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The Use of Design of Experimentation Software in Applied Flotation Testing

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Abstract

The successful application of flotation is now over 100 years old. However in a practical sense, it still remains predominantly an art rather than a quantifiable science. Moreover, the laboratory testing, interpretation and application of the technology can still be tedious, time consuming and costly. This paper outlines the use of statistical design of experimentation for rapid optimization of flotation testing with limited sample utilization. This result in less costly required testing, a more thorough understanding of the results and the ability to simultaneously optimize several variables and outcomes at once.

Keywords: Design; Flotation; STAT-EASE; Pyrrhotite; Processing

Introduction

While flotation technology is now 100 years old, the testing, interpretation and application of lab results can be tedious, costly and time consuming requiring extensive sample collection and preparation. In addition, applied flotation still remains more of an art than a quantifiable science. This paper will elucidate the application of STAT-EASE Design-Expert software to minimize required laboratory flotation testing while rapidly optimizing multiple results and outcomes in a statistically valid manner. The STAT-EASE [1-13] program is based on proven design of experiment fundamentals. In this paper, the real world application of this methodology to a copper and gold ore and a copper, cobalt and gold ore will be cited.

Application to a copper and goldore

Based on previous work along with current legal issues concerning limiting cyanide use in Montana, flotation with gravity concentration was the process chosen to develop the Elkhorn copper gold ore deposit. A review of previous scoping level test work revealed significant results on optimal collector and frother usage, grind time, and float time were missing on Elkhorn ore deposits such as the Mt. Hagen.

Because of client budget constraints and a limited quantity of representative core samples material available, STAT-EASE [1] statistical software was used to minimize the number of flotation experiments required to identify a statistical representative experimental set. This commercially licensed program based on fundamentals of design of experiments provides highly efficient:

1. Two-level factorial screening studies so that the vital factors which affect a process can be identified.
2. Response surface methods to find ideal process settings and achieve optimal performance.
3. Mixture design techniques to discover optimal formulations.

Among other features, the program offers rotatable 3D plots for visualization of response surfaces. Again, the key feature is the ability to set up statistically valid design of experiment matrices which allow a minimum amount of experimentation to take place. This saves time and money allowing robust flotation testing and optimization to occur with a minimal amount of ore sample used.

Elkhorn ore composite development

The Mt. Hagen ore composite was collected from different drill holes going across the deposit from north to south and top to bottom. No special considerations were given to the sample other than ensuring that the sample was taken from an ore run and the appropriate interval assigned. Approximately twelve inches of sample were taken from the appropriate interval and recorded. No special considerations were made for oxide, sulfide, or waste. Upon arrival at the CAMP laboratory, all samples were crushed to minus 3/8" and thoroughly mixed. A sample for assaying was split from the material using a Jones Splitter. This composite was assayed for gold, silver, and copper. The gold assays were completed using metallic analysis at 100 mesh to identify any coarse gold. Multi-element ICP and X-ray diffraction analysis were also completed [2]. Table 1 identifies the composite ore average analysis.

Elkhorn ore flotation testing

Flotation testing was guided and completed using STAT-EASE

Composite, Weighted Average	23-Sep	AU, OZ/TN	CU, %		
Composite Assay		0.204	0.40		
Hole	Weight	AU Grade	CU Grade	AU Grade	CU Grade
CEG 04-12	21.2	0.180	0.55	3.825	11.58
CEG 04-18	9.6	0.151	0.02	1.452	0.23
CEG 04-11	25.3	0.260	0.39	6.589	9.82
CEG 04-10	10.5	0.133	0.40	1.394	4.15
CEG 04-24	50.3	0.210	0.41	10.544	20.85
		-	-	-	-
		-	-	-	-
		-	-	-	-
		-	-	-	-
Total	116.9	0.204	0.40	23.80	46.63

