Economic analysis of rare earth element processing methods for Mountain Pass ore

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Synopsis

The increasing demand for rare earth elements (REE) in highly strategic sectors such as hybrid electric vehicles, renewable energy, communication technologies, and the defense industry has made REE production methods important. In recent years, studies on REE have increased rapidly; however there are many studies on REE, there are not enough studies in the literature on the economics of the beneficiation process. RE ores are generally leached after beneficiation by gravity, magnetic and flotation methods. In this study, direct leaching, attrition scrubbing and leaching, and flotation and leaching methods are evaluated economically based on the data for the Mountain Pass (MP) facility. According to the sensitivity analysis performed as a function of capital cost (CAPEX), operating cost (OPEX), and rare earths oxides (REO) recovery, REO recovery has the biggest effect on the process economies. Although the flotation method entails additional investment and operating costs, transportation and operating costs are significantly reduced result of the higher grade and recovery. The flotation method is more profitable, with larger NPV and IRR values and a shorter payback period.

Keywords

economic analysis, rare earth elements, flotation, attrition scrubbing.

Introduction

The rare earth elements lanthanide group includes 17 elements consisting of scandium and yttrium. Rare earth elements, with their light emission, magnetism, and electronic properties resulting from their unsaturated 4f electronic structure, are used in the production of permanent magnets, the production of rare earth phosphors, in hydrogen storage materials and in the production of catalysts. In addition, owing to their different chemical, metallurgical, optical, electrical, and catalytic properties, the REE have different uses in high-technology industries such as, hybrid electric vehicles, rechargeable batteries, mobile phones, wind turbines, medical imaging devices, radar systems, catalytic converters, metal alloys, aircraft engines, ceramics, and defense (Adibi *et al.*, 2014; Dushyanthaa *et al.*, 2020; Suli *et al.*, 2017).

Although the REEs are included in more than 250 discrete minerals, 95% of commercial production from bastnasite [Ce, La, Nd]$(CO_3)F$, monazite [Ce, La, Nd](PO_4), and xenotime (YPO_4) ores. The most important REE producers are China and the USA. It is estimated that China produced 132 000 t rare earths oxides (REO) in 2019, while the USA produced 26 000 t (REO equivalent) of ores and compounds. The estimated global total REO production is 210,000 metric tons (USGS, 2020). China imposed export restrictions on REE between 2010 and 2014, resulting in dramatic increases in REE prices in those years. These high prices accelerated exploration for new deposit on a global scale and increased the number of active REE facilities (Laurent, 2014).

Bayan Obo (China) and Mountain Pass (USA) are the world's largest REE deposits. The Mountain Pass (California, USA) deposit, the second largest REE deposit in the world, is operated by MP Materials. In this deposit, the main REE minerals are bastnasite and monazite, and gangue minerals are barite, calcite, silicate, apatite, and dolomite (Abaka-Wood, Addai-Mensah, and Skinner, 2016; Yang *et al.*, 2015).

REE ores are beneficiated by physical and/or chemical (leaching) methods. Physical REE beneficiation methods are gravity, magnetic, electrostatic, and flotation, or combinations of these methods (Jordens, Cheng, and Waters, 2013; Zhang and Edwards, 2012). Gravity beneficiation is widely used for the

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separation of REE minerals with relatively high densities (4-7 g/cm³) and gangue minerals with low specific gravity such as quartz, calcite and fluorite (Ferron, Bulatovic and Salter, 1991). In the attrition scrubbing method, the different resistance of the minerals to abrasion leads to a significant upgrading in the coarse or fine sizes. Pre-concentrate or concentrate is obtained by size classification of the attrition scrubbing product. Flotation vital in the beneficiation of low-grade and complex ores, which were previously uneconomic to mine and process (Wills, 2006). As the particle size decreases, beneficiation by gravity methods becomes more difficult and mineral losses increase. For this reason, flotation is used to beneficiated the minerals that are liberated between 100 μm and 15 μm. For selective flotation, the surfaces of REE minerals are rendered hydrophobic, while the gangue minerals are coated with depressants to increase surface hydrophilicity (Jordens, Cheng, and Waters, 2013). Beneficiation methods and feed and concentrate grades of active facilities producing REE are given in Table I. MP ore is beneficiated by flotation and leaching method, and the flow sheet of the facility is depicted in Figure 1.

