

# WAS THAT LOCKED CYCLE TEST ANY GOOD ?

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## ABSTRACT

Locked cycle testing has become more common practice in the last 10 years. Reasons vary from a desire to avoid pilot plant testing, demand for more variability testing within deposits, and perhaps most importantly, a request from the financial institutions who invariably finance many of the projects. Surprisingly, many people don't understand locked cycle testing, analysis and balancing. This paper provides a brief overview of locked cycle testing, and then progresses into a more detailed discussion on the analysis and balancing of locked cycle test data. The paper endeavors to educate CMP personnel on how to determine if the test was good and if a reasonable metallurgical projection was made. The paper uses case studies to illustrate the key points.

## INTRODUCTION

A locked cycle test is a repetitive batch used to simulate a continuous circuit. The basic procedure has a complete batch test performed in the first cycle which is then followed by similar batch tests which have "intermediate" material from the previous cycle added to the appropriate location in the current cycle. These batch tests, or cycles, are continued in this iterative manner for an arbitrary number of cycles. The final products from each cycle, i.e. final concentrate and final tailings, are filtered and thus removed from further processing. At the end of the test, all the products, final and intermediate, are dried, weighed and subjected to chemical analysis. The test is balanced and a metallurgical projection is made.

This description can be found in many of our classical textbooks for the mineral engineer<sup>1, 2, 3, 4</sup>. Unfortunately, none of these textbooks provide any discussion beyond the basic procedure. Often, they provide comments such as in Taggart where he states; "It is questionable whether in any case it approximates mill results any more closely than the standard batch test." It is truly surprising that our classic textbooks promote that locked cycle tests are more art than science, and suggest that they can be of dubious value. None of the textbooks provide meaningful insight or discussion in how to assess:

- the number of cycles to perform,
- how to assess if the test has achieved steady state,
- how to produce a metallurgical projection,
- is the metallurgical projection valid.

It is also surprising that the textbooks with examples not only do not provide any discussion on the above subjects, but have also used examples, which did not achieve steady state, and then have produced a metallurgical projection of dubious quality. The only conclusion to be drawn is that most mineral engineers have not been properly taught nor shown how locked cycle tests should be conducted and the data from the test handled.

### OBJECTIVES OF A LOCKED CYCLE TEST

Locked cycle tests are conducted for two main reasons:

- produce a metallurgical projection for the sample tested, and
- Assess if the flowsheet and reagent suite is stable.

Locked cycle testing is the preferred method for arriving at a metallurgical projection from laboratory testing. The reason for this is simple, the final cycles of the test should mimic a continuous circuit. In a batch test the department of the intermediate streams to concentrate or tailings is unknown. A cycle test has these streams recycled and at the end

of the test the material in these streams should report to either concentrate or tailings. Thus there will be no need to estimate how the intermediate streams divide between concentrate and tailing.

Cycle tests are also used to assess the suitability of a flowsheet and reagent suite. If the cycle test does not come to steady state then this indicates there is problems. Typical flowsheet problems are recovery intensive flowsheet (i.e. countercurrent) for ores with challenging mineral selectivity, or aggressive flotation in the recovery stages and too selective in the latter cleaner stages which forces a circulating load. Typical reagent problems stem from either too much or too little.

### STEADY STATE, STABILITY AND MASS CONSERVATION

These terms are used interchangeably when locked cycle tests are discussed. But I feel that these terms have different meanings. Mular<sup>5</sup> provides an excellent description of steady state. "At steady-state, the mass input rate equals the mass output rate, whether it is entire process that is being considered, or

individual unit operations. For a system at steady-state, no material accumulates internally; each unit operation is functioning with an unchanging volume of material already in the circuit.” Mular’s description of steady state brings forward the need for stability and mass conservation.

Stability implies constancy. For example, the concentrate weight and assay remain the same for the last 3 cycles of the locked cycle test. Mass conservation implies “what goes in must come out.” In the context of a locked cycle test, 1000 grams in, 1000 grams out as final concentrate and tailing. But, mass conservation must also apply to the metal units. Thus, 100 grams of chalcopyrite in, 100 grams of chalcopyrite out. Invariably, most people look for stability when studying locked cycle test results, it’s easy to see by looking at the data. Most people ignore mass conservation because it is not easily determined by quickly glancing at locked cycle test results. Steady state implies both stability and mass conservation. A good locked cycle test achieves steady state.

The following two examples in Table 2 and 3 demonstrate the concepts of stability and mass conservation. Both tests used a simple counter-current rougher with two stages of cleaning flowsheet. Test LC-1 appears to be very stable. The concentrate and the assays of the final 4 cycles of the six-cycle test are constant. Test LC-2 looks horrible, the weights and assays are all over the place. Is either test any good?

