

Presidential Address: How the MacArthur-Forrest cyanidation process ensured South Africa's golden future

by C.E. FIVAZ*



SYNOPSIS

Tribute is paid to J.S. MacArthur and the Forrest brothers for their invention. The opinion is expressed that the successful application of their process, not only saved the gold-mining industry on the Witwatersrand from stagnation for an indefinite but probably prolonged period, but also made a major contribution to the economic growth of the country in the twentieth century. A background is given of the activities of prominent chemists who researched the solubility of gold in cyanide solution prior to the MacArthur-Forrest invention.

An account is given of the invention and patenting of the cyanidation process, and of the golden rule that the patentees laid down for themselves, which came close to wrecking the invention.

The South African gold-mining scene from the discovery of gold on the Witwatersrand in 1886 up to 1890 is sketched. An account is given of how, when unoxidized ores were first encountered, the recovery efficiency dropped alarmingly, gold shares were sold on an unprecedented scale, and doom and despondency seized the town of Johannesburg.

The complete turnabout in the fortunes of the South African gold-mining industry after the introduction of the cyanidation process in 1890, the steady rate of increase in production after the Anglo-Boer War, and its effect on the South African economy are described. A brief look is taken at the effect of gold mining on secondary industry.

The department of the gold that is not dissolved from the ore by the cyanidation process is illustrated. Some thoughts are expressed on what can be done to increase the gold recovered by cyanidation.

SAMEVATTING

Daar word aan J.S. MacArthur en die Forrest-broers hulde gebring vir hul uitvinding. Die mening word uitgespreek dat die geslaagde toepassing van hul proses nie alleen die goudmynbedryf aan die Witwatersrand van stagnasie vir 'n onbepaalde maar waarskynlik langdurige tydperk gered het nie, maar ook 'n belangrike bydrae tot die ekonomiese groei van die land gedurende die twintigste eeu gelewer het. Die agtergrond van die bedrywighede van vooraanstaande skeikundiges wat voor die MacArthur-Forrest uitvinding navorsing in verband met die oplosbaarheid van goud in sianiedoplossing gedoen het, word geskets.

Daarna volg 'n beskrywing van die uitvinding en patentering van die sianiedproses, en van die goue reël wat die patenthouers vir hulself voorgeskryf het en wat byna die uitvinding verongeluk het.

Die Suid-Afrikaanse goudmynopset vanaf die ontdekking van goud aan die Witwatersrand in 1886 tot 1890 word geskets. Daar word beskryf hoe die herwinningsdoeltreffendheid onrusbarend gedaal het, goudaandele op 'n ongekende skaal verkoop is, en 'n gevoel van verlorenheid en neerslagtigheid op Johannesburg neergesak het toe ongeoksideerde erts die eerste maal teëgekomp is.

Daarna word die algehele omkeer in die lotgevalle van die Suid-Afrikaanse goudmynbedryf na die invoering van die sianiedproses in 1890, die bestendige toename in produksie na die Anglo-Boereoorlog en die uitwerking daarvan op die Suid-Afrikaanse ekonomie beskryf. Vervolgens word daar kortliks gekyk na die uitwerking van die goudmynbedryf op die sekondêre nywerhede.

Die gedrag van die goud wat nie deur die sianiedproses uit die erts opgelos word nie, word geïllustreer. Dan word daar 'n paar gedagtes uitgespreek oor wat gedoen kan word om die hoeveelheid goud wat deur die sianiedproses herwin word, te verhoog.

Introduction

Before assuming office, an incoming president has to select a subject for his Presidential Address. In this respect, I am probably fortunate since the year 1988 marks the centenary of the filing, by J.S. MacArthur, R.W. Forrest, and W. Forrest, of the complete patent specification on 'Improvements in obtaining gold and silver from ores and other compounds'—British Patent No. 14174. The patent was granted on 10th August, 1888, a century and one week ago today.

The provisional patent was applied for on 19th Oc-

tober, 1887, but this did not contain the all-important and less-general claim that dilute, as opposed to concentrated, cyanide solutions should be used since these selectively dissolved gold and silver from the ore in preference to base metals. An application for a patent dealing with cyanidation and having substantially the same wording as that contained in the complete specification of British Patent No. 14174 was filed in the South African Republic, and Patent No. 47 was granted and signed by S.J.P. Kruger, State President, on 28th November, 1888. A second patent, No. 74, dealing with zinc precipitation was granted in 1889.

The success of the first large-scale metallurgical experiments using the process on ore from the New Zealand Crown Mine dates back to June and July 1888¹.

* Metallurgical Consultant, Chamber of Mines Research Organization and Chamber of Mines of South Africa, P.O. Box 91230, Auckland Park, 2092 Transvaal.

© The South African Institute of Mining and Metallurgy, 1988. SA ISSN 0038-223 X/\$3.00 + 0.00.

It therefore seemed appropriate to address you on the topic of cyanidation this afternoon. I shall attempt to do it in a way that will be of interest to the many disciplines that are represented in our Institute. The form of the address will differ from that of my predecessors since it is also intended as a tribute to J.S. MacArthur and R.W. and W. Forrest: the successful application of their process not only saved the gold-mining industry on the Witwatersrand from stagnation for an indefinite but probably prolonged period², but also made a major contribution to the economic growth of the country in the twentieth century.

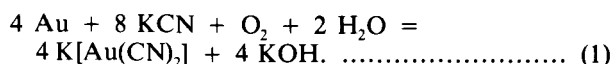
At the outset, I wish to state that I make no apology for quoting freely, particularly from MacArthur, who was directly involved, and from Cartwright, who gives an inimitable account of the early years; any version of mine would not depict the situation as brilliantly as they did.

Background

As early as 1783, Scheele³ knew that metallic gold is soluble in potassium cyanide, and a number of eminent chemists studied the dissolution reaction in the nineteenth century.

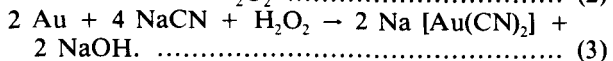
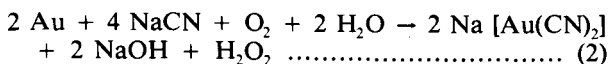
Dr Wright in Birmingham, England, used gold cyanide solution for electroplating in 1840; this was done as a consequence of his studies of Scheele's report on the solubility of gold in a potassium cyanide solution. J.R. and H. Elkington patented Wright's invention. Bagration⁴, who alludes to Elkington's process, preserved potassium cyanide solution in a gilded dish. He observed that, after several days, the whole gold surface on the inside had been attacked. He then experimented with finely divided gold under the influence of a galvanic current, but soon recognized that this did not have any beneficial effect on the dissolution process. His further studies concerned the solubility of gold plates in cyanide solution, which showed that gold in this form dissolved at a considerable rate at a temperature of 30 to 40°C. He also noticed the influence of air on the reaction.

