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Cutoff grade determination for mines producing direct-shipping iron ore

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ABSTRACT

A number of high grade ores such as iron are sold at defined marketing grade specifications. The traditional cutoff grade theory cannot be used with these ores as the direct-shipping grades are fixed by the sale contract. The optimum cutoff grade for these cases is redefined as the grade that maximizes the marketable reserves.

A method is described in this paper to determine these optimum cutoff grades for iron ore mines producing direct-shipping ore. An iterative approach is developed which allows the maximization of marketable reserves while maintaining the grades of iron and impurities of silica and alumina within market contract specifications. The larger reserves allow a longer mine life and increased operation profitability.

Keywords: *Blending, cutoff grade, grade-tonnage curves, iron ore.*

INTRODUCTION

The grade distribution is never perfectly uniform within a mineral deposit. Areas of high grade mineral concentration are often found intermixed with areas of lower concentration, and there may be an erratic trend with subeconomic levels of mineral concentration towards the boundaries of the deposit. Under these conditions, some form of selective mining is usually practised. In order to select what to mine as ore and what to consider as waste, a cutoff grade policy has to be determined. Taylor (1972) defined cutoff grade as "any grade that for any specified reasons, is used to separate two courses of action, e.g. to mine or to leave, to mill or to dump". Only that material with a grade above the cutoff grade is mined as ore, and selection is usually made on "ore blocks" or "parcels" which are bodies of material large enough to be wholly selected or rejected by the mining system. Ore block or parcel size is determined during the ore reserve estimation study, and depends on the nature of mineralization, and the density of sampling.

In mine valuation it is important to determine a cutoff grade which achieves the financial objectives of the company and maximises the total profits. With the traditional cutoff grade theory as applied to base metal deposits, the mill head grade can be adjusted according to the orebody characteristics and the economics of the mining operation. It has been shown by a number of authors that a maximum present value policy requires a declining cutoff grade. Studies on cutoff grade theory usually fall into two basic categories. The fixed cutoff grade concept assumes a static cutoff for the life of a mine, while the variable cutoff grade concept assumes a dynamic cutoff maximizing the mine net present value. Callaway (1958), Vickers (1961), Carlson *et al.* (1966), Erickson (1968), Halls, Bellum and Lewis (1969), Soderberg and Rausch (1968), Plewman (1970), Douglass (1971) and Nilsson (1982), adopt a fixed cut-off grade approach, whereas Henning (1963), Lane (1964, 1979), Johnson (1969), Noren (1969), Blackwell (1971), Taylor (1972), Roman (1973), Elbrond and Dowd (1976), Wells (1978) and Rudenno (1979), favoured a variable cutoff grade concept.

These approaches, however, are not directly applicable to high grade deposits of iron where the direct-shipping ore grades are fixed and defined by the contract grade specifications. Therefore, the usual definition of cutoff grade for these ores is different. For these, Royle (1981) defined the "economic optimum" as the "maximum tonnage of ore reserves with a mean grade above a given cut-off grade". Royle's approach with slight modification will be used in this paper, and the optimum cutoff grade is defined as the grade of ore that maximises the marketable reserves of ore.

GENERAL REQUIREMENTS

The following are required before any cutoff grade determination can be made.

Reliable ore block estimates

Reliable ore block values are essential for any mining project and most estimation approaches use geometric, distance-weighing and geostatistical methods. Distance-weighing and geostatistical techniques have become popular since the advent of computers. David (1977), Journel and Huijbregts (1978), Barnes (1979), and Hughes and Davey (1979), provide detailed descriptions of these techniques. The selection of an ore block size is an important factor in the determination of orebody values. This decision is influenced by considerations of the density of sampling, type and nature of mineralization and the size of mining equipment. Once reliable ore block estimates have been obtained, they are stored in a mineral inventory file. This file is later updated with the design of the open pit to exclude those blocks which lie outside the pit limits.

Grade-tonnage curves

The ore block grades and tonnages in the mineral inventory file and some cutoff grades selected incrementally across a suitable range are used to calculate the total tonnages and the average grades of orebody reserves above each cutoff grade point. These values are plotted to produce grade-tonnage curves.

Three hypothetical iron ore deposits, one major (X) and two smaller (Y and Z), have been evaluated and the values of ore blocks with dimensions of 15 m × 25 m × 12 m within the relevant pits have been used to produce the grade-tonnage curves shown in Figs. 1, 2, and 3. On these curves, the grades for iron and for the impurities of silica and alumina have been plotted. A specific gravity of 4.0 tonne/m^3 for ore has been assumed.

