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THE DISCOVERY, DEVELOPMENT, AND DIFFUSION OF NEW TECHNOLOGY: THE CYANIDE PROCESS FOR THE EXTRACTION OF GOLD, 1887-1914

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In the 1880s the gold mining industry encountered severe problems in the extraction of gold from unoxidised ores which were being met more frequently. The gold extraction technology of mercury amalgamation became more inefficient to the extent that little more than half the assayed gold content of the ore was being extracted. Clearly, a major breakthrough in metallurgy was required to overcome this problem. This occurred through the development of the cyanide process which not only raised the percentage of gold extracted from unoxidised ores but also, because of its cheapness, allowed much lower grade ores to be mined and treated than had been possible previously.

Keywords: gold mining, gold extraction, metallurgy, cyanide process, Cassel Gold Extracting Company, J.S. MacArthur.

INTRODUCTION

A new scientific discovery does not occur in a vacuum; it is normally a response to an unsatisfied demand or a perceived need for a solution to an encountered problem. Often the initial breakthrough requires testing and improving to turn it into a practical proposition. In addition, capital and entrepreneurial skill must be available to convert a technically-feasible breakthrough into an economic reality and to diffuse the discovery throughout an industry. Such diffusion will be achieved rapidly or slowly, depending to a large extent upon the degree to which the cost-reducing and/or productivity-generating capacity of the innovation departs substantially from the technology it displaces. Often, secondary, incremental, innovations occur to expand the uses of the process and/or to overcome specific problems encountered in the use of the primary innovation. The overall impact of the invention and its improvements on an industry will determine whether the innovation which springs from invention is important or not.[1]

The following is a case study in the discovery and diffusion of new technology — the development of the cyanide process and its successful application to the recovery of gold from its ores.

THE PROBLEM

The cyanide process was developed in response to a problem confronting the world's gold-mining industry in the 1880s. In many centres, the shallow reefs of gold-bearing material yielded their free-milling gold when the ore was crushed by stamp batteries and then passed in water over corrugated copper plates covered with mercury. The mercury attracted the gold and formed an amalgam, while the residue material (called "tailings") was dumped. The mercury-gold amalgam was taken off the plates and was heated in retorts to a temperature at which the mercury vaporised, leaving the gold.[2] Little of the gold in the ore found its way over the plates and into the tailings. The occurrence of such free-milling gold suddenly declined, however, as mine shafts extended to greater depths (below the water level) and the (unoxidised) ore encountered at depth failed to yield up much of its gold when subjected to amalgamation. As J.S. MacArthur noted

> The water level is generally regarded as the point where atmospheric and weather influences cease, . . . down to that point the rain water had penetrated . . . (over the centuries) . . . and gradually washed away the oxidisable base metals leaving the inert gold . . . (the ore is oxidised and its gold free-milling) . . . whereas the ore found below the water level, not having been subjected to oxidising influences, retains all its metals untouched and unchanged.[3]

Mercury amalgamation of this unoxidised (refractory) material extracted less of the gold than that obtained from oxidised ore because the gold was still combined with base metals in the form of pyrites, sulphides or other compounds which the mercury found difficult or impossible to penetrate.[4]

To improve the recovery rate, the gold extraction plant was enlarged to treat the material coming off the plates. First, the gold bearing particles which escaped amalgamation were separated from the other material by the use of vanners (shaking tables), then ground finely in various types of pans which contained mercury, but the overall results were far from satisfactory. In addition, industrial chemists developed a number of processes based on the application of chlorine to such refractory material. The tailings were placed in large vats and chlorine was pumped through them. The chlorine solution dissolved most of the gold and when the solution was drained off the gold could be recovered. The problem with chlorination was its cost, generally around four pounds to the ton of material treated. It could not be applied profitably to material containing less than an ounce to the ton and thus lower grade material had to remain in the ground.

A technological breakthrough was required to produce a cheaper, more efficient process which could also be applied to low-grade gold-bearing material containing a few pennyweight of gold to the ton.[5] This occurred with the discovery of the cyanide process, described as one of the most important metallurgical advances of the last thousand years.[6]

THE DISCOVERY OF THE CYANIDE PROCESS

The circumstances surrounding the invention revolve around the activities of an industrial chemist, John Stewart MacArthur, who first obtained employment as an apprentice in the Tharsis Copper and Sulphur Company in Glasgow in 1871. Among other activities, MacArthur participated in a project aimed at discovering a method of extracting the small quantities of gold and silver contained in the copper and sulphur ores mined by the Company at Tharsis in Spain and, later, a method of extracting gold from pyrites.[7] So intense was his interest in metallurgical research that, in 1885, he established a small, part-time, research syndicate with three of his friends, including the Forrest brothers.

