THE ECONOMICS OF BENEFICIATING COPPER OXIDE ORES PRIOR TO LEACHING

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Except in unusual circumstances, copper ores must be beneficiated prior to smelting. In leaching however, ores are often processed without prior beneficiation, and beneficiation may not even be considered as a preparatory step.

With mixed ores, flotation has been used to segregate the oxide and sulphide components[1] to avoid sulphur deficiency in the smelter, but for such processing, the chief oxide mineral must be malachite. Oxide ores of chrysocolla and other copper silicate minerals unfortunately cannot be concentrated by conventional upgrading techniques.

Only two examples are available, each having unique and unusual features. At Nchanga, Zambia,[2] low-grade (4-10% Cu) oxide concentrates and high-grade (0.4-0.6% Cu) tailing material consisting of chrysocolla and cupriferous vermiculite were stock-piled for many years, to await future processing. Today, modern solvent extraction technology is employed to economically recover copper from these materials.

List of symbols

A = Acid consumption rate (kg/mt of leach plant feed)
CC = Capital costs (1979 \$ x 10^6)
CF = Annual cash flow (1979 \$ x 10^6)
Cop = Annual operating costs (1979 \$ x 10^6)
D = Annual depreciation (1979 \$ x 10^6)
$DCFROR$ = Discounted cash flow rate of return (%)
F = Present value factor
H_0 = Copper head grade (%Cu)
H_L = Leach plant feed grade (%Cu)
i = Interest rate (fractional)
i^* = Desired interest rate (fractional)
NPV = Net Present Value (1979 \$ x 10^6)
n = Project lifetime (years)
P = Copper production rate (mtpd)
R_B = Beneficiation plant tonnage rate (mtpd)
R_L = Leach plant recovery (%)
Rev = Annual revenue (1979 \$ x 10^6)
T_B = Beneficiation plant tonnage rate (mtpd)
T_L = Leach plant tonnage rate (mtpd)

At Twin Buttes, Arizona,[3] flotation can be used to recover up to 80% of the copper in oxide ores at a ratio of concentration of 5 to 10. This result was considered unacceptable, with acid consumption varying between 200 and 400 Lb per ton, and so an alkali leach process was developed. Currently the availability of cheap acid allows direct leaching with sulphuric acid.

The Twin Buttes experience suggests that the concentrate-grade constraint should be examined. Certainly, a decline in acid consumption together with a reduction in leach plant size might justify the addition of a beneficiation plant. However, the process conditions at which beneficiation is viable need to be defined.

In this light, this paper presents an economic model for treating oxide copper ores. The model is derived from available data on current operating plants and examines two cases where beneficiation could be applied: 1) in the development of a new orebody, and 2) by the addition of a beneficiation plant to an existing operation.

BASIC MODEL EQUATIONS

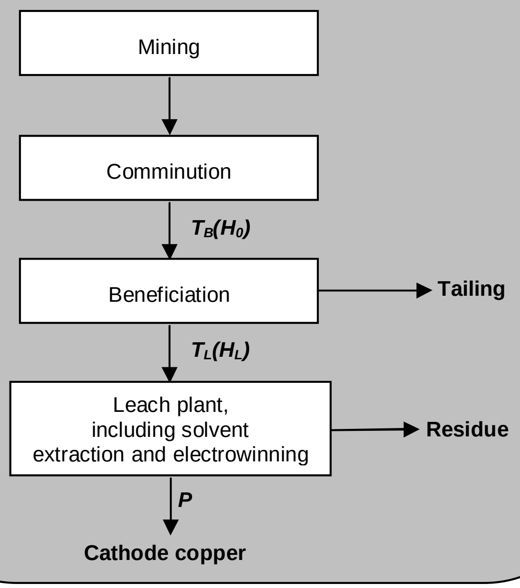
The tonnage rate to a beneficiation plant T_B, in metric tons per day, can be expressed in terms of four variables: copper production rate P, in metric tons per day; ore feed grade H_0, in percent copper; beneficiation plant recovery R_B, as a percentage; and leach plant recovery R_L, as a percentage:

$$T_B = \frac{P}{H_0 R_B R_L} \times 10^6 \tag{1}$$

Similarly, the leach plant feed rate T_L, in metric tons per day, can be expressed in terms of three variables: copper production rate P, in metric tons per day; leach plant feed grade H_0, in percent copper; and leach plant recovery R_L, as a percentage:

$$T_L = \frac{P}{H_L R_L} \times 10^4 \tag{2}$$

Fig. 1–Process steps in economic model for processing chrysocolla ores



By fixing the value of P, H_0, and R_L, at 150, 1.0, and 85, respectively, the two tonnage rates can be expressed simply as a function of the beneficiation plant performance:

$$T_B = \frac{17{,}650}{0.01 R_B} \tag{3}$$

$$T_L = \frac{17{,}650}{H_L} \tag{4}$$

Clearly, when $H_L = H_0$, then $T_B = T_L$ and $R_B = 100\%$; and the beneficiation plant is not part of the process flowsheet (Fig. 1).

