Application of SPI for Modeling energy consumption in Sarcheshmeh SAG and ball mills

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Abstract

In this research, the efficiency of the comminution circuit as well as the efficiency of size classification equipment of the concentrator plant 2 of Sarcheshmeh copper complex was studied. The comminution circuit of this plant includes one SAG mill in a closed circuit with a vibrating screen and one ball mill with a size classification system of hydrocyclone. The goal of this work was to calculate the proportion of each of these mills at energy consumption and generating suitable product for flotation as a further process. Three stages of sampling were performed and consumed energy was also modeled. The average efficiency of the initial ball mill was obtained which was equal to 72.96%. The average of the proportion of (consumed) energy by SAG and ball mills from total consumed energy at mills, was 44.65% and 55.35% respectively. The proportion of SAG and ball mills in producing the final product (particles finer than 74 μm) was 55.38% and 44.62% respectively. That is, the SAG mill produces about 10.76% more than the ball mill in the final product. The average consumed energy at SAG and ball mills to produce one ton of final product was 23.16 kWh/t and 36.05 kWh/t respectively. Thus, the ball mill consumes 12.89 kWh/t, more energy than the SAG mill in producing the final product. The average cyclones' imperfection was 0.361 and therefore the average efficiency of cyclones' separation was equal to 63.9% and the average efficiency of the vibrating screen was equal to 99.89%. As overflow of the initial cyclones (final product of comminution circuit) forms feed of rougher cells, cyclones' inappropriate performance could severely influence the whole flotation process.

Keywords: *Sarcheshmeh, comminution; SAG mill; ball mill; SPI; energy; modeling*

1. Introduction

Autogenous (AG) and semi-autogenous (SAG) mills are usually used as comminution stage, especially for copper minerals which cause an increase in mill capacity and decrease of operational and investment costs [1]. At mineral processing plants, comminution circuits have the most proportion in energy consumption. For this reason, optimum performance of these circuits causes decrease of consumed energy and costs. Thus, determining the proportion of each of circuit parts at consumed energy, to produce suitable product, helps circuit performance optimization trend. Also considering that most of the energy at mineral processing plants is consumed at the grinding part, it is always tried to reduce consumed energy by offering new methods and equipment. However, in most cases, because of the operation's intrinsic complexity, multiplicity of involved factors, and

inappropriate initial design, comminution circuit efficiency is less than expected value.

Sarcheshmeh Copper Complex (SCC) is the largest producing copper plant in Iran which is located in the Kerman province, at the 60 km distance of the Rafsanjan city. In recent years, some projects were introduced to study on existing problems at "the concentrator plant 2 of the SCC and improving its performance accordingly. So this project was to examine and complete previous works. In previous studies, a SAG mill sampler was designed and constructed, and sampling sites were also prepared. In addition, a laboratory mill was designed and constructed in order to determine the SAG mill power index (SPI), and a formula for the SAG mill consumed power prediction was introduced [2]. The formula is as Equation 1[2]:

$$P = 0.55\ (SPI)^{0.01} - 7.36\ (K_{80})^{0.01} + 0.69 \left(\frac{H}{1000}\right) + 2.81 \left(\frac{p}{1000}\right) \quad (1)$$

where, P is specific consumed power of the SAG mill (kWh/t), SPI is SAG mill Power Index (min.), K80 is the size of final product of the SAG mill (underscreen) (μm), H is time period of shell liner function (h), and P is trunnion pressure of the free head of the SAG mill (kPa). The relation between trunnion pressure and consumed power in the SAG mill was also obtained and explained in Equation 2[3].