Table 1: Elkhorn Goldfields – Mt. Hagen Ore Weighted Average Composite

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diagnostic software. The software requires the development of a statistically valid design of the experiment matrix using several variables and outcomes. In the case of the Mt. Hagen deposit testing, the variables used were grind time, pH, flotation time, and the addition or not of sodium sulfide. In addition, the testing was used to simultaneously identify four outcomes: gold and copper grade and recovery. The grind time variable was developed to review the effects of grinding and liberation at a base size of 150 mesh. A shorter grind time would add capacity and lower costs. A longer grind time will better liberate the ore and typically improve recovery. Based on previous testing, a twenty-five minute grind time gave an 80 % passing 150 mesh ore size. The grinding pulp density was 50% solids by weight in a laboratory ball mill. Sodium sulfide was used as a sulfidizing agent variable to promote flotation of oxidized copper and gold bearing minerals. Testing was completed to identify a response based on use or no use. A variable pH of 8.5 or 10.5 was chosen to both promote and depress pyrite and pyrrhotite. At pH 8.5, pyrite and pyrrhotite tend to be promoted [4]. At pH 10.5, both pyrite and pyrrhotite are effectively depressed. This difference in pH was used to assist in identifying the source of the gold and how to best optimize the gold recovery. Flotation testing was completed with a Denver Laboratory flotation machine. The density of the flotation pulp was a constant 40% solids by weight. Each ore charge for the testing was 1000 grams. Variable float times were used to optimize the float machine size requirements. The collector chosen for this project was Cytec Aerofloat 3477. It was used at a constant dosage. This collector is a common dithiophosphate based collector. It was chosen because of its selectivity towards gold and copper and its positive results in previous testing of other Elkhorn ore deposits. The frother chosen for the testing was pine oil. It was also used at a constant dosage. Pine oil was chosen in other Elkhorn ore deposit flotation testing because it minimized effects of specific minerals with the deposit. With the development of the pertinent variables and measurable outcomes, several choices of matrix sizes and sample numbers can be developed. Accordingly, a higher number of tests can improve the statistical reliability of the data being developed. In the case of Mt. Hagen ore testing, four variables with four measurable outcomes were identified. The total number of samples and the size of the matrix required two to the power of four or sixteen total possible tests. The user of STAT-EASE can select a total, half, or quarter of this testing matrix to identify a statistically valid outcome. For this real world project, there were significant restraints on both budget and

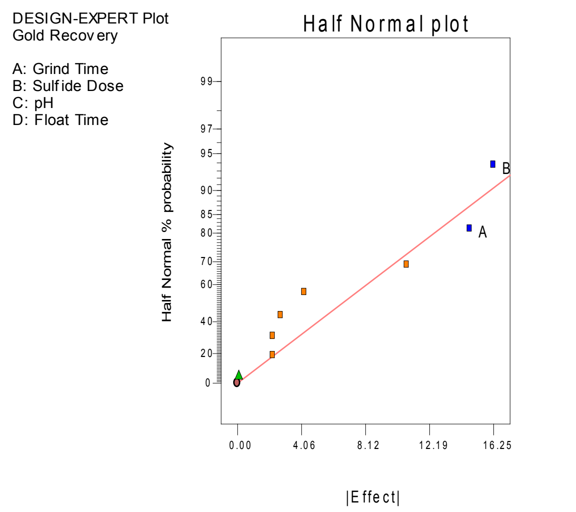

Figure 1: Example STAT-EASE Half Normal Plot.

TEST	GRIND TIME, MIN	SULFIDE DOSAGE, GRAMS	pH	FLOAT TIME
1	30	1.0	8.5	15
2	20	0.0	8.5	15
3	25	0.5	9.5	17.5
4	30	1.0	10.5	20
5	30	0.0	10.5	15
6	25	0.5	9.5	17.5
7	20	1.0	10.5	15
8	20	0.0	10.5	20
9	20	1.0	8.5	20
10	30	0.0	8.5	20

Table 2: STAT-EASE One Quarter Design of Experiment Matrix.

