The effect of head grade on recovery efficiency in a gold-reduction plant

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SYNOPSIS

As the grade of the gold (head grade) in the ore supplied to a reduction plants falls, the efficiency of recovery of the metal drops. This is not simply due to a fixed grade lost in the residue, since the residue grade is itself a function of the head grade.

A multi-disciplinary approach was used in the construction of a model to represent the relationship between head grade and recovery efficiency. The model is a physicochemical one based on

(i) the reaction characteristics of cyanidation,
(ii) the milled-ore selection characteristics of gravity concentration, and
(iii) the nearly lognormal distribution of gold grades and particle sizes in ore reserves.

The model was used to set sound target levels for recovery efficiency for a given head grade at a given plant, against which the performances of the plant equipment can be judged for control purposes.

SAMEVATTING

Na gelang die gehalte van goud (die graad van goud) in die erts wat aan 'n reduksie aanleg verskaf word, afneem, daal die herwinnings doeltreffendheid van die metaal. Dit is nie bloot net as gevolg van 'n bepaalde goud gehalte verlies in die residue nie, aangesien die residue opsig self 'n funksie van die graad van goud is.

'n Meervoudige dissipline benadering is gevolg om 'n model vir die verwantskap tussen die graad van goud en die herwinnings doeltreffendheid te konstrueer. Die model is 'n fisies-chemiese een wat gegrond is op

(i) die reaksie eienskappe van sianietloog
(ii) gemaalde erts keuse-eienskappe van swaartekrag konsentrasie, en
(iii) die byna lognormaal verdeling van die graad van goud en die deeltjie groottes in ertsreserwes.

Die model wat gebruik word om gesonde peile vir die herwinnings doelwitte van 'n gegewe goudgraad vir 'n gegewe aanleg te bepaal, waarteen die werking van die aanleg toerusting vir beheer doeleindes, geevalueer kan word.

Introduction

The study described here was aimed at the establishment of an equitable method of making allowance for the effect of head grade when judging the performance of a gold plant in terms of productivity. The current 'norms' of productivity as indicated by recovery efficiency were set on the basis of achievements during a given period when the gold price happened to be fairly low. Subsequently, major increases in the gold price resulted in significant reductions in the average head grades to the gold plants operated by Anglo American Corporation (A.A.C.). It was known that, as the head grade to a gold plant falls, the recovery efficiency also falls, but, at the time of the study, it was not generally known how large the expected drop should be. The loss is not due simply to a fixed grade lost in the residue, since the residue grade is itself a function of the head grade.

Initially, an examination of annual data for the period 1969 to 1976 from 11 gold mines indicated that there were statistically significant positive correlations between recovery efficiency and head grade for 6 of those 11 mines. Monthly data were available for the period April 1974 to June 1977 and, despite the much larger variability, the greater sample size resulted in significant positive correlations for 8 mines. It was recognized that the correlations between recovery efficiency and head grade also coincided with time, so that the true causal effect could have been ascribed to some other variable. An attempt was made to construct a mathematical model, based on known aspects of gold ore and plant behaviour, that would explain the variations in the recorded figures for recovery efficiency at the gold plants. Such a model, if able to explain past behaviour, would command more confidence in its ability to predict future behaviour than one based solely on regression analysis.

This paper outlines such a model and indicates some predictions in respect of plant behaviour that are incidental to the original purpose of finding the relationship between recovery efficiency and head grade. Definitions of the symbols used are given at the end of the paper.

Basic Assumptions

Each gold mine records the mass distribution of its current ore reserves for all relevant band-widths of grade (in grams of gold per ton of ore). Such distributions can be shown to be nearly lognormal in most instances and, further, to be fairly well represented by a gamma function, $\Gamma(2, c)$, where c is a grade characteristic of an ore deposit. An example of a cumulative mass distribution is shown in Fig. 1 with the appropriate cumulative gamma function. Not all of A.A.C.'s gold-mine distributions fit such a function as well as this, but the ease of mathematical manipulation led to the use of the gamma function in the present modelling study, rather than the better known lognormal or *ad hoc* listing.

