27th CIRP Life Cycle Engineering (LCE) Conference

Applying Design of Experiments to Evaluate Economic Feasibility of Rare-Earth Element Recovery

Supporting Information

1. Existing 36 laboratory data for leached REEs (data for Fig. 1)

Under different combinations of pulp density and operation type, the amount of REEs extracted from a 500 mL bioreactor.

Pulp Density	Operation Type	Y (mg)	Eu (mg)	Tb (mg)	La (mg)	Ce (mg)	Pr (mg)	Nd (mg)	Dy (mg)
0.75	Batch	54.10	26.45	0.00	51.11	10.90	39.35	41.39	191.77
0.75	Batch	57.17	62.13	283.58	50.54	11.12	40.54	42.28	230.35
0.75	Batch	57.36	31.02	63.70	50.92	11.71	40.00	41.69	210.15
1.5	Batch	55.95	25.07	44.04	50.63	12.87	38.68	40.68	192.53
1.5	Batch	55.42	25.63	43.51	51.31	12.52	39.74	40.47	182.30
1.5	Batch	54.77	21.92	42.37	51.24	12.01	39.07	40.73	186.17
3	Batch	53.23	21.96	40.34	49.47	12.04	36.95	37.96	170.54
3	Batch	51.88	23.97	38.95	48.19	11.26	36.11	36.93	165.63
3	Batch	50.50	24.61	39.59	48.77	10.26	36.06	37.52	173.44
6	Batch	49.45	18.52	26.01	42.32	12.48	31.19	31.72	142.04
6	Batch	48.15	18.09	25.26	44.05	11.89	30.89	31.82	140.42
6	Batch	47.72	17.20	25.17	39.26	11.65	29.53	30.16	135.82
12	Batch	52.40	17.97	26.92	42.28	11.60	31.39	32.12	139.02
12	Batch	49.53	16.16	25.56	40.61	10.19	28.18	28.85	124.87
12	Batch	55.23	18.18	28.91	43.03	12.00	31.56	32.32	141.53
18	Batch	48.69	15.52	26.29	41.67	10.05	32.30	27.43	123.85
18	Batch	49.64	15.73	26.54	41.64	10.30	31.92	27.74	123.65
18	Batch	50.14	15.17	26.14	40.88	9.62	32.19	27.46	119.69
30	Batch	48.75	18.10	32.12	34.46	25.67	33.11	31.27	140.25
30	Batch	52.50	19.17	34.78	36.40	28.85	35.45	33.09	151.02
30	Batch	44.86	15.51	28.33	39.32	30.45	30.30	28.30	123.58
50	Batch	35.02	12.64	22.86	29.32	22.82	23.17	23.29	108.64
50	Batch	36.93	13.06	23.46	28.48	21.07	24.11	23.20	106.43
50	Batch	35.68	13.21	23.53	26.88	21.08	23.44	22.26	104.62
1.5	Cont.	76.79	22.01	53.34	53.05	39.61	48.69	0.00	172.04
1.5	Cont.	85.01	17.06	60.36	55.36	42.87	56.74	0.00	208.89
1.5	Cont.	90.13	16.71	61.58	60.17	48.30	54.94	0.00	208.12
1.5	Cont.	83.61	14.95	57.20	51.11	41.24	53.05	0.00	196.25
1.5	Cont.	76.01	10.74	50.02	53.15	39.99	49.10	0.00	172.02

1.5	Cont.	81.32	13.09	52.88	54.37	38.72	52.49	0.00	185.67
1.5	Cont.	57.49	26.55	28.08	50.57	15.31	36.54	37.97	179.27
1.5	Cont.	49.34	32.21	33.09	47.76	14.67	38.52	35.68	181.68
1.5	Cont.	52.84	27.43	25.31	47.86	15.90	38.97	38.78	217.91
1.5	Cont.	55.48	25.46	28.21	50.07	16.04	38.80	39.17	230.46
1.5	Cont.	52.37	24.92	35.73	48.92	16.44	38.86	38.47	182.22
1.5	Cont.	54.86	23.47	38.64	51.40	16.97	40.20	40.46	202.10

2. Data for curve fitting (data for Fig.2)

(a)

Glucose concentration (g/L)	Glucose acid concentration (mM)	pH
5	8	3.38
10	10	2.91
20	20	2.51
40	149	2.25
60	291	2.32
80	407	2.40

(b)

Glucose acid concentration (mM)	pH	REE leached percentage (%)
184	2.19	51
174	2.22	49
116	2.41	46
68	2.61	42

3. TEA output example in DOE

Under the following parameters setting:

- Glucose concentration = 40 g/L
- Pulp density = 50%
- Operation type = Continuous

Below are the simulation results for one particular instance. Each instance will yield a different result. 60 simulations will performed to obtain 60 annual profit outputs for DOE analysis.