> We certainly were not capitalists, only a quartet of enthusiasts carrying out research in the evenings in a glory-hole under the consulting rooms of the two Forrests . . . We worked hard and made plenty of mistakes, but kept acquiring knowledge and gathering data.[8]

MacArthur left the Tharsis Company in November 1886 to become the technical manager of the Cassel Gold Extracting Company in which the Tharsis directors had invested heavily. This company's main asset, an electro-chlorination gold-extraction process, had become suspect when its discoverer, Henry Cassel, suddenly left Britain to return to the United States after disposing of all his shares in the Company. MacArthur was employed to turn the Cassel process into a profit-making asset (an impossible task). Under the terms of his employment, the Cassel Company obtained the rights to any successful outcome of the MacArthur-Forrest Syndicate's research, in return for an appropriate financial reward.[9]

The syndicate aimed to discover a chemical substance which, when applied to refractory gold-bearing ore, would dissolve the gold without affecting the base metals with which the gold was combined. After countless experiments and some mistakes, in October 1887 the team found that potassium cyanide was the chemical sought when an experiment illustrated that the cyanide selectively extracted all the gold from a sample ore. The gold was precipitated from the auro-cyanide solution by the use of zinc.[10] MacArthur applied for patent protection on 19 October 1887. The invention had become a fact.[11]

DEVELOPMENT

Invention by itself is not enough, however. Innovation must follow if the act of invention is to be of some consequence. But, before innovation must come the development of the discovery from the laboratory tests into a viable commercial proposition which can then be introduced into the productive process. In December 1887, the Cassel Company converted a section of its plant at Kinning Park, Glasgow, into a workshop for MacArthur to refine the process, all at the Company's expense. MacArthur and a group of assistants conducted tests on many kinds of gold-bearing ores obtained from overseas mining sites.

Within the first twelve months, the team discovered that different types of ores required specialised treatment; that some auriferous ores, especially those containing copper, could be treated only with great difficulty and/or expense; that a very dilute solution of potassium cyanide (under one per cent) was generally more efficient than a strong one; that acidic ores required washing with lime or another cheap alkali before being subjected to cyanidation; and that zinc in shavings form was the most effective precipitant of the gold from the auro-cyanide solution. The last two of these discoveries were patented in July 1988. Plant design also occupied the energies of the team during this period. In other words, a considerable amount of technical knowledge was built up for future reference when the process was eventually transferred to the goldfields.[12] In addition, these discoveries formed part of the development of the process to the stage that innovation could occur.

INNOVATION AND INTERNATIONAL DIFFUSION

In the practical implementation of the MacArthur-Forrest cyanide process, innovation and international diffusion occurred almost simultaneously. MacArthur soon realised that fieldwork was an essential factor in the perfecting of the process for use on the goldfields. He persuaded the Cassel Board to despatch a small team to Ravenswood in Queensland, Australia, where the Company still owned a plant, a relic of the unsuccessful Cassel process. This team left Glasgow in June 1888 and, in November, banked the first 'cyanide gold' produced on a goldfield.[13] The Ravenswood staff experimented for four years with different types of highly refractory ores obtained from several Queensland goldfields and transmitted its results to MacArthur in Glasgow.

Also in 1888, the Cassel Board began to discuss methods of transferring the process abroad. The secrecy surrounding MacArthur's success could not be maintained indefinitely. Soon after the initial discovery, representatives of a group floating the New Zealand Crown Mines Company interviewed the Cassel Board to obtain permission to use the process at their mining site at Karangahake in the north island of New Zealand. Subsequent deliberations led to the formation of a joint venture under which a Cassel team set up a cyanide plant near the Crown mine and treated the ore delivered to it by the Crown Mine's staff.[14] Cyanide operations commenced there in June 1889.