Sedimentological studies[1] have shown that higher gold grades occur in the more proximal part of an alluvial system and are associated with larger gold particles, whereas the reverse is true further downstream. The present model presumes that there is a strong positive correlation between gold particle size and gold grade, even where a mine lease area forms only part of an ore deposit.

Before any gold can be recovered from an ore or reef,

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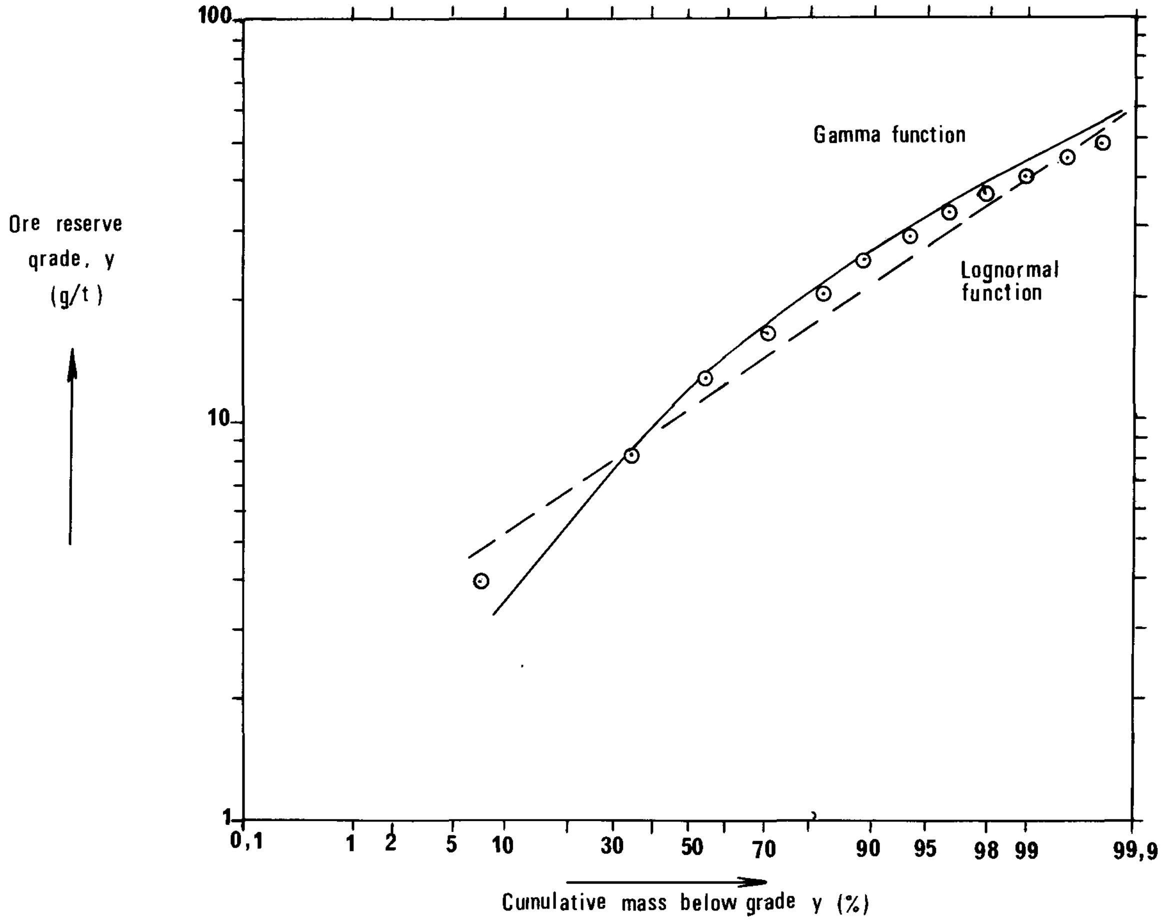

Fig. 1—An example of the mass distribution of ore-reserve grades (President Steyn Gold Mine, 30th June, 1963, parameter c=0,150)

the latter must be ground finely by a series of crushing and milling operations in order to expose the gold particles. In A.A.C. gold plants, the final milled reef typically has 70 per cent of its mass with sizes less than 74 μm. Even after milling, the tiniest gold particles are most likely to be still locked inside rock particles, whereas the largest gold particles are least likely to be attached to rock and are thus available for recovery by amalgamation. Particles with in-between sizes are available for recovery by cyanidation.