Sample #	Assays					
	Concentrate			Tails		
	Au (oz/t)	Ag (oz/t)	Cu (%)	Au (oz/t)	Ag (oz/t)	Cu (%)
1	0.608	0.18	0.87	0.056	0.14	0.026
2	0.474	0.38	0.66	0.182	0.14	0.035
3	0.606	0.58	0.61	0.052	0.14	0.024
4	0.592	0.48	0.73	0.068	0.24	0.026
5	0.524	0.54	0.71	0.068	0.24	0.027
6	0.452	0.32	0.46	0.064	0.14	0.019
7	0.618	1.40	0.96	0.062	0.18	0.020
8	0.918	1.34	1.25	0.124	0.08	0.051
9	0.508	0.36	0.60	0.088	0.10	0.059
10	0.416	0.50	0.46	0.102	0.12	0.026

Table 3: Elkhorn Goldfields – Mt. Hagen STAT-EASE Matrix Assay Results.

Sample #	Recoveries to Concentrate		
	Au (%)	Ag (%)	Cu (%)
1	80.8%	33.32%	92.9%
2	45.1%	46.12%	85.6%
3	78.7%	56.82%	89.0%
4	74.2%	39.83%	90.3%
5	75.3%	47.13%	91.2%
6	81.4%	58.54%	93.7%
7	77.2%	72.52%	92.1%
8	47.5%	67.21%	75.0%
9	69.9%	59.20%	80.4%
10	68.5%	68.96%	90.4%

Table 4: Elkhorn Goldfields – Mt. Hagen STAT-EASE Matrix Recovery Results.

sample quantity. A one half STAT-EASE matrix was chosen containing eight tests that would statistically validate the testing of the sixteen total possible combinations. STAT-EASE software also has the ability to add midpoints into the data testing [10,11]. Although this adds to the size of the sample matrix, midpoint testing adds extra results which can improve the outcome. In the Mt. Hagen ore testing two replicate mid-point tests were conducted based on the STAT-EASE testing matrix. Thus, a total of 10 tests were utilized as follows: This represents the eight tests determined by the software along with two midpoint replicate tests (i.e. test numbers 3 and 6 above) (Table 2).

Results

Upon completing the initial ten diagnostic flotation tests based on the above STAT-EASE matrix, the test results are illustrated in (Table 3,4).

The above recovery data was entered into the STAT-EASE statistical software and modeled to optimize the flotation requirements for the MT. Hagen deposit. STAT-EASE gives several options to transform the

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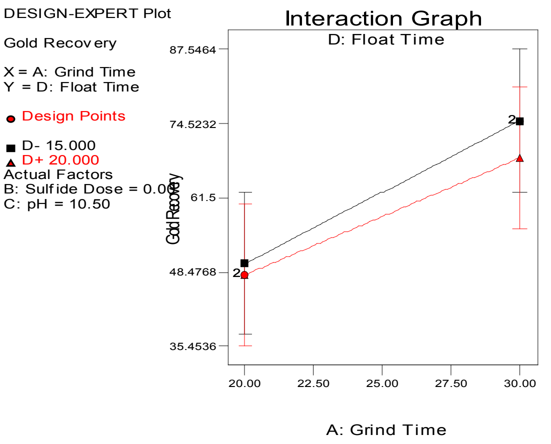

Figure 2: Variable Interaction Graph for Gold Recovery.

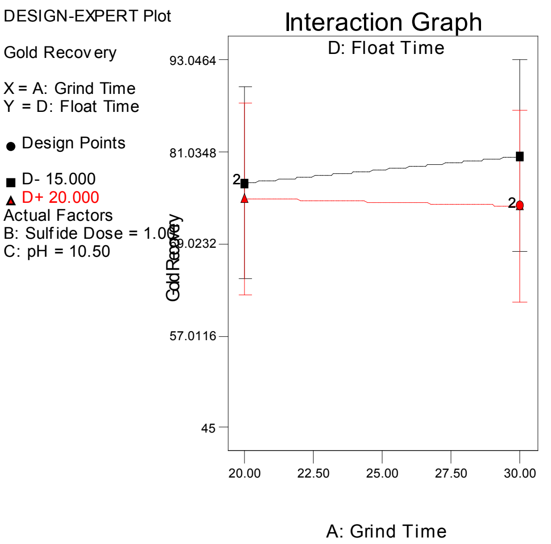

Figure 3: Variable Interaction Graph for Gold Recovery.

data into a statistical probability plot that allows for the best statistical presentation of each outcome. Figure 1 is an example of the half normal plot for gold recovery of the Mt. Hagen deposit.

