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The development of a model for the simulation of the radiometric sorting of gold and uranium ores

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SYNOPSIS

This report outlines the development of a model to simulate the radiometric sorting of gold- and uranium-bearing ores.

The developed program indicates the optimum mass, reject percentage, and expected reject gold and uranium grades for a radiometric sorter. It achieves this by statistical analysis of the data gathered from a large sample of rocks in the required size range for a particular mine.

The program can be used in the optimization of existing sorters, as a design tool for new radiometric sorters, and in feasibility studies on radiometric sorting.

SAMEVATTING

Dié verslag beskryf die ontwikkeling van 'n rekenaar model om die radiometriese sortering van goud- en uraandraende erts te simuleer.

Die program wat sodoende ontwikkel is, toon die optimale massa, uitskot persentasie en verwagte uitskot goud en uraan inhoud, vir 'n radiometriese sorteerder. Dit is bereik deur die statistiese ontleding van data. Dié data is versamel van 'n groot monster rotse van die bepaalde grootte van 'n spesifieke myn.

Die program kan aangewend word om huidige radiometriese sorteerders te optimiseer. Dit kan ook gebruik word as 'n ontwerp hulpmiddel vir nuwe radiometriese sorteerders asook om die winsgewendheid te bepaal.

Introduction

The major aim of sorting is to remove waste material from the ore fed to a metallurgical recovery plant. The removal of ore reduces the costs of treatment or allows its replacement by higher-grade material, thus providing greater revenue from plants running at full capacity. Sorting is a viable proposition in certain mines where, because of the thinness of the gold-bearing seams, a large percentage of waste is hoisted with the reef or in the retreatment of waste heaps.

Since there is a natural correlation between the gold and the uranium content in the Vaal Reef, the radiometric sorting of gold ore based on its uranium content was developed at Buffelsfontein Gold Mine (Addenda 1, 2, and 3). Fig. 1, which shows the uranium grade of rocks against their gold grade, would suggest from the sporadic pattern that this correlation is poor. However, since approximately 70 per cent of the ore particles have a grade of less than 0,05 kg of U_3O_8 per ton, the correlation becomes significant.

Owing to the natural radioactive decay of uranium, its quantitative measurement is relatively simple without recourse to the normal assay procedures (Addenda 2 and 3). Fig. 2, which is a graph of the uranium content of rocks in the Vaal Reef against their radiometric counts per 10 seconds, shows that there is a good correlation between a rock's emission of gamma particles and its uranium content. However, if the mass of each rock is included and the uranium content of the rocks is plotted against their measured counts per gram per 100 seconds as in Fig. 3, the correlation becomes excellent, with the production of a clearly definable straight line. This shows that radiometric sorting of gold ore from uranium-bearing ore is an achievable proposition.

For the present and future development of radiometric sorting, the theory needs to be understood so that predictions of machine operating performance can be made. These predictions can be used in the optimization of machine performance and in the production of feasibility studies on proposed new radiometric-sorting machines.

The Sorting Program

Since radioactivity is by definition a totally random emission, it can be measured accurately only as a rate of emission over a relatively long period. Uranium and its gamma-emitting daughter elements are reasonably stable isotopes with long half-lives, and their rate of gamma emissions does not alter significantly within decades. Their rates of emission can be measured by use of a laboratory scintillation counter, which can measure, for a period of 30 seconds, the amount of radiation emitted by each rock taken from a large rock sample. With this information, the radiometric sortability of an orebody can be determined.

However, to be cost effective, radiometric sorters are required to operate with very short counting times (typically 0,24 second for the Buffelsfontein minus 120 mm plus 65 mm sorter). At these short counting times, a straight accept–reject decision about a fixed cut-off point will not always produce a reproducible result for any particular rock. For example, around a cut-off value of 14 counts, a rock may measure anything between 10 and

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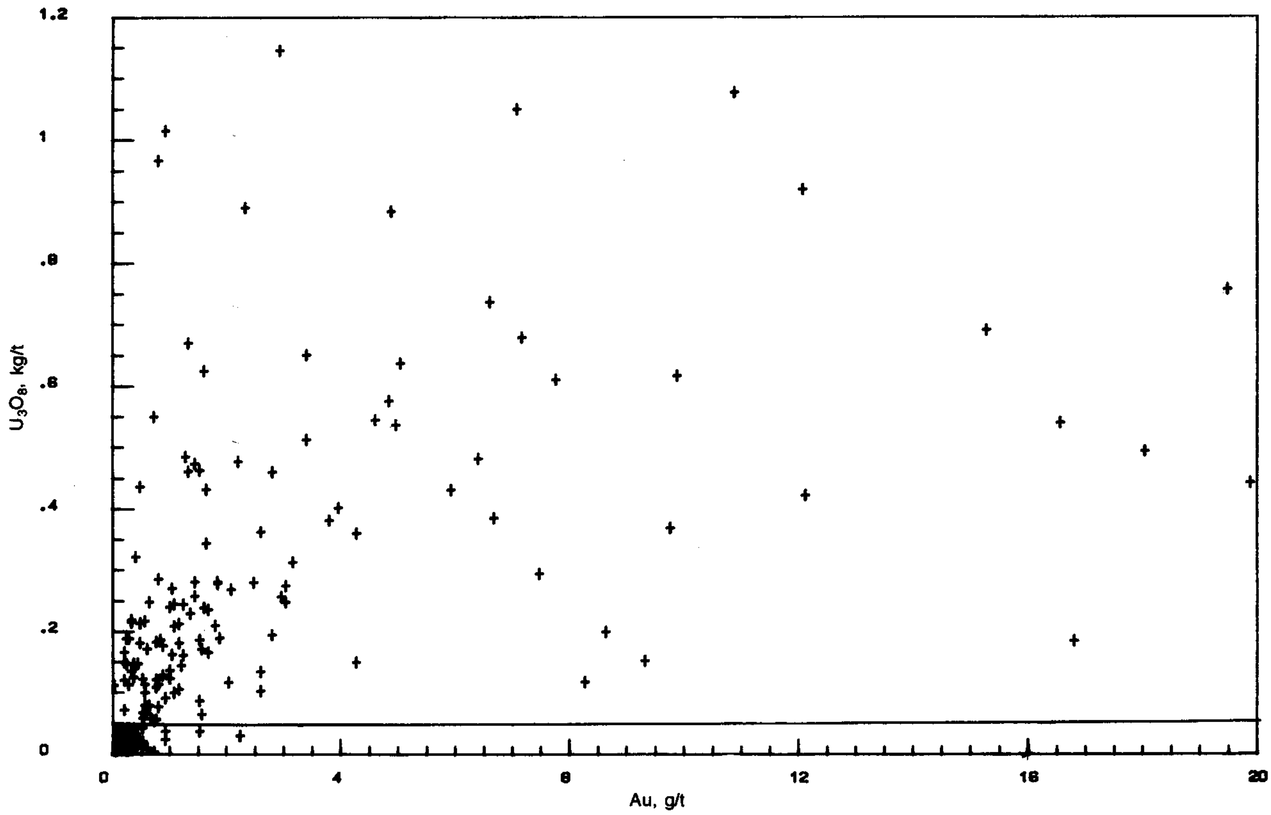


Fig. 1—Correlation of gold and uranium grades in the Vaal Reef (plus 65 mm minus 120 mm material)