Table 1 takes a closer look at the output from the tests. Note that output refers to what reports to concentrate and tailings, i.e. the final products. Examination of the data in Table 1 reveals that in Test LC-1 that only 900 grams are coming out in each of the last 4 cycles when 1000 grams of ore was being ground. In test LC-2, the average weight out is 1000 grams out per cycle over the last four cycles, but the weight and assays vary tremendously. LCT shows good mass conservation, but poor stability. Thus, neither test has achieved steady state. Figures 1 and 2 plot the results from Table 1. LC-1 is stable, but has poor mass

Table 1 Weight and Copper Output by Cycle for LCT-1 and LCT-2

CYCLE TEST OUTPUT, LCT-1		
Cycle#	Wt, g	%(Cu Units)
A	820	72.3
B	880	85.4
C	900	92.6
D	900	92.6
E	900	92.6
F	900	92.6

CYCLE TEST OUTPUT, LCT-2		
Cycle#	Wt, g	%(Cu Units)
A	820	71.9
B	930	91.1
C	1015	100.5
D	970	99
E	1040	104.2
F	975	96.3

conservation as is shown by none of the cycles approaching 100%. Test LC-2 has good mass conservation as the last 4 cycles hover around 100%, but is not very stable.

So stability is easy to check, mass conservation more difficult. The weight mass conservation is easily followed by summing up the product weights

Table 2: Example LCT-1 Results

PRODUCT	Wt, gram	Wt%	Assay %Cu	Distribution Cu
Cu Cl Conc A	70	1.17	34.0	11.3
Cu Cl Conc B	90	1.5	31.0	13.3
Cu Cl Conc C	100	1.67	30.0	14.3
Cu Cl Conc D	100	1.67	30.0	14.3
Cu Cl Conc E	100	1.67	30.0	14.3
Cu Cl Conc F	100	1.67	30.0	14.3
Cu Cl 2 Tail F	200	3.3	7.6	7.20
Cu Cl 1 Tail F	500	8.3	2.00	4.80
Cu Ro Tail A	750	12.5	0.20	0.7
Cu Ro Tail B	790	13.2	0.25	0.9
Cu Ro Tail C	800	13.3	0.30	1.1
Cu Ro Tail D	800	13.3	0.30	1.1
Cu Ro Tail E	800	13.3	0.30	1.1
Cu Ro Tail F	800	13.3	0.30	1.1
Head (calc)	6000	100	3.50	100

per cycle. At the end of the test they should be similar to the starting weight. The metal mass conservation can be tracked through the distribution. The sum of the distribution for the final products multiplied by the number of cycles provides the check. For example, cycle D of LCT has 14.3% and 1.1% copper distribution which yields only 92.4% copper out ( $6 * (14.3 + 1.1) = 92.4\%$ ). It is suggested that all cycle tests include a table similar to Table 1 to track the stability and mass conservation. It is easily calculated in spreadsheets and really is one of the few ways to assess if the test has come to steady state. The need for this becomes apparent when the metallurgical projection is made.

**METALLURGICAL PROJECTIONS**

Producing a valid metallurgical projection from a locked cycle test is one of the most important components of the test. It is the final numerical summary of the tests metallurgical performance. Since it is so important, it seems strange there are three different procedures to come up with the metallurgical projection.

- n-product formula (balance on assays from final products),
- SME procedure (balance on final product weights and assays),
- Concentrate production balance (balance on final concentrate weights and assays).

It is important to note that no procedure

is ideal for a test that is not at steady state. But, for a test that is at steady state, all three procedures will produce the same metallurgical projection.

The following provides a brief description of the procedures.

**N-Product Formula**

The n-product formula is a simple material balance technique that utilizes the assays from the final products to determine the mass balance. Taggart provides an excellent description of the procedure. In the case of a simple ore with only a concentrate and tailing, the procedure uses the assay of the feed, concentrate and tailing in the familiar formula:

$$C = F * (f - t) / (c - t)$$

The remainder of the balance is calculated once C (the concentrate mass) is determined. In application for locked test balancing, the weighted average assay for the final 2 to 4 cycles is used. One of the important requirements for using the n-product formula is that the circuit must have mass conservation, input material = output material. If the circuit does not have mass conservation, then the n-product formula should not be used, as it will provide an erroneous result. It is important to mention that using computer mass balance programs such as MATBAL or BILMAT is essentially the same approach as the n-product formula when applied to locked cycle tests.