ECONOMIC CRITERIA

For convenience, the deposit in this study is considered to contain 127.1 million mt of ore, yielding a 20-year lifetime for a leach plant operating 360 days and with no beneficiation of feed. The head grade selected for the example, 1.0% Cu, is typical for an oxide copper porphyry deposit, while the leach plant recovery of 85% is typical for an ore of the type to be evaluated, one with high acid consumption characteristics.[3]

The model is analyzed by comparing the leach plant operating alone to one operating with beneficiated feed. Evaluation, in terms of concentrate grade and recovery, is made at a variety of performance levels.

Net Present Value (NPV) is used as the economic criterion for comparing projects to avoid errors that can occur using a discounted cash flow rate of return (DCFROR) alone for project alternatives with unequal lives and different investment levels.[4] These factors are calculated as follows:

Annual Cash Flow

$$CF = (1 - t)(Rev - Cop) + tD \tag{5}$$

Present Worth Factor

$$F = CC / CF \tag{6}$$

By trial and error, a suitable value of "i" is found from:

$$F = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{7}$$

Then:

$$DCFROR = 100i \tag{8}$$

Net Present Value is obtained by selecting a desired value of i^* and solving equation (7) for $F(i^*)$. So, for zero salvage value:

$$NPV = CF[(F(i^*)] - CC \tag{9}$$

To study the base case, the following assumptions are made:

1. **Revenue** is based on a cathode copper price of \$1,875 per mt (85¢ per lb).
2. Annual **depreciation** of capital costs is calculated by the straight line method.
3. A **tax rate** of 50% is used for simplicity.
4. The evaluation is made in 1979 **US dollars**, with the expectation that the effect of inflation on income will exactly wash out its effect on operating costs.
5. For simplicity, **salvage value** is assumed to be zero.
6. **Depletion allowance**, a significant tax deduction in many countries, is not used in this analysis.
7. **Capital costs** are scaled to tonnage rate, using an exponent value of 0.6.[5]
8. Mining, grinding, and beneficiation plant **operating costs** are taken as totally variable (i.e., no fixed costs) over the range of tonnage rates studied.

In most comparisons an interest rate of 10% was used to calculate NPV. However, in some cases, a lower interest rate was required to ensure the comparison of two alternate projects was made with a positive NPV for at least one option. For a mining venture of this type, *10% would not be a satisfactory rate of return*. However, it must be remembered that the economics for development of the orebody considered in this study would be marginal, at best, using current technology. By relaxing some of the assumptions listed above, the DCFROR would increase. For example, accelerated depreciation and depletion allowance together could improve the base case rate to 15%. Leverage could also raise the rate to an acceptable value.

CAPITAL COST ITEMS

The capital costs used are shown in Table 1. All costs have been inflated into 1979 US dollars using the Marshall and Stephens Equipment Index from Chemical Engineering. Mining costs were obtained from Bell Copper in British Columbia.[6] This cost estimate can be viewed as high, because an oxide deposit of similar size would be unlikely to require the amount of site preparation required at the Bell Copper mine, where preproduction stripping totalled 10 million st.

Crushing and grinding costs are taken from the Gibralter mine in British Columbia.[7] The work index of an oxide ore would probably be much lower than Gibralter ore, but the required product size would be finer. Thus scale-up is related to tonnage rate alone. In addition, for simplicity, the crushing and grinding requirements for direct leaching have been assumed to be equivalent to those for beneficiation.

The capital costs of the beneficiation process are based on data for the Magnex Process.[8] Since this item is a key issue, the sensitivity of the model to this variable is examined.

Leach plant costs are based on the tailing treatment plant commissioned in 1973 at Nchanga in Zambia.[9] This source

Table 1–Derivation of capital costs

(base case: $T_B = T_L$ = 17,650 mtpd)

Item	Source	Year	Amount ($ x 10^6)	Inflation Factor	Tonnage Factor	Capital Cost (1979 $ x 10^6)
Mining	Bell Copper	1969	16.8	$\left[\frac{600}{286}\right]$	$\left[\frac{17{,}650}{9{,}070}\right]$	52.4
Crushing-grinding	Gibraltar	1970	17.0	$\left[\frac{600}{303}\right]$	$\left[\frac{17{,}650}{43{,}000}\right]$	19.7
Beneficiation	Magnex	-	-	-	-	15.2
Leach plant*	Nchanga	1969	(23.8 + 0.073*A*)	$\left[\frac{600}{286}\right]$	$\left[\frac{17{,}650}{30{,}000}\right]$	(36.3 + 0.111*A*)
SX/EW	Nchanga	1969	16.8	$\left[\frac{600}{286}\right]$	$\left[\frac{150}{150}\right]$	76.3

* for A = 175 kg per mt of feed; the total costs (base case) are $204.1 million.

was especially useful, because separate costs were available for acid handling facilities. As a result the capital costs have been scaled according to tonnage rate and acid consumption.