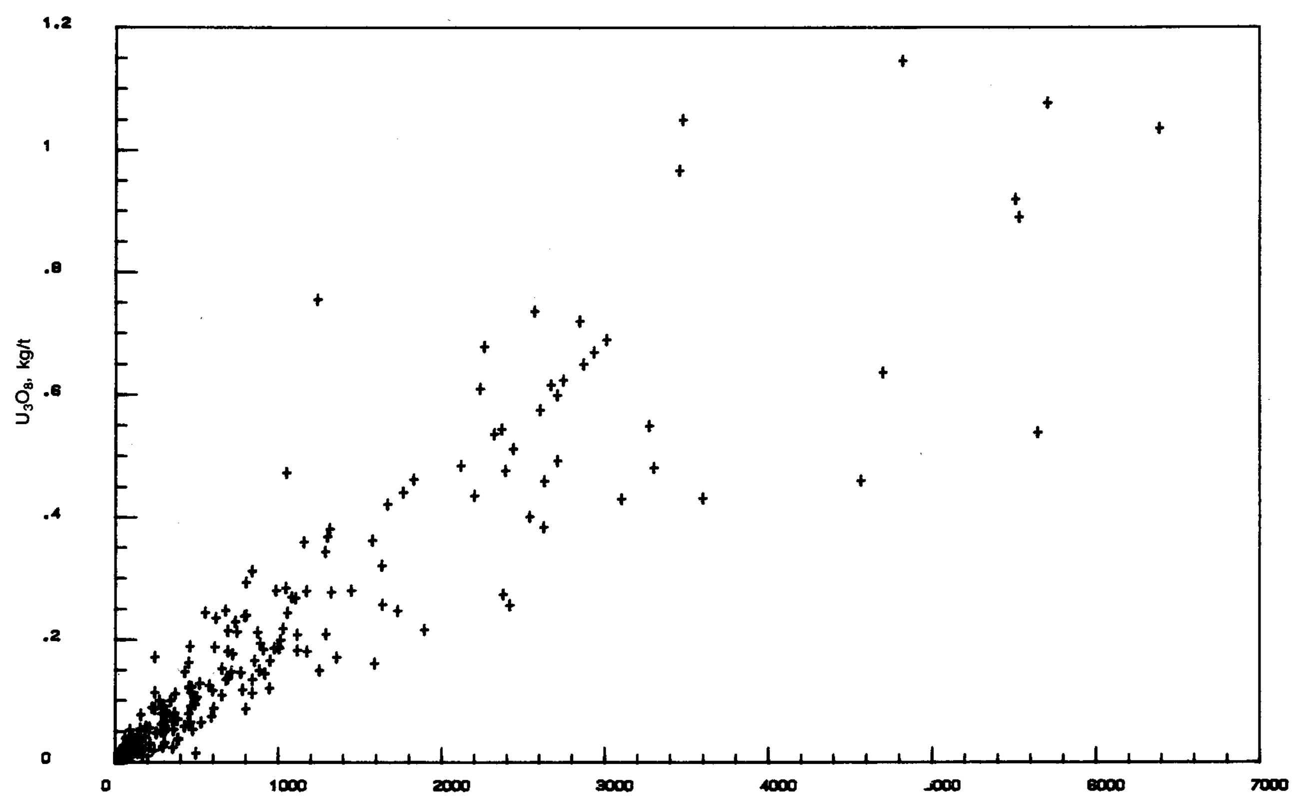


Fig. 2—Uranium in the Vaal Reef versus radiometric counts in 10 seconds (plus 65 mm minus 120 mm material)

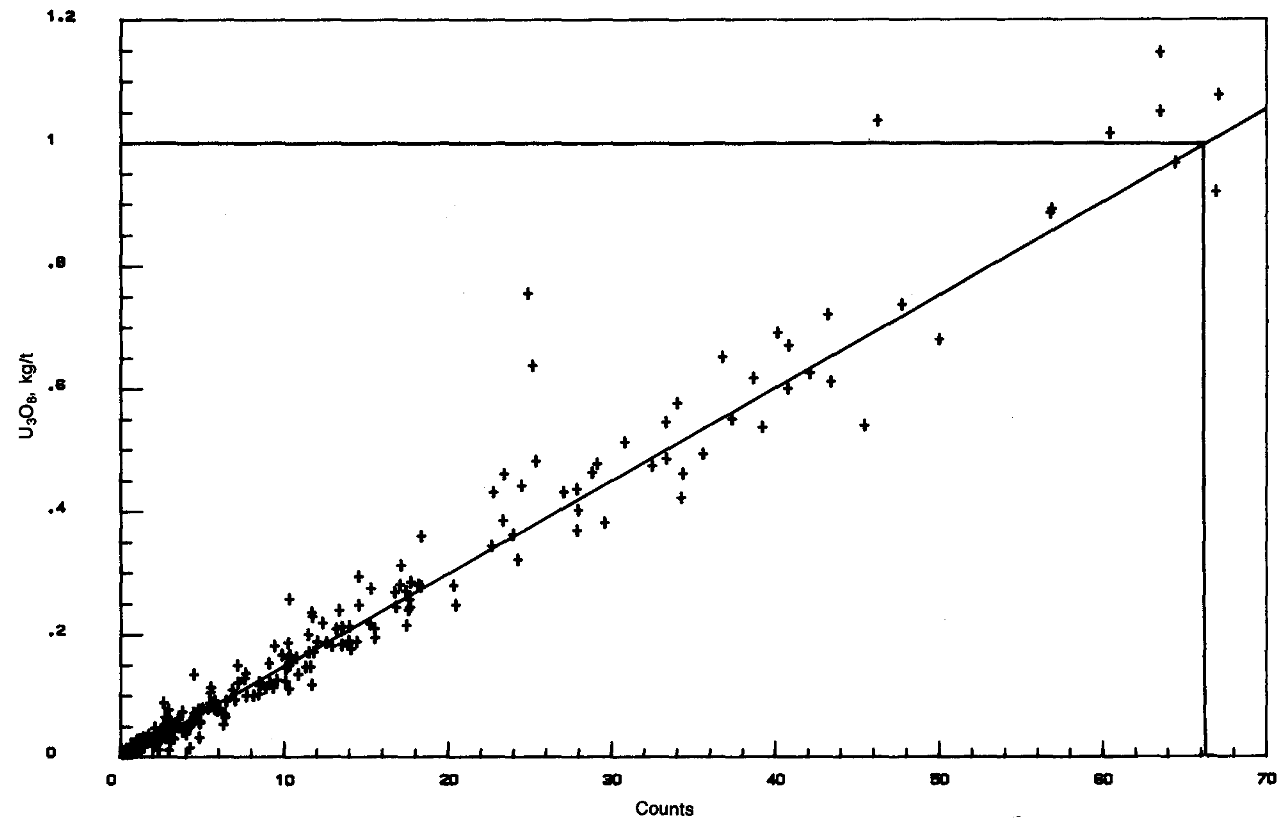


Fig. 3—Uranium in the Vaal Reef versus radiometric counts per gram in 100 seconds (plus 65 mm minus 120 mm material)

16 counts on any specific occasion. Another important consideration is that, as the counts are integer values, there are only a finite number of measurements that can occur. These factors play a major role in the feasibility of sorting and must be accounted for in any simulation program.