**SME Procedure**

The SME procedure is described in the SME handbook. The procedure is more direct and should be easier to apply than the n-product formula. In the case of a simple ore with only a concentrate and a tailing, the concentrate is projected as the average mass and assay of the concentrate produced in the last few cycles of the test, the tailing is projected in a similar basis. The feed for the test is then calculated as the sum of the products. This procedure works fine as long as the test has come to steady

Table 3: Example LCT2 Results

PRODUCT	Wt, gram	Wt%	Assay %Cu	Distribution Cu
Cu Cl Conc A	70	1.17	34.0	11.3
Cu Cl Conc B	90	1.5	33.0	14.1
Cu Cl Conc C	115	1.92	28.0	15.3
Cu Cl Conc D	100	1.67	32.4	15.3
Cu Cl Conc E	120	2.00	27.8	15.8
Cu Cl Conc F	95	1.58	32.8	14.8
Cu Cl 2 Tail F	50	0.83	12.0	2.8
Cu Cl 1 Tail F	200	3.33	3.5	3.3
Cu Ro Tail A	750	12.5	0.20	0.7
Cu Ro Tail B	840	14.0	0.28	1.1
Cu Ro Tail C	900	15.0	0.35	1.5
Cu Ro Tail D	870	14.5	0.28	1.2
Cu Ro Tail E	920	15.3	0.36	1.6
Cu Ro Tail F	880	14.7	0.31	1.3
Head (calc)	6000	100	3.52	100

Figure 1: Mass and Copper Output by Cycle for test LCT-1

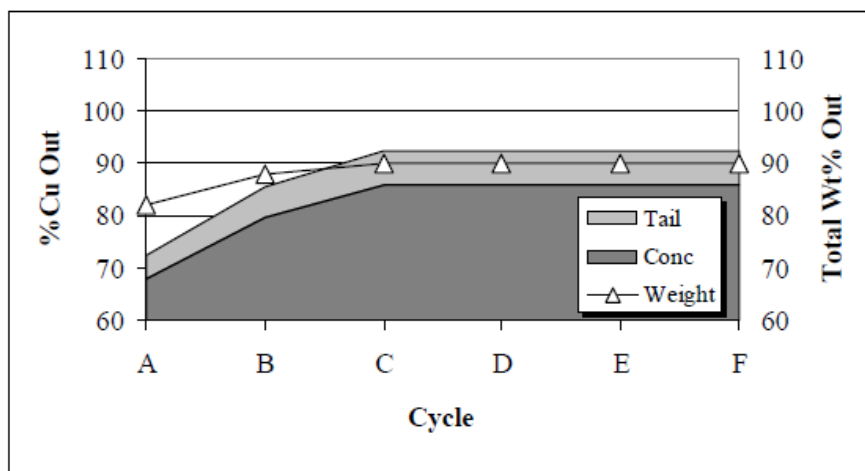
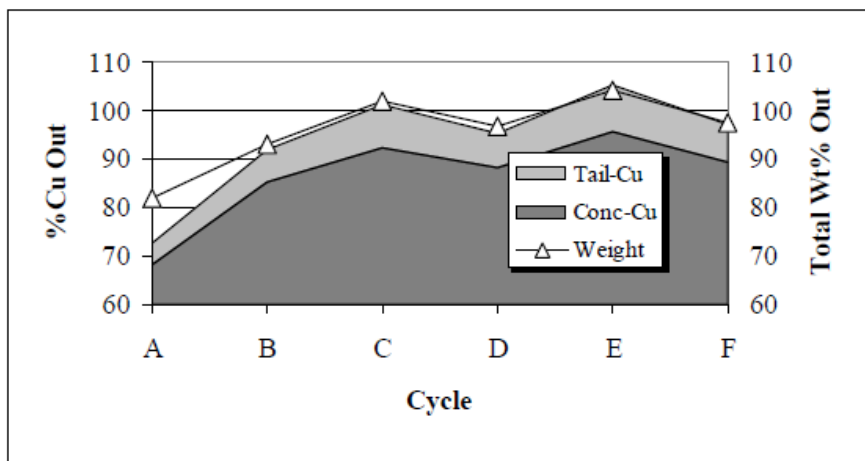


Figure 2: Mass and Copper Output by Cycle for test LCT-2



state. If the test has not achieved mass conservation then it will provide an erroneous result since it completely ignores the material not reporting to the final products.

**Concentrate Production Balance**

This procedure is not explicitly described in any text. This procedure is an offset from the SME procedure where the concentrate is projected the same way as for the SME procedure. The tailings are then calculated as the difference between the feed and the concentrate. An advantage of this procedure is that does not overstate the metallurgy when the test does not

have mass conservation. The premise for the procedure is that the concentrate produced is the concentrate produced. All other material must therefore be tailings. In many respects this procedure resembles a month end production balance at an operating plant.