In December 1888, the Cassel Board outlined its initial method of diffusion:

> The chief object we have now in view and are endeavouring to accomplish is the establishment of centres where the precious ores are abundant, in New Zealand, Australia, and soon in South Africa, and we are sending our best men there . . . At home . . . (we are) . . . improving and perfecting the working details of our process.[15]

The Company's interest in the Transvaal had been kindled in July 1888 when two South African mining company representatives were interviewed at the Cassel offices. These men emphasised the perilous financial state of a number of mining companies in the Transvaal and the urgent need for a successful gold extraction process to improve the yield from the highly refractory, chiefly low-grade, ores discovered at depth. Just over half the assayed gold content of the ore was being recovered at most mining sites. In August 1888, the Cassel Board sent Alfred James to South Africa to investigate the possibility of using cyanide on the Transvaal ores. James returned in June 1889 with ore samples and an offer of £50,000 for the patent rights to the process in the Transvaal, subject to a satisfactory demonstration.[16] While the Cassel Board refused this offer, its attitude towards the method of transferring the process abroad was rapidly altered.

For South Africa, a syndicate of mining representatives was established to form a company, the African Gold Recovery Company, to control the process in that region. This Company's capital was set at £170,000 of which £85,000 was to be paid to Cassel's in cash and fully-paid shares for its patent rights in Africa.[17] To popularise the process within the Transvaal MacArthur performed a demonstration near Johannesburg in mid-1890.

This example set in motion attempts by the Cassel Board to float similar companies to operate in Canada, Mexico, Australia, New Zealand, India, and south-east Asia. Of these only the Australian and Mexican companies were established. In the United States, MacArthur performed a successful demonstration in Denver, Colorado, late in 1889. By June 1890, a proposal from the Tabor Investment Company of Denver for the setting up of an American gold extraction company was considered by the Cassel Board. Cassel's was to receive $3,000,000 in paid-up shares for its United States patent rights.[18] The Board accepted the proposal.

The four affiliated companies acted as the media through which the process was diffused throughout the goldfields of their respective countries of operation. Mining companies operating in other countries such as Canada, New Zealand, India, the Straits Settlements, Philippines, other Latin American countries and Russia, many with their head offices in Britain, obtained the right to use the process through direct dealings with the Cassel Company or its agents and the payment of a royalty of five to ten per cent of the proceeds obtained from the sale of the gold produced by the process.

The Company also fostered the use of the process by offering free of charge many of the improvements achieved at Kinning Park and by supplying dozens of expert chemists who had completed the training programmes conducted by MacArthur and his technicians.

EARLY BARRIERS TO INTERNAL DIFFUSION

While the international diffusion was achieved within three years of the MacArthur-Forrest discovery, there were barriers to the use of the process in every major gold-mining country into which it was introduced. In the Transvaal, the lag between the international diffusion of the process and its acceptance by gold-miners was shortest for the new technology was essential for the expansion of gold-mining there at the time.[19] But a delay still occurred because of the uncertainty surrounding the costs of cyanidation.[20] It was only after the Gold Extraction Syndicate[21] recorded large profits from its treatment of tailings between October 1890 and February 1891 that the first royalty contracts were negotiated.[22] Early in 1891, the breakthrough was effected and the use of cyanide became common within this region.

Elsewhere, the internal diffusion of the MacArthur-Forrest process was delayed for several years. In the United States, initial attitudes towards the process ranged from outright incredulity to widespread suspicion, largely because of its simplicity and because of the unrewarding experiences many mine-owners had had with other new but unsuccessful processes. Some opposition to the process grew when it failed at some sites primarily, however, because of the lack of expertise in the use of the chemical[23] and in other instances because of the nature of the ores which required specialised attention. In addition, low extraction costs were often not as critical as in South Africa and chlorination processes continued to be used for many years where they were still profitable. The advantages of cyanidation were eventually accepted, however, and in the second half of the 1890s the quantity of gold produced by this means rose rapidly from year to year.

It was not until 1896 that Australian mining companies were attracted to the process. Its need at Kalgoorlie was not apparent until sulpho-telluride ore was discovered at depth in that year and because the companies operating on this young field possessed ample supplies of oxidised ores until the turn of the century. At Charters Towers and other adjacent goldfields in Queensland, little effort was made to treat the large heaps of accumulated tailings, principally because of the reluctance of local mining firms to adopt new techniques and because their profits from the gold extracted by amalgamation were high. At other mining centres in Australia, there was little need to use cyanide because amalgamation was sufficient to extract most of the gold from the free-milling oxidised ores found at depth. In New Zealand, it was not until a sales drive was undertaken in 1893 by Alfred James that the process was widely accepted.[24] In India, it was not until 1894 that the cyanide process was adopted, after three years of tests and experiments on Indian ores at Kinning Park.