Upon finding a graphical transformation to fit the variables with the outcomes, STATEASE allows you to add and remove effects generated from the variables to statistically optimize the data. Based on the reviewing the statistical outcome of gold recovery, the probability that the gold recovery would be maximized using this data was 98.7%. A review was completed on all the outcomes (gold and copper recovery and gold and copper grade) and all outcome were found to have probabilities over 90%. Based on this data no further testing was completed on the Mt. Hagen deposit. In reviewing the STAT-EASE variable data, plots such as (Figure 2,3) can be created.

The above noted interaction graphs plot grind time against recovery with float time, pH, and sulfide dose as variables. As noted on the first graph, the sulfide dose is zero and on the second graph the sulfide dose is 1.00. Based on a review of the graph, the expected gold recovery would be identified as shown in Table 5.

By reviewing the above data, sulfide dose is extremely important for low grind times in that recovery is improved approximately 30%. Sulfide dose is not very important for higher grind times and recovery is only improved approximately 3.5%. In the case of a small ball mill with low grind times, sulfide dose optimizes recovery. Sulfide dose would not be important in the case where excess grinding capacity exists. All of the variables can be manipulated together using various graphing techniques to optimize the specific flotation requirements for the specific ore body. In the case of the Mt. Hagen deposit, Table 6 identifies the rougher flotation variables that would be expected to maximize the recoveries in Mt. Hagen ore. In summary, in real world situations where limited representative testing material is available or cost and time are significant issues, proper design of experimentation using STAT-EASE has the ability to identify statistically valid subsets and allow for rapid optimization and design.

Application to a copper, cobalt and goldore

The Idaho Cobalt Project deposits owned by Formation Capital Corporation are situated within the Idaho Cobalt Belt, a mineral district characterized by stratiform occurrences of cobalt, copper, and gold. The Sunshine, East Sunshine, and Ram deposits occur associated with biotite-rich interbeds of volcanic origin within a series of coarsening-upward sequences of argillite, siltite, and quartzite of the middle unit of the Yellow jacket Formation. The main cobalt ore mineral is cobaltite (Co, Fe)AsS while the main copper mineral is chalcopyrite (CuFeS2). The cobaltite grains are generally small, ranging from less than 10 microns to 1 mm. The mineralization in the nearby Sunshine and Ram deposits is low in sulfides. Oxidation is prevalent near surface especially where pyrite is present. Gold and silver is present in most of the ores in the area. The Proven and Probable reserves, containing an average of 30% dilution mainly due to narrow high-grade horizons amount to 1,

VARIABLE	GRIND TIME, MINS	SULFIDE DOSE, GRAMS	RECOVERY, %
GRIND TIME	20.00	0.00	48.5
GRIND TIME	20.00	1.00	78.0
GRIND TIME	30.00	0.00	74.5
GRIND TIME	30.00	1.00	78.0

Table 5: Statistical Model Predicted Gold Recoveries

FACTOR	PARAMETER
GRIND TIME	30 MINS
FLOAT TIME	15 TO 17.5 MINS
pH	10.5
SULFIDE ADDITION	YES

Table 6: Mt. Hagen Optimal Rougher Flotation Parameters

Sample	Co, %	Cu, %	Au, t.o../ton
4-3021	0.482	0.074	0.018
5-3021	0.364	0.360	0.018
6-3021	0.932	0.286	0.044
3-3022	0.162	0.028	0.014
4-3022	2.130	0.050	0.032
5-3022	0.109	0.366	0.016
7-3022	0.123	0.123	0.046
2-3023	0.025	0.929	0.014
3-3023	0.851	0.037	0.038
4-3023	0.284	0.074	0.016
5-3023	0.834	0.389	0.018
6-3023	0.494	1.630	0.012
7-3023	1.010	0.285	0.048

Table 7: The Analysis of Ram Ore Core Samples.