**Case Study of Balance Procedures**

The best way to demonstrate the different balancing procedures and their metallurgical projections is on an actual data. Two data sets have been selected from the public domain. The first example is taken from the SME handbook and is an example of a locked cycle test that has not achieved steady

state. The second example is taken from Agar et al and is one of the very few locked cycle test examples in the public domain which has come very near to steady state.

Tables 4 and 5 present the SME and Agar examples respectively. The second part of each table provides the check on steady state and the results of the four metallurgical projections. The fourth projection is another offset from the concentrate production balance whereby the balance assumes the tailings are correct and the concentrate is calculated as the difference between the feed and tailings.

Table 4: Raw Data from Agar Matte Separation Example

PRODUCT			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Cu 3rd Cl Conc A	454.2	3.9	74.9	2.2	20.1	6.9	0.3	3.5
Cu 3rd Cl Conc B	675.5	5.8	75.7	3.2	20.3	10.3	0.5	5.3
Cu 3rd Cl Conc C	675.4	5.8	73.9	3.6	20.1	10.1	0.6	5.2
Cu 3rd Cl Conc D	654.9	5.6	74.3	3.4	20.0	9.9	0.6	5.0
Cu 3rd Cl Conc E	631	5.4	75.6	3.0	20.1	9.7	0.5	4.9
Cu 3rd Cl Conc F	646.2	5.6	75.3	3.3	20.3	9.9	0.5	5.1
Cu 3rd Cl Conc G	654.2	5.6	74.1	3.4	20.1	9.8	0.6	5.1
Cu 3rd Cl Conc H	648.6	5.6	75.6	3.5	20.1	10	0.6	5.0
Cu 3rd Cl Conc I	651.3	5.6	75.3	3.5	19.8	10	0.6	5.0
Cu 3rd Cl Tail I	88.9	0.8	63.2	14.3	20.4	1.1	0.3	0.7
Cu 2nd Cl Tail I	104.7	0.9	52.1	24.4	20.9	1.1	0.6	0.8
Cu 1st Cl Tail I	159.5	1.4	29.9	45.2	22.6	1.0	1.8	1.4
Cu Tail (Ni Conc) A	533.5	4.6	4.7	70.3	25.0	0.5	9.5	5.1
Cu Tail (Ni Conc) B	551.7	4.7	5.4	67.7	24.8	0.6	9.5	5.3
Cu Tail (Ni Conc) C	617	5.3	8.3	65.7	24.7	1.0	10.3	5.9
Cu Tail (Ni Conc) D	643.4	5.5	9.3	65.0	24.8	1.2	10.6	6.1
Cu Tail (Ni Conc) E	688.4	5.9	13.1	61.8	24.6	1.8	10.8	6.5
Cu Tail (Ni Conc) F	645.1	5.6	9.7	64.6	24.7	1.3	10.6	6.1
Cu Tail (Ni Conc) G	638.1	5.5	9.3	64.6	24.5	1.2	10.5	6.0
Cu Tail (Ni Conc) H	663.1	5.7	10.1	64.2	24.6	1.4	10.8	6.3
Cu Tail (Ni Conc) I	598.6	5.2	9.3	64.8	24.4	1.1	9.9	5.6
Head (calc)	11620.3	100	42.4	33.9	22.3	100	100	100

Combined Products

PRODUCT			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Cu Conc	5688.3	49	75	3.27	20.1	86.6	4.7	44
Midds	353.1	3	44.9	31.3	21.5	3.2	2.8	2.9
Ni Conc	5578.9	48	8.97	65.2	24.7	10.2	92.5	53
Head (calc)	11620.3	100	42.4	33.9	22.3	100	100	100

Table 4 cont: Stability Check and Metallurgical Projections for Matte Separation Example

Stability/Mass Conservation

CYCLE	wt	Cu	Ni	S
A	76.5	66.8	88	77.9
B	94.8	98.5	90.3	94.8
C	100.1	100.6	98.2	99.9
D	100.6	99.9	100.7	100.7
E	102.2	103.7	101.6	102.7
F	100	100.4	100.2	100.7
G	100.1	99.5	99.3	99.8
H	101.6	101.9	102.5	101.8
I	96.8	99.8	93.9	95.4
Ave E-I	100.1	101.1	99.5	100.1

3 product formula cycle E-E (calculate mass dist from assumed steady state assay)