If a particular rock is measured many times over a short counting period, a distribution pattern emerges similar to the normal distribution. This can then be converted into a probability distribution from which its probability of rejection for a fixed cut-off point can be calculated.

Normal Distribution

The probability of rejection, P_R, is as follows:

$$P_R = \sum_{N=O}^{N=M} P_N.$$

In normal distribution, the mean value is the most likely occurrence. When a rock is measured over a long period of time, the recorded number of counts for the counting time of the sorter equals that mean value.

For high-grade particles, which give a high count rate, the normal distribution is followed but, for particles of lower count rate, the distribution is skew. This occurs because an integer count of less than zero cannot occur, whereas measured counts greater than the mean can tend to infinity. This skew distribution is closely mapped by Poisson's distribution, which can be calculated statistically.

Poisson's Distribution

This leads to the statistical probability that, for a particular cut-off point, a rock will be either rejected as waste or accepted as reef by a radiometric sorter.

Poisson's distribution can be represented by the formula

$$P_N = (\bar{N}^N \times e^{(-\bar{N})})/N!,$$

where P_N = The probability that any rock measured over the sorter counting time will give an integer reading of N

$\bar{N}$ = The mean count expected

= The counts per sorter counting time calculated from the measured counts per sample counting time.

∴ The probability, P_R, that a given rock will give an integer count value (N) from 0 up to the cut-off value M is the probability of rejection:

$$P_R = \sum_{N=0}^{N=(M)} (\bar{N}^N \times e^{(-\bar{N})})/N!$$

Probability of accept, $P_A = 1 - P_R$.

Before the sorting capability of an orebody can be evaluated, the sample data must be representative of the format in which a sorting machine would observe each rock. These data must take account of the short counting times and the different spatial arrangements of the scintillation counters between the machine and the laboratory counter. Different spatial arrangements can cause any rock if measured by two systems to give different mean counts for the two systems. This is due to the shielding effect of air and the radiation acceptance angle, which change with the distance of the object rock from the scintillation counter.

Radiation Acceptance Angle

Therefore, a calibration from counts measured in the laboratory to counts measured by a sorter must be included in all the calculations. The correlation between uranium grade and the counts measured by each system can be used in the calculation of a calibration factor. Since the correlation is linear, the relationship between the sorter and the laboratory counter is assumed to be a fixed ratio. The respective correlations can be found by calculation of the gradient of the line using a least-squares straight-line fit on the sample data (Fig. 3).

U_3O_8 grade = Gradient × Counts/g per 100 s + Constant

Since at U_3O_8 = 0 counts/g per 100 s = 0,

the constant factor = 0.

∴ Calibration factor

$$= \frac{\text{Sorter gradient correlation}}{\text{Laboratory counter gradient correlation}}$$

Counts/mass in time

$$= \frac{(\text{Counts/time} - \text{Factor 1} \times \text{Background})}{\text{Factor 2} \times \text{Area}}$$

where Factor 1 = Background correction

Factor 2 = Correlation of the area to the mass.

If the counts/mass in time are less than the cut-off value, the rock is rejected.

To statistically account for the effect of Poisson's distribution, the cut-off point and the mean counts must be converted to a counts per sorter counting time for each rock, N. The cut-off point must then be converted to include each rock's mass for its respective calculations.

$$\frac{\text{Mean counts}}{\text{Sorter counting time}_N} = \frac{\text{Mean counts}}{\text{Sample counting time}_N} \times \frac{\text{Sorter counting time}}{\text{Sample counting time}} \times \text{Calibration factor} + \text{Background}$$

$$(\text{Cut-off point})_1 = \text{Counts/g in 100 s} \times \text{Sorter counting time (s)} \times \text{Mass}_1\text{ (kg)} \times 10 + \text{Background}$$

Note: A factor of 10 converts the units.

The probability of rejection can then be calculated by use of Poisson's formula for each rock in the sample at varying cut-off points.

Conversion of Probability to Rejection Percentages

The calculated probability of rejection (P_R) for each rock (N) in the sample at the chosen cut-off point can then be used in the calculation of the mass percentage of ore, gold, and uranium that would be rejected by a sorting machine. These rejection percentages can then be used in the calculation of accept and reject grades.

It can be assumed that a fraction of each rock will be rejected as defined by the probability of rejection, and that the remainder will be accepted. For a continuous ore sorter, that percentage of similar rocks as defined by the probability will be rejected as waste and the remainder accepted as reef.

Therefore, it can be calculated that, for any rock N,

Fractional mass rejected (kg) = $(P_R)_N \times \text{Mass}_N$ (kg)

Fractional gold rejected (mg) = $(P_R)_N \times \text{Gold grade}_N$ (g/t) × Mass_N (kg)

Fractional U_3O_8 rejected (g) = $(P_R)_N \times U_3O_8\ \text{grade}_N$ (kg/t) × Mass_N (kg).

Therefore, for a large sample of M rocks,

$$\text{Total mass rejected} = \sum_{N=1}^{N=M} (P_R)_N \times \text{Mass}_N$$

Mass rejection percentage

$$= \frac{\text{Total mass rejected}}{\text{Total mass of sample}} \times 100.$$

Since $P_A = 1 - P_R$,

$$\text{Total mass accepted} = \sum_{N=1}^{N=M} (1 - P_R)_N \times \text{Mass}_N$$

$$\text{Reject gold grade (g/t)} = \frac{\text{Total gold rejected (mg)}}{\text{Total mass rejected (kg)}}$$

$$\text{Reject } U_3O_8 \text{ grade (kg/t)} = \frac{\text{Total } U_3O_8 \text{ rejected (g)}}{\text{Total mass rejected (kg)}}.$$

If the cut-off point is increased from 0 to ∞, the rejection masses are calculated, and the resulting factors are plotted (Figs. 4 and 5), a machine's potential performance can be visualized.

Optimization of Radiometric Sorters

The optimum running point for any sorter is the point at which the recovery of revenue is greatest when the working costs are discounted from the accrued revenue.

The evaluated accept gold and uranium masses at the various cut-off points can be converted into revenue values and the optimum point (i.e. maximum revenue) found by an iterative or graphical method.

Gold revenue treated (R/t)

$$= \text{Gold mass}_A\text{ (mg)} \times \text{Gold recovery (\%)} \times \frac{\text{Gold price (R/mg)}}{\text{Total mass of sample (t)} \times 100}$$

Similarly,

Uranium revenue treated (R/t)

$$= \frac{(U_3O_8\ \text{mass}_A\text{ (g)} \times U_3O_8 \text{ recovery (\%)} \times U_3O_8 \text{ price (R/g)}}{\text{Total mass of sample (t)} \times 100}$$

The gold and uranium recoveries are those corresponding to the metallurgical plant on which the sorter is to be sited when no recycle streams or waste streams are in operation.

The uranium price is the price that the particular mine received for its uranium.