In 1844, Elsner⁵ stated that the dissolution of metals resulted from the action of oxygen, which, absorbed from the air, decomposed part of the cyanide. His reaction has been expressed by others (unnamed) in the following equation, which is generally called Elsner's equation:



Faraday⁶ later made use of the solubility of gold in cyanide solution for reducing the thickness of gold films. He contended that 'air voltaic circles' were formed, and that the gold dissolved almost exclusively under their influence.

Bodländer⁷ confirmed the contention that oxygen is necessary for the dissolution as claimed by Elsner and Faraday, and doubted by MacArthur. He discovered that hydrogen peroxide is formed as an intermediate product during the dissolution of gold, and therefore proposed the following equations for the dissolution reaction:



Later work by Habashi⁸ showed that equation (2) was the more important during leaching.

Although the action of cyanide solution on gold remained somewhat of a mystery for many more years, the basis of the modern process for the extraction of gold had been provided. It took many years, however, before the previously mentioned information was used for the extraction of gold from ores.

In 1867, J.H. Rae¹ took out United States patent No. 61866 for an 'improved method of treating auriferous and argentiferous ores' with a current of electricity in conjunction with suitable liquids such as potassium cyanide. He proposed to expose the auriferous or argentiferous rock to the combined action of a current of electricity and suitable solvents, and to separate the gold or silver from the ore by the action or aid of electricity. The principle of Rae's process as stated by him distinguishes his method from the MacArthur-Forrest process, and it does not appear to have found extensive and successful practical application.

The application of potassium cyanide solution for the extraction of gold and silver directly from their ores, which had been neglected since Rae's work, was taken up again by J.W. Simpson eighteen years later¹. He obtained a United States patent, the essence of which related to the separation of gold and silver from their ores by 'subjecting the ore to the action of a solution of cyanide of potassium, carbonate of ammonia, and chloride of sodium, and subsequently precipitating the dissolved metals'. Simpson's patent appears to indicate that he had not discovered or realized the very important property of dilute cyanide solutions, namely that of dissolving, without the addition of other chemicals, the noble in preference to the base metals. As far as could be established, there is no record in the technical literature of the application of Simpson's process before the application and granting of the MacArthur-Forrest patents in 1887 and 1888.

The Invention of the MacArthur-Forrest Process

Although the literature does not state this in so many words, I feel that MacArthur was the prominent figure among the foursome who were involved in the work that led to the invention of the cyanidation process.

MacArthur was trained in practical chemistry and metallurgy in the Glasgow Laboratory of the Tharsis Sulphur & Copper Co., by which he was employed and which owned mines in the south of Spain. The ores were high in iron and sulphides, and contained less than 2 per cent copper, 0,025 oz of gold, and 1,0 oz of silver per ton of ore⁹. Among other assignments, he had to investigate various methods, devised by other investigators, for the extraction of gold from ores containing pyrite. None of these proved to be successful.

The Cassel Gold Extracting Co. was formed in Glasgow to develop a patented process for the extraction of gold from what were then termed 'refractory' ores⁹. This involved the electrolytic production of chlorine from weak brine solution in the presence of ground ore. In 1886, the inventor, Cassel, disposed of his interest and left the company in a state of chaos. MacArthur continued the work with the assistance of an electrician friend, who made his premises and facilities available for

the purpose. Although gold was extracted, MacArthur states that no information was available on the technical efficiency and cost of the process. The results of his work were published anonymously, but information about the identity of the author leaked out and, as a result, he was invited to discuss the matter with the Gold Extracting Co. (now devoid of its previous Cassel prefix). He declined.

At that point, MacArthur's friends, Robert W. and William Forrest, with a certain George Morton advised him to continue his research work and promised their co-operation and support. The four men formed a 'research syndicate', and Morton guaranteed MacArthur's salary in the event that his services with the Tharsis Company, by whom he was still employed, were discontinued. MacArthur⁹ states: 'We were certainly not capitalist, only a quartet of enthusiasts carrying out research in the evenings in a glory-hole under the consulting rooms of the two Forrests, both of whom were [medical] doctors. We did most of our work between 8 p.m. and 2 a.m. when the Forrests had finished their day's work, as I had finished mine. It was usual to have pies and a pot of tea sent in from the nearest restaurant about 11 p.m. and when we were more than usually sleepy Dr. Robert Forrest brought out a bottle of a weird mixture labelled "kid-reviver" and gave us a dose all round to keep us awake. . . . We worked hard and made plenty of mistakes, but kept on acquiring knowledge and gathering data.'

As a result of a close association between the two companies, MacArthur was transferred from the Tharsis Sulphur & Copper Co. to the Gold Extracting Co. as technical manager. It was a condition of his engagement that his new employers should have the first call on any invention resulting from the work of the MacArthur-Forrest research syndicate, but the Gold Extracting Co. assumed no responsibility for expenses unless it took over the invention if it ever did eventuate.

The Research Syndicate then took an important and decisive step that was to affect the destiny of gold recovery from 'refractory' ores. They decided not to use electricity. This was done mainly for two reasons. Firstly, MacArthur experienced serious problems when applying electric current to wet masses of ore and, secondly, the process using electricity was not uniformly successful on different types of ores. They also laid down a golden rule that 'we would not reckon gold extracted as the difference between the assay of the original ore and that of the tailing, but in every case the gold must be put on the table'.

They were aware of the fact that aqua regia dissolved gold but also knew of the problems associated with its use in the presence of pyrite minerals. Aqua regia was therefore never considered. They decided to set their sights on a simple solvent that would primarily attack gold in preference to base sulphides. Shortly after this decision was taken, during November 1886, they used potassium cyanide as a solvent and followed their rigid rule of 'putting the gold on the table'. They used hydrogen sulphide to precipitate any dissolved gold, forgetting that it does not precipitate gold.

The rigid rule of 'putting the gold on the table' almost led to disaster since they regarded as unsuccessful the experiment using potassium cyanide as a solvent for gold. Fortunately, it was their standard procedure to store samples of all the residues for possible future reference,

and so the residue from this experiment landed on the shelf with many others.

Almost a year later, in October 1887, MacArthur had occasion to separate gold from mercury in a cyanide solution. While the separation was being carried out, he recalled his cyanide trial eleven months before. Cyanide solution was again tried on several ores, and on these occasions the residues assayed showed that most of the gold had been extracted. MacArthur states: 'We then went to the shelf, selected the parcel of residue that had been sleeping there holding its secret for nearly a year, assayed it, and found no gold. Then followed the usual hurry and excitement of consultation with the patent agent, drafting of specifications, and the plunge into the sea of troubles that await the successful inventor.'⁹

Work up to that point had led to the filing of British patent No. 14174, the full text of which, for ease of reference, is given in the Addendum¹.

