ounce of gold produced. Accordingly, a DC plasma smelting route will tend to be increasingly favourable with higher precious metal levels in the concentrate.

CONCLUSIONS

DC plasma smelting offers an alternative method for the extraction of gold and other precious and platinum group metals from refractory and 'difficult' ores in circumstances where more conventional extraction methods lead to low recovery rates and high operating costs.

The main factors leading to this set of circumstances include those ores displaying refractory or double refractory behaviour, as a result of sulphide-based, carbon-containing and/or silica-based encapsulation mineralogies. The presence of mixed precious metals and platinum group metals in the same ore is an additional factor that would tend to favour DC plasma smelting, where the overall recovery efficiency may be compromised by the less amenable elements within the structure. Inevitably, the higher electrical power used in the DC smelting route will tend to favour locations in which electrical power is relatively inexpensive, whereas higher precious metal levels in the concentrate will tend to favour a DC plasma smelting route as a result of reducing the smelting costs per ounce of gold produced.

In these circumstances, DC plasma smelting, with its well-established ability of to recover precious metals and platinum group metals with equal efficiency and its suitability for a wide range of base material compositions, provides an attractive alternative route to existing conventional methods for maximising the extraction of value from unconventional ores.

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