The costs for the solvent extraction plant and electrowinning tankhouse are also taken from Nchanga. In this case, the cost is scaled to copper production rate.

The data in Table 1 show total capital costs of $204 million (1979) for a leach plant operating alone. A recent independent estimate[10] of the capital required for a leach plant producing 50,000 mtpy has been given as $120 million (1978). Converting this to 1979 dollars for a plant producing 150 mtpd and adding in the mining cost gives a total development cost of $191 million (1979). Clearly the individual costs are in line with the independent estimate.

OPERATING COSTS

The operating costs using in this model are as shown in Table 2. The sources for each cost items are the same as those for the capital requirements, respectively, with the exception of the mining cost. The mining cost estimate, including maintenance and replacement, for oxide ores is taken from Sudderth.[11] The operating costs for mining, comminution, and beneficiation have all been taken as variable over the range of tonnage rates examined. Clearly, should the proportion of fixed to variable costs be high, the economic comparison would improve significantly.

The leach plant operating cost is broken down into three elements: two variable cost components, with one based on acid consumption; and one fixed component, based on Cu production.

All cost items were converted into 1979 dollars, using the CHEMICAL ENGINEERING Plant Index. This treatment may seem harsh, but it was considered a realistic manner for working with data from such a variety of sources. Recent data on copper production verify the validity of this approach. With an acid consumption of 175 kg per mt for direct leaching, the total operating costs are $9.66 per mt of ore, or 52¢ per lb of copper. Anamax recently reported an overall cost of 60¢ per lb of copper for its Twin Buttes leach operation.[13]

BASE CASE: LEACH PLANT ALONE

Using the above cost data, the base case produces the following economic results:

Annual revenue = $101.2 million
Annual operating costs = $61.4 million
Capital costs = $204.1 million
DCFROR = 10.6%
NPV at 10% = $8.8 million.

With these results, the project would likely be unacceptable to most developers, who demand a DCFROR of at least 15% for most mining ventures. It is important then, to determine and understand the sensitivity of the model to changes in the key parameters. To do this, the model has been evaluated for high and low values of each key variable in turn (Table 3).

Acid consumption. With a unit cost of 2.95¢ per kg ($26.75 per st), the data in Table 3 shows that the project becomes unacceptable as acid consumption exceeds 110 kg per mt.

Table 1–Derivation of operating costs

(base case: $T_B = T_L$ = 17,650 mtpd)

Item	Source	Year	Amount ($/mt ore)	Inflation Factor	Capital Cost (1979 $/mt ore)
Mining	Sudderth	1974	0.85	$\left[\frac{230}{165}\right]$	1.18
Crushing-grinding	Gibraltar	1973	0.36	$\left[\frac{230}{144}\right]$	0.58
Beneficiation	Magnex	-	-	-	2.45
Leach plant*	Nchanga	1974	$\left(\frac{178P}{T_L}+0.45\right)$	$\left[\frac{230}{165}\right]$	2.74
Acid cost*	-	-	-	-	0.0295*A*

* for A = 175 kg per mt of feed; the total operating costs (base case) are $9.66 per mt of ore.

Table 3–Sensitivity of base case economics

Acid consumption		Copper production	
kg/mt	DCFROR %	mtpd	DCFROR %
12.5	21.0	150	10.6
125	14.0	187.5	11.3
175	10.6	225	11.7
225	7.3	300	12.2
Copper price		**Ore reserves**	
¢/lb	DCFROR %	mt x 10^6	DCFROR %
70	4.7	63.6	7.8
85	10.6	95.3	9.9
100	15.6	127.1	10.6
Head grade		**Leach plant recovery**	
%Cu	DCFROR %	%	DCFROR %
0.8	6.0	85	10.6
1.0	10.6	90	11.8
1.2	14.0	95	13.1

If the cost of acid is high, say 5.5¢ per kg ($50 per st), the overall operating costs at an acid consumption of 65 kg per mt would equal those at 125 kg per mt using cheap acid. Although capital costs are lower by $7 million, the rate of return is only slightly higher.

Thus both acid cost and the level consumption are critical variables in defining the economic viability of this project.

Copper price. During most of the past decade, copper prices have fluctuated between 50¢ and 70¢/lb, having reached a high of $1.25 in 1974 and a low of 50¢ in 1976. In the past year, prices have fluctuated around the $1-per-lb level.

Table 3 shows an acceptable project only when copper sells at ~98¢ per lb. Without this price, any copper venture is likely uneconomic, unless head grade is unusually high.