The Amalgamation Process

In most A.A.C. gold plants, some of the gold is recovered by amalgamation with mercury. The gold particles recovered by this process are removed from the later stages of the grinding circuit by hydrocyclone, the underflow containing the heaviest particles. If the gold sent to amalgamation is considered to be that with particle sizes above a critical effective size, which is equivalent to a critical effective grade y_A, then the grade recovered by amalgamation is

$$\epsilon\left\{H + 2fy_A + \frac{2f^2y_A^2}{H}\right\}e^{\frac{-2fy_A}{H}}, \quad . \; . \; . \; . \; . \qquad (1)$$

where ϵ is an 'efficiency' parameter of A.A.C. gold plants and the remainder of the expression is from equation A4 in the Addendum. The grade of amalgamated gold was plotted against head grade for all the relevant mines from six-monthly average data, and the points were found to fit the above form when $\epsilon = 0{,}502$ and $fy_A = 13{,}60$ as shown in Fig. 2.

Locked Gold

Even after the gold-bearing reef has been ground very finely, some of the very small gold particles are still totally occluded by rock[2]. If the occluded (locked) gold is assumed to be that with particle sizes below a critical effective size, which is equivalent to a critical effective grade y_L, then the grade that is *not* available to the cyanidation process due to occlusion is (from equation A5 in the Addendum)

$$\triangle = H - \left\{H + 2fy_L + \frac{2f^2y_L^2}{H}\right\}e^{\frac{-2fy_L}{H}} \quad . \; . \qquad (2)$$

The Cyanidation Process

The cyanidation of gold, in which gold is dissolved by an aqueous solution of cyanide, was assumed to be a first-order process. The rate of change in the grade of gold at a given time is then proportional to the available gold grade. The available gold grade at a given time is

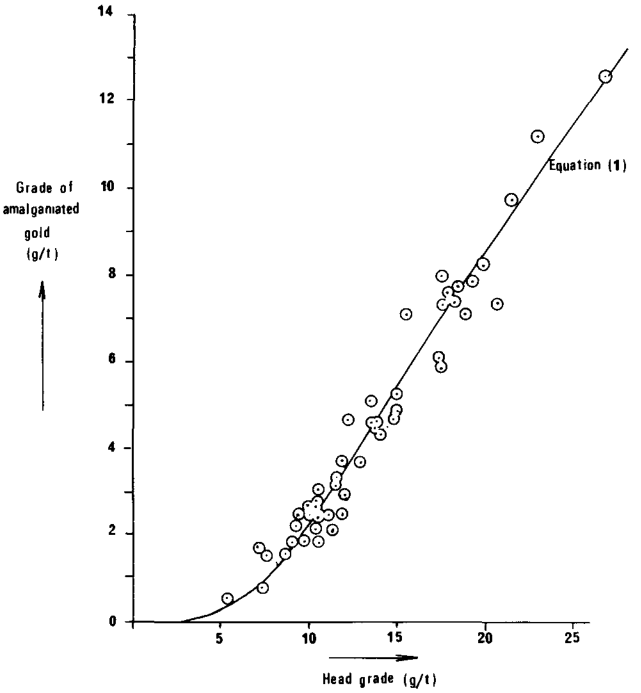

Fig. 2—Grade of amalgamated gold versus head grade for all relevant A.A.C. mines, based on six-monthly data for 1972 to 1976 (ϵ = 0,502 and fy_A = 13,60)

the difference between the total grade at that time and the locked grade. Then, after appropriate integration, the grade left at the end of the cyanidation process, which is also the final residue grade, is

$$\delta = \triangle + (H_C - \triangle)e^{-\beta T}, \quad \ldots\ldots\ldots \quad (3)$$

where β is the reaction rate parameter,

T is the cyanidation, or 'contact', time,

$\triangle$ is the grade of locked gold,

H_C is the grade of gold input to the cyanidation process.

The value of H_C is given by the total gold grade less the gold grade recovered by amalgamation.