093, 818 tons at a grade of 0.65% cobalt, 0.49% copper and 0.6 grams per tonne of gold.

Previous idaho cobalt belt flotation testing

Initial information on the milling characteristics of the ores from the Sunshine deposit comes mainly from test work on bulk samples and drill composites performed by Blackbird Mining Company (BMC). There is much information on the metallurgy of the Blackbird ores based on past operations and laboratory test work through 1981. All except one of the drill holes that were used to make the composite sample were closest to section 200 North. Some additional information is available from the processing of ores from the nearby Blackbird Mine, which was operated from 1951 to 1959 and again, from 1963 to 1966.

Three types of ore have been recognized in the district: high-sulfide complex ores such as those mined and processed at the Blackbird Mine, siliceous ores, and chloritic ores. No high-sulfide ores have been seen in the Ram or Sunshine deposits. All of the ores are of the siliceous and chloritic types with low total sulfide contents. In general, the low-sulfide ores produced better recoveries and higher-grade concentrates than the high-sulfide ores.

Co, %	Cu, %	Au, t.o./ton
0.574	0.294	0.020

Table 8: Composite Ram Ore Head Grade.

1000 grams of ore at 50% ball mill solids with a 43% volume charge.
Frother is always AF 65 at 0.1 grams.
Copper sulfate activator conditioning is always 10 minutes.
Solids Density is 400 g/L.
Float cell volume is 2.5 liters.
Rougher collector conditioning is always 5 minutes.
Rougher flotation is always 5 minutes.
Scavenger collector conditioning is always I minute.
Scavenger flotation is always 5 minutes.
PAX is Potassium Amyl Xanthate.
SIX is Sodium Isopropyl Xanthate.
Scavenger flotation is always 5 minutes.

Table 9: Flotation Recovery Testing Criteria.

Test	Grind Time	Activator Dosage	Rougher Collector	Rougher Dosage	Scavenger Collector	Scavenger Dosage
1	75 min	0.0 g	PAX	1.0 g	SIX	0.25 g
2	75 min	0.0 g	SIX	1.0 g	PAX	1.0 g
3	75 min	1.0 g	PAX	1.0 g	PAX	0.25 g
4	45 min	0.0 g	SIX	1.0 g	PAX	0.25 g
5	45 min	1.0 g	PAX	1.0 g	PAX	1.0 g
6	45 min	1.0 g	SIX	1.0 g	SIX	0.25 g
7	45 min	1.0 g	SIX	0.25 g	PAX	1.0 g
8	75 min	1.0 g	SIX	0.25 g	PAX	0.25 g
9	75 min	0.0 g	PAX	0.25 g	PAX	1.0 g
10	75 min	0.0 g	SIX	0.25 g	SIX	0.25 g
11	45 min	0.0 g	SIX	0.25 g	SIX	1.0 g
12	75 min	1.0 g	SIX	1.0 g	SIX	1.0 g
13	45 min	1.0 g	PAX	0.25 g	SIX	0.25 g
14	75 min	1.0 g	PAX	0.25 g	SIX	1.0 g
15	45 min	0.0 g	PAX	1.0 g	SIX	1.0 g
16	45 min	0.0 g	PAX	0.25g	PAX	0.25 g
17	75 min	1.0 g	SIX	1.0 g	SIX	1.0 g
18	75 min	1.0 g	SIX	1.0 g	SIX	1.0 g
19	60 min	0.5 g	SIX	0.625g	PAX	0.625g
20	60 min	0.5 g	SIX	0.625g	PAX	0.625g

Table 10: Design of Experiments One Quarter Matrix for Six Variables.