MacArthur⁹ himself appeared to see far less significance in the subject matter of their second patent, British patent No. 10223 of 14th July, 1888, which deals with the precipitation by zinc of gold from an aurocyanide solution. He knew that, if he could dissolve the gold, he could easily find a precipitant, and he had known for some time that zinc could precipitate gold from cyanide solutions. Zinc sheets were first used for this purpose, but the reaction was so slow as to be impracticable. Zinc sawdust produced by the milling of cakes of cast zinc was tried, but the results still did not satisfy MacArthur. He confided his problem to his foreman-mechanic, who 'made a thin shaving while using one of his tools; he then made a handful, brought them to me, and the thing was done'.

MacArthur⁹ concludes a section of the article written in 1916 by stating, 'The further history of cyanide in South Africa is a story still being told volume by volume as the years pass'.

The Gold-mining Scene 1886-1890

It is not my intention to dwell on the discovery of gold on the Witwatersrand, momentous and historic though it was, but rather to focus on the occurrence of gold and the means by which it was recovered from the ore at that time.

When milling started in 1886, the material being treated was obtained from surface mining. The recovery of gold from this oxidized or 'free-milling' ore was achieved entirely by amalgamation, which was conducted both inside stamp-mill mortar boxes and on external amalgam plates over which the minus-30-mesh pulp flowed². The extraction from this oxidized outcrop zone was between 75 and 80 per cent. Combined with the fact that, in several instances, the grades were of the order of ounces per ton, there was little incentive to attempt to improve the levels of extraction. It also appears that the operators in South Africa were unaware of the MacArthur-Forrest cyanidation process until about 1890.

Mining was flourishing. In 1887 E.P. Mathers published a list of the registered owners of mining leases on proclaimed farms on which the Main Reef outcrop had been traced between Roodepoort and Driekop¹⁰. The list contained twenty mining leases covering an area of approximately 2137 morgen, which varied in size from 12 to 450

morgen. The list contained a further seventeen unregistered mining leases totalling a further approximately 2974 morgen ranging from 46 to 700 morgen in size. Cartwright¹⁰ states that 'It would take . . . ten years hard work to record all the changing of hands of the various claims that took place, the hundreds of purchases that were made by syndicates and the gradual shaping of the pattern that led to the rise of the big gold mining companies. But as an example of what happened in those days it is of interest to trace (with the assistance of Gray's researches) the history of Claim No. 19, the original discoverer's claim awarded to George Harrison. Harrison sold it to F.W. Marsden for £10 on 16th November, 1886. Three months later, Marsden sold it to Alfred Hepple for £50. From Hepple it passed to the Little Treasure Gold Mining Co. for £1500 and shares to the value of £150. On 30th September, 1887, the Little Treasure Company sold it to the Northey Gold Mining & Exploration Company for £2000 in cash and £5000 in shares'—a 700-fold increase in less than eleven months. Such were the good fortunes until 1890.

But it was not all smooth sailing. The first disaster came in 1890. The cuttings and primitive shafts had reached depths where a new type of banket ore containing gold, copper, lead, iron, and zinc sulphides was encountered, and recovery by the amalgamation process dropped disastrously. At that time, a recovery by amalgamation of 65 to 70 per cent was considered satisfactory.

When the pyritic ore was first encountered, the recovery efficiency dropped alarmingly to below 50 per cent. According to Cartwright¹⁰, 'This meant a drop in the returns of about 30s a ton, and at that rate there was clearly no future for mines that were not drawing ore from the rich Main Reef Leader'.

Doom and despondency seized the town of Johannesburg, where just about all the inhabitants were dependent on the prosperity of the mines. Gold shares were sold on an unprecedented scale, companies crashed, and mines closed down. Shares could not be sold for 5 per cent of their previous value. 'The brokers in desperation offered parcels of thousands of shares'. Sir Percy Fitzpatrick is quoted by Cartwright¹⁰ as having said 'Grass will grow in the streets of Johannesburg within a year'. So much for the despondency.

The Gold-mining Scene after 1890

As mentioned previously, J.S. MacArthur⁹, while researching the cyanidation process referred to in the patents mentioned earlier, was transferred to the Gold Extracting Co. Before the end of 1888, the Gold Extraction Co. had sent expeditions to Queensland and New Zealand while MacArthur went to America. Soon afterwards Allan James was despatched as a scout and pioneer to South Africa. At that time, Barberton was waning, and Johannesburg, only three years old, was asserting itself as the centre of the gold industry. After a few months, James reported that there was a good potential for the cyanidation process and that a small syndicate, later called the Gold Recovery Syndicate, was ready to take up the process of the Gold Extracting Co. and would prove it on the spot. A great demonstration was arranged for the following year. James and a number of 'mechanics' accompanied the plant on its way to the Salisbury

Mine. When the plant had been erected in May 1890, MacArthur followed and supervised the demonstration. According to MacArthur, several types of ore and tailings were tested with successful results. A large group of metallurgists and engineers attended the testwork at the Salisbury Mine to 'assist' in the demonstration. Among those present was one Hennin Jennings, later to be elected President of the Institution of Mining and Metallurgy. At the beginning, Jennings made it clear that he was there to watch and to check everything and everybody, especially MacArthur. However, it turned out to be the start of a lasting friendship. MacArthur⁹ states, 'I was fortunate in having such a man to investigate our process . . . It was a fitting and happy coincidence that in 1903, he, as President of the Institution of Mining and Metallurgy, should hand out the medal of the Institution on the occasion of its first award'.

Cartwright¹⁰ also mentions the fact that the MacArthur-Forrest demonstrations showed that they could treat pyritic ore, free-milling concentrates, residues, and tailings with equal success, and that the extraction varied from 85 to 90 per cent. In this regard, Adamson² states that the overall recovery by amalgamation and cyanidation was nearly 90 per cent, and 'hence the efficiency of the combined methods of extraction was firmly established'.

The testwork had been carried out on what I consider would have been called pilot-plant scale in today's terminology: 70 000 pounds of material had been treated in three months. The successful demonstration of the process gave the Robinson Gold Mining Co. sufficient confidence to enter into an agreement with the Gold Recovery Co., signed on 23rd November, 1890, by which the latter company undertook to treat 10 000 tons of tailings on a royalty basis. The royalty was based on the assay value of the tailings, and it was part of the agreement that tailings assaying 8 dwt per ton or less were not to be paid for. Cartwright¹⁰ could not refrain from remarking: 'Those were the days!'. I can only agree. (The royalty payable in South Africa for the use of the MacArthur-Forrest patents was stated by Scheidel¹ in 1894 to be US\$ 1,25 per standard ounce of gold (22 carat), which is equivalent to US\$ 1,36 per fine ounce.)

Despite some commissioning problems, which are not unknown by today's metallurgists and engineers, 6000 ounces of gold were recovered from the 10 000 tons of tailings¹⁰. These 6000 ounces would previously have reported to waste since there was no known method for the treatment of tailings.

'The news that the cyanide process could not only deal with the pyritic ore but also extract the "lost gold" in the dumps was all that was required to restore confidence in the Rand and start another immense boom in shares'¹⁰.