Despite the initial opposition throughout the world, by 1896 the use of the cyanide process was assured. In 1897, according to one source, the annual output of cyanide gold rose to around 1,200,000 fine ounces, 10.4 per cent of the world's gold production in that year. On these figures, South Africa contributed about half of the total, Australia, nineteen per cent, New Zealand, sixteen per cent, and the United States, twelve per cent. By 1897, it is suggested that the Transvaal had produced 2,500,000 fine ounces using the process.[25] In the years from 1902 to 1914, increasingly larger amounts of gold were produced by cyanidation from year to year and its use was also extended to the treatment of low grade silver ores. By 1900, it had displaced chlorination at almost every gold-mining centre. It was almost as efficient as chlorination in extracting gold from refractory ore but its costs per ton of material treated were much lower. Because of this, low-grade ores and tailings, even down to three pennyweight per ton, which would otherwise have remained in the ground or refuse heaps could be treated profitably. The benefits to be gained from transferring from chlorination to cyanidation were therefore substantial and a major breakthrough in gold extraction technology had occurred.

SECONDARY INNOVATIONS

Few important inventions are incapable of improvement. Most pave the way for secondary innovations and such was the case in the development of cyanide technology. The diffusion of the new process led to incremental innovation at a number of mining centres to overcome local problems encountered in the extraction of the gold. Cyanidation as implemented in the Transvaal in 1891 involved the application of a dilute potassium cyanide solution to the suitably prepared tailings which emerged from the amalgamation plates. The cyanide solution was percolated through the tailings contained in large vats for periods extending from several hours up to a month, depending on the nature of the tailings. The gold-cyanide solution was then drawn off and passed through precipitation boxes containing zinc shavings. Agitation of the mixture would have reduced the time taken to extract the gold but it was more costly than percolation and, thus, percolation was preferred on the Rand at that time. In the next few years, finer crushing of the ore by heavier stamps was introduced to reduce the extraction time by producing smaller concentrates but this led to the production of slimes which, when settled in the cyanide vats, virtually prevented the percolation of the cyanide solution.[26]

By the mid-1890s, modifications to the original process were necessary to treat concentrates and slimes effectively and to cater for all types of refractory ore. Such problems were addressed by the Cassel research team in Glasgow and several improvements to the process were developed and patented. Some were taken up immediately, others were ignored at first only to be 're-discovered' later by other researchers.[27]

In the Transvaal, the major changes in the 1890s included the use of more dilute cyanide solutions and the construction of larger plants, both of which reduced the costs of cyanidation to below five shillings a ton, the mixing of clean sand with slimes to allow the cyanide solution greater penetration, the development of classifiers to separate the concentrates from the sands, the introduction of a successful decanting method for treating slimes, and the application of direct cyanidation at a few sites.[28] All these innovations were relatively inexpensive and ensured a high rate of gold extraction.

At sites where richer ores or ores more complex than those in the Tranvaal predominated, other more costly incremental innovations occurred. In Western Australia and the United States, the roasting of the ore before the application of a cyanide solution expelled the sulphides and reduced the time of treatment. Also, the use of a bromo-cyanide solution was adopted on some goldfields, especially Kalgoorlie, to accelerate cyanidation.[29] Indeed, at Kalgoorlie an important cluster of incremental innovations appeared between 1897 and 1902. Tube (or ball) mills were introduced as adjuncts to or replacements of the stamp mills to grind the local ores more finely to create slimes, and filter presses were adopted to obviate the need for decantation in the extraction of the gold-bearing solution from the slimes.[30] In the 1900s, a further advance in the United States led to the replacement of filter presses by vacuum filters for this purpose. Other minor improvements also appeared at this time. While impressive in their application, these secondary innovations performed the role of stream-lining the process of cyanidation by facilitating gold extraction from certain types of ores and reducing the time taken to recover the gold. Yet, where low-grade ores were being treated, the methods adopted before 1896 were generally maintained throughout the 1900s. A result of the later innovations was the boost to manufacturing production in Germany, Britain, and the United States to meet the demand for tube mills, filter presses, vacuum filters, furnaces, and other equipment used in cyanidation throughout the world.[31]