Total revenue = Gold revenue + Uranium revenue

When the working costs are included:

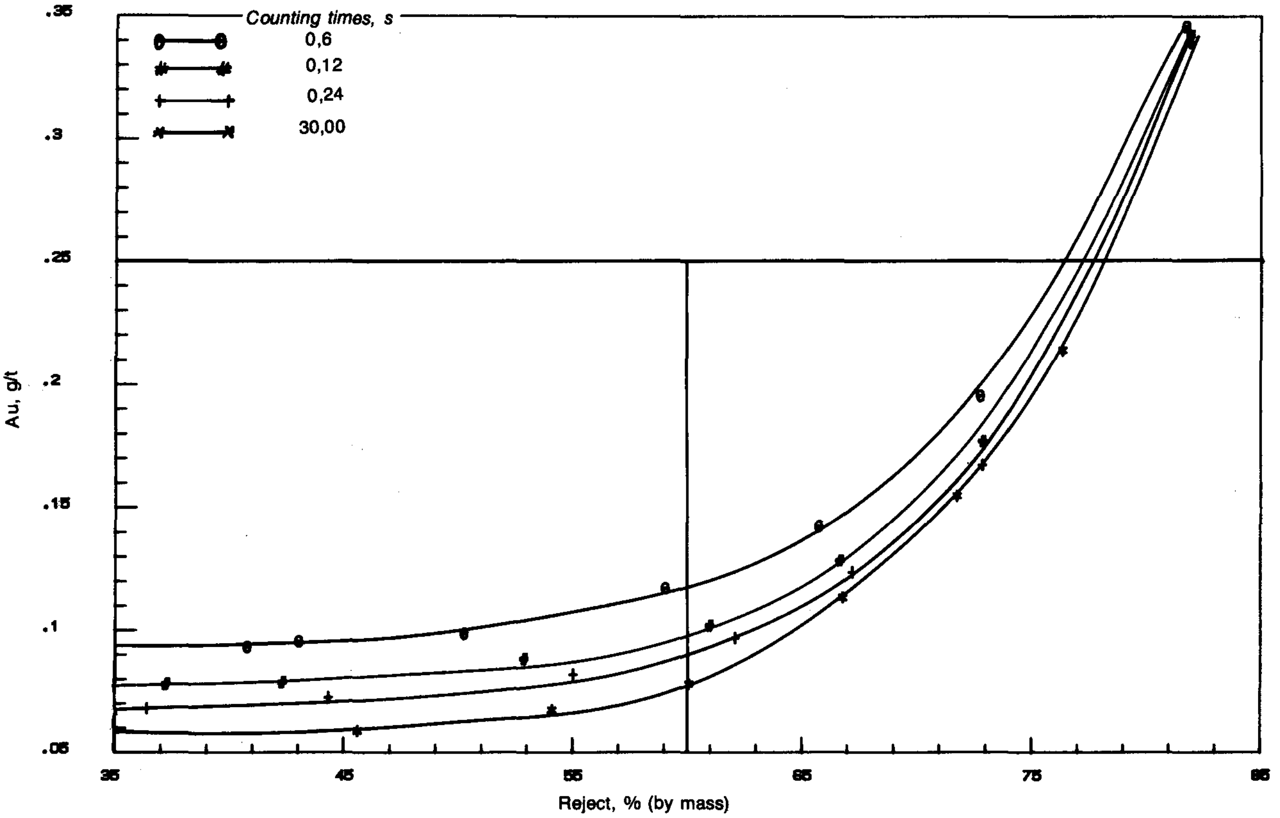


Fig. 4—Gold reject grade versus percentage reject material for different counting times at a sorter contractual limit of 0,25 g of gold per ton and a reject mass of 60 per cent (plus 65 mm minus 120 mm material)

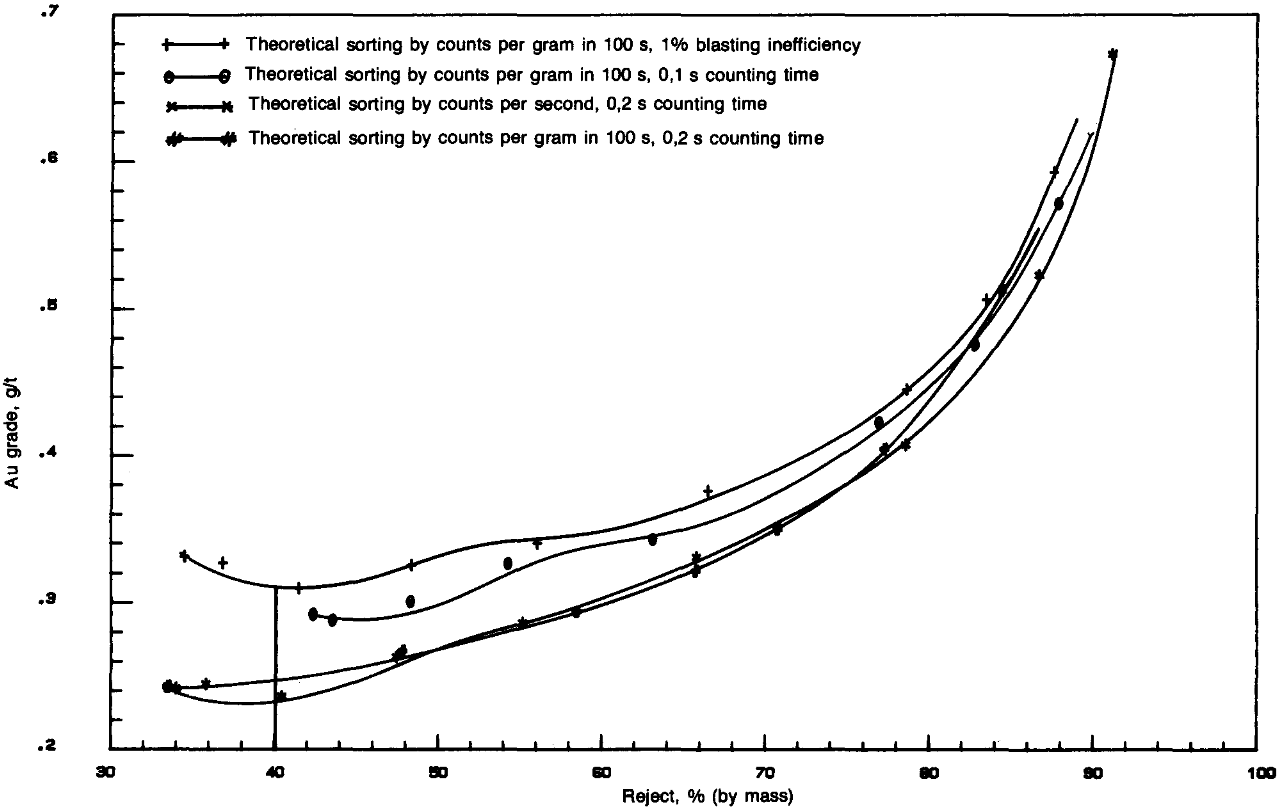


Fig. 5—Gold grade versus percentage reject material for various conditions (plus 35 mm minus 65 mm material)

Actual revenue per ton treated

= (Total revenue − Fixed plant treatment cost − Incremental plant treatment costs × (Accept (%/100) − (Sorter incremental costs + Fixed working costs)),

where the incremental plant-treatment cost is the cost of treating an additional ton of ore through the plant.

Since the fixed treatment costs and the incremental sorter costs are not affected by changes in the cut-off point, the optimum running point occurs when the

Total revenue − Incremental treatment costs × (Accept %/100).

is at a maximum. When the actual revenue is plotted against the reject percentage at various cut-off points and the resultant curve is drawn, this maximum can be found.