Marketing contract grade specifications

The direct-shipping grades of ore are defined in international trade by the marketing contract specifications and there usually exists a long-term contract between the buyer and the producer. The marketing grade specifications normally include some tolerance limits before any kind of penalty is imposed. The principal metal, iron, has a minimum acceptable average grade, whereas the impurities which are silica and alumina in this study are limited by the maximum allowable grades.

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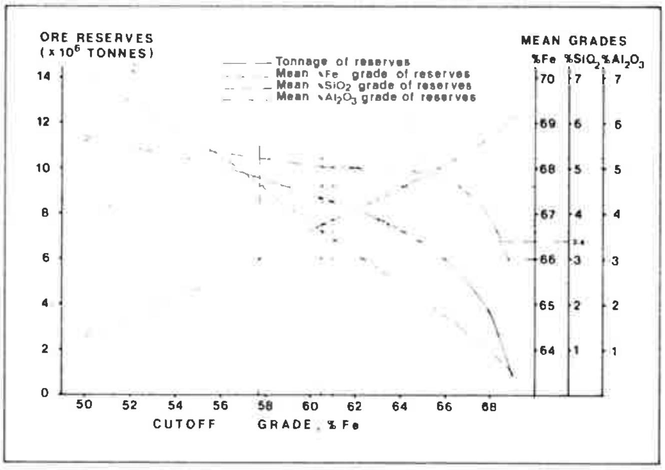

FIG. 1—Grade-tonnage curves for pit X.

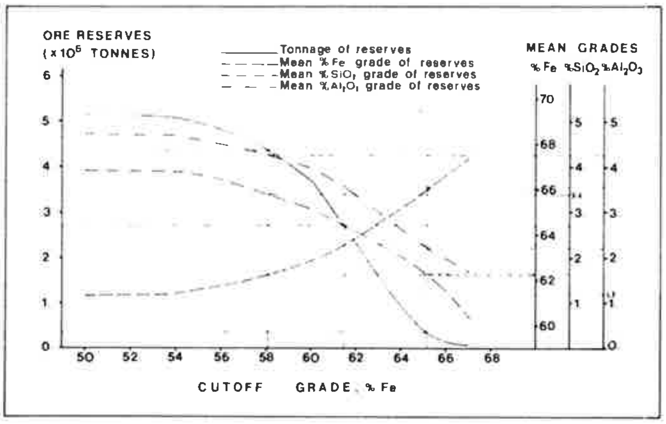

FIG. 2—Grade-tonnage curves for pit Y.

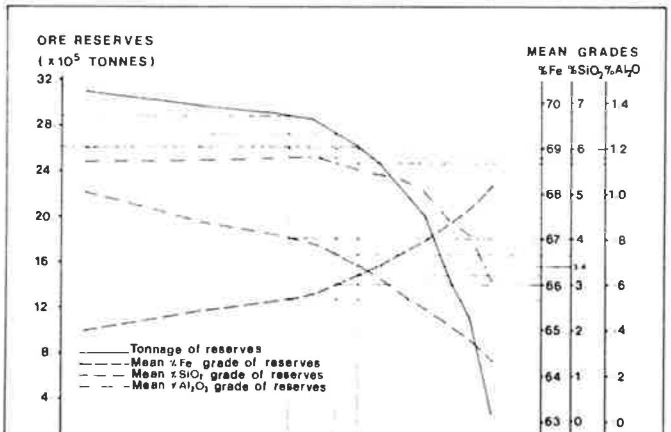

FIG. 3—Grade-tonnage curves for pit Z.

The following contract grades are assumed in this paper; iron grade minimum 66.0 per cent; silica and alumina maximum 3.4 and 1.2 per cent respectively, and these are considered to be critical decision grades.

DETERMINATION OF CUTOFF GRADES

Simple case: ore from a single source

The cutoff grade for a mine producing ore from a single source is obtained in the following way. With the single source of ore being pit X, horizontal lines are drawn on grade-tonnage curves (Fig. 1) from the critical grades until they intersect the corresponding average reserve grade curves. From these points, vertical lines are dropped and the cutoff (per cent Fe) grade corresponding to the critical grades are read. Further, these vertical lines are extended to intersect the reserve tonnage and average grade curves and appropriate values determined as shown in Table 1.

As the critical grades are minimum marketing requirements, the highest of the cutoff (per cent Fe) grade values (corresponding to either iron, silica or alumina) is the optimum cutoff grade which satisfies the contract requirement. From Table 1, it can be seen that the optimum cutoff (per cent Fe) grade for pit X is 61.0 per cent. In other words, the impurity silica content is the restricting influence on the cutoff grade.