The major transformation of gold-milling technology between 1895 and 1914 occurred at those mining sites where the method involving the stamp-crushing of the ore, mercury amalgamation, the cyaniding of the tailings and zinc precipitation was eventually replaced by stamp-crushing and/or tube milling, cyaniding, filter-pressing or vacuum filtering, and zinc precipitation. Cost reductions in cyaniding also occurred between 1888 and 1914 from around 25 shillings a ton to around three shillings (without the use of sophisticted equipment). Much of the cost reduction had occurred by 1897 when the average costs in the Transvaal were around four shillings a ton,[32] allowing low grade material of four to six pennyweight per ton to be treated profitably. These reductions were achieved largely by the use of larger-scale plant, economies in the use of chemicals, a rapid fall in the cost of cyanide, new types of apparatus, the employment of cyanide experts, improved organisation of the flow of the material through the plant and, later, the greater strength of sodium cyanide when it replaced the potassium salt. A spin-off from the developments in cyanide technology in the 1900s was the adaptation of the process to the extraction of silver from low-grade ores. As a result, the output of silver in the United States and Mexico rose rapidly after 1907 despite the decline in silver prices.[33]

The outcome of the introduction of the cyanide process into gold recovery technology was an increase in the world output of the precious metal after the early 1890s. Directly, it is said, cyanide treatment accounted for between 25 and 33 per cent of the total output each year to 1914 but, indirectly, it accounted for more. For example, without cyanide, the goldfields of the Transvaal and Western Australia, major producing regions of this period, would have been far less prolific. One estimate of the contribution of the process to gold output suggests that at least 42 per cent of the world production of 1906, worth $408 million, could be attributed to the use of the cyanide process.[34]

From 1890 to 1914, therefore, the 'old' technology of mercury amalgamation and the chlorination of the tailings wherever necessary and profitable was completely transformed by the introduction of cyanide and the various secondary innovations which appeared from time to time. Even so, as the nature of the gold-bearing material differed from place to place, so too did the method of cyanidation.

THE PRODUCTION OF CYANIDE

There was yet another spin-off from the introduction of the MacArthur-Forrest cyanide process: it influenced the growth of the cyanide manufacturing industry and research into its manufacturing technology. Up to 1888, the major demand for potassium cyanide came from the electroplating trade. World production of the chemical did not exceed 190 tons, all was produced in Germany.[35] In 1888 it sold at around two shillings a pound for 98-100 per cent purity.

In the early years, the technology available for the production of cyanide was crude. Potassium ferrocyanide (also called yellow prussiate of potash) was the major raw material and the outcome was a greyish product of around 72 per cent pure cyanide.

The Cassel Company added the production of potassium cyanide to its other activities as early as 1889 and eventually a healthy competition developed with its German counterparts. By 1895, industrial chemists in both countries discovered new synthetic and cheaper methods of producing the salt. The combination of technological innovation and keen market competition led not only to a halving of the price of cyanide by 1896 but also a vast improvement in its quality. Further technical advances produced other production improvements in the 1900s, the substitution of sodium for potassium cyanide, reductions in prices, and a price-fixing, market-controlled international cyanide cartel, of which the Cassel Company was a major participant. As a condition of the acceptance of the cyanide process a new and profitable manufacturing industry was thus created.

A SUMMARY AND THE REWARDS OF INNOVATION

The discussion above is an attempt to outline the various aspects of the introduction of a successful technical process: its invention, innovation, technological diffusion and the technological 'spin-offs' (the indirect effects) associated with the initial scientific discovery and its implementation.

It was fortunate for the inventor that, by the time he made his discovery, he was employed by a company desperately searching for a successful gold extraction process and one with the capital and expertise for the development, innovation, and diffusion of the new process. So many potentially useful ideas have failed to come to fruition for the want of capital and enterprise. In this case, however, the problem did not exist.