			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Feed	1291.1	100.0	42.4	33.9	22.3	100.0	100.0	100.0
Cu Conc	637.7	49.4	75.2	3.34	20.1	87.6	4.9	44.4
Ni Conc	653.5	50.6	70.4	64.0	24.6	12.4	95.6	55.7

SME handbook (based on final weights out, balance only on final products)

			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Feed	1292.9	100.0	42.8	33.7	22.3	100.0	100.0	100.0
Cu Conc	646.3	50.0	75.2	3.34	20.1	87.9	5.0	45.0
Ni Conc	646.7	50.0	10.4	64.0	24.6	12.1	95.0	55.0

Concentrate Production (based on concentrate out, assume unaccounted for into tails)

			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Feed	1291.1	100.0	42.4	33.9	22.3	100.0	100.0	100.0
Cu Conc	646.3	50.1	75.2	3.34	20.1	88.8	4.9	45.0
Ni Conc	644.9	49.9	9.49	64.5	24.6	11.2	95.1	55.0

"ALT" (based on tail out, assume unaccounted for into conc)

			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	Cu	Ni	S	Cu	Ni	S
Feed	1291.1	100.0	42.4	33.9	22.3	100.0	100.0	100.0
Cu Conc	644.5	49.9	74.5	3.69	20.1	87.8	5.4	44.9
Ni Conc	646.7	50.1	10.4	64.0	24.6	12.2	94.6	55.1

Table 5: Raw Data from SME Handbook PbZn ore Example

	wt, g	wt%	ASSAY, %			DISTRIBUTION, %		
			%Pb	%Zn	opt Ag	Pb	Zn	Ag
Pb 4th CI Conc A	27.8	0.5	72.1	5.46	31.0	8.5	0.3	7.4
Pb 4th CI Conc B	56.2	1.0	58.3	8.21	24.9	13.8	0.9	12.1
Pb 4th CI Conc C	59.8	1.0	56.6	8.95	24.8	14.3	1.1	12.8
Pb 4th CI Conc D	54.6	0.9	55.9	8.25	25.1	12.9	0.9	11.8
Pb 4th CI Conc E	54.9	0.9	51.9	8.74	23.1	12.0	1.0	10.9
Pb 4th CI Conc F	57.8	1.0	54.3	8.14	23.8	13.3	0.9	11.9
Pb 4th CI Tail F	16.1	0.3	21.9	12.8	9.59	1.5	0.4	1.3
Pb 3rd CI Tail F	28.0	0.5	23.0	13.1	7.98	2.7	0.7	1.9
Pb 2nd CI Tail F	28.3	0.5	19.1	13.0	5.92	2.3	0.7	1.4
Pb 1st CI tail F	108.1	1.8	7.18	13.2	3.66	3.3	2.8	3.4
Pb Scav Conc F	73.6	1.3	3.6	12.0	2.48	1.1	1.8	1.6
Zn 3rd CI Conc A	104.6	1.8	0.99	54.2	1.62	0.4	11.3	1.5
Zn 3rd CI Conc B	113.8	1.9	0.92	55.4	1.57	0.4	12.6	1.5
Zn 3rd CI Conc C	116.3	2.0	0.91	53.5	1.51	0.4	12.4	1.5
Zn 3rd CI Conc D	131.8	2.2	1.03	52.6	1.4	0.6	13.8	1.6
Zn 3rd CI Conc E	140.9	2.4	1.18	51.5	1.73	0.7	14.5	2.1
Zn 3rd CI Conc F	130.7	2.2	1.24	55.0	1.73	0.7	14.4	1.9
Zn 3rd CI Tail F	21.0	0.4	2.9	24.7	2.8	0.3	1v	0.5
Zn 2nd CI Tail F	21.5	0.4	3.05	14.1	2.38	0.3	0.6	0.4
Zn 1st CI Tail F	168.5	2.9	1.51	8.49	1.29	1.1	2.9	1.9
Zn Scav Conc F	53.4	0.9	1.36	4.02	1.08	0.3	0.4	0.5
Zn Scav Tail A	590.0	10.0	0.42	0.45	0.21	1.0	0.5	1.1
Zn Scav Tail B	726.0	12.4	0.43	0.45	0.32	1.3	0.7	2.0
Zn Scav Tail C	721.0	12.3	0.52	0.48	0.21	1.6	0.7	1.3
Zn Scav Tail D	741.0	12.6	0.52	0.56	0.21	1.6	0.8	1.3
Zn Scav Tail E	763.0	13.0	0.52	0.62	0.32	1.7	0.9	2.1
Zn Scav Tail F	765.0	13.0	0.57	0.6	0.32	1.8	0.9	2.1
Head (calc)	5873.7	100.0	4.03	8.53	1.97	100.0	100.0	100.0