Test	Co Rec., %	Cu Rec., %	Au Rec., %	Co %, Rougher Conc. Grade	Cu %, Rougher Conc. Grade	Au o/T, Rougher Conc. Grade	Test
1	92.82	90.86	73.13	4.47	3.06	0.104	92.82
2	90.88	91.25	73.38	7.78	3.49	0.072	90.88
3	93.81	91.15	47.98	6.00	3.84	0.180	93.81
4	87.26	90.79	72.92	5.68	2.19	0.066	87.26
5	90.00	90.08	86.33	6.17	4.25	0.066	90.00
6	85.54	88.90	53.36	10.05	6.92	0.112	85.54
7	80.44	87.69	72.16	10.24	5.66	0.278	80.44
8	92.28	85.86	72.30	8.04	4.65	0.092	92.28
9	91.99	92.47	74.47	5.76	2.51	0.582	91.99
10	89.63	89.28	73.75	4.70	2.52	0.120	89.63
11	64.04	89.70	72.48	4.33	7.52	0.192	64.04
12	91.23	89.38	86.99	5.92	3.02	0.108	91.23
13	88.49	89.67	73.21	9.45	6.24	0.246	88.49
14	92.68	89.66	73.18	5.35	3.08	0.24	92.68
15	90.82	92.66	68.05	3.71	2.00	0.10	90.82
16	91.99	92.74	75.38	7.01	4.46	0.16	91.99
17	94.73	91.71	66.37	3.88	3.07	0.11	94.73
18	93.47	88.14	73.86	6.11	4.76	0.17	93.47
19	91.33	91.81	67.89	3.97	1.87	0.13	91.33
20	92.64	91.32	76.09	4.03	3.16	0.11	92.64
Average	89.30	90.26	71.66	6.13	3.91	0.16	89.30

Table 11: Flotation Recovery Optimization Testing Results.

Past test work focused on producing two concentrates, cobalt and copper. The copper concentrate would go directly to a copper smelter while the cobalt concentrate, due to its high arsenic content, would go to a hydrometallurgical or bio-oxidation treatment facility for further processing. Current plans call for the production of one bulk cobalt, copper, gold sulfide concentrate with recovery via a hydrometallurgical treatment plant.

Test work on material from the Sunshine deposit appears to have started in 1980 by BMC. The initial testing by BMC, on drill hole composites of siliceous and chloritic ore types indicated that, for a 60% siliceous/40% chloritic ore blend, recoveries of over 80% could be achieved, producing a concentrate grading over 13% cobalt. The results were from bench flotation tests performed on feed with an average grade of about 1.05% Co. The only problem encountered by BMC in the early testing was related to oxidized, near-surface, chloritic ore, where recoveries dropped to around 50%. The problem appeared to be related to the fine-grained minerals and the relatively coarse grind being used in the pilot plant. These previous test results should not be considered representative of future operations.

The initial work by BMC produced two concentrates; a copper concentrate, which would go to a smelter and a cobalt concentrate for shipment to a hydrometallurgical treatment facility. BMC also did some preliminary testing on a bulk concentrate where the concentrate would go to a hydrometallurgy plant where the copper would be recovered as a cathode product or as a copper-rich slime, depending on plant design. Cobalt would be produced as a cathode product following jarosite precipitation. Gold would be recovered in this circuit in the copper slimes and the jarosite.

BMC's test work indicated that high recoveries and high-grade concentrates could be achieved from low sulfide material. Almost

Table 11: Flotation Recovery Optimization Testing Results.