In the chemical beneficiation methods, raw ore and/or concentrate is leached with acidic or alkaline solutions. The pregnant leach solution is generally purified by solvent extraction (SX) and precipitation methods, and REO are obtained by calcining the purified product (Demol *et al.*, 2019; Qi, 2018; Wang *et al.*, 2017).

Direct leaching of the ore avoids beneficiation methods such as gravity and flotation will be eliminated, thus reducing the cost. However, direct leaching of raw ore will increase reagent, and transportation costs, and valuable mineral losses, while reducing the efficiency of chemical beneficiation. In this case, preconcentration by physical beneficiation becomes necessary both technically and economically. The main purpose of this study is to assess the economic importance of beneficiation and the selection of the economic beneficiation method. Direct leaching, attrition scrubbing, leaching, and flotation and leaching were investigated economically. Attrition scrubbing method is given as an example because it is generally used in the pre-beneficiation of minerals with different abrasion resistances. The profitability of these beneficiation methods was evaluated together with the economic analysis.

Materials and methods

Crushing, grinding, classification, and attrition scrubbing methods are used to obtain pre-concentrate from the raw ore. Crushing, grinding, classification and flotation are used to obtain concentrate from raw ore. The data is based on data from the MP facility and published (preliminary) feasibility studies. In the absence of data on individual items, reasonable assumptions have been made using information from similar studies in the literature.

According to the report published by MP Materials, (2020a), MP raw ore with 8.7% REO content is upgraded to an average REO grade of 60% by flotation. Since attrition scrubbing is not applied to the MP ore, an assumption was made based on attrition scrubbing of carbonatite ore similar to this deposit. According to

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Table I

Beneficiation methods and grade data of active facilities producing REE (Abaka-Wood, Addai-Mensah and Skinner, 2016; Huleat, 2019; Krishnamurthy and Gupta, 2015; Verban 2015)

| Mine	Beneficiation method	Feed, %REO	Concentrate, %REO
Lynas (Australia)	Flotation	15	40
Mountain Pass (USA)	Flotation	6-12	60
Bayan Obo (China)	Magnetic-flotation	6	>60
Sichuan Mianning (China)	Gravity- magnetic-flotation	3-6	60
Shandong Weishan (China)	Magnetic-flotation	3	60
Lovozersky (Russia)	Flotation	1	38
Steenkampskaal (South Africa)	Magnetic -dense media separation	14.4	30
Toyotsu Rare Earths (India)	Magnetic	0.35	–
Browns Range (Australia)	Magnetic-flotation	0.66	20
Port Hope Simpson (Canada)	Non-whole ore leach	1.07	NA
Serra Verde (Brazil)	Non-whole ore leach (desorption of ionic clays)	0.16	NA
Zandskopdrift (South Africa)	Non-whole ore leach (desorption of ionic clays)	1.9	NA
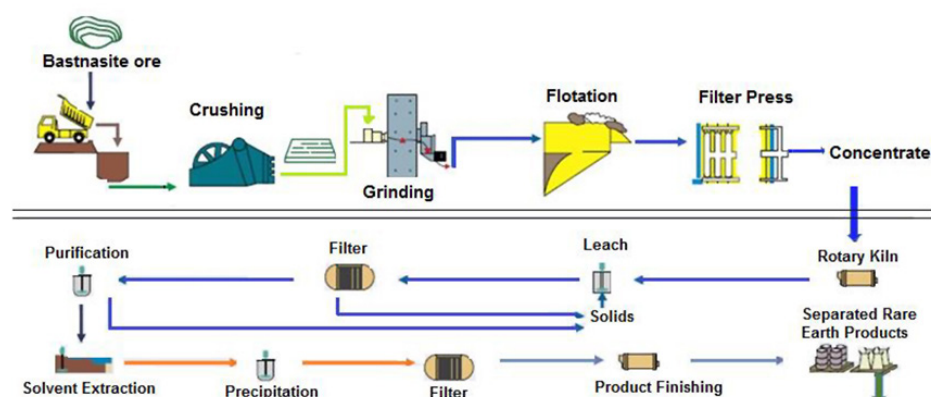
Figure 1—REO production flow sheet for Mountain Pass ore (MP Materials, 2020a)