(1) Cost breakdown

Cost Components	Amount($/year)	Percentage
Direct Cost	$2,556,661.43	79.44
Capital Cost	$120,899.80	3.76
Indirect Cost	$250,499.80	7.78

General Cost	$290,159.53	9.02
Total Cost	$3,218,220.57	100.00

(2) Revenue from selling REE breakdown

Element	Price ($/kg)	Amount (kg/year)	Revenue ($/year)
Y	$36.34	80.60	$1,171.61
Eu	$346.45	4.01	$555.59
Tb	$788.76	1.74	$550.41
La	$5.52	75074.99	$165,706.65
Ce	$5.35	4243.78	$9,081.34
Pr	$107.32	79.58	$3,416.44
Nd	$59.51	198.79	$4,732.24
Dy	$356.43	1.64	$234.13

(3) TEA summary:

Total Cost ($/year)	$3,218,220.57
Total Revenue ($/year)	$3,953,067.40
Annual Profit ($/year)	$734,846.83

4. DOE Response table

Below is the responses for 60 experimental trails obtained from simulations. Statistical analysis in section 4 was conducted based on this table.

x1	x2	x3	Replication	Response
-1	-1	-1	1	-68756323.24
1	-1	-1	1	-80889872.22
-1	-0.5	-1	1	-15139907.02
1	-0.5	-1	1	-19099354.40
-1	0	-1	1	-3274514.50
1	0	-1	1	-4176159.22
-1	0.5	-1	1	-941944.59
1	0.5	-1	1	-1226848.87
-1	1	-1	1	569867.65
1	1	-1	1	-5929.53
-1	-1	1	1	-53891461.38
1	-1	1	1	-68471891.18
-1	-0.5	1	1	-11332362.13
1	-0.5	1	1	-13446316.30
-1	0	1	1	-1838458.95

1	0	1	1	-2607650.32
-1	0.5	1	1	-71761.90
1	0.5	1	1	-625748.37
-1	1	1	1	1167788.37
1	1	1	1	759813.61
-1	-1	-1	2	-67848079.60
1	-1	-1	2	-80219115.11
-1	-0.5	-1	2	-14150570.04
1	-0.5	-1	2	-17349944.05
-1	0	-1	2	-3053197.73
1	0	-1	2	-4603582.53
-1	0.5	-1	2	-821234.26
1	0.5	-1	2	-1729313.40
-1	1	-1	2	503443.41
1	1	-1	2	97122.46
-1	-1	1	2	-56165984.64
1	-1	1	2	-63301508.99
-1	-0.5	1	2	-10943844.95
1	-0.5	1	2	-14446568.03
-1	0	1	2	-1697883.17
1	0	1	2	-2829813.58
-1	0.5	1	2	40754.23
1	0.5	1	2	-447186.62
-1	1	1	2	1058768.23
1	1	1	2	751382.44
-1	-1	-1	3	-68143594.74
1	-1	-1	3	-80906006.53
-1	-0.5	-1	3	-13535037.24
1	-0.5	-1	3	-17790991.02
-1	0	-1	3	-3287359.67
1	0	-1	3	-4418916.46
-1	0.5	-1	3	-967267.44
1	0.5	-1	3	-1676615.62
-1	1	-1	3	513225.50
1	1	-1	3	223044.03
-1	-1	1	3	-58794579.77
1	-1	1	3	-63532575.70
-1	-0.5	1	3	-11138208.72
1	-0.5	1	3	-14682501.10
-1	0	1	3	-1932201.54
1	0	1	3	-2618135.66

-1	0.5	1	3	159.31
1	0.5	1	3	-619146.97
-1	1	1	3	1000606.62
1	1	1	3	807188.43

5. Statistical summary from regression analysis

Below is the statistical summary for the regression model that Fig. 6 was based on.