Fig. 6 indicates that, for the Buffelsfontein minus 120 mm plus 65 mm sorter, the optimum running point occurs at a mass reject of 60 per cent, which corresponds to a reject gold grade of less than 0,1 g/t. Fig. 7 indicates that, for the Buffelsfontein minus 65 mm plus 35 mm sorter, the optimum running point occurs at a mass reject of 40 per cent, which corresponds to a reject gold grade of less than 0,25 g/t.

These graphs indicate that the sorting of minus 65 mm plus 35 mm-rocks is probably not a feasible proposition once blasting error is taken into account.

The optimum cut-off point must not be used as the setting for the machine, but the sorter must be set to produce the mass percentage reject occurring at the evaluated optimum cut-off point.

Factors Affecting Design

There are many available methods for the sorting of gold ore. These include radiometric sorting, optical sorting, and neutron-activation sorting. The potential of each method to sort a particular ore can be established by the assumption of perfect sorting around a specified cut-off value for a chosen criterion, i.e. gold grade, uranium grade, counts per gram in 100 s, or counts/per second.

For perfect sorting on gold grade, the probability of rejection, P_R, for any rock N with grade x g/t is

$$P_R = 1 \text{ if } x < y \text{ (g/t)}$$
$$P_R = 0 \text{ if } x > y \text{ (g/t)},$$

where y is the cut-off value.

One would expect perfect sorting based on gold grade to be the best proposition owing to the great difference between the revenue recoverable from gold and that recoverable from uranium. However, as Fig. 8 shows, there is little difference as to the sorting procedure adopted. For the sample of ore analysed, a maximum additional recovery of only R0,2 per ton treated was attained when the sorting was done by gold grade rather than by uranium grade. Since the neutron-activation method of gold sorting is not yet fully developed and is also costly, radiometric sorting of gold ore is still the most efficient means of sorting. However, it is evident that a combined gold–uranium sorter would provide the best option.

The mechanical efficiency of a sorter must be given serious consideration. Factors affecting this include inefficiency of developed blasting values, incorrect targeting of rocks, and imperfect feed distribution to the machine. (For example, when two or more rocks are grouped