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Response: Recovery, %

Factor	Name	Units	Type	-1 Level	+1 Level
A	Grind, min	Minutes	Numeric	45.00	75.00
B	Rougher Collector Type		Numeric	0.000	1.00
C	Rougher Dosage, lb/ton		Numeric	0.50	2.00
D	Scavenger Collect Type		Numeric	0.000	1.00
E	Scavenger Dosag lb/ton		Numeric	0.50	2.00
F	Activator Dosage, lb/ton		Numeric	0.000	2.00

ANOVA for Selected Factorial Model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1370.02	11	124.55	18.23	0.0064
Residual	27.32	4	6.83		
Cor Total	1397.34	15			

Root MSE	2.61	R-Squared	0.9804	
Dep Mean	71.82	Adj R-Squared	0.9267	
C.V.	3.64	Pred R-Squared	0.6872	
PRESS	437.15	Adeq Precision	16.410	Desire > 4

Figure 4: Gold Analysis of Variance Data.

Factor	Coefficient Estimate	DF	Standard Error	t for Ho Coeff=0	Prob>(t)	VIF
Intercept	71.82	1	0.65			
A-Grind, min	0.081	1	0.65	0.12	0.9077	1.00
B-Rougher Collector	0.35	1	0.65	0.54	0.6200	1.00
C-Rougher Dosage	-1.55	1	0.65	-2.37	0.0767	1.00
D-Scavenger Collector	-0.048	1	0.65	-0.074	0.9448	1.00
E-Scavenger Dosage	4.06	1	0.65	6.22	0.0034	1.00
F-Activator Dosage	-1.13	1	0.65	-1.73	0.1593	1.00
AB	4.36	1	0.65	6.67	0.0026	1.00
AD	4.91	1	0.65	7.52	0.0017	1.00
AF	-0.66	1	0.65	-1.01	0.3716	1.00
BF	0.16	1	0.65	0.25	0.8151	1.00
AB	4.36	1	0.65	6.67	0.0026	1.00
ABF	4.66	1	0.65	7.13	0.0020	1.00

Table 12: Statistical Model Final Fit as a Function of Variables and Variable Interactions

Recovery, %=	
+71.82	
+0.081	* A
+0.35	* B
-1.55	* C
-0.048	* D
+4.06	* E
-1.13	* F
+4.36	* A * B
+4.91	* A * D
-0.66	* A * F
+0.16	* B * F
+4.66	* A * B * F

Table 13: Final Statistical Model Equation in Terms of Coded Factors

all of the Sunshine and Ram deposit reserves can be classed as low-sulfide material. Testing has not been completed for oxidized material, however, BMC indicated problems with oxidized material containing high iron and clay.

Recently, CAMP has completed flotation test work on core from the 1999-2000 Ram drilling program and large diameter PQ core. The PQ core drilling yielded samples of the quality listed in Table 7.

A bulk composite sample was made up for metallurgical testing from a combination of these samples. As well, samples of 4-3021, 4-3022, 2-3023, 3-3023, 6-3023 and 7-3023 were split out and saved for comparative flotation testing of individual horizons. The metallurgical testing ore composite assays are illustrated in Table 8.

Flotation testing and optimization

In order to provide pay metal maximum recovery, simplify the milling circuit design and operation and minimal environmental tailings impact, it was decided to produce a bulk copper, cobalt and gold bearing concentrate. A statistically valid test matrix was setup using STAT-EASE modeling software and lab bulk flotation testing was carried out on composite ore sample. Variables tested included grind time, rougher collector type and dosage and scavenger collector type and dosage and the use or not of copper sulfate as an activator. Not including replicates, full factorial flotation testing would require sixty four tests to validly determine the affects of these variables. A statistically valid one quarter (i.e. sixteen tests) STAT-EASE test matrix was set up along with midpoints and replicates. This amounted to only twenty tests as opposed to sixty four. Then, sequential rougher and scavenger flotation testing was carried out on the composite ore sample. The details are shown in Tables 9,10.

The rougher testing grade and recovery results are as provided in Table 11.

All of these test results were extensively modeled using the software. Due to space constraints not all of the results will be presented. However, illustrative of the robustness of this testing methodology, even minor ore constituents such as gold were effectively modeled with limited statistical testing [13]. The computer results for gold are shown in Figure 4 and Table [14].