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Noble *et al.* (2014) Bear Lodge REE ore was upgraded to 19.06-20.51% TREO (total REO) with 60-90% recovery in the -500 mesh size. Similarly, Özbayoğlu and Atalay (1995) state that Eskişehir (Turkey) REE ore reached a grade of 23.5% REO as a result of beneficiation by attrition scrubbing. Based on these results, it is assumed that MP ore can be upgrade to 20% REO by attrition scrubbing. The flow sheets for attrition scrubbing and leaching and flotation and leaching for REO production are given in Figure 2. The production and beneficiation data for the years 2018-2020 are given in Table II.

According to MP Materials (2020b), the overall flotation recovery was 72%, calculated by the formula given in Equation [1]. The attrition scrubbing recovery is assumed to be lower than flotation recovery and it was taken as being 62% after evaluating the literature data (Noble *et al*, 2014). The ore beneficiation and chemical beneficiation losses, which are not included in the literature or published reports, are also assumed to be approximate. Accordingly, the ore beneficiation losses are taken as 10%, the chemical beneficiation loss of the raw ore is 10%, and the chemical beneficiation loss of the concentrate is 5%.

$$Recovery = \frac{Concentrate\ weight\ (t) \times Concentrate\ grade\ (REO\%)}{Feed\ weight\ (t) \times Feed\ grade\ (REO\%)} = 100 \qquad [1]$$

Cost and revenue analysis

In the cost analysis, CAPEX and OPEX were determined separately. CAPEX inputs mainly include machinery and equipment, installation, piping, instrumentation, engineering, construction, and contingency costs. For CAPEX, data from Williams (2018) was used. The investment cost for the chemical plant is taken as 60% of that of the physical beneficiation plant. OPEX inputs are mainly reagents, energy, transportation and labour costs. These costs are given on the basis of the current reports and are included in the facility costs. The operating costs per ton TREO for the Mountain Pass operation are given in Table III, and the key performance indicators in Table IV.

As seen in Table IV, the operating cost per ton REO in 2020 was $1 430. Operating cost per ton in the REO metric excludes costs attributable to selling obsolete stocks, shipping, freight, and depreciation. It has been added to OPEX costs as a separate item since shipping cost is not included. In this study, the transportation cost of raw ore and concentrate was taken as $8 per ton, based on the average cost in the mining industry (Sterba *et al.*, 2019).
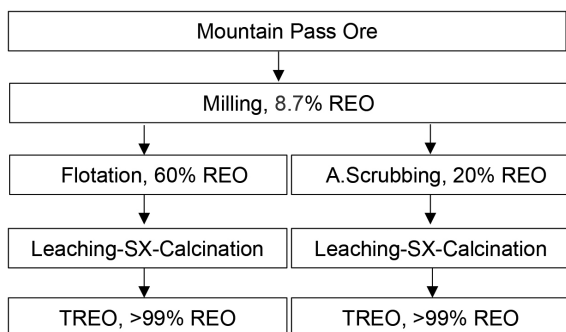

Figure 2—Attrition scrubbing & leaching and flotation & leaching flow sheets

Table II

Summary of operating results 2018-2020 (MP Materials, 2020b)

	2020 (6 months)	2019	2018
Ore mined (t)	682 775	598 683	564 228
Mill feed (dry t)	331 556	542 668	342 891
Concentrate production (dry t)	34 535	56 892	29 453
Concentrate grade (REO%)	60	53 5	52 1
TREO production (t)	18 969	27 620	13 914
TREO recovery to concentrate (%)	65 8	58 9	51 1

Table III

Operating costs per ton TREO of the Mountain Pass operation (SRK, 2010)

	Cost ($000)	Cost ($/ton TREO)	Distribution (%)
Mining	144 452	44 906	8.455
Milling	427 079	133 000	25.040
Flotation	106 769	33 000	6.213
Chemical plant*	1 033 150	320 242	60.292
Operation costs	1 711 450	531 148	100.00

*Chemical plant includes the costs of leaching, solvent extraction, precipitation, combined heat and power (CHP) plant, chlor-alkali plant, and brine treatment

Table IV

Key performance indicators (MP Materials, 2020c, 2021)

	2020	2019	2018
REO production (t)	38 503	27 620	13 914
REO sales (t)	38 367	26 821	13 378
Realized price per ton REO t ($)	$3 311	$2 793	$3 382
Cost of production per ton REO t	$1 430	$1 980	$2 822

The data from Norgren (2018) wase used for income analysis. Current sales prices, percentage distribution ratios and sales percentages of REOs produced from MP ore are shown in Table V. Income was calculated based on these figures and prices.