Final Residue Grade and Recovery Efficiency

By the combination of equations (1), (2), and (3) above, an expression for the final residue grade δ is obtained as shown in equation (4) below,

$$\text{where} \quad L = 2fy_L$$
$$A = 2fy_A$$

After further manipulation, equation (5) is obtained, which gives some insight into the roles played by the two main recovery processes.

The appropriate expression for recovery efficiency, R

$$R = 1 - \frac{\delta}{H}$$

Discussion of Model Behaviour

It can be seen from equation (5) that, other things being equal, amalgamation must reduce δ, the residue grade, and therefore must improve the recovery efficiency. However, in practice, the improvement to be gained by very low grade mines is negligible and, in gold plants that choose not to use amalgamation, longer contact times are normally employed, thus dispensing with the amalgamation effect.

Values of βT and fy_L were inferred for each sub-group of mines based on the recorded six-monthly average plant values (1972 to 1976). In general, it was found that βT and fy_L could be regarded as common to all mines from a given depositional system, whereas ϵ and fy_A

$$\underbrace{\delta}_{\text{Residue gold}} = \underbrace{H}_{\text{Total gold}} - \underbrace{\left\{1 - e^{-\beta T}\right\}\underbrace{\left\{\underbrace{\left\{H + L + \frac{L^2}{2H}\right\}e^{-\frac{L}{H}}}_{\text{Total gold that is not Locked}} - \underbrace{\epsilon\left\{H + A + \frac{A^2}{2H}\right\}e^{-\frac{A}{H}}}_{\text{Gold recovered by mercury.}}\right\}}_{\text{Gold available for attack by cyanide.}}}_{\text{Gold recovered by cyanide}} - \underbrace{\epsilon\left\{H + A + \frac{A^2}{2H}\right\}e^{-\frac{A}{H}}}_{\text{Gold recovered by mercury}} \quad \ldots\ldots (4)$$

$$\underbrace{\delta}_{\text{Residue gold}} = \underbrace{H}_{\text{Total gold}} - \underbrace{\left\{1 - e^{-\beta T}\right\}\left\{H + L + \frac{L^2}{2H}\right\}e^{-\frac{L}{H}}}_{\text{Gold that would be recovered if cyanide process alone were used.}} - \underbrace{\epsilon e^{-\beta T}\left\{H + A + \frac{A^2}{2H}\right\}e^{-\frac{A}{H}}}_{\text{Extra gold recovered as a result of the use of the mercury process}} \quad \ldots\ldots (5)$$