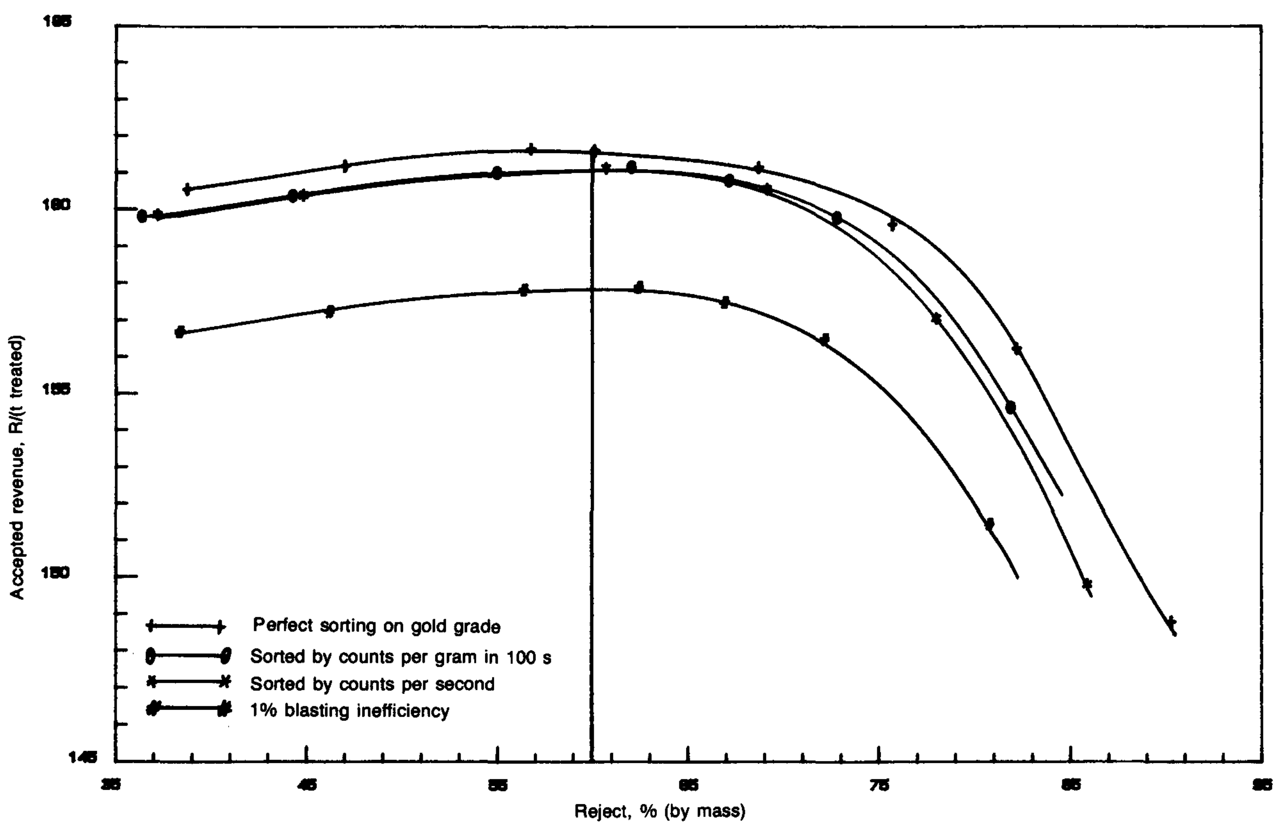


Fig. 6—Optimum cut-off point for the plus 65 mm minus 120 mm sorter

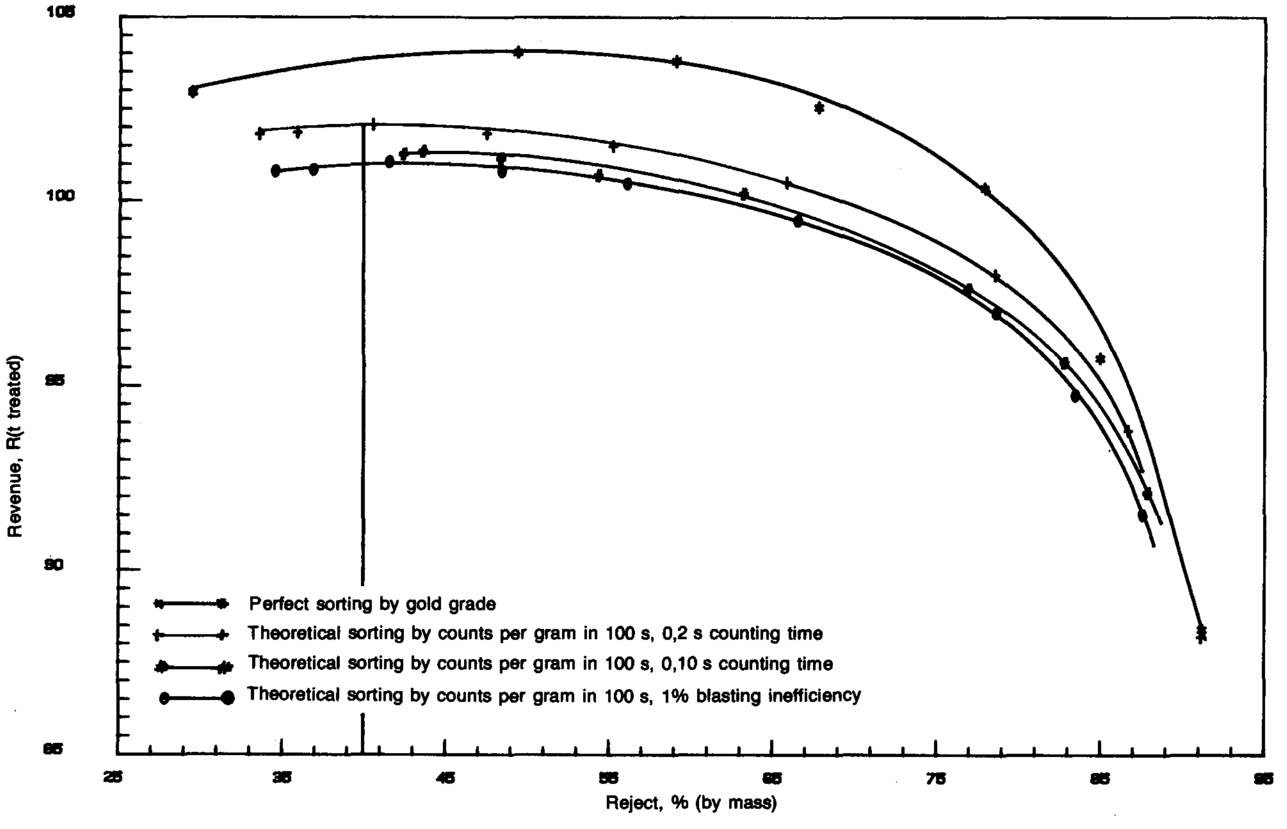


Fig. 7—Optimum cut-off point for the plus 35 mm minus 65 mm sorter

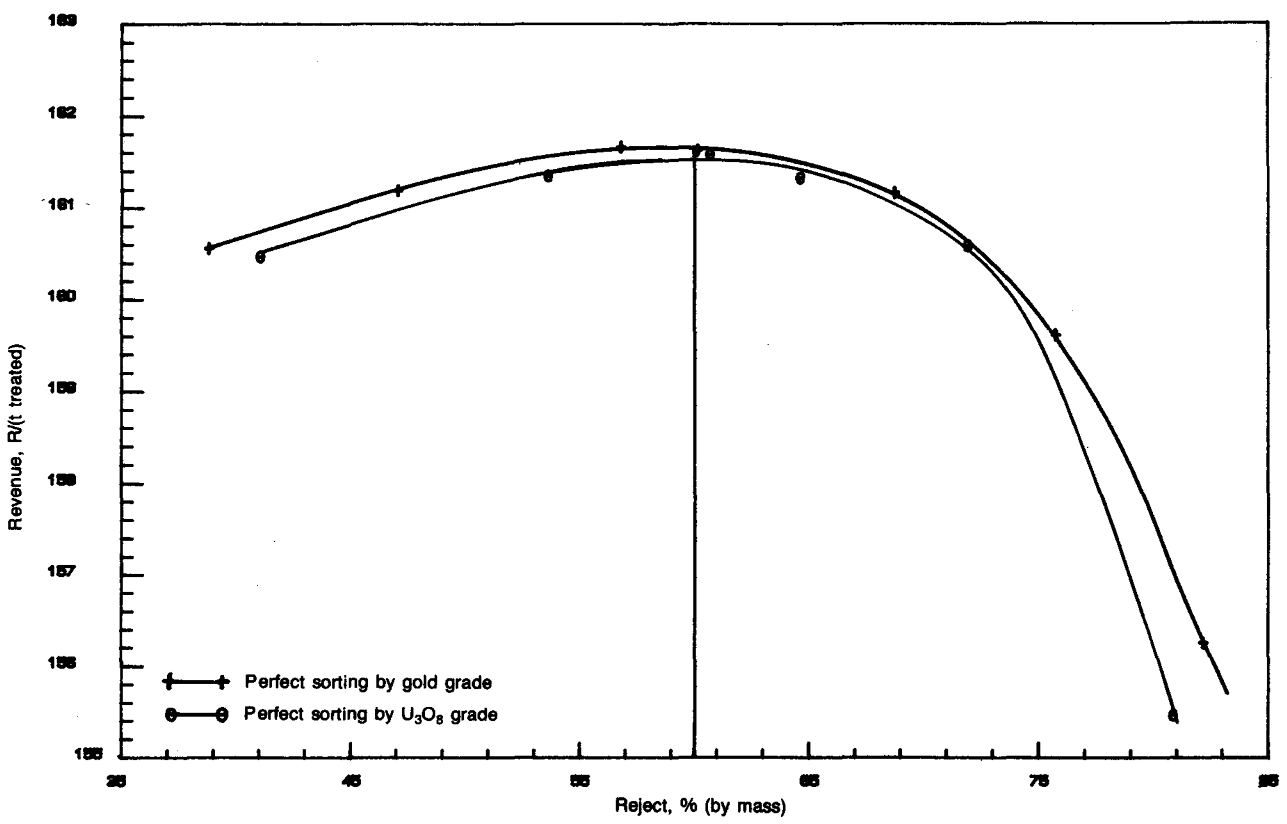


Fig. 8—Sorting by gold grade and sorting by uranium (plus 65 mm minus 120 mm material)

together while being counted and presented for blasting, a large inefficiency can occur.) In statistical calculations of probability, these inefficiencies can be included as a simple algorithm:

$$P_R = P_R + \text{Reject blasting error.}$$

If $P_R > (1 - \text{Accept blasting error})$, then

$$P_R = 1 - \text{Accept blasting error.}$$

The accept blasting error can be taken into account only at the outer limits since it would otherwise negate the effect of the reject blasting error in the statistical calculations.

As shown in Figs. 5 to 7 and 9, this blasting inefficiency can have a considerable effect on sortability. As indicated in Fig. 9 for minus 120 mm plus 65 mm rocks, a 2 per cent inefficiency causes the sorter reject grades to rise above the plant residue values, thus undermining the entire profitability of sorting as a unit process. It is therefore important to know the maximum limits of this error before sorting is used. It also suggests that an intensive maintenance programme must be included for every machine and that the actual reject grades should be closely monitored.

Figs. 5 and 9 indicate that, for the Buffelsfontein ore, radiometric sorting could provide reject gold grades as good as 0,24 g/t from the minus 65 mm plus 35 mm sorter, and 0,1 g/t for the minus 120 mm plus 65 mm sorter. However, owing to high blasting inefficiencies, unacceptable reject grades were produced and the sorters were subsequently shut down.

Practical studies at Buffelsfontein showed that the rocks were probably grouped together during counting and were subsequently blasted together, rather than that the blasting mechanism missed the intended rock. This was concluded when a change was made from the blasting of reef to the blasting of waste and the residues were observed. This study indicated that it is better to blast reef.