Cartwright¹⁰ records that Eckstein's firm immediately began to acquire large blocks of land south of the best outcrop mines. 'Thus began the first "deep levels" boom with the Corner House well ahead of everybody else and Consolidated Gold Fields second in the running. Within twelve months of the first deep level boom all the ground south of the outcrop was pegged to a depth of three miles. There was no lack of capital for the new mines. The banking houses of Europe now regarded them as an invest-

ment that could be recommended to clients who were prepared to risk their money for big profits.'

Several mine owners and mining engineers began to calculate the potential value of the 'deep level' claims they held. 'Finally', states Cartwright¹⁰, 'John Hays Hammond, at that time the most eminent of all mining engineers, who had been engaged by Rhodes as consulting engineer to the gold fields of South Africa, capped every other testimonial by declaring that he saw no reason why the mines should not be worked to a depth of 5000 feet and prophesied that before the turn of the century the value of the annual output would exceed £20 000 000.' As the total annual output of the gold mines of the world at that time was not much more than £20 000 000, it can be imagined what a sensation this caused¹.

In my view, the following is the most momentous statement made by Cartwright¹⁰: 'Deep level mining, and the knowledge that the Rand Mines might live for years and produce prodigious quantities of gold, shaped the destiny of South Africa'. The connotation that was given to 'deep level' mining at that time as opposed to what the term means today gives even more weight to Cartwright's statement.

At the risk of repeating myself or stating the obvious, this complete turnabout in the fortunes of the South African gold-mining industry could be attributed almost entirely to the invention of the MacArthur-Forrest cyanidation process. The invention could not have come about at a more opportune time, only two years after the discovery of gold on the Witwatersrand. It is remarkable to note that 100 years later it is still being used with only minor modifications.

Validity of the Patents

As indicated earlier, the royalty payable in South Africa for the use of the MacArthur-Forrest patents was US\$ 1,36 per fine ounce of gold produced. In November 1892, the Chamber of Mines began negotiations with the African Gold Recovery Co., which held the two South African patents (numbers 47 and 74) covering the MacArthur-Forrest cyanidation process, in an attempt to obtain a reduction in what were regarded as excessive demands^{2,11}. When no positive results were forthcoming after four months, the Chamber decided to contest the validity of the patents before the High Court. President Kruger appears to have facilitated delays, which resulted in the case at last coming before the Supreme Court in Pretoria on 17th February, 1896. Judgement in the case was given in favour of the Chamber of Mines on 5th November, 1896, on the grounds that gold had 'earlier, in 1885, been extracted from ore samples by a solution of potassium cyanide after which it had been precipitated on zinc plates. MacArthur's subsequent use of potassium cyanide on a production scale, even with exceptionally dilute solutions, and zinc in the form of shavings could not therefore be regarded as invention'.² The MacArthur patents were cancelled.

Considering the very substantial impact that the MacArthur-Forrest invention made on the gold-mining industry, it is ironical that the inventors gained relatively little financial reward during the six years that their patents were valid on the Witwatersrand. Although the following is obviously not a businesslike statement from

a gold producer's point of view, a monument in honour of the inventors would perhaps have been more fitting.

Gold Production from 1884-1986 and Its Effect on the Economy

To illustrate a number of important points, I give some information about gold production¹² separately for the early years from 1884 to 1900 and then from 1901 to 1986. Table I and Fig. 1 reflect the tonnage treated and the gold production for the first period, while Fig. 2 gives the same information for the second period.

TABLE I
ORE TREATED* AND GOLD PRODUCED IN SOUTH AFRICA DURING THE PERIOD 1884 TO 1900

Year	Fine gold produced kg	Year	Ore treated t × 10 ⁶	Fine gold produced kg
1884	74	1893	2,010	40 130
1885	44	1894	2,568	56 142
1886	254	1895	3,136	62 758
1887	1 240	1896	3,639	63 005
1888	7 084	1897	4,831	85 336
1889	10 915	1898	6,651	118 923
1890	13 690	1899	6,023	113 151
1891	21 413	1900	*	10 852
1892	33 251			

* Figures are not available for the tonnage of ore treated in 1884 to 1892 and in 1900

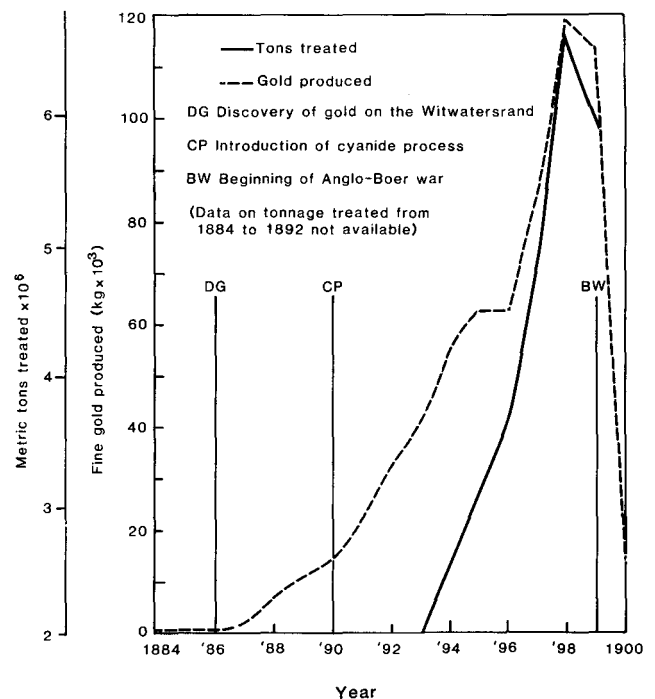


Fig. 1—Ore treated and gold produced in South Africa during the period 1884 to 1900 (based on a table published by the Chamber of Mines¹²)

From Fig. 1 and Table I it is evident that the gold produced increased rapidly after the discovery of gold on the Witwatersrand in 1886. (Information about the tonnage treated is not available until 1893.) However, the rate of increase in production shows a downward trend between

1887 and 1890. This could be indicative of increasing problems with the recovery of gold from the ore below the outcrop, i.e. the amalgamation process was becoming less effective as unoxidized ore had to be treated. From late 1890, when the cyanidation process was first introduced, until 1898, the year before the outbreak of the Anglo-Boer War, the downward trend in the rate of increase in production was reversed. The lower production in 1899 than in 1898 shows the effects of the beginning of the war, while the catastrophic decrease in gold production in 1900 to a level equal to that achieved in 1889 reflects the effect of the war in full swing.