Head grade. The copper content of the orebody is an important variable in defining the economics of the project. At the price of copper and acid consumption used in the base case, the head grade would have to be 1.27% Cu before the project could be considered attractive.

Copper production rate. As the copper production rate increases from 150 to 300 mtpd, the model yields a small increase in DCFROR. Since the lifetime of the project falls to less than 10 years at higher rates of production, the rate of return exhibits a peak at about 300 mtpd. However, extrapolation to higher production rates cannot be considered strictly valid, since the largest current SX-EW plant produces 150 mtpd.[11]

Ore reserves. Provided the project has at least a 15-year life, the size of the deposit has a minor effect on project economics.

Leach plant recovery. Variations in leach plant recovery produce an effect similar to variations in head grade, with the additional feature of increasing the project lifetime as recovery increases. However, recovery is not likely to change to the same extent as head grade.

CASE 1: A NEW DEVELOPMENT

In the following discussion, the key factors discussed above for the base case (leach plant alone) are comparable with a case in which a new project is developed with a beneficiation plant ahead of the leach plant. The beneficiation plant is evaluated at various performance levels, with performance defined in terms of concentrate grade and recovery. The critical question is:

At what level of performance are the reduction in leach plant capital and operating costs economically equivalent to the additional mining, comminution, and beneficiation costs?

The analysis is presented in the form of grade/recovery curves (Figs. 2-5), which separates the regions of beneficiation plant performance that have better and worse economics than that of direct leaching. If the beneficiation plant performance lies to the right of the curve, then the use of beneficiation instead of direct leaching is recommended.

The cross-hatched box in each diagram indicates the area of beneficiation performance reported for Twin Buttes ore using flotation.[3] This ore has properties similar to those of the ore being considered in this study. The three points on each diagram at a recovery of 90% signify the concentrate grade required to achieve a 15% DCFROR for the indicated conditions.

Acid consumption. Fig. 2 shows the effect of acid consumption on the required beneficiation performance. As consumption increases, the necessary grade/recovery is less stringent. At the medium and high values selected (curves A and B), the results for Twin Buttes ore are acceptable. Also note that a DCFROR of 15% can be obtained at a consumption of 125 kg per mt, with a concentrate grade as low as 4% Cu at 90% recovery.

The data in Fig. 2 are based on the assumption that acid consumption per metric ton of leach plant feed remains constant irrespective of the beneficiation plant performance. In fact, acid consumption will probably decrease as material is rejected during beneficiation, especially if selectivity is achieved between copper mineralization and acid-consuming gangue. This will improve the situation depicted in Fig. 2.

On the other hand, use of some beneficiation techniques conceivably might lead to an increase in acid consumption per metric ton of leach plant feed after upgrading.[8] For such situations, a worst-case effect can be evaluated by assuming a constant change in acid consumption per metric ton of feed regardless of the beneficiation plant performance. Fig. 3 shows this effect for two possible changes: 175 → 200 kg of acid and 175 → 350 kg of acid per mt of feed.

The diagram shows that acid consumption rate would have to double before serious changes in the required performance levels occur. This degree of change is extremely unlikely.

Beneficiation plant operating costs. The cost of operating the beneficiation plant is significant, as is shown in Fig. 4. As the cost increases above $3.50 per mt, the performance level required to produce an equivalent net present value rises above the area of success reported for Twin Buttes ore. Also, to achieve a 15% DCFROR for the project at this level of beneficiation operating expense, a very high grade/recovery relationship is required – 21% Cu at 90% recovery.

Some reduction in this effect will occur if there is a high proportion of fixed to variable costs in the process, but this condition is unlikely for most beneficiation processes that would be considered. Nevertheless, the Magnex Process has been reported to be able to meet this cost constraint.[8]

Beneficiation plant capital cost. Fig. 5 shows that increasing the capital cost of beneficiation by as much as 50% does not severely influence the required beneficiation performance.

Other variables. The effects of all other key parameters on the comparison are minor. An increase in copper price and/or a decrease in head grade cause a minor decrease in the required level of beneficiation performance.