If the measurement of mass is removed from the calculation of cut-off point, the unimportance of weighing each rock (directly or indirectly) can be demonstrated. Evidence for this is supplied by Figs. 5 and 6, which show that, when no account of the mass is taken in the calculations, the resultant curves are not significantly different.

However, when the sorter counting time is varied in the calculations, the importance of as long a counting time as practicable becomes apparent, particularly for the sorters of smaller size fractions. Fig. 4 indicates that, for the Buffelsfontein minus 120 mm plus 65 mm sorter, a counting time of 0,06 second would not drastically affect performance. However, as Fig. 9 indicates, even a counting time of 0,1 second would make the sorting unfeasible on the minus 120 mm plus 65 mm sorter.

The effect of counting time on the probability of reject flow is shown in Table I for a hypothetical rock.

Feasibility of Sorting

Once a simulation program has indicated the optimum mass rejection percentage together with the expected grades, the information can be used to decide whether sorting for a particular mine is a feasible proposition.

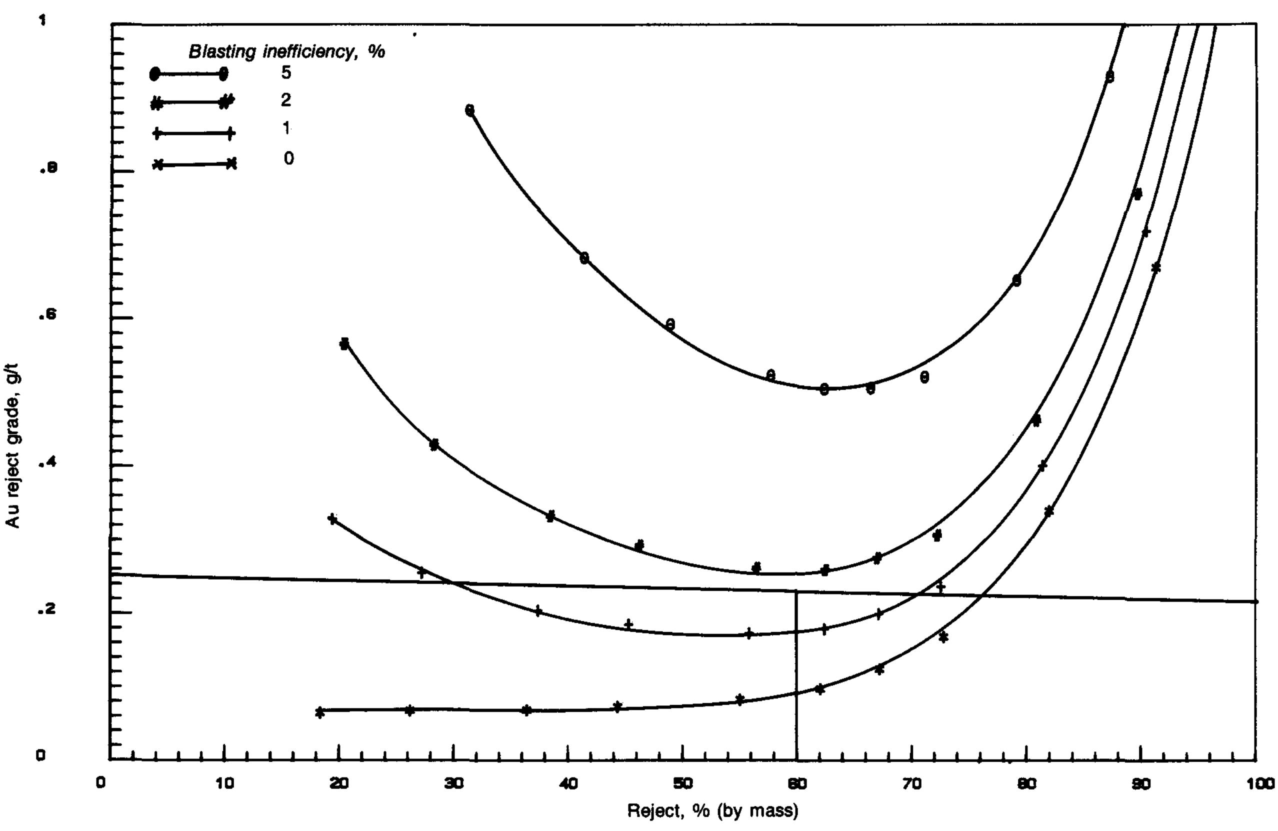


Fig. 9—Effect of blasting inefficiency on sortability (plus 65 mm minus 120 mm material) at a sorter contractual limit of 0,25 g of gold per ton and a reject mass of 60 per cent

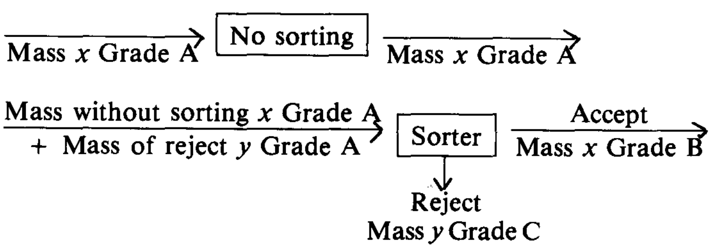
TABLE I
EFFECT OF COUNTING TIME

Mean counts Counts/g	Counting time s	Cut-off Counts/g	Probability of rejection
48	1	44,2	0,313
24	0,5	22,1	0,392
12	0,25	11,05	0,459
6	0,125	5,525	0,446
3	0,0625	2,2625	0,423

Depending on the mine in question, the studies would follow either of the following two paths.

Path 1

When the sorter has to replace low-grade ore with high-grade ore and the existing plant is running to full capacity,



Increased gold recovery

$= xB - xA$
$= x/A + yA - yC - x/A$
= Reject mass (Feed grade − Reject grade).

∴ Additional revenue per month

= Tons rejected/month × (Feed grade − Reject grade) × Recovery × Price.

For both gold and uranium, providing that the plant recovers uranium, the calculations are based on optimum grades and reject mass percentages as predicted by the sorting program.

Monthly working costs:

= Sorter working costs + incremental mining costs × expected rejects (t)

Capital expenditure:

= Installation cost of machine + screening plant.

Feasibility studies generally show that this type of situation is a good economic proposition, but this should be gauged against the extension of the plant to treat the additional ore.

Path 2

Where the sorter must be economic as a unit process,

Revenue = Savings in treatment costs − Possible revenue recovery from treating waste material

Working costs = Machine working costs

Capital expenditure = Installation cost of machine + Screening plant.

For this situation, sorting is generally a very borderline process unless the optimum reject grades are well below the normal plant-residue values.

Conclusions

The development of a radiometric-sorting simulation program is of great importance for the optimization of existing sorters and the prediction of their performance.

The program outlined here indicates the optimum mass reject percentage and the expected reject gold and uranium grades for a radiometric sorter. It achieves this by statistical analysis of the data gathered from a large sample of rocks in the required size range for a particular mine.

The program can highlight the effect of factors such as short radiometric counting time or mechanical inefficiency. It can also highlight the effect of mass measurement in the calculations, and whether other methods of sorting would prove more beneficial. Thus, the program can also be used as a design tool.

Calculated optimum mass reject percentages and reject grades can also be of value in feasibility studies.

Addendum 1: Collection of Data

The computer program, which was developed on an IBM Personal Computer in the BASIC language compiled on the DOS system, statistically sorts the data collected from the analysis of the feed material to a radiometric sorter.