From Table I it is of interest to note that, if 1890, the effective date of the introduction of the cyanidation process, is taken as the baseline, the gold production increased 4,58 times by 1895 and 8,69 times by 1898—phenomenal growth, indeed, by any standard. Naturally, this increase was due, not only to the use of the combined process of amalgamation and cyanidation with its accompanying higher levels of gold extraction than were attainable with amalgamation alone, but also to the increased tonnages treated. Unfortunately, a direct comparison of the rates of increase in tonnages treated and gold production over the 1890 figures is not possible since the annual tonnages treated are not available until 1893. However, with 1893 as the baseline, it can be shown that, between 1893 and 1898, the tonnage treated increased 3,31 times while the gold production increased 2,96 times. It can only be speculated that this difference may be due to a drop in the grade of the ore mined, since the recovery efficiency during that period is not likely to have decreased by as much as almost 12 per cent.

It is evident from Fig. 2 that there was a steady rate of increase in the tonnage treated from 1901 to 1986, except for downward trends in the rate of increase coinciding with the First World War, the miners' strike, and the Second World War^{12,13}. Gold production showed a similar trend until it reached a peak of 1 000 417 kg in 1970, after which it started declining and stood at a level of 638 047 kg in 1986.

Table II sets out the gold produced in the Witwatersrand Triad for 1986. It can be seen that the forty-six mines treating current ore were responsible for about 68 per cent of the 161 million tons of ore and tailings treated during 1986. Also, 82,7 per cent of the gold produced in the Witwatersrand Triad originated from the West Wits Line, and the Klerksdorp and Orange Free State areas.

The total gold produced by the mines in the Witwatersrand Triad amounted to 628 675 kg, compared with a total South African gold production¹⁴ of 638 047 kg during 1986. This represents 39,2 per cent of the total world production, with a total sales value of R17,283 billion.

Worrall¹⁵ stated in 1971 that, despite the two wars and the worldwide economic depression of the early 1930s, the South African economy over the previous sixty years had expanded at an average rate of about 5 per cent per annum. The role of gold in sustaining the expansion rate was, however, unlikely to remain at the same level.

The role of mining expressed in terms of its contribution to the gross domestic product (GDP) is shown in Table III for selected years during the period 1950 to 1987. The data indicate that the contribution to the GDP

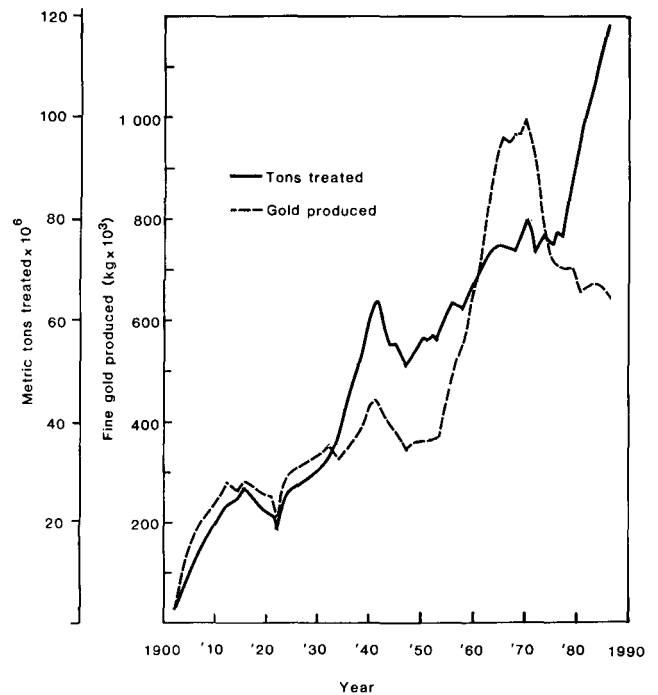


Fig. 2—Tonnage treated and gold produced in South Africa during the period 1901 to 1986 (based on a table published by the Chamber of Mines¹²)

TABLE II
GOLD PRODUCED IN THE WITWATERSRAND TRIAD FOR 1986¹⁴

Gold field	Number of		Ore milled kt	Tailings treated kt	Gold produced kg
	Operating mines	Retreatment plants			
Evander	4	0	6 752	0	32 679
East Rand	8	5	6 014	23 608	30 172
Central Rand	7	5	2 493	9 015	12 866
West Rand	4	4	9 279	735	33 304
West Wits Line	11	0	27 672	0	198 037
Klerksdorp	5	1	19 278	2 629	143 479
Orange Free State	7	1	37 892	15 613	178 138
Total	46	16	109 380	51 600	628 675

by gold mining fell from 9,4 per cent in 1950 to 5,7 per cent in 1970, but rose to a high of 16,3 per cent in 1980 and then again fell to 8,8 per cent in 1987.

It is noteworthy that, during the period 1976 to 1985, gold mining contributed a low of 34,4 per cent in 1977, a high of 52,4 per cent in 1980, and 42,3 per cent in 1985 to South Africa's exports and re-exports of merchandise (Exports-*ISIC* basis)¹⁶.

The Effect of Gold Mining on Secondary Industry

I believe it fair to state that the gold-mining industry in South Africa is the flywheel for a large part of the secondary industry. I also believe that, in the context of this address, it would be appropriate to refer to the cyanide industry and to use it to illustrate the multiplying effect of a unit process within the mining industry

TABLE III

CONTRIBUTION OF MINING TO THE GROSS DOMESTIC PRODUCT OF SOUTH AFRICA, EXCLUDING SOUTH WEST AFRICA/NAMIBIA AT CURRENT PRICES, 1950-1987 (SELECTED YEARS)¹⁶

Year	Total GDP R million	Contribution of mining to GDP, %		
		Gold	Other	Total
1950	2 494,0	9,4	3,4	12,8
1955	3 699,0	8,4	3,1	11,5
1960	4 838,0	10,1	3,1	13,2
1965	7 252,6	8,3	3,2	11,5
1970	11 610,0	5,7	3,8	9,5
1975	25 182,0	8,2	3,3	11,5
1980	57 817,0	16,3	5,9	22,2
1985	109 604,0	10,7	5,1	15,8
1987	151 084,0	8,8	4,7	13,5

on the economy of the country.

Until 1937 cyanide was imported from Europe and Canada^{17,18}. In that year, a pilot plant was erected by one of the two companies who together manufacture the cyanide requirements of the gold-mining industry. The year 1937 also marked the establishment of the second cyanide-manufacturing company.

Of the numerous processes available worldwide for the production of cyanide, three are used in South Africa.

- (i) In the Shawinigan process, ammonia and methane are reacted at 1600°C to produce hydrogen cyanide, which, in turn, is absorbed in caustic soda or lime to produce sodium or calcium cyanide respectively.
- (ii) The Andrussow process is similar to the Shawinigan process, but incorporates a platinum-based catalyst and the reaction takes place at 900°C. The hydrogen cyanide is absorbed as in (i).
- (iii) A proprietary process produces solid calcium cyanide from calcium cyanamide. The raw material for this process is calcium carbide, which is produced from anthracite and lime. The calcium carbide is reacted with nitrogen at high temperature using an electric arc to produce calcium cyanamide, which, in turn, is reacted with sodium chloride to produce solid calcium cyanide.