Dep. Variable:	y	**R-squared:**	0.999
Model:	OLS	**Adj. R-squared:**	0.999
Method:	Least Squares	**F-statistic:**	2205.
Date:	Sat, 14 Dec 2019	**Prob (F-statistic):**	1.17e-22
Time:	19:15:41	**Log-Likelihood:**	-368.26
No. Observations:	24	**AIC:**	752.5
Df Residuals:	16	**BIC:**	761.9
Df Model:	7		
Covariance Type:	nonrobust		

	coef	**std err**	**t**	**P>|t|**	**[0.025**	**0.975]**
Intercept	-6.825e+07	7.89e+05	-86.497	0.000	-6.99e+07	-6.66e+07
C(x1)[T.1.0]	-1.242e+07	1.12e+06	-11.132	0.000	-1.48e+07	-1.01e+07
C(x2)[T.1.0]	6.878e+07	1.12e+06	61.637	0.000	6.64e+07	7.11e+07
C(x3)[T.1.0]	1.197e+07	1.12e+06	10.723	0.000	9.6e+06	1.43e+07
C(x1)[T.1.0]:C(x2)[T.1.0]	1.2e+07	1.58e+06	7.603	0.000	8.65e+06	1.53e+07
C(x1)[T.1.0]:C(x3)[T.1.0]	3.604e+06	1.58e+06	2.284	0.036	2.59e+05	6.95e+06
C(x2)[T.1.0]:C(x3)[T.1.0]	-1.142e+07	1.58e+06	-7.236	0.000	-1.48e+07	-8.07e+06
C(x1)[T.1.0]:C(x2)[T.1.0]:C(x3)[T.1.0]	-3.483e+06	2.23e+06	-1.561	0.138	-8.21e+06	1.25e+06

Omnibus:	10.871	**Durbin-Watson:**	2.833
Prob(Omnibus):	0.004	**Jarque-Bera (JB):**	11.586
Skew:	-0.920	**Prob(JB):**	0.00305
Kurtosis:	5.863	**Cond. No.**	17.9

	coef	std err	t	P>|t|	[0.025	0.975]
Intercept	-6.825e+07	7.89e+05	-86.497	0.000	-6.99e+07	-6.66e+07
C(x1)[T.1.0]	-1.242e+07	1.12e+06	-11.132	0.000	-1.48e+07	-1.01e+07
C(x2)[T.1.0]	6.878e+07	1.12e+06	61.637	0.000	6.64e+07	7.11e+07
C(x3)[T.1.0]	1.197e+07	1.12e+06	10.723	0.000	9.6e+06	1.43e+07
C(x1)[T.1.0]:C(x2)[T.1.0]	1.2e+07	1.58e+06	7.603	0.000	8.65e+06	1.53e+07
C(x1)[T.1.0]:C(x3)[T.1.0]	3.604e+06	1.58e+06	2.284	0.036	2.59e+05	6.95e+06
C(x2)[T.1.0]:C(x3)[T.1.0]	-1.142e+07	1.58e+06	-7.236	0.000	-1.48e+07	-8.07e+06
C(x1)[T.1.0]:C(x2)[T.1.0]:C(x3)[T.1.0]	-3.483e+06	2.23e+06	-1.561	0.138	-8.21e+06	1.25e+06

6. Predicted profits under each parameter setting

- X1: glucose concentration; X1 = 0 for 32g/L, X1 =1 for 40g/L
- X2: pulp density; X2 = 0 for 1.5%, X2 = 1 for 50g/L
- X3: operation type; X3 = 0 for batch operation, X3 = 1 for continuous operation

The setting that yields highest expected profit is highlighted.

X1	X2	X3	Predicted Profit
0	0	0	-$68,249,332.53
1	0	0	-$80,671,664.62
0	1	0	$528,845.52
0	0	1	-$56,284,008.60
1	1	0	$104,745.65
1	0	1	-$65,101,991.96
0	1	1	$1,075,721.07
1	1	1	$772,794.82