Economic analysis

Different static and dynamic capital budgeting methods and a combination of these methods are applied to compare the profitability of projects. The first method is the payback period, a static method. This is a simple method often used for initial estimation, but does not provide an adequate basis for deciding between different investment projects. The second method is net present value (NPV) and internal rate of return (IRR), the most common dynamic capital budgeting method, for more detailed analysis. The NPV method is used to decide which project will be most profitable from an investor's point of view, as the IRR method alone is not always suitable for making the right investment decisions (Jaroni, Friedrich, and Letmathe, 2019). In this study, NPV, IRR, and payback period values were calculated and evaluated together.

Sensitivity analysis is a risk analysis technique that measures the extent to which NPV changes as a result of changes in the key variables that can affect the NPV of the project. In this context,

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Table V

Current REO sales prices, percentage distribution, and sales rates (**Metal, 2021; Norgren, 2018**)

Product	$/t	% of REO product	% of product sold
Cerium oxide (>99.5%)	1 436	50.0	50
Lanthanum oxide (>99.5%)	1 374	33.0	100
Praseodymium oxide (>99%)	138 141	4.0	100
Neodymium oxide (>99.5%)	142 851	12.0	100
SEG* + others	1 436	1.0	100

*SEG: Samarium, europium, and gadolinium oxides

Table VI

Comparison of capital costs of different circuits (**Williams, 2018**)

Machinery/equipment	Attrition scrubbing and leaching	Flotation and leaching
Mining	958 648	958 648
Milling	7 016 966	7 016 966
Attrition scrubbing unit	86 720	–
Flotation	–	2 156 001
Chemical plant	13 759 450	13 759 450
Total cost	21 821 784	24 079 038

Table VII

Total capital cost estimate using Mular's Factored Capital Cost Estimate Guide (**Mular, 2002**)

Cost	Scrubbing and leaching	Flotation and leaching	Factor	Explanation
Equipment cost	21 821 784	24 079 038	–	–
Installed equipment cost	31 205 152	34 433 025	1 43	Multiplied by equipment cost
Piping	6 241 030	68 86 605	0 2	Multiplied by total installed equipment cost
Instrumentation	39 00 644	4 304 128	0 125	Multiplied by total installed equipment cost
Total plant cost	63 168 610	69 702 796	–	–
Engineering and construction	22 109 014	24 395 979	0 35	Multiplied by total plant cost
Contingency	6 316 861	6 970 280	0 1	Multiplied by total plant cost
Total CAPEX	91 594 485	101 069 054	–	–

sensitivity analysis is used to identify and estimate potential risk in project efficiency. It is used to estimate the effects of variables on NPV rather than finding the risk value. The greater the change in NPV, the greater the risk. Sensitivity analysis provides important information about which inputs have the greatest impact on the project. In this study, the changes in NPV as a function of CAPEX, OPEX, and REO recovery were investigated.

Results and discussion

Cost and revenue analysis

CAPEX and OPEX values for Attrition Scrubbing & Leaching and flotation & leaching circuits were determined. The investment costs for both circuits are compared in Table VI, and the estimated total investment cost using the Mular factor is given in Table VII.

According to Table VII, capital costs are calculated as $91 594 485 for Attrition scrubbing & leaching and $101 069 054 for flotation & leaching. The operating cost is calculated by adapting the percentage cost rates of each input in the SRK (2010) report to the REO operating cost (1 430 $/per ton) in the MP (2020) report and is given in Table VIII. Since the operating cost   of

attrition scrubbing is unknown, it is assumed that it will be half of the flotation cost.