Ore from several sources

The three pits X, Y, and Z are assumed to be mined to produce the marketable ore. The pits are first analysed individually in order to determine their prospects as individual sources of marketable ore. The cutoff grades, reserve tonnages and average grades are determined at the critical grades, in the same manner as detailed for ore from a single source and results are tabulated in Tables 1, 2, and 3. The overall reserves are calculated for the highest feasible cutoff grades for each pit and are set down in Table 4.

Examination of the average grades for overall reserves in Table 4 shows that while the silica grade is almost at the critical level, that for iron is 0.70 per cent higher and that for alumina is 0.56 per cent lower than their restricting grades. As a consequence, the total ore reserves can be increased with the inclusion of low iron and high alumina content material while maintaining critical grade levels. By referring to the grade-tonnage curves, pit Y appears potentially suitable as a source of additional material because of its low iron and high alumina grades. As a check, it is seen that the silica content of this pit will not detrimentally affect average grades. By decreasing the cutoff (per cent Fe) grade for pit Y gradually in stages to 61.6 per cent and calculating reserve tonnage and average grades at every step from the grade-tonnage curves in Fig. 2, additional tonnage is added to overall reserves and the results after this inclusion are shown in Table 5. Any further addition of material from pit Y at this stage will push the overall reserve alumina grade past its critical point.

The total reserves in Table 5 can be increased further by adopting this iterative approach to bring both iron and all impurity grades towards their critical levels. An increase in the silica impurity grade close to its critical value of 3.4 per cent can be achieved by including some more ore from pits whose grades are high in silica and low in alumina, such as pits X and Z. The correct choice of pit will maximise the marketable reserves and can be achieved by adding tonnage from either pit X or Z while allowing minor balancing adjustment from pit Y in order to keep the overall alumina grade close to its critical level. To implement this procedure, the cutoff (per cent Fe) grade for pit X was gradually lowered to a level of 60.5 per cent by holding the

TABLE 1
Critical grades and the corresponding cutoff (%Fe) grades, and reserve values obtained from the grade-tonnage curves for pit X.

	Critical contract grades (%)	Cutoff grade (%Fe)	Ore Reserves				Remarks
			Tonnes (× 10³)	Average grades			
				%Fe	%S_iO_2	%Al_2O_3	
Iron	66.0	57.7	9 600	66.00	4.60	0.52	Silica grade too high.
Silica	3.4	61.0	8 500	66.85	3.40	0.50	Satisfies the grade requirement at critical silica grade.
Alumina	1.2	<50.0	>11 200	<64.30	>6.95	1.20	Iron grade is too low, and silica grade is too high.

TABLE 2
Critical grades and the corresponding cutoff (%Fe) grades, and reserve values obtained from the grade-tonnage curves for pit Y.

	Critical contract grades (%)	Cutoff grade (%Fe)	Ore Reserves				Remarks
			Tonnes (× 10³)	Average grades			
				%Fe	%S_iO_2	%Al_2O_3	
Iron	66.0	65.2	350	66.00	1.65	2.20	Alumina grade is too high.
Silica	3.4	58.1	4 350	62.25	3.40	4.25	Iron grade is too low and alumina grade is too high.
Alumina	1.2	>67.0	<50	>67.35	<0.70	1.20	Grades satisfactory but tonnage is too low (negligible).

TABLE 3
Critical grades and the corresponding cutoff (%Fe) grades, and reserve values obtained from the grade-tonnage curves for pit Z.

	Critical contract grades (%)	Cutoff grade (%Fe)	Ore Reserves				Remarks
			Tonnes (× 10³)	Average grades			
				%Fe	%S_iO_2	%Al_2O_3	
Iron	66.0	61.1	2 720	66.00	3.65	1.17	Silica grade too high.
Silica	3.4	62.1	2 610	66.20	3.40	1.10	Grades are satisfactory.
Alumina	1.2	<50.0	>3 100	<65.00	>5.05	1.20	Iron grade too low and silica grade too high.

pit Z cutoff grade fixed at the same value as achieved in Table 5 but by allowing minor adjustment in the pit Y tonnage contribution. With this exercise, cutoff (per cent Fe) grades have been achieved which produce feasible overall average grades that are within the contract requirements. Results are set down in Table 6 and indicate an overall reserve of 13 960 000 tonne and overall average grades which are very close to the critical contract grades and so further iterative steps are unnecessary. Similarly, a study was undertaken where pit X values were held constant at the same level as in Table 5. These results are shown in Table 7 and overall reserves of 13 930 000 tonne were calculated. As this value is lower than that derived by the inclusion of material from pit X, it was disregarded. The final results obtained were optimum cutoff (per cent Fe) grades of 60.5 per cent for pit X, 61.5 per cent for pit Y and 62.1 per cent for pit Z and overall reserves of 13 960 000 tonne.