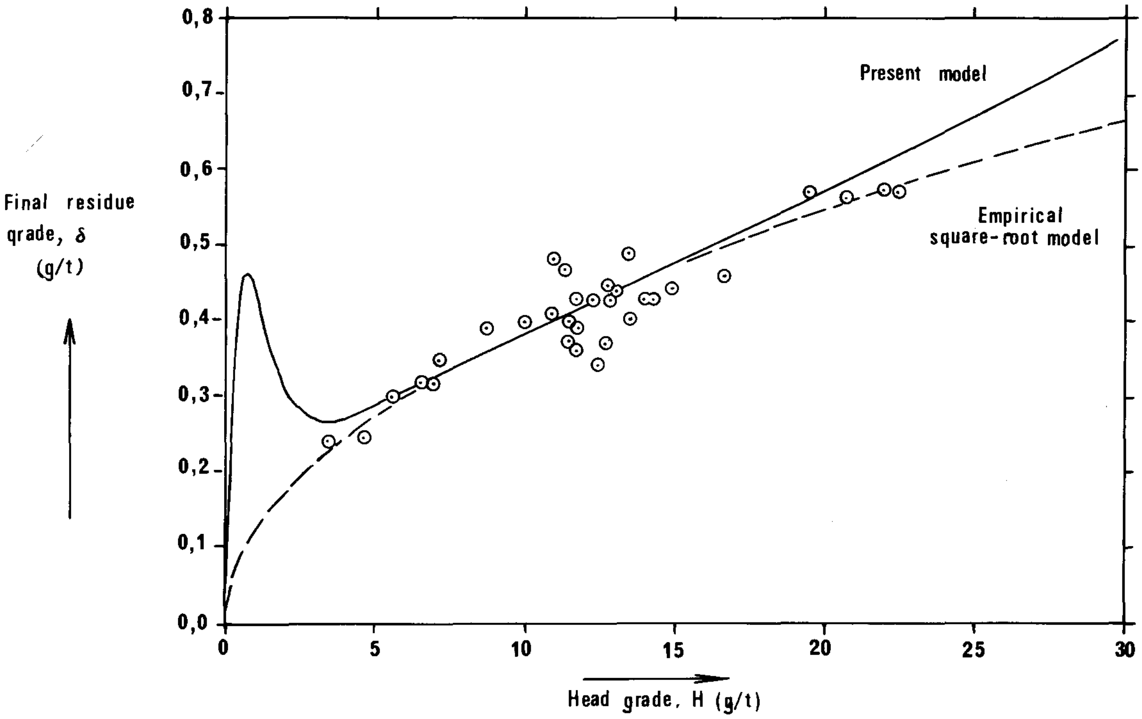

Fig. 3—Final residue grade (δ) versus head grade (H) for four A.A.C. Steyn Reef mines in the O.F.S., based on annual data for 1969 to 1976 (ϵ = 0,502 fy_A = 13,60 βT = 3,020 fy = 1,152

could be regarded as common to all A.A.C. gold plants.

As an example, values of δ against H are plotted in Fig. 3 for the group of four A.A.C. mines belonging to the Steyn Reef system in the Orange Free State (annual values from 1969 to 1976). These mines are Free State Saaiplaas, President Brand, President Steyn, and Welkom. The continuous line is 'model' δ versus observed H, with the depositional parameters fitted to six-monthly average values, giving $\beta T = 3{,}020$ and $fy_L = 1{,}152$.

The broken line shows the function $\delta = M\sqrt{H}$ with $M = 0{,}1219$ chosen to fit those points. It is ironic that this simple, empirical model fits the data rather better than the physicochemical model. However, the empirical model gives no insight into how recovery efficiency might be changed by other factors (e.g. temperature).

Fig. 4 shows the behaviour of equation (5) (with Steyn Reef parameters as in Fig. 4) over a much wider range of H, using logarithmic scales, to illustrate some of the properties of this rather clumsy-looking function. Log δ could be described as approximately cubic in log H, with δ proportional to H at very low values of H. With normal values of locked gold ($y_L \approx 1$ g/t), the constant of proportionality is 1, so that recovery is zero for very small H. In the special case of zero locked gold ($y_L = 0$), the constant of proportionality is $e^{-\beta T}$ (usually $\approx 0{,}05$), so that recovery is about 95 per cent even at vanishingly small H. However, this special case is believed not to occur in practice. At very high values of H, δ is also proportional to H, with a constant of proportionality equal to $(1-\epsilon)e^{-\beta T}$, implying that recovery remains fixed at about 97,5 per cent at very large H.

The slope of log δ against log H approximates to 0,5 over the range of H from about 5 g/t to about 25 g/t, which happens to include most of the data points from the period considered. This observation explains the success of the empirical 'square-root' model relating δ to H.

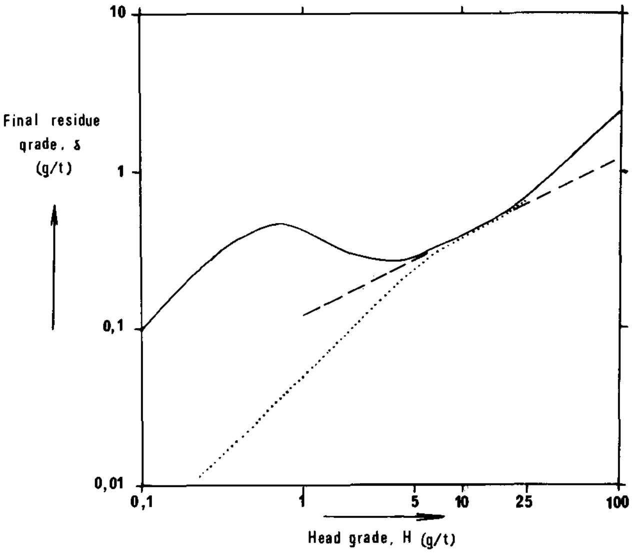

Fig. 4—The present model (for A.A.C. Steyn Reef mines) extrapolated over a wide range of head grades and plotted with logarithmic scales