It was also fortunate for the inventor and the innovating company that, after the process had been refined to the stage where it could be incorporated in gold recovery plants, there appeared an important potential source of demand for it in the Transvaal where its adoption became critical to the continued profitable exploitation of the gold-bearing ores of that region.[36]

The rate of diffusion differed from one gold-producing region to another. In the Transvaal it was most rapid, it was slower in Australia and slower still in the United States, despite its cost-reducing and output-generating attributes. International diffusion was rapid enough, it was the rate of internal diffusion which differed from country to country. Largely, the differential rates of diffusion occurred because of technical problems associated with the application of the process to a variety of different ores, each producing its own problems of extraction, the early lack of expertise in mining plants in dealing with a completely new technology, suspicion arising out of the failures experienced in the use of some chlorination processes, and a lack of the need for treating refractory ore when sufficient quantities of oxidised ore were still available for treatment. It is doubtful if the payment of a royalty for the use of the process substantially prevented its adoption.

Secondary, incremental, innovations appeared to meet the perceived need for improvements in the treatment of different types of gold-bearing material but they generally streamlined procedures, they did not alter drastically the accepted methods of using the chemical. Not all of these innovations were used by all firms adopting the cyanide process, yet most were useful wherever they were introduced. Because of the nature of the process, a new chemical industry was created to provide gold-extraction plants with their cyanide but, because it was used in very small quantities for each ton of material treated, the cyanide manufacturing industry did not become a major section of the world's chemical sector. In addition, the engineering supplies industry was provided with another range of products for development and production.

The success of the invention arose not only from its technical efficiency in gold extraction for some chlorination processes were equally efficient in this way but also because of its economic efficiency in that its costs were very much lower per ton than those of alternative processes and thus its adoption ensured the working of much lower grade ores than what was possible before the innovation. It also added to the profits of most mining companies using it. Perhaps most important of all, the overall outcome was a major expansion in the output of gold[37] with all its implications for international monetary relations during the period of rising international trade, prices, and economic activity from 1895 to the outbreak of World War I.[38]

Finally, what were the rewards to the Cassel Company for its endeavours? Clearly, in the early 1890s, with the success of the process in the Transvaal and the growing supply of unoxidised gold-bearing ore in other areas of the world, the Cassel Company considered that its rewards for offering the gold mining industry a cheap and efficient method of recovering the precious metal from recalcitrant material would be substantial during the remaining life of the patent protection. It is estimated that the overall costs to the Company of developing and diffusing the process exceeded £100,000.[39] In return, the sale of patent rights to the process to the subsidiary companies (allowing them to exact royalty payments from the users of the process) and to mining firms exceeded £75,00 cash and many thousands of shares in the subsidiaries. Dividends from the African and Australian subsidiaries presented the Company with some £30,000, and the subsequent sale of shares of the subsidiaries a further £3,000.[40] Directly, therefore, the Company received in cash around £108,000 from the use of the process. These returns barely covered the Company's costs.

What prevented the Company from gaining substantial rewards for its efforts was the loss of its patent rights, especially in the Transvaal in 1896, thus preventing the African Company from charging royalty dues.[41] Following the loss of its patent rights, the Cassel Company concentrated its efforts on the production of cyanide and gained substantially. In every year after 1897 until its take-over by I.C.I. in 1927, it paid annual dividends to its shareholders in excess of 25 per cent of its capital and accumulated large reserves.

Despite the legal decisions concerning the validity of the MacArthur-Forrest patents, however, it was entirely due to the efforts of the Cassel Company that large benefits accrued to the world's gold mining industry in the form of expanded output, lower costs, and larger profits. The Cassel Company gained little directly from its 'epoch-making success'.[42]