Case 1: A new development

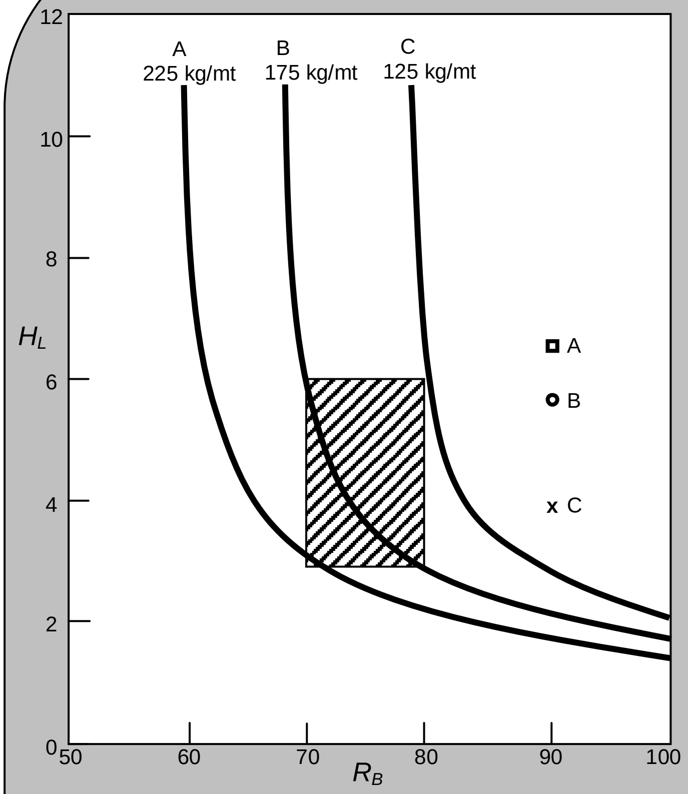


Fig. 6–The effect of leach plant recovery on the beneficiation performance required to achieve a DCFROR of 15%.

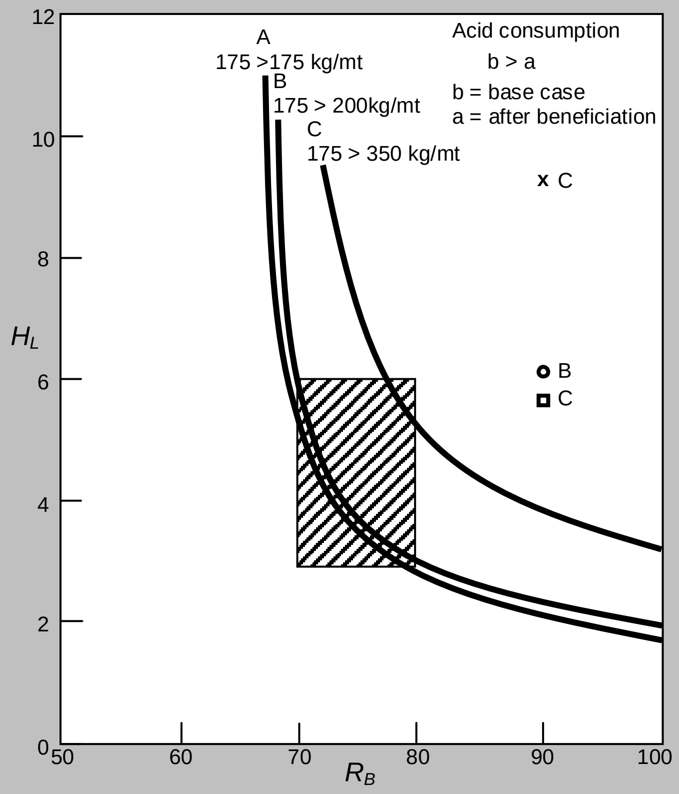


Fig. 7–The effect of acid consumption rate on the beneficiation performance required to achieve a DCFROR of 15%.

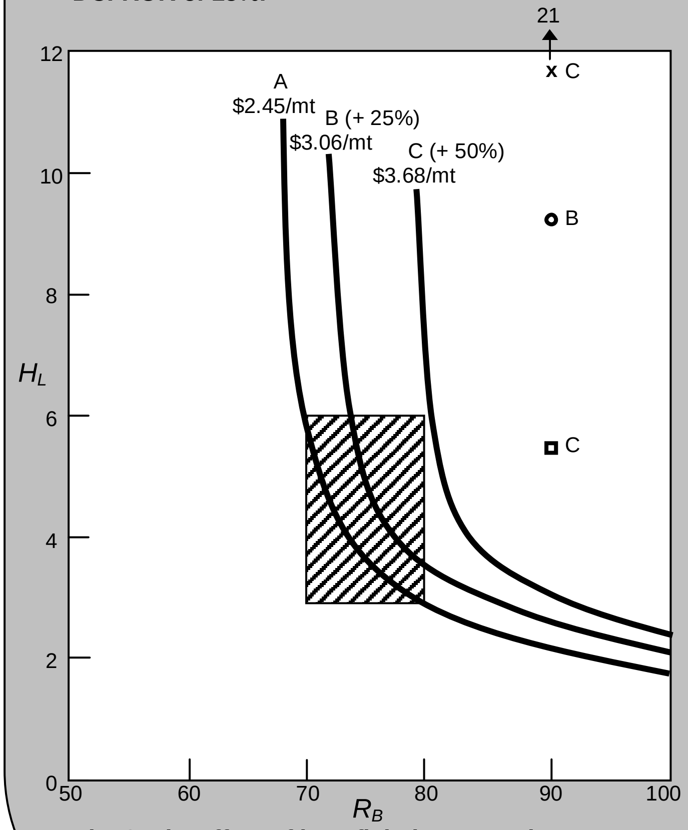


Fig. 8–The effect of beneficiation operating cost on the beneficiation performance required to achieve a DCFROR of 15%.