—Present model ϵ = 0,502 fy_A = 13,60 βT = 3,020 fy_L = 1,152

...Empirical square root model M = 0,1219

......Present model with zero locked gold fy_L = 0,0

If the physicochemical model is a reasonable picture of the truth, large adverse changes in δ await producers from very low-grade deposits (≈ 1 g/t) if their expectations are based on an extrapolated 'square-root' model.

The parameter β of the cyanidation process is the constant of proportionality in a first-order process and is thus a reaction rate coefficient. The classical statistical mechanics approach to the behaviour of chemical reactions gives the temperature dependence of reaction rate coefficients as

$$\beta = A_1 e^{-\frac{E}{R_1 K}},$$

where A_1 is a positive parameter
E is the activation energy of the rate-controlling process
R_1 is the universal gas constant
K is the absolute temperature.

The relationship between β and temperature makes it possible to examine the effect of temperature on recovery according to the present model. Adamson concluded that cyanidation of gold can be regarded as a diffusion-controlled process with an activation energy of 13×10^3 J $K^{-1}mol^{-1}$. From a base value of 20°C for the cyanidation process, a rise in temperature of 1°C would cause an increase of 1,83 per cent in the model parameter βT. For a head grade of 25 g/t, the corresponding reduction in the model's value of δ is 0,018 g/t/°C. This estimate accords fairly well with the value of 0,015 g/t/°C over the temperature range 18°C to 30°C found by Brittan and McLeod[4] during experiments on the high-grade stream of one of the A.A.C. gold plants.

Effect of Head Grade on Recovery Efficiency

Fig. 5 shows values of recovery efficiency against head grade for the two groups of A.A.C. mines in the Orange Free State, from data for the years 1969 to 1976. The information from the first group, the Steyn Reef mines, has already been shown in Fig. 3, but the behaviour of residue grade, δ, does not always convey the implied behaviour of recovery. The second group, the Basal Reef mines, comprises the then Freddies Consolidated and the then Free State Geduld mines. The marked difference in levels of recovery from different depositional systems can be seen in Fig. 5, and the underlying effect of head grade on recovery is also demonstrated. It is emphasized that the general shape of this relationship is a direct result of the properties of the distribution of gold grades and/or gold particle sizes and of the assumptions that locked gold is of small sizes and that amalgamated gold is of large sizes.

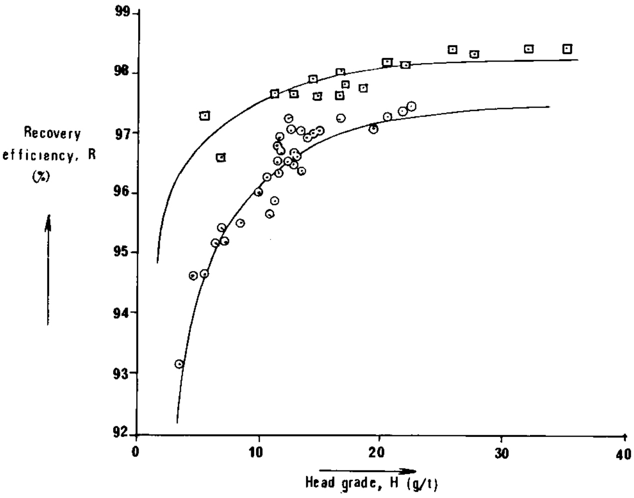

Fig. 5—Recovery efficiency versus head grade for A.A.C. mines in the O.F.S. with different depositional systems, the present model being shown for each group of mines
○ Steyn Reef mines $\beta T = 3{,}020$ $fy_L = 1{,}152$
☐ Basal Reef mines $\beta T = 3{,}417$ $fy_L = 1{,}000$ ($\epsilon = 0{,}502$ and $fy_A = 13{,}60$)

The model has been used to set sound target levels for recovery efficiency for given head grades at given plants, against which plant performance can be judged for control purposes.