$$p = 0.2525\ P + 3213.2, r^2 = 0.865 \quad (2)$$

where, p is SAG free trunnion pressure (kPa) and P is consumed power at the SAG mill (kW). The surface changes of liner during its life due to abrasion were examined and its consumption pattern was obtained by modeling of the performance of a liner. In addition, a three-dimensional model provided the possibility of calculation of liner weight and volume at each stage of operation [4]. Considering this modeling, abrasion rates were calculated with high accuracy and as a result estimation of liner life or prediction of their replacement time became possible at this stage [4]. In 1996, Starkey and Dobby obtained a relation to calculation of consumed power of the industrial SAG mill, using information from four plants in Canada [5]. This relation well-known as a MinnovEX relation for a cycle under standard condition is as followed in Equation 3. A "Standard Cycle" is a cycle which the F80 of the input feed to SAG mill is between 120–180 mm and the circuit does not use pebble [5].

$$P = (K_{80})^{-0.33}\ (2.2 + 0.1\ SPI), r^2 = 0.94 \quad (3)$$

where, P is power of the industrial SAG mill (kWh/t), K80 is size of final product of the SAG mill (mm), and SPI is time of the test (min.).

This study aims to calculate the comminution circuit efficiency of the concentrator plant 2 of the SCC, which consists of one SAG mill and one ball mill operating in closed circuits with vibrating screens and hydrocyclones respectively. For this reason, it is necessary to calculate the proportion of each mill's energy consumption and production of suitable final product for flotation (particles finer than 74 microns). Also it is necessary to obtain comminution efficiency of size classification equipment at milling circuit.

2. Methodology

In order to examine comminution circuit efficiency, it is essential to prepare the required samples. To determine apparatus performance condition as well as circuit balance, samples from SAG mill feed, SAG mill discharge, overscreen materials, SAG mill final product (underscreen), initial cyclone feed, initial cyclone underflow, and initial cyclone overflow are necessary to be taken. In addition, the laboratory work index of the ball mill feed, the standard Bond ball mill was implemented. To estimate/predict the amount of consumed energy, and SAG mill feed hardness, Bond equation or Bond's laboratory work index cannot be used, thus a Starkey mill was used to measure SAG mill power index [5]. To determine efficiency of mills and size classification equipment, three different sampling campaigns from comminution circuit were done on different dates. The first sampling was carried out from out flows of the SAG mill, overscreen, cyclone feed, cyclone underflow, and cyclone overflow. After sampling from these streams, the feeding conveyor belt to the SAG mill stopped and contents of 6 meters of the conveyor belt were completely discharged into the barrels. After sampling, the recorded operational information within first sampling period was provided from plant control room which is presented in Table 1

Each 15 minutes, one sample was taken from overscreen, cyclone feed, and cyclone underflow streams. Thus, during sampling time, 7 samples of these flows were gathered, which were mixed with one another. The sample of cyclone overflow was provided using an automatic sampler of a X-ray analysis instrument installed at the concentrator plant 2, in this manner that each 10 minutes, 5 cuts were transferred into the sampling vessel using

predicted facilities over this instrument. One sample was provided from out flow of the SAG mill, and then this sample was discharged into a barrel. After the end of sampling and material settling inside the barrel, its extra water was discharged. After drying the sample, the entire sample was size-analyzed to sizes coarser than 6730 μm, and materials finer than 6730 μm divided using a splitter (rifle type), and

about 1.5 kg of them were then used for size analysis test, to sizes finer than 37 μm. The taken samples of overscreen, cyclone feed, cyclone underflow, and cyclone overflow flows, were size-analyzed down to 37 μm. Also, solid weight percentage of cyclone feed, cyclone underflow, and cyclone overflow flows were determined.

Table 1. The control room information within the first sampling[6]

	minimum	Maximum	Average
SAG mill consumed power (kW)	6675	7246	6917
Ball mill consumed power (kW)	7568	7794	7668
Input wet feed tonnage to the SAG mill (t/h)	726.3	791.4	754.6
wet reject tonnage (t/h)	98.3	128.9	117.9
Pressure of the initial cyclone cluster (kPa)	62.88	90.80	83.43
Pressure of the SAG mill free trunnion (kPa)	4962	5169	5036

Moreover, the sample prepared from the feeding conveyor belt to the SAG mill with total weight 965 kg (without moisture) was analyzed. First, the whole sample was analyzed to sizes coarser than 6730 μm, then the rest of the sample (finer than 6730 μm) which had a weight of 238 kg divided by a splitter and 1.5 kg of the new sample was used in size analysis down to 37 μm.