Between them the two producing companies operate four cyanide plants, which produce liquid calcium and sodium cyanide, and solid calcium cyanide.

Fig. 3^{12,17,18} gives a comparison of the tonnages of ore treated for gold recovery, together with the cyanide production from 1938 to 1987. Although one of the cyanide companies started production as early as 1938, the production data for one of the other plants until 1973 had to be estimated since actual data are not available.

It can be calculated from the information in Fig. 3 that, even after 1973, the ratio of cyanide production to tonnage treated was steadily increasing. Although I have not attempted to explain this phenomenon quantitatively, I believe that the increase in cyanide production in South Africa has kept pace with the increasing tonnages being treated over the years. This serves to illustrate that the growth in the gold-mining industry was passed on to the cyanide industry and also, undoubtedly, further down the line, leading to and playing its part in the growth of the economy of the country.

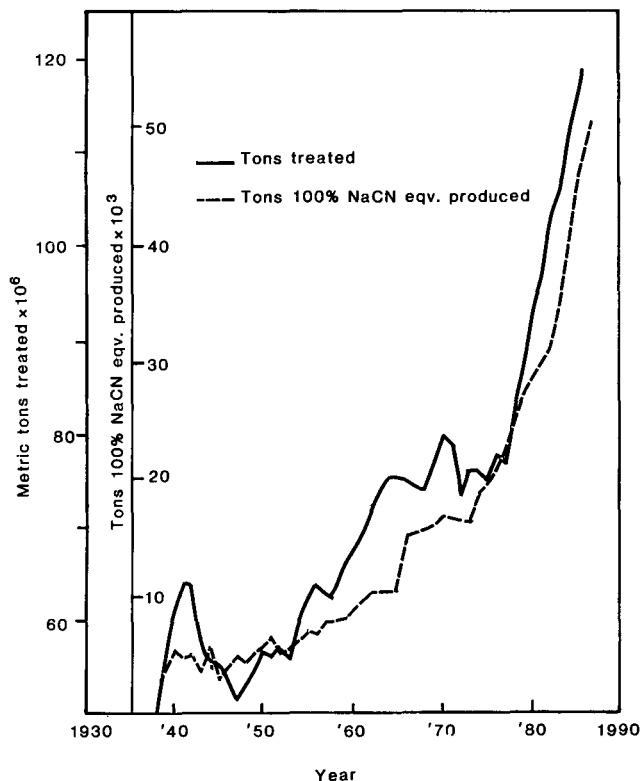


Fig. 3—A comparison between the tonnage treated for gold recovery and the cyanide produced in the period 1938 to 1987

The Department of the Undissolved Gold

Over the years, the basic MacArthur-Forrest process, although it has changed very little in principle, has been refined to become the highly efficient process that until recently was used exclusively in the treatment of gold ores from the Witwatersrand and the Orange Free State. Typically, between 0,4 and 0,5 per cent of the gold contained in the ore is lost in soluble form, and between 2,5 and 3,5 per cent in insoluble form.

The question arises as to what fraction of the residue contains the gold that remains undissolved after cyanidation. The following information, provided by Gold Fields of South Africa¹⁹, illustrates the situation. The distribution of gold in residues is determined by the bulk flotation technique shown schematically in Fig. 4.

The residue sample is subjected to bulk flotation, which produces a bulk sulphide concentrate and siliceous tailings. The bulk concentrate and tailings are then leached with cyanide, and the gold amenable to cyanidation in the two products is determined. The bulk concentrate is then subjected to further flotation to give a carbon concentrate and sulphide tailings. All the flotation products are assayed for gold and sulphide sulphur. The fractional distribution of the total refractory gold in the siliceous gangue minerals, sulphides, and carbon is calculated from a material balance carried out over the complete flotation route.

The distribution of the undissolved gold in the residues of the Driefontein East and Driefontein West gold mines is presented in Fig. 5 and Table IV.

Fig. 5 indicates the following for Driefontein East.

- (i) 53,3 and 46,7 per cent of the gold in the residue is associated with silicates and sulphides respectively.

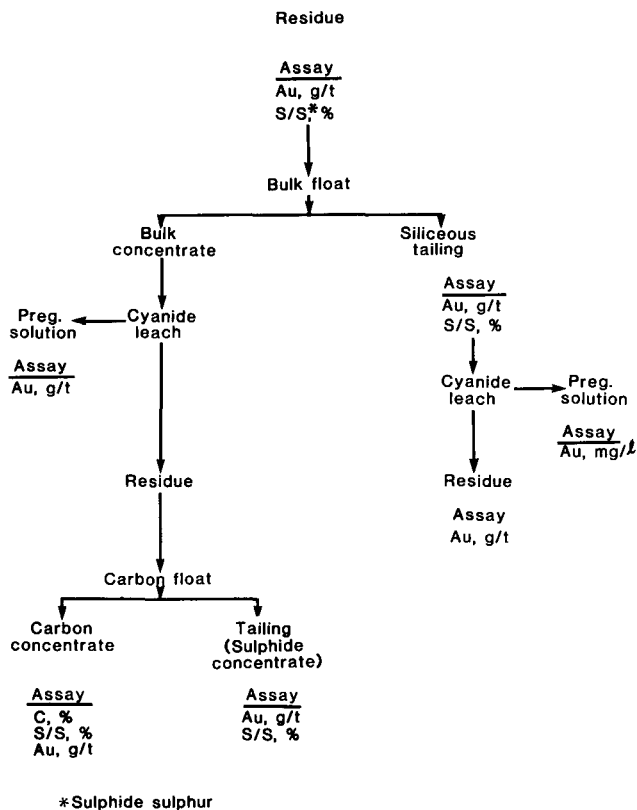


Fig. 4—Schematic diagram of the bulk-flotation technique¹⁹

- (ii) $17,1 + 7,3 = 24,4$ per cent of the gold in the residue is readily soluble by cyanidation under ideal conditions.
- (iii) Sulphide flotation could recover $7,3 + 39,4 = 46,7$ per cent of the gold into a sulphide concentrate of 1,5 per cent by mass at 100 per cent recovery (42 per cent at 90 per cent recovery).
- (iv) Further milling or other treatment would be required to recover any of the gold in the $39,4 + 36,2 = 75,6$ per cent fractions, which are not amenable to cyanidation.

The following apply to Driefontein West.

- (i) 66,0, 33,8, and 0,2 per cent of the gold in the residue is associated with silicates, sulphides, and carbon respectively.
- (ii) $25,5 + 6,2 = 31,7$ per cent of the gold in the residue is readily soluble by cyanidation under ideal conditions.
- (iii) Sulphide flotation could recover $6,2 + 27,6 = 33,8$ per cent into a sulphide concentrate of 1,6 per cent by mass at 100 per cent recovery (30,4 per cent at 90 per cent recovery).
- (iv) Further milling or other treatment would be required to recover any of the gold in the $27,6 + 40,5 + 0,2 = 68,3$ per cent fractions, which are not amenable to cyanidation.