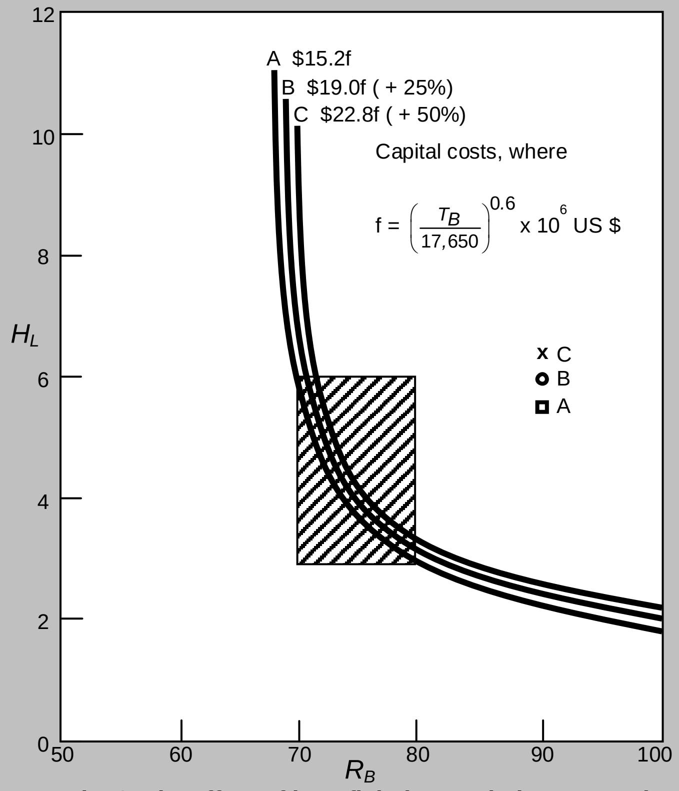


Fig. 9–The effect of beneficiation capital costs on the beneficiation performance required to achieve a DCFROR of 15%.

Copper production rates and/or leach plant recovery changes have negligible effects on the comparison. However, an increase in either variable improves the ability of the beneficiation plant to significantly increase the rate of return. For example if the copper production rate increases to 225 mtpd or the leach plant recovery improves to 95%, a 15% DCFROR is obtained when concentrate grade is as low as 3.1% Cu at a recovery of 90%.

CASE 2: PLANT ADDITION

For an existing leach plant, the question becomes: *At what performance levels is 15% DCFROR obtained on an investment in a beneficiation plant from a reduction in acid and other leach plant operating costs?*

In this case, no reduction in leach plant size can be obtained, since the facility already exists. Thus the incremental investment can only be justified from savings in operating costs.

Lower operating expenses are obtained in two ways: 1) from a direct reduction in the cost of acid and other variable leach plant items; and 2) from an increase in leach plant recovery due to increased residence time.

As in Case 1 above, the evaluation is presented in terms of grade/recovery curves (Fig. 6-9). In this instance, each curve represents the beneficiation conditions that are required to generate a 15% DCFROR at the parameter levels shown.

The effects of copper price, head grade, and copper production rates were shown to be minimal for Case 1 over the range of values studied. Since their major influence occurs with revenue, these variables are not examined here. Leach plant recovery, acid consumption, and beneficiation operating and capital costs are the key variables in this case.

Leach plant recovery. Although leach plant recovery will probably increase if the plant feed is beneficiated, the relationship between leaching recovery and beneficiation recovery cannot be defined with sufficient accuracy.

The effect of change in beneficiation recovery can be partially explained by assuming a constant change in leach plant recovery after a beneficiation step is added, regardless of the beneficiation recovery level.

The results of this analysis are shown in Fig. 6. As was found in Case 1, if the leach plant recovery does not change (Curves A and D), the required beneficiation performance does not change, regardless of the *level* of leach plant recovery. However, with beneficiation results reported for ores of this type, a change in leach plant recovery must occur. As shown by Curves B and C, a 5-10% increase in recovery is necessary.

In reality, at high levels of beneficiation plant recovery, the system will approach the performance represented by Curves A and D, while at lower recovery levels ($R_B < 80\%$), Curves B or C would be more typical.

For the remainder of this analysis, the conditions depicted by Curve C are used.

Acid consumption rate. The higher the initial acid consumption rate, the easier it is to justify beneficiation (Fig. 7). The graph shows the model to be very sensitive to acid consumption. If current acid consumption for leaching an ore is below 125 kg per mt, it is doubtful that beneficiation would be justified.