NOTES AND REFERENCES

1. For an overview of these processes see, for example, J.E.S. Parker, *The Economics of Innovation,* Longman, London, 1978; Nathan Rosenberg, 'Factors affecting the diffusion of technology', *Explorations in Economic History,* 10, 1, 1972, pp. 3-33.
2. After it was cooled, the vaporised mercury liquified and could be used again.
3. 'The MacArthur-Forrest process of gold extraction', *Journal of the Society of Chemical Industry,* 9, 3, 1890, p. 269.
4. In some gold-bearing regions with high rainfall, such as in Victoria, Australia, oxidised ores were to be found at relatively deep levels of 1,000 feet or more, whereas in relatively dry regions, such as the Transvaal and Western Australia, the water level was reached at a few hundred feet.
5. To convert to metric measure: one pennyweight per ton equals 1.86 grammes per tonne and one ounce per ton equals 37.3 grammes per tonne.
6. Geoffrey Blainey, *The Rush That Never Ended,* Melbourne University Press, Melbourne, 1963, p. 271.
7. J.S. MacArthur, 'The discovery of cyanidation', *Mining and Scientific Press,* 112, 24, 1916, p. 851. The interest in pyritic ores undoubtedly stemmed from the problems confronting certain Indian gold mining companies in which Sir Charles Tennant, the chairman of Tharsis, had large shareholdings. See S.G. Checkland, *The Mines of Tharsis,* George Allen and Unwin, London, 1967, pp. 126-7.
8. MacArthur, *loc. cit.,* (1916).
9. The Cassel Gold Extracting Company, *Board Minutes* (henceforth *C.B.M.*) (housed in the Cheshire County Records Office in Chester), 12 November 1886. The Company agreed to refund to the Syndicate all its cash outlays, pay a sum of £2,000 and one-third of the profits from the use of the invention with the option of capitalising such profits with shares on an agreed basis.
10. *Ibid.* It should be noted that it was widely known that potassium cyanide and other chemicals would dissolve gold in refined form. In addition, two American patents for the extraction of gold from its ores (those of Rae, 1867 and Simpson, 1885) included potassium cyanide in their specifications but the MacArthur-Forrest patent was the first to specify solely a dilute cyanide solution. Also, no one had used cyanide on any goldfield for this purpose before 1887.
11. The Research Syndicate was well rewarded for its efforts by the Cassel Company. In June 1892, an agreement between the two parties led to the former being allotted 60,000 paid-up shares in the Company. At the prevailing market prices of between 28s. and 33s., these shares could have been sold for over £84,000 at the time.
12. *C.B.M.,* 1888-1892, *passim;* C.J. Ellis, 'Notes on the testing of gold ores, etc., in relation to their treatment by the cyanide process', *Journal of the Society of Chemical Industry,* 17, 2, 1898, pp. 127-30; G.T. Beilby, 'Ten years' progress of the cyanide process for the extraction of gold', *ibid.,* pp. 130-40.

13. J.S. MacArthur, *loc. cit.*, (1916) p. 852.
14. J. McCombie, 'The beginnings of cyanidation', *The Mining Magazine,* VI, 6, 1911, p. 456; *C.B.M.*, 1888 and 1889, *passim.*
15. *C.B.M.*, 12 December 1888.
16. *C.B.M.*, 20 June 1889.
17. See the Prospectus of the Company, *The Times,* 14 March 1891.
18. *C.B.M.*, 17 June 1890.
19. It has been noted that:
    The rich surface zones were becoming exhausted, the grade of ore was falling and the dread of unoxidised pyritic reef, termed "blue-ground" . . . was tending to develop into widespread panic. While the rich outcrops had yielded a fair percentage of their gold to simple amalgamation, treatment of the unoxidised pyritic reefs was presenting considerable difficulty and recovery percentages were steadily falling. James Gray and J.A. McLachlan, 'A history of the introduction of the MacArthur-Forrest cyanide process to the Witwatersrand goldfields', *Journal of the Chemical, Metallurgical and Mining Society of South Africa,* 33, 2, 1933, p. 375. The authors also noted that only 55 per cent of the assayed gold in the ore was being recovered on average in 1890.
20. This stemmed from MacArthur's failure to reveal his costs of extraction during the public demonstration. In fact, he later admitted that he had used a strong cyanide solution to guarantee success (J.S. MacArthur, 'Reminiscences of the early Rand', *Engineering and Mining Journal,* 88, 8, 1909, p. 357). Hennen Jennings (in T.A. Rickard, 'Hennen Jennings and mining on a big scale', *Mining and Scientific Press,* 111, 26, 1915, p. 965) later noted that he and other mining magnates present at the demonstration considered the costs to be too high — as much as 30s. a ton. In 1890, the average yield of the ore on the Rand was 42s. a ton. Mining and amalgamation costs also had to be taken into account.
21. The Syndicate began cyanide operations before it completed the floating of the African Gold Recovery Company.
22. The Syndicate's costs at the Robinson site were given as 10s. a ton, which was acceptable to the mining companies. In fact, cyanide costs were halved shortly afterwards as larger production units were constructed, weaker cyanide solutions were used successfully, and the agitation of the cyanide-ore mixture gave way to percolation.
23. See J. MacDonald, 'The cyanide process and some practical results', *Engineering and Mining Journal,* 57, 12, 1894, p. 268.
24. For a discussion of the technical and other problems confronting the process in New Zealand, see Sybil Jack, 'The introduction of cyaniding in New Zealand: a case study of the role of technology in history', *Prometheus,* 2, 1, 1984, pp. 30-1.
25. These figures are derived from Beilby, *loc. cit.*, pp. 132-4.
26. In the terminology of the times, the pulverised material could be classified into three types: sands, concentrates, and slimes. The sands were the easiest to treat by cyanide; the concentrates formed the larger particles of the refractory material, difficult to treat in that state by cyanide and were often sent to the smelters; slimes consisted of the smallest particles which, when subjected to water, tended to set like cement and it was difficult to penetrate them with the cyanide solution without much agitation.
27. For example, the use of zinc coated with precipitated lead for improving the precipitation of gold from copper-bearing ores, patented by MacArthur in 1894, was rejected by South African miners until 1898, when Betty re-discovered it. See J.S. MacArthur, 'Gold extraction by cyanide a retropsect', *Journal of the Society of Chemical Industry,* 24, 7, 1905, p. 314.
28. Direct cyanidation eliminated mercury amalgamation. The ore was crushed and then subjected to cyanide treatment. The method was used first in the United States in the early 1890s.
29. The combination of bromine and cyanide was suggested by the Sulman-Teed patent of 1895 and was used in the Diehl process by the London and Hamburg Gold Refining Company at Kalgoorlie at the turn of the century.
30. The use of tube or ball mills tended to turn all types of gold-bearing ore into slimes as the tubes containing the material revolved and the steel balls or other hard material