Combined Products

	wt, g	wt%	ASSAY, %			DISTRIBUTION, %		
			%Pb	%Zn	opt Ag	Pb	Zn	Ag
Pb Conc A-F	311.1	5.3	56.9	8.19	24.9	74.8	5.1	66.9
Pb Midds F	254.1	4.3	10.2	12.8	4.42	10.9	6.5	9.7
Zn Conc A-F	738.1	12.6	1.05	53.6	1.6	3.3	78.9	10.2
Zn Midds F	264.4	4.5	1.72	9.33	1.46	1.9	4.9	3.3
Zn Tail A-F	4306.0	73.3	0.5	0.53	0.27	9.1	4.6	9.9
Head (calc)	5873.7	100.0	4.03	8.53	1.97	100.0	100.0	100.0

Stability/Mass Conservation

CYCLE	wt	Pb	Zn	Ag
A	73.8	59.7	72.9	59.8
B	91.5	93.7	84.9	93.6
C	91.6	98.0	85.0	93.6
D	94.7	90.6	93.3	88.5
E	97.9	86.5	98.2	90.7
F	97.4	94.7	97.3	95.6
Avg. E-F	97.7	90.6	97.7	93.2

3 product formula cycle E-F (calculate mass dist from assumed steady state assay)

	wt, g	wt%	ASSAY, %			DISTRIBUTION, %		
			Pb	Zn	AG	Pb	Zn	AG
Feed	979	100.0	4.03	8.53	1.97	100.0	100.0	100.0
Pb Conc	63.1	6.45	53.1	8.43	23.4	85.0	6.4	76.6
Zn Conc	138	14.1	1.21	53.2	1.73	4.2	87.9	12.4
Tail	778	79.4	0.55	0.61	0.32	10.7	5.7	12.9

SME handbook (based on final weights out, balance only on final products)

	wt, g	wt%	ASSAY, %			DISTRIBUTION, %		
			%Pb	%Zn	opt Ag	Pb	Zn	Ag
Feed	956	100.0	3.74	8.54	1.88	100.0	100.0	100.0
Pb Conc	56.4	5.89	53.1	8.43	23.4	83.8	5.8	73.4
Zn Conc	136	14.2	1.21	53.2	1.73	4.6	88.5	13.0
Tail	764	79.9	0.55	0.61	0.32	11.6	5.7	13.6

Concentrate Production (based on concentrate out, assume unaccounted into tails)

	wt, g	wt%	ASSAY, %			DISTRIBUTION, %		
			%Pb	%Zn	opt Ag	Pb	Zn	Ag
Feed	979	100	4.03	8.53	1.97	100.0	100.0	100.0
Pb Conc	56.4	5.76	53.1	8.43	23.4	75.9	5.7	68.4
Zn Conc	136	13.9	1.21	53.2	1.73	4.2	86.5	12.2
Tail	787	80.4	1.0	0.83	0.48	20.0	78.0	19.5

“ALT” (based on tails ou, assume Zn conc ok, unaccounted for into Pb Conc)

			ASSAY, %			DISTRIBUTION, %		
	wt, g	wt%	%Pb	%Zn	opt Ag	Pb	Zn	Ag
Feed	979	100.0	4.03	8.53	1.97	100.0	100.0	100.0
Pb Conc	79.2	8.09	42.5	8.39	18.4	85.3	7.9	75.2
Zn Conc	136	13.9	1.21	53.2	1.73	4.2	86.5	12.2
Tail	764	78.0	0.55	0.61	0.32	10.6	5.6	12.6

Table 4 shows the Agar Matte Separation example. Reviewing the assessment of the steady state for the test, we see that the test was in steady state from cycle C onwards. The metallurgical projections for the test are all very similar, 75 %Cu at 88% copper recovery. Thus, a good test will produce a good metallurgical projection from any balancing procedure. Figure 3 presents the data points on a grade vs. recovery plot. Note how close together all the points are.

Table 5 shows that the SME example did not come to steady state, and in fact was quite far from steady state for lead. Knowing this, the data must be reviewed with caution. This is borne out when the projected lead recoveries are checked, they range from 75% to 85%. Quite a difference! Why ?

The difference stems from the assumption the three balance procedures make. The n-product formula by definition assumes that the test has achieved steady state. Thus, it assumes there is no accumulation of material to the intermediate products, which is a wrong assumption for this test. The n-product formula has projected that 63.1 g of lead concentrate was produced on average for cycles E and F, while in fact only 56.4 g of lead concentrate was produced.