Beneficiation plant operating cost. The effect of beneficiation operating expenses is similar in this case to their effect in Case 1 (Fig. 8). Again beneficiation is probably not justified at operating costs above $3.50 per mt.

Beneficiation plant capital cost. Fig. 9 shows that the capital costs are not a significant factor in the incremental analysis for the range of costs examined.

CONCLUSIONS

1) A beneficiation-leaching economic model has been developed for oxide copper ores based on available capital and operating cost data of existing operations.

2) The model shows low-grade concentrations (3-6% Cu) of an ore prior to leaching can be justified in certain situation.

3) For the ore type evaluated in this study, direct leaching is not economically attractive unless one or more of the following are met: acid consumption below 110 kg/mt; head grade greater than 1.27% Cu, copper price greater than 98¢ per lb (1979).

4) **For a new development.** Low-grade beneficiation (3-6% Cu) can be used prior to leaching to achieve a satisfactory DCFROR of 15% and ease the constraints noted above to these levels: acid consumption as high as 200 kg per mt, head grade as low as 0.95% Cu, copper price as low as 80¢ per lb.

5) The comparison is insensitive to copper production rate, orebody size (for at least a 15-year life), or leach plant recovery.

6) The beneficiation operating cost–not including crushing and grinding–must be less than ~$2.60 per mt for the process to be attractive at the above conditions. The Magnex Process applied to copper ores is capable of meeting this cost constraint.

7) **For an existing operation.** The addition of a beneficiation plant is justified, provided an improvement of 5-10% can be achieved in leach plant recovery.

8) Current acid consumption rate must be greater than 125 kg per mt to justify addition of a beneficiation plant.

9) For an operating cost of $2.45 per mt and an acid consumption of 175 kg per mt, the flotation testwork results on Twin Buttes ore are within the region of economic justification.

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Case 2: Addition to an existing leach plant

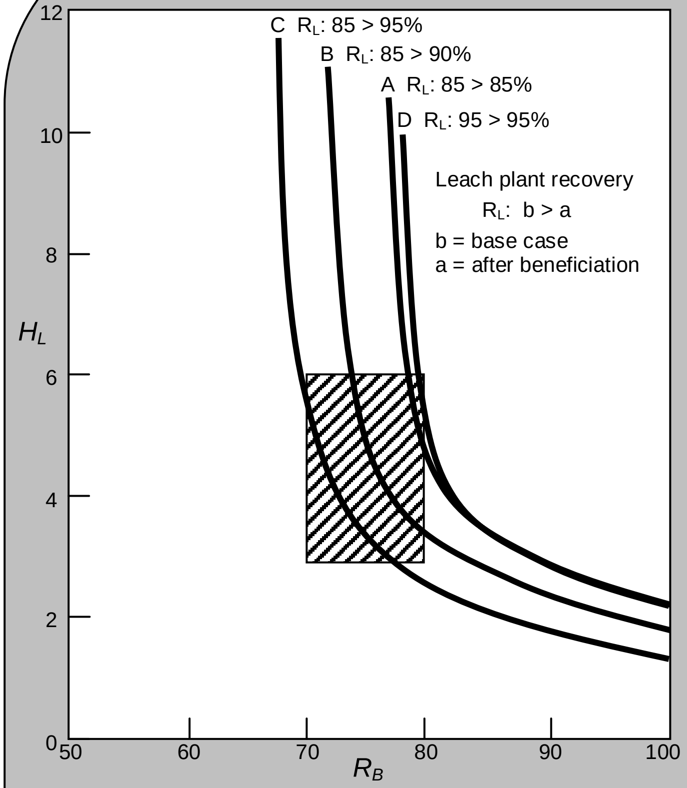

Fig. 6–The effect of leach plant recovery on the beneficiation performance required to achieve a DCFROR of 15%.