pulverised the ore. The slimes were then placed in filter presses into which the cyanide solution was injected under pressure and eventually squeezed out as a gold-cyanide solution, leaving the dry material which was discarded.

31. It must therefore be stressed that the secondary innovations were incremental to the initial, primary, innovation: the application of a dilute solution of potassium cyanide to gold-bearing material and the precipitation of the gold by means of zinc shavings.
32. See Beilby, *loc. cit.*, pp. 131-2. Note that the major cost-reducing advances had been achieved before the introduction of the major changes in technology, most of which added to the capital costs of the users.
33. For silver, as for gold, the costs of extraction of the ore from the mine and administrative costs were always factors to consider. There was a limit below which reduced cyanide costs could not make the exploitation of the (very low-grade) ore a viable economic proposition, given the price of the metal.
34. See papers by Philip Argall, cited in *Engineering and Mining Journal*, 84, 24, 1907, p. 1128, and William Neill, 'The cyanide industry', *ibid.*, 91, 19, 1911, p. 902. By 1900, the use of cyanide was an integral part of the whole process of gold extraction at many plants and the division of output by milling and by cyanide was impossible.
35. See Anon., 'Deutsche gold und silber scheideanstalt 1873-1923', *Die Chemische Industrie*, 46, 1, 1923, p. 101.
36. By the turn of the century, Western Australia was also highly dependent upon the process for the extraction of gold from its highly refractory ores.
37. This expansion was also due to the new discoveries of gold in South Africa, Canada, Alaska and Australia.
38. It is not claimed that the connection between increased gold production and expanding economic activity is necessarily a causal one. See W. Arthur Lewis, *Growth and Fluctuations 1870-1913*, George Allen and Unwin, London, 1978, pp. 82-93.
39. See Alfred James, 'The difficulties of developing invention: the story of the cyanide process', *Engineering and Mining Journal*, 113, 1, 1922, p. 11. James attributes these costs to:

    > the training of many metallurgists, the erection of cyanide manufacturing works to prevent the supply of cyanide to the mines being restricted, the dispatch of six expeditions, the fighting of two law suits, and the carrying out of much mechanical research . . . (into) . . . the effects of cyanide.

    The balance sheets of the Company confirm this estimate.
40. Most of the shares in the subsidiary companies were distributed as bonuses to the Cassel shareholders, mainly in 1896.
41. The MacArthur-Forrest B and C patents were set aside by the Transvaal Supreme Court (two judges against the patent and one in favour of it) because of the 'want of novelty'. It was judged that they had been anticipated by the American patents of Rae and Simpson (see footnote 10 above). The British Court of Appeal judged the patent novel but set it aside because of weak specifications. Had the term 'dilute' been included, the judges would have upheld the patent.
42. See James, *loc. cit.*, p. 11.