The SME procedure has projected the correct lead concentrate weight at 56.4 g, but the projection is based on only 956 g of ore per cycle while 979 g were actually used. This procedure has completely ignored 23 g of intermediate product.

The concentrate production method has projected the lowest lead recovery. This procedure assumes that the entire intermediate product has reported to

tailings. This assumption is potentially pessimistic as some of the intermediate product would likely report to the lead concentrate, but certainly not at final lead concentrate grade.

Figure 4 plots the results for the different metallurgical projections from the SME example. The metallurgical projection from the latter two procedures represents achievable metallurgical data points. The concentrate and the tailings are actual data from the test. The 3-product formula and SME procedures essentially assumes that all the accumulated intermediate product will report to concentrate at final concentrate grade. This is obviously an over estimate of what is likely to happen. If the test was carried on to steady state, the final projection should lie in the triangle defined by the individual data points. The dotted line through the triangle is one possible estimate of the metallurgy from this test. The procedure to develop the line was to add the data

from the middling stream, in this case the Pb 4 Cl tail, to the actual concentrate produced. If all the 4 cleaner tailing is added to the last two cycles of the test, the projected metallurgy would be 46.2 %Pb at 84.8 % Pb recovery. The test would be very near to 100% mass conservation for weight and lead. Hence, there is no indication that the intermediate streams will report to the final concentrate at final concentrate grade. Data manipulation such as this should be avoided.

**DISCUSSION ON METALLURGICAL PROJECTION FOR UNSTABLE TESTS**

Two case studies were reviewed and discussed. The Matte Separation test had achieved steady state and all the metallurgical projection procedures produce the same result. The SME Pb-Zn example was not at steady

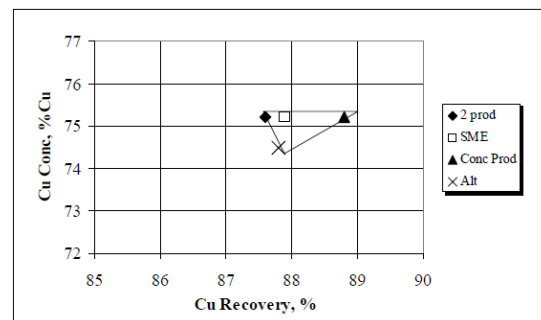


Figure 3: Grade vs. Recovery of Metallurgical Projections – Matte Separation Example

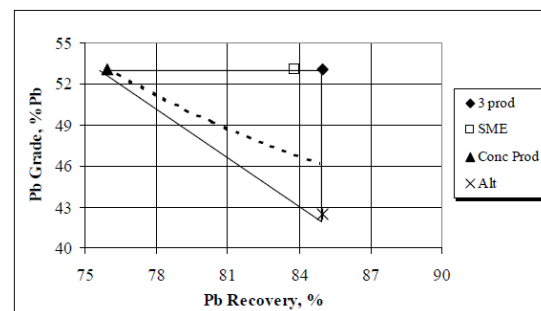


Figure 4: Grade vs. Recovery of Metallurgical Projections - SME Example

state and the different procedures for producing metallurgical projections gave widely differing results. Do any of these procedures produce valid data in this case? It is felt that the concentrate production procedure can be used since it at least makes a projection of achievable metallurgy. The n-product formula and SME procedures were shown to overstate the metallurgical result. Figure 5 is a visually presents how the n-product formula and SME procedure consider the test data from at test not in steady state. These procedures balance on only 91 % of the pie for lead in the SME example. They ignore the 9% lost to the middlings. These two procedures should not be used on a test that has not come to steady state. The further the test is from



steady state, the more the recovery is overstated.

This brings up the question of how close to 100% steady state is acceptable. Note that I have never been observed a test is at 100.00% steady state. Good tests will be at 100% for weight and 100%  $\pm$  2% for the metals. Any test which is  $>5\%$  from 100% should be deemed as not near steady state, and thus the data viewed with caution. Any test which is  $>10\%$  from steady state should probably be considered a bad test and must be ignored or repeated.

How many cycles should be performed? Most tests are conducted for six cycles. There is no basis for this length of test. Tests should be conducted until they achieve steady state. Agar presented a relatively simple numerical simulation technique that can be used to estimate the number of cycles and the potential stability for the test. The technique found to have the most success was the tracking of the wet cake weights during the test. Each of the final products are weighed and recorded during the test. Target weights are established prior to the test so that the technician (s) can gauge the success of the test. The target weights can be derived from the weights produced during the batch tests, or using a simple calculation to account for the filter paper weight and the cake moisture content. The test is deemed to be in steady state when the all the target weights are being met. It should be pointed that carrying out a test for 20 cycles does not necessarily ensure the test comes to steady state. All it guarantees is a longer test. It is felt that if a test must be greater than 9 cycles, then the operators are trying to force the concentrate grade high and the tailings lower than they naturally want to be.