From Table IV it is evident that significant percentages of the undissolved gold are to be found over the three size fractions shown. On the other hand, most of the sulphides, with which the gold is often associated, are in the finest fraction.

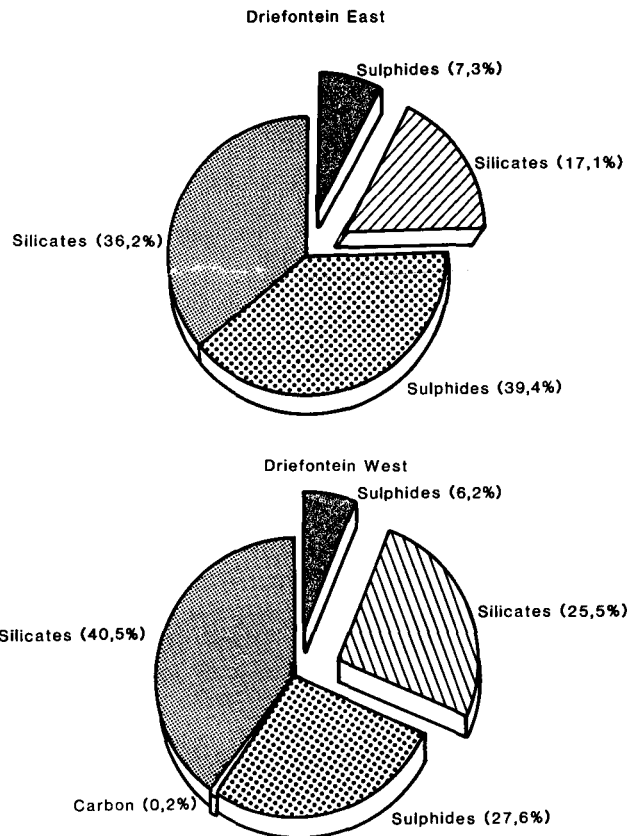


Fig. 5—Distribution of undissolved gold in cyanidation residues¹⁹ (the exploded slices represent the gold amenable to cyanidation)

TABLE IV
FRACTIONAL DISTRIBUTION OF GOLD AND SULPHIDE SULPHUR IN THE RESIDUES OF DRIEFONTEIN EAST AND DRIEFONTEIN WEST GOLD MINES¹⁹

Size fraction μm	Driefontein East					Driefontein West*				
	Mass %	Gold		Sulphur		Mass %	Gold		Sulphur	
		g/t	Distn %	Distn %	g/t		Distn %	Distn %	Distn %	
+ 75	25,5	0,36	48,4	0,1	5,9	34,7	0,26	37,5	0,2	8,5
- 75	18,3	0,26	25,0	0,7	29,5	16,2	0,29	19,6	1,3	25,7
+ 45										
- 45	56,2	0,09	26,6	0,5	64,6	49,1	0,21	42,9	1,1	65,8

* Low grade

Possible Ways to Improve Gold Recovery by Cyanidation

In the first place, the information obtained from Fig. 5 provides a guide as to how much capital and operating expenditure can be incurred on process development and plant to recover gold that is lost to residues. Obviously, the incremental revenue would have to justify the incremental expenditure. It can be estimated that, if the recovery efficiency were improved by 1,0 per cent, an additional gross revenue of a about R200 million per year could be obtained from mines that are members of the Chamber of Mines of South Africa. This is based on Chamber statistics²⁰, an estimated average recovery efficiency of 96 per cent from current ores, a gold price of US\$ 430 per fine ounce, and an exchange rate of US\$1 = R2,40.

There is no doubt in my mind that, at the present time, the major problems facing the underground situation (namely, the environment, rock mechanics, stoping, the human aspect, and gold exploitation) are of paramount importance, and the very survival of the industry could depend on finding solutions to these problems in certain instances. On the other hand, while the metallurgical operations could be seen to be highly efficient and without elements posing a threat to the industry, it is my opinion that, although it is difficult to envisage another technological development like the MacArthur-Forrest invention, research projects should be considered individually on the basis of risk and the after-tax return on the 'investment' normally required by the company concerned. Industry-wide, the carrot of additional potential revenue of the order indicated earlier should not be ignored. The objective of most metallurgical research in the gold-mining industry in South Africa is improved gold recovery and reduced costs.

In the field of improved gold recovery by cyanidation, the following are some areas that are, or should be in my opinion, receiving attention.

- (i) Research into leaching circuits and the control of leaching reagents to establish what is necessary to achieve additional dissolution. This would include the possibility of gold re-precipitation and adsorption, and the reduction of gold values in solution by countercurrent decantation, split leaching, or double filtration.
- (ii) Investigation of the flotation of sulphides and the recovery of gold from the flotation concentrates.
- (iii) Investigation of the degree of grind of silicates and sulphides (including carbons) that is required to liberate meaningful quantities of gold for cyanidation.
- (iv) Further development of instrumentation for milling circuits and milling control to optimize the particle-size distribution and rate of production of minus 75 μm material in the final product from the cyclone overflow to give better utilization of mills and optimum grinds for improved gold liberation and subsequent dissolution. Even research into new concepts of particle-size reduction, such as inter-particle crushing, could be considered.

Conclusion

Had it not been for the invention of the MacArthur-Forrest cyanidation process, there is every likelihood that South Africa's economic development would have died before it had even had a real chance to begin its true growth. I rank this invention in the extractive-metallurgical field along with great ones in the mining field such as the development of explosives and the reciprocating rockdrill.

I trust that you will join me in paying tribute to the inventors of the MacArthur-Forrest cyanidation process for what, in my opinion, was the most significant technological development in the extractive-metallurgical industry during the past century.

Note

The views expressed in this address are those of the author and not necessarily those of the Chamber of Mines

of South Africa.