List of Symbols used

A_1	positive parameter for temperature-dependent reaction rate
A	amalgamation parameter ($= 2fy_A$)
β	reaction-rate parameter for cyanidation
c	parameter for grade of mined ore $(= \frac{2}{\bar{y}})$
δ	final residue grade from gold plant
$\triangle$	grade of locked gold
e	base of natural logarithms
ϵ	efficiency parameter of amalgamation process
E	activation energy of cyanidation
f	block call factor (= block factor × mine call factor)
$\Gamma(2,c)$	gamma function, which describes the distribution of gold grades in mined ore
H	head grade to gold plant
H_C	head grade to the cyanidation process
K	absolute temperature
L	locked gold parameter ($= 2fy_L$)
M	constant of proportionality for δ versus $\sqrt{H}$
R	recovery efficiency
R_1	universal gas constant
T	contact time of cyanidation
W	total tons mined
W_Y	tons per unit grade width at grade y
$\underline{y}$	grade of ore mined
$\bar{y}$	mean grade of ore mined
y_A	critical grade mined, above which gold reports to amalgamation
y_L	critical grade mined, below which gold is locked

Addendum

It is assumed that the mass distribution of gold grade is given by the $\Gamma(2, c)$ function

$$W_y = Wc^2ye^{-cy},$$

where W_Y is tons per unit grade width at grade y
c is a parameter of the mined ore
W is the total tons mined.

In gold-mining practice, the grade of ore delivered to a plant is f times the grade of ore mined, where f is the block call factor. By the use of standard integrals, it can be shown that

(i) the mean grade of ore mined $= \frac{2}{c}$ g/t . . . A1

(ii) the proportion of gold content that lies above grade y_A

$$= \tfrac{1}{2}\left\{2 + 2cy_A + c^2y_A{}^2\right\}e^{-cy_L} \quad . \; . \; . \; . \; . \; . \; . \; . \; A2$$

(iii) the proportion of gold content that lies below grade y_L

$$= 1 - \tfrac{1}{2}\left\{2 + 2cy_L + c^2y_L{}^2\right\}e^{-cy_L} \quad . \; . \; . \; . \; . \; A3$$

Then, if H is the head grade delivered to the plant,

$$H = \frac{2f}{c},$$

and it follows from equations A1, A2, and A3 that the mean grade of gold in the plant above mined grade, y_A, is

$$\left\{H + 2fy_A + \frac{2f^2y_A{}^2}{H}\right\}e^{-\frac{2fy_A}{H}} \quad \text{(g/t)} \quad . \; A4$$

and that the mean grade of gold in the plant below mined grade y_L is

$$H - \left\{H + 2fy_L + \frac{2f^2y_L{}^2}{H}\right\}e^{-\frac{2fy_L}{H}} \quad \text{(g/t)} \quad . \; A5$$

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Two Atlas Copco travel bursaries for study tours of Swedish mines may be awarded annually to younger mining graduates. One bursary is open to engineers in any country who have at least three year's practical mining experience; the second bursary will be awarded to an engineer who is studying at a British university and has a minimum of one year's practical mining experience

The awards, which are established by the Atlas Copco organization in collaboration with the Swedish Mining Association, will comprise a three- to four-week tour of Swedish mining operations in the month of September in the year of the award. Return travel expenses from any country will be paid for one bursar and from London for the bursar engaged in post-graduate work at a British university; accommodation expenses will be met for both bursars. The Council of the Institution of Mining and Metallurgy is responsible for the selection of the bursars, who will be required to present a written report to the Institution on any aspect of Swedish mining practice, methods, or organization that they found of particular interest, before 1st December in the year of the award. Applications should be sent to the Secretary, Institution of Mining and Metallurgy, 44 Portland Place, London W1N 4BR, England before 15th March each year.

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The first course of a series entitled 'Statistics of Correlated Variables' is to be held at Palo Alto from 14th to 19th March, 1982.

The course is the first of a series of continuing education short courses aimed at geologists, mining engineers, and other professionals in Earth Sciences who are concerned with the quantitative, risk-qualified evaluation of natural resources and its impact on production planning.

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