Can an unstable test with mass conservation have a good metallurgical projection? Yes, because there will be no net accumulation of material in intermediate products over a series of cycles. Refer back to example LCT-2. The average weight and copper output for the last 4 cycles is 100% and thus a good metallurgical projection is possible. Thus the number of cycles which should be used for producing the

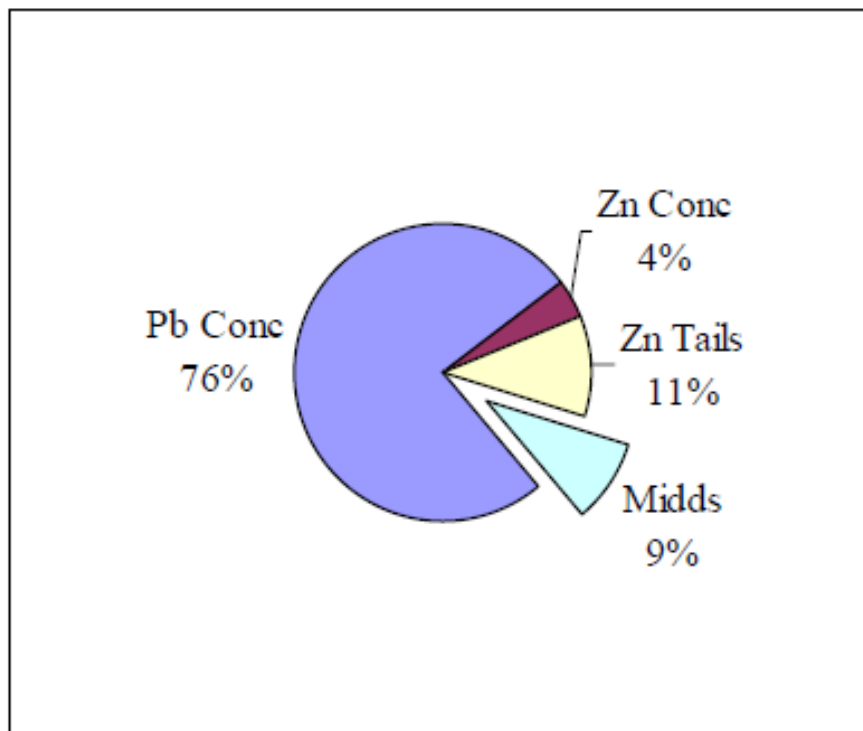


Figure 5: Lead Distribution in SME Example

metallurgical projection can be based on the number of cycles which give good mass conservation. In example LCT-2, 4 cycles is good. In the Matte separation example, any number from cycle C through I would be acceptable (note that cycle I balance was poor), as long as a minimum of 2 cycles are used.

The recovery by cycle can be easily checked from the raw data. In the SME example, the cycle D lead recovery to Pb concentrate is  $\sim 77\%$  ( $12.9\% * 6 = 77.4\%$ ). Reviewing the lead distribution to the Pb concentrate for this test shows that the lead recovery was around 80% from cycle B through F. There is no indication that a lead recovery of 85% can be expected from this test. If 85% recovery is desired, then more concentrate must be produced. Lowering the tailings assay only increases the recovery if the extra metal values report to concentrate.

## SUMMARY

Two items pertaining to locked cycle tests were discussed in detail. The first item was steady state, but in particular the issue of mass conservation. A primary objective of locked cycle testing should be to have the test achieve mass

conservation so that a good metallurgical projection can be made. Methods to assess if the test came to steady state were presented. It is recommended that those who practice locked cycle tests include an analysis of the cycle by cycle results as part of the test summary. It is perhaps the easiest way to assess the stability and mass conservation for the test.

The second item discussed was metallurgical balancing for the metallurgical projection. It was shown that good tests, i.e. tests that achieved steady state, are insensitive to the balancing procedure and good projections will be made. Tests that did not achieve steady state must have their data reviewed with caution. It was suggested that the balancing procedure for a test that did not achieve steady state was the concentrate production procedure. The reason is because the projected metallurgy is achievable, while the n-product formula and SME procedure were shown to over estimate the metallurgical recovery.

It is hoped that the paper has been informative so that the individuals will be able to intelligently answer the question "was that locked cycle test any good?"

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