The operating cost of the flotation and leaching circuit is $44 423 higher per ton raw ore than that of the attrition scrubbing and leaching circuit. The 10-year operating cost calculation, is based on the data in Table VIII.

Economic analysis

The 10-year pre-tax cash flow models the two circuits are shown in Table IX and Table X. No acceleration period is included in this analysis, although it is likely to exist in practice. NPV, IRR, and payback periods were calculated using the information in Tables IX and X. These values are shown in Table XI, assuming a discount rate of 8%.

Table XI shows that the NPV and IRR values of the flotation & leaching circuit are greater and the payback period is lower. The difference between the NPVs was found to be $1 565 498 542 and it is clearly seen that the flotation & leaching circuit is more profitable from these values. Economic analysis of the direct leaching circuit revealed that the NPV value is –$365 019 511. This is not an economical method and physical beneficiation is

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Table VIII

Circuit operating costs of the MP plant per ton of REO

Operational Items	Attrition scrubbing and leaching, $/ton	Flotation and leaching, $/ton
Mining	120 900	120 900
Milling	358 073	358 073
Attrition scrubbing	44 423	–
Flotation	–	88 845
Chemical plant	862 180	862 181
Total	1 385 576	1 430 000

Table IX

Cash flow for attrition scrubbing and leaching circuit

Year	0	1	2	3	4	5	6	7	8	9	10
Mill feed, t/a	0	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112
Preconcentrate production, t/a	0	178 841	178 841	178 841	178 841	178 841	178 841	178 841	178 841	178 841	178 841
REO recovered, t/a	0	32 131	32 131	32 131	32 1 31	32 131	32 131	32 131	32 131	32 131	32 131
CeO$_2$, t/a	0	16 096	16 096	16 096	16 096	16 096	16 096	16 096	16 096	16 096	16 096
La$_2$O$_3$, t/a	0	10 623	10 623	10 623	10 623	10 623	10 623	10 623	10 623	10 623	10 623
Pr$_2$O$_3$, t/a	0	1288	1 288	1 288	1 288	1 288	1 288	1 288	1 288	1 288	1 288
Nd$_2$O$_3$, t/a	0	3 863	3 863	3 863	3 863	3 863	3 863	3 863	3 863	3 863	3 863
Other, t/a	0	322	322	322	322	322	322	322	322	322	322
Gross revenue, t$	0	756 323	756 323	756 323	756 323	756 323	756 323	756 323	756 323	756 323	756 323
Transport cost, t$	0	1 431	1 431	1 431	1 431	1 431	1 431	1 431	1 431	1 431	1 431
Operat. costs, t$	0	501 264	501 264	501 264	501 264	501 264	501 264	501 264	501 264	501 264	501 264
Capital costs, t$	91 595	–	–	–	–	–	–	–	–	–	–
Net cash flow, t$	-91 595	253 629	253 629	253 629	253 629	253 629	253 629	253 629	253 629	253 629	253 629
Cumulative cash flow, t$	-91 595	162 034	415 663	669 292	922 920	117 6549	1430 178	168 3806	193 7435	219 1064	2444 692

Table X

Cash flow for the flotation and leaching circuit

Year	0	1	2	3	4	5	6	7	8	9	10
Mill feed, t/a	0	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112	663 112
Preconcentrate production, t/a	0	69 070	69 0 70	69 070	69 070	69 070	69 070	69 070	69 070	69 070	69 070
REO recovered, t/a	0	39 370	39 370	39 370	39 370	39 370	39 370	39 370	39 370	39 370	39 370
CeO$_2$, t/a	0	19 685	19 685	19 685	19 685	19 685	19 685	19 685	19 685	19 685	19 685
La$_2$O$_3$, t/a	0	12 992	12 992	12 992	12 992	12 992	12 992	12 992	12 992	12 992	12 992
Pr$_2$O$_3$, t/a	0	1 575	1 575	1575	1 575	1 575	1 575	1 575	1 575	1 575	1 575
Nd$_2$O$_3$, t/a	0	4 724	4 724	4 724	4 724	4 724	4 724	4 724	4 724	4 724	4 724
Other, t/a	0	394	394	394	394	394	394	394	394	394	394
Gross revenue, t$	0	924 980	924 980	924 980	924 980	924 980	924 980	924 980	924 980	924 980	924 980
Transport cost, t$	0	553	553	553	553	553	553	553	553	553	553
Operat. costs, t$	0	436 079	436 079	436 079	436 079	436 079	436 079	436 079	436 079	436 079	436 079
Capital costs, t$	101 069	–	–	–	–	–	–	–	–	–	–
Net cash flow, t$	–101 069	488 346	488 346	488 346	488 346	488 346	488 346	488 346	488 346	488 346	488 346
Cumulative cash flow, t$	–101 069	387 279	875 628	1 36 3976	1 85 2325	2 340 673	2 829 021	3 317 370	3 805 719	4 294 067	4 782 416