Over a period of one week, a composite sample of about 400 rocks in the correct size range for sorting was collected. Each rock in the sample was weighed and its radiometric counts measured three times over at least a 10-second period. The background count was subtracted from the measured counts to provide the mean count rate for each rock. Each rock was then assayed for gold and uranium.

Once the data have been collected, the program can be run to analyse the feasibility of sorting.

Addendum 2: Radiometric System

The purpose of a radiometric sorting system is to differentiate between, and thus sort, ore particles containing radio-active material above and below a preset concentration or cut-off point.

In the gold-bearing ores of the Vaal Reef, the gold is closely associated with the radio-active element uranium. Therefore, when the ore is sorted for uranium, the gold is sorted indirectly. In uranium-bearing ores, the uranium and its daughter element formed by radio-active decay emit radiation that can then be measured quantitatively and the uranium content assessed. This radiation is proportional to the mass of uranium and its daughter elements present.

Radiation is the random emission of alpha, beta, and gamma particles from a radio-active material. However, only the gamma radiation can be recorded by scintillation counters because of its penetrating power. Uranium itself emits only alpha particles but, fortunately, two of its daughter elements (a lead isotope Pb–214 and a bismuth isotope Bi–214) are strong gamma emitters (Table II).

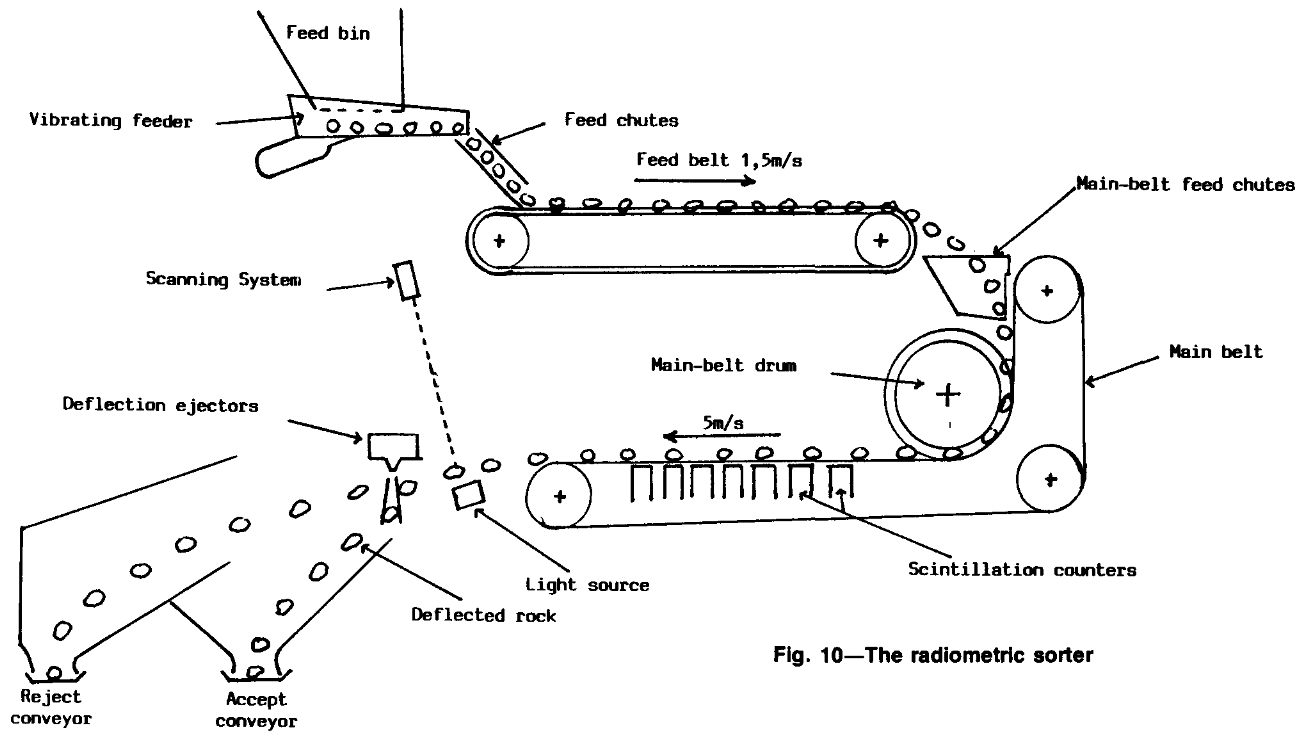


Fig. 10—The radiometric sorter

TABLE II

DISINTEGRATION SERIES OF URANIUM-238

(Only the principal nuclides are included. Nuclides constituting less than 0,2 per cent of the decay products are omitted.)

Nuclide	Decay	*γ-rays*	*β-particles*
Uranium-238 [4,51 × 10^9y]	↓ α		
Thorium-234 [24,10d]	↓ β		
Protactinium-234 [1,14m]	↓ β		
Uranium-234 [2,48 × 10^5y]	↓ α		
Thorium-230 [8,0 × 10^4y]	↓ α		
Radium-226 [1,622y]	↓ α	186 keV	
Radon-222 [3,825d]	↓ α		
Polonium-218 [3,05m]	↓ α		
Lead-214 [26,8m]	↓ β	242 keV 295 keV 352 keV	590 keV 650 keV
Bismuth-214 [19,7m]	↓ β	609 keV 1120 keV 1764 keV	400 keV 1000 keV 1510 keV 1880 keV 3260 keV
Polonium-214 [1,50 × 10^{-4}s]	↓ α		
Lead-210 [22y]	↓ β		
Bismuth-210 [5,02d]	↓ β		
Polonium-210 [138d]	↓ α		
Lead-206 [stable]			

As the concentration of these daughter elements is in fixed proportion to the concentration of uranium present in a particle of ore, the uranium content can be determined by measurement of the gamma emissions.

This measurement is complicated by the presence of a natural background radiation from cosmic rays. Lead shielding round the detectors reduces this background radiation, but the levels remaining must still be taken into account in all the calculations.

The scintillation detector, which measures gamma radiation, consists of a large crystal of radiation-sensitive sodium iodide coupled optically to a photomultiplier tube. When a gamma ray is absorbed in the crystal, a minute pulse of light is generated. The photomultiplier tube converts this light into an electrical signal and amplifies it to give an output voltage that can be recorded as a count.

Addendum 3: Operation of the Radiometric Sorter

The radiometric sorter that was used in this work is shown schematically in Fig. 10.

Material that has been washed and screened into the correct size fraction is fed via a hopper, vibrating feeder, washing screen, and transfer feeder onto a channelled top belt travelling at 1,5 m/s. The rocks are accelerated by gravity off the top belt, hitting the top section of the L-shaped main belt, which is travelling at 5 m/s. The rocks (stabilized by centrifugal force) are presented to a row of scintillation counters, which measure the gamma radiation.

As a rock flies off the end of the main belt, its size and position are determined by a scanning system. A processor determines, from the measurements of size and radio-active counts, the particular grade of that particle. If the grade is above a set cut-off point, the rock is accepted; otherwise, it is rejected. A high-pressure air nozzle is used to deflect reef rocks into an accept bin, while the waste rocks fly untouched into a reject bin.