The individual fitted results of all the computer modeling for cobalt, copper and gold recovery and grade were then simultaneously optimized. To do this, the individual derived flotation model equation results were input to a spreadsheet in terms of maximizing recovery of metal content and value. The total recovery value was calculated in the model by using prices of $ 0.90 USD /lb of Cu, $ 10.00 USD /lb of Co and $ 275.00 USD/t.o. of Au for the metals values recovered. The optimized and fitted model output was as provided in Table 15.

Analogous, cleaner flotation optimization work was also undertaken but due to space limitations in this paper it will not be illustrated here.

Recovery, %=	
+84.10	
-0.26	* Grind, min
+2.82	* Rougher Collector
-2.07	* Rougher Dosage, lb/ton
-39.40	* Scavenger Collector
+5.42	* Scavenger Dosage, lb/ton
+19.98	* Activator Dosage, lb/ton
+0.041	* Grind, min * Rougher Collector
+0.66	* Grind, min * Scavenger Collector
-0.35	* Grind, min * Activator Dosage, lb/ton
-36.97	* Rougher Collector * Activator Dosage, lb/ton
+0.62	* Grind, min * Rougher Collector * Activator Dosage, lb/ton

Table 14: Final Statistical Model Equation in Terms of Actual Factors.

Predicted Co Recovery	94.68 %	Co Value	$108.70
Predicted Cu Recovery	90.97 %	Cu Value	$4.81
Predicted Au Recovery	68.86 %	Au Value	$3.79

Spreadsheet	Optimized Conditions	Total Value
Grind Time	75 min	$117.30
Rougher Collector	PAX	
Rougher Dosage	1.0 g	
Scavenger Collector	SIX	
Scavenger Dosage	1.0 g	
$CuSO_4$ Activator Dosage	1.0 g	

Table 15: Stat-Ease Statistical Model Flotation Equation Spreadsheet Optimization Model.

1000 grams of ore at 50% solids ground in a ball mill for 75 minutes with a 43% volume ball charge.
Frother is always AF 65 at 0.1 grams.
Solids Density is 400 g/L
Float cell volume is 2.5 liters
Copper sulfate activator at 1.0 grams with conditioning of 10 minutes.
Rougher PAX collector at 1.0 grams with conditioning at 5 minutes.
Rougher flotation at 5 minutes.
1000 grams of ore at 50% solids ground in a ball mill for 75 minutes with a 43% volume ball charge.

Table 16: Confirmatory Locked Cycle Flotation Testing Criteria.

Co, %	Cu, %	Au, o/T
14.4	7.41	0.396

Table 17: Final Locked Cycle Cleaner Concentrate Grade.

Co, %	Cu, %	Au, o/T
92.7	92.8	72.9

Table 18: Overall Locked Cycle Concentrate Recoveries.

Confirmatory locked cycle flotation testing

Based on the optimized results, locked cycle flotation testing was undertaken in a standard sequence of consecutive tests to simulate the proposed circuit. The proposed locked cycle circuit consisted of rougher flotation carried out as in Table 16.

Scavenger flotation was undertaken on the rougher tails by adding 1.0 gram of SIX, conditioning for 1 minute and floating for 5 minutes. Both of the scavenger concentrates and rougher concentrates were then cleaned with starvation quantities of 0.025 g SIX and no activator at 100 g/L solids content. The final concentrates and the scavenger circuit tails were recovered, filtered and dried. The rougher cleaner tails reported back to the scavenger cleaner and the scavenger cleaner tails reported back to the initial rougher flotation step [14]. Seven consecutive cycles of testing provided an equilibrium circuit scenario and produced good recoveries and grades. The results were provided in Tables 17,18. This completely confirmed the validity of the testing and design of experiment methodology and optimization modeling.

Summary

This paper has illustrated the successful use of statistically valid design of experiments using STAT-EASE software. This methodology provides a low cost and rapid process for real world laboratory flotation testing, optimization, application and flow sheet development, particularly when minimal financial resources, time and representative samples are a constraint.

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