References

1. SCHEIDEL, A. The cyanide process. California State Mining Bureau, *Bull.* 5. 1894. pp. 9-15.
2. ADAMSON, R.J. *Gold metallurgy in South Africa*. Johannesburg, The South African Institute of Mining and Metallurgy. pp. 88, 80.
3. HABASHI, F. One hundred years of cyanidation. *CIM Bull.*, vol. 80, no. 905.
4. BAGRATION, P. *Bulletin de l'Académie Imperiale des Sciences de St. Petersbourg*, 1843. t. 11, p. 136.
5. ELSNER, L. *J. Fr. Chem.*, 1844. p. 441.
6. FARADAY, M. *Proc. Royal Inst.*, vol. 2. 1857. p. 308.
7. BODLÄNDER, G. Die Chemie des Cyanidverfahrens. *Z. Angew. Chem.*, vol. 9. 1896. pp. 583-587.
8. HABASHI, F. Kinetics and mechanism of gold and silver dissolution in cyanide solution. *Bull.* 59, Bureau of Mines and Geology, Butte, Montana, 1967.
9. MACARTHUR, J.S. *The discovery of cyanidation*. Mining and Scientific Press, 10th Jun., 1916. pp. 851-857.
10. CARTWRIGHT, A.P. *The gold miners*. pp. 79-105.
11. Bullion Johannesburg. *Men, mines and the challenge of conflict*. John Lang. pp. 63, 64.
12. 1986 statistical tables, Chamber of Mines of South Africa. p. 12.
13. WAGNER, H. The challenge of deep-level mining in South Africa. Presidential Address SAIMM. *J. S. Afr. Inst. Min. Metall.*, vol. 86, no. 9. Sep. 1986. p. 378.
14. *South Africa's mineral industry 1986*. Johannesburg, Minerals Bureau, Department of Mineral and Energy Affairs, Republic of South Africa. pp. 21, 23, 6.
15. WORRALL, D. *South Africa: Government and politics*. Pretoria, J.L. van Schaik, 1975. p. 168.
16. Private Communication, Chamber of Mines of South Africa, Statistical Survey of the South African Mining Industry; Source: Central Statistical Services.
17. Private Communication, South African Cyanamid.
18. Private Communication, AECI Chlor-Alkali & Plastics Ltd.
19. Private Communication, Gold Fields of South Africa Ltd.
20. Analysis of working results, January to December 1987. Johannesburg, Chamber of Mines of South Africa. p. 4.

Addendum: The Cyanide Process¹

No. 14, 174

A.D. 1887

Date of application, 19th Oct., 1887; complete specification left, 26th July, 1888, accepted 10th Aug., 1888.

Provisional Specification

Improvements in Obtaining Gold and Silver from Ores and Other Compounds

We, John Stewart MacArthur, Analytical Chemist, of 15 Princes Street, Pollokshields, in the County of Renfrew, North Britain, Robert Wardrop Forrest, M.D., and William Forrest, M.B., both of 319 Crown Street, Glasgow, in the County of Lanark, North Britain, do hereby declare the nature of this invention to be as follows:

This invention has principally for its object the obtaining of gold from its ores or other compounds, but it is also applicable for obtaining silver from its ores or compounds; and it comprises an improved process, which, whilst applicable to ores or compounds generally, is effectual with ores and compounds from which gold or silver have hitherto not been easily obtainable.

In carrying out the invention the ore or other compound in a powdered state is treated with a solution containing cyanogen or a cyanide (such as the cyanides of potassium, sodium, or ammonium), or other substance

or compound containing or yielding cyanogen, till all or nearly all of the gold and the silver are dissolved; the operation being conducted in a wooden vessel or a vessel made of or lined with a material not acted on to any considerable extent by the solution or substances contained therein. The solution is then drawn off and the metal or metals are recovered by any suitable process, and the cyanogen, cyanide, or substance containing or yielding cyanogen may be regenerated. The cyanogen or substance containing or yielding cyanogen may be used as such, or such material may be taken as will by mutual action form cyanogen or substances containing or yielding same.

Under certain circumstances it may be found desirable to conduct the operation under pressure, in which case a closed vessel must be employed, and in any case, if found advisable, such operation may be carried on under varying conditions of temperature.

Dated this 19th day of October, 1887.

ALLISON BROS.,
Agents for the Applicants.

Complete Specification

Improvements in Obtaining Gold and Silver from Ores and Other Compounds

We, John Stewart MacArthur, Analytical Chemist, of 15 Princes Street, Pollokshields, in the County of Renfrew, North Britain, Robert Wardrop Forrest, M.D., and William Forrest, M.B., both of 319 Crown Street, Glasgow, in the County of Lanark, North Britain, do hereby declare the nature of this invention, and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement, that is to say:

This invention has principally for its object the obtaining of gold from its ores or other compounds, but it is also applicable for obtaining silver from its ores or compounds; and it comprises an improved process, which, whilst applicable to ores or compounds generally, is effectual with ores and compounds from which gold or silver have hitherto not been easily obtainable because of the presence of various other metals or their compounds, or because of the physical or chemical conditions of the gold or silver in the ores or compounds.

In carrying out the invention the ore or other compound in a powdered state is treated with a solution containing cyanogen or cyanide (such as cyanide of potassium, or of sodium, or of calcium), or other substance or compound containing or yielding cyanogen. In practice we find the best results are obtained with a very dilute solution, or a solution containing or yielding an extremely small quantity of cyanogen or a cyanide, such dilute solution having a selective action such as to dissolve the gold or silver in preference to the baser metals. In preparing the solution we proportion the cyanogen to the quantity of gold or silver or gold and silver estimated by assay or otherwise to be in the ore or compound under treatment, the quantity of a cyanide or cyanogen-yielding substance

or compound being reckoned according to its cyanogen. We mix the powdered ore, or compound, with the solution in a vessel made of or lined with wood or any other convenient material not appreciably acted on by the solution. The process is expedited by stirring the mixture of ore and solution intermittently, or continuously for which purpose any convenient mechanical agitator may be fitted to the vessel. When all or nearly all the gold or silver is dissolved the solution is drawn off from the ore or undissolved residue, and is treated in any suitable known way, as for example with zinc, for recovering the gold and silver. The residuary cyanogen compounds may also be treated by known means for regeneration or reversion into a condition in which they can be used for treating fresh charges of ores or compounds.

Any cyanide soluble in water may be used, such as ammonium, barium, calcium, potassium, or sodium cyanide, or a mixture of any two or more of them, or any mixture of materials may be taken which will, by mutual action, form cyanogen, or a substance or substances containing or yielding cyanogen.

In dealing with ores or compounds containing, per ton, twenty ounces or less of gold or silver, or gold and silver, we generally use a quantity of cyanide, the cyanogen of which is equal in weight to from one to four parts in every thousand parts of the ore or compound, and we dissolve the cyanide in a quantity of water of about half the weight of the ore. In the case of richer ores or compounds, whilst increasing the quantity of cyanide to suit the greater quantity of gold or silver, we also increase the quantity of water so as to keep the solution dilute. In using free cyanogen, the cyanogen obtained as a gas in any well known way is led into water to form the solution to be used in our process; or any suitable known mode of setting cyanogen free in solution may be employed.

In some circumstances it may be found desirable to conduct the operation under pressure in a closed vessel; and a higher than the ordinary temperature may be used if found desirable.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to be performed, we declare that what we claim is—

1. The process of obtaining gold and silver from ores and other compounds, consisting in dissolving them out by treating the powdered ore or compound with a solution containing cyanogen or a cyanide or cyanogen-yielding substance, substantially as hereinbefore described.
2. The process of obtaining gold and silver from ores and other compounds, consisting in dissolving them out by treating the powdered ore or compound with a dilute solution containing a quantity of cyanogen or a cyanide or cyanogen-yielding substance, the cyanogen of which is proportioned to the gold or silver or gold and silver, substantially as hereinbefore described.

Dated this 16th day of July, 1888.

ALLISON BROS. Agents for the Applicants.