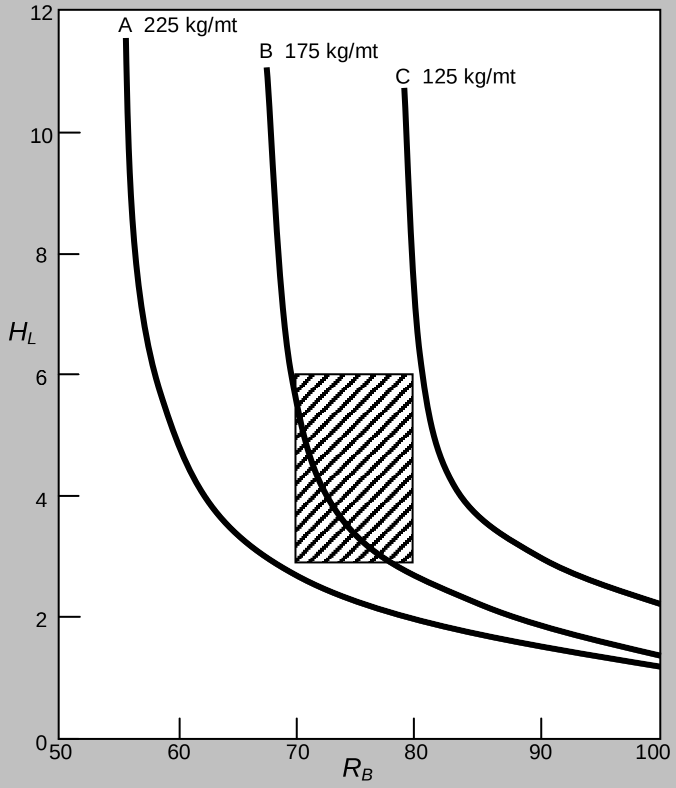

Fig. 7–The effect of acid consumption rate on the beneficiation performance required to achieve a DCFROR of 15%.

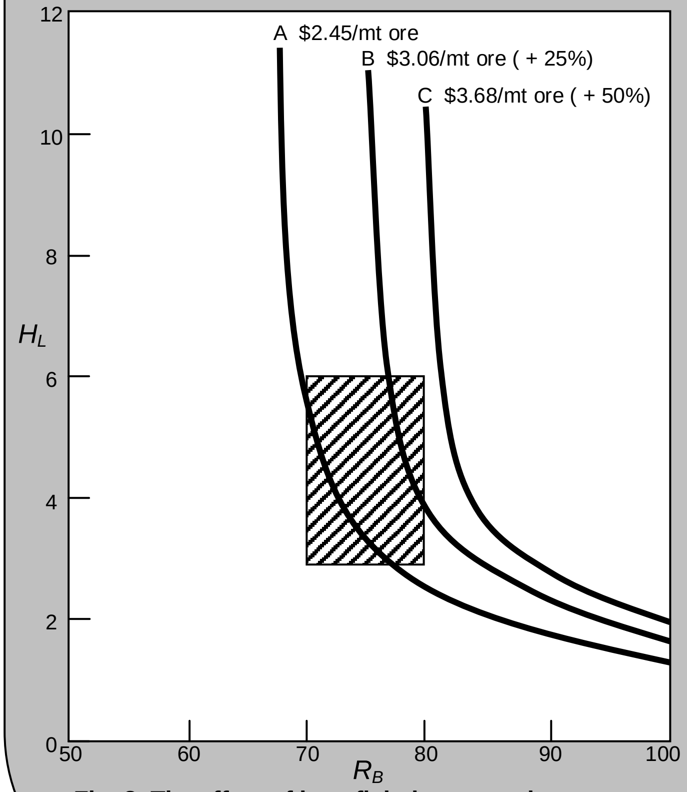

Fig. 8–The effect of beneficiation operating cost on the beneficiation performance required to achieve a DCFROR of 15%.

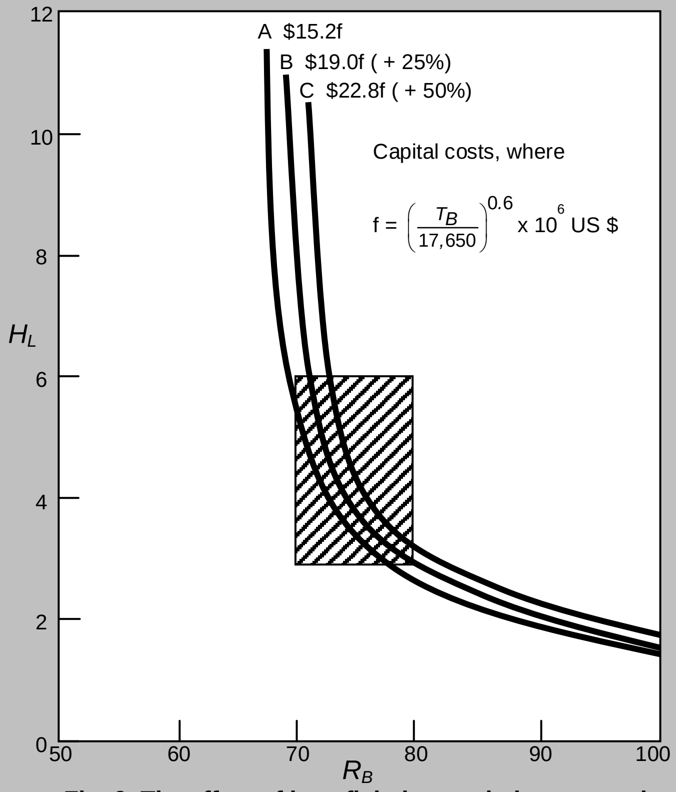

Fig. 9–The effect of beneficiation capital costs on the beneficiation performance required to achieve a DCFROR of 15%.