Note: t$: thousand dollars / t/a represents annual tons

Table XI

NPV, IRR, and payback period for each circuit

Material	Attrition scrubbing and leaching	Flotation and leaching
NPV (i: 8%)	$1 610 274 499	$3 175 788 806
IRR	277%	483%
Payback period (years)	0 36	0 21

required for this ore. Sensitivity analyses as a function of CAPEX, OPEX, and REO recovery for both circuits are given in Figures 3 and 4.

Figurs 3 and 4 show that for both circuits NPV is most sensitive to the total REO recovery. The most important parameters affecting the total REO recovery are the REO grade and recovery. In both beneficiation circuits, OPEX was severely affected, while CAPEX showed no significant effect. In addition, it was determined that NPV increased linearly as the REO recovered increased for both circuits, and decreased linearly as OPEX amount increased. In the attrition scrubbing and leaching circuit, the REO recovery amount is below -32%, while the NPV is negative. The NPV for the flotation and leaching circuit is positive at all rates of change. From this, it was determined that the attrition scrubbing and leaching circuit is more affected by the REO recovery and OPEX value.

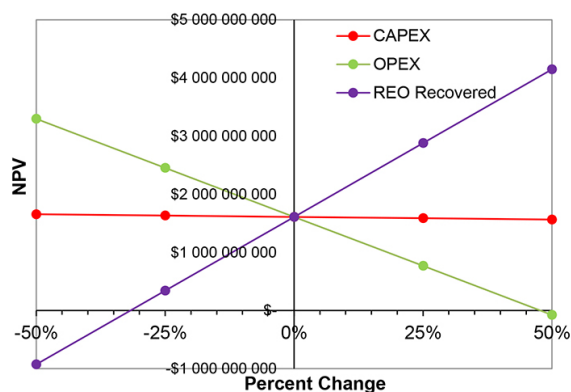# Economic analysis of rare earth element processing methods for Mountain Pass ore

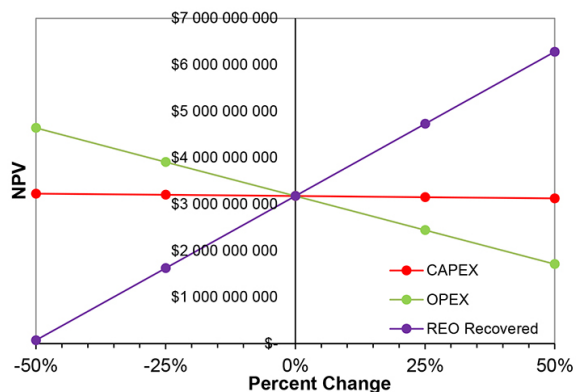Figure 3—Sensitivity analysis of the attrition scrubbing and leaching circuit

Figure 4—Sensitivity analysis of the flotation and leaching circuit

Conclusions

An economic analysis was carried out on attrition scrubbing and leaching and flotation and leaching circuits used in the beneficiation of REE ores. It was found that the NPV and IRR values for the flotation and leaching circuit were higher and the payback period was lower. Accordingly, the flotation and leaching circuit is the more profitable investment. Sensitivity analyses as a function of CAPEX, OPEX, and REO recovery were also performed. Iit was determined that while REO recovery amount and OPEX were seriously affected in both circuits, CAPEX did not show a significant effect. The sensitivity analysis indicated that the biggest effect was due to the amount of REO recovery, and this value was significantly affected by the REO grade and recovery values.

Acknowledgement

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