DISCUSSION AND PRACTICAL APPLICATIONS

The method described in this paper is applicable to high grade ores such as iron that are mined to produce direct-shipping ore. As the minimum grade of direct-shipping ore is fixed by contract, the most important parameters controlling the profitability of a mining operation are the sale tonnage, price, operating and fixed costs and the life of the mine. If production rate, price and costs are assumed constant, the most important factor which affects the profitability of a mine is its production life which, in turn, is controlled by the effective use of available reserves. The available reserves are best utilised through the selection of the correct cutoff grades which maximise the reserves and so increase the life and the profitability of the mine. The optimum cutoff grades can be determined successfully and relatively easily by the outlined method with the aid of a computer.

TABLE 4
The maximum feasible cutoff (%Fe) grades and the reserve values for pits X, Y and Z

Pit	Cutoff grade (%Fe)	Reserves Tonnes (×10³)	Average grades %Fe	%S_iO_2	%Al_2O_3
X	61.0	8 500	66.85	3.40	0.50
Y	>67.0	<50	>67.35	<0.70	1.20
Z	62.1	2 610	66.20	3.40	1.10
Total/ Average		11 160	66.70	3.39	0.64

TABLE 5
The cutoff (%Fe) grades and reserve values for pits X, Y and Z at an intermediate stage of the iterative procedure

Pit	Cutoff grade (%Fe)	Reserves Tonnes (×10³)	Average grades %Fe	%S_iO_2	%Al_2O_3
X	61.0	8 500	66.85	3.40	0.50
Y	61.6	2 670	63.60	2.68	3.50
Z	62.1	2 610	66.20	3.40	1.10
Total/ Average		13 780	66.10	3.26	1.20

TABLE 6
Cutoff (%Fe) grades and reserve values with the inclusion of additional material from pits X and Y. These form the optimum cutoff grades, pit and overall reserve values.

Pit	Cutoff grade (%Fe)	Reserves Tonnes (×10³)	Average grades %Fe	%S_iO_2	%Al_2O_3
X	60.5	8 650	66.75	3.60	0.50
Y	61.5	2 700	63.55	2.70	3.55
Z	62.1	2 610	66.20	3.40	1.10
Total/ Average		13 960	66.03	3.39	1.20

TABLE 7
Cutoff (%Fe) grades and reserve values with the inclusion of additional material from pits Y and Z.

Pit	Cutoff grade (%Fe)	Reserves Tonnes (×10³)	Average grades %Fe	%S_iO_2	%Al_2O_3
X	61.0	8 500	66.85	3.40	0.50
Y	61.7	2 550	63.65	2.65	3.50
Z	59.0	2 880	65.65	4.00	1.18
Total/ Average		13 930	66.02	3.39	1.19

However, there have been a number of assumptions made in applying this method. In the example given in this paper, the cutoff grades are determined for the hypothetical pits through use of pit grade-tonnage curves. This, of course, involves an assumption that all ore blocks with average grades above the optimum cutoff grades are mined from the pit or pits and are available for blending. If the grade distribution of ore between the benches within the individual pits is not great, then the optimum cutoff grades provide a practical guide for quality control. However, in the situation where the grade distribution between the mining benches within a pit varies significantly and a large tonnage blending of ore is not an economical proposition, the method can still be used. In this case, instead of using the grade-tonnage curves for the whole pit, the curves for a selected number of benches that are likely to be mined within a short period such as a year can be used to determine the cutoff grades applicable for those benches. This will mean that rather than there being one fixed cutoff grade for the whole pit, different cutoff grades may be employed for different benches or a group of benches to give the most practical and economical blending combinations.

CONCLUSIONS

The traditional approach to the cutoff grade theory is not directly applicable to some high grade ores such as iron which are sold as direct-shipping ores. The minimum grades of direct-shipping ore are defined and fixed by a contract, which is usually on a long term basis.

The marketable ore reserves and other factors such as the production rate, price of direct-shipping ore per tonne and the operating and fixed costs form the most important factors affecting the profitability of a mine. Maximizing the marketable reserves means a longer mine life and a higher profitability level. An iterative approach is developed to calculate the optimum cutoff grades which maximise the marketable reserves while maintaining the grades of iron and impurities of silica and alumina within the marketing contract specifications. The method described in this paper can be successfully applied to mines whether the direct-shipping ore comes from one pit or several pits. The cutoff grades determined by this method can be used by quality control personnel as a guide and by mine planning engineers in the preparation of mining extraction schedules.

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