The second sample was provided about 4 months after the first sampling campaign. Sampling of outflows of the SAG mill, overscreen, cyclone feed, cyclone underflow, and cyclone overflow was performed. Again after the end of sampling of these streams, the feeding conveyor belt to the SAG mill stopped and its 6 meters content was

completely discharged into the barrels. Sampling stages, preparation, and performed operation over the samples were similar to the first sampling. At the second sampling, total weight of the provided sample over the feeding conveyor belt to the SAG mill (without moisture) was 792 kg. Also, weight of materials finer than 6730 μm was 78 kg. The

recorded operational information within the second sampling period was provided from plant control room which is presented in Table 2.

The third sampling campaign was done about three months after the second sampling. It was performed over out flows of the SAG mill, overscreen, cyclone feed, cyclone underflow, and cyclone overflow.

After the end of sampling of these streams, the feeding conveyor belt to the SAG mill stopped and its 6 meters contents was completely discharged into the barrels. Sampling stages, preparation, and performed operation over the samples was similar to the first and second samplings.The weight of third sample which was prepared from the feeding conveyor belt to the SAG mill was 1010 kg (without moisture). In addition, weight of materials finer than 6730 μm was 244 kg. The recorded operational information within the third sampling period was taken from plant control room which is presented in Table 3.

Table 2. The control room information within the second sampling[6]

	minimum	Maximum	average
SAG mill consumed power (kW)	6254	6964	6754
Ball mill consumed power (kW)	7837	8090	7904
Input wet feed tonnage to the SAG mill (t/h)	750	850	793.8
wet reject tonnage (t/h)	40	114	93.0
Pressure of the initial cyclone cluster (kPa)	54	80	69.11
Pressure of the SAG mill free trunnion (kPa)	4482	4598	4560

Table 3. The control room information within the third sampling[6]

|	minimum	Maximum	average
SAG mill consumed power (kW)	5041	5628	5234
Ball mill consumed power (kW)	7574	7850	7710
Input wet feed tonnage to the SAG mill (t/h)	586.5	1101	1022
wet reject tonnage (t/h)	59.53	124.90	72.84
Pressure of the initial cyclone cluster (kPa)	88.11	104.7	96.8
Pressure of the SAG mill free trunnion (kPa)	4393	4567	4436

3. Results and Discussion

There are two methods to examine the performance of a system. The first method is examination of performance of individual system parts and finally conclusion to system performance. The second method is to consider the whole system as a part with distinct inputs and outputs, and examination of performance of this system and comparing it with the system design targets. This method is called black box method. In this research, the second method was used to determine comminution circuit efficiency of the concentrator plant 2 of the SCC. At comminution circuit of this plant, two disparate systems with distinct inputs and outputs are definable. The SAG mill and vibrating screen could be considered as a system the input of which is SAG mill feed and its output is passing materials of the vibrating screen (underscreen) (system 1). The initial ball mill and initial cyclones would be considered as a system the input of which is underscreen flow and its output is cyclone overflow (rougher feed) (system 2), Figure 1. An existing problem is that sampling underscreen flow is impossible at the plant. But, considering previous

studies, because of high efficiency of the vibrating screen (99.89%), with sampling of SAG mill out flow (screen feed) and separating particles coarser than 5 mm (reject or over screen) of it, underscreen sample can be obtained with 0.1% error.

3.1. Results of the first sampling

Based on recorded information at the control room, average tonnage of dry input ore to the SAG mill during sampling was 721 t/h, which is equivalent to 67% of nominal capacity of the plant (1080 t/h). Additionally, the average moisture percentage of ore was 4.5% at that time. At the time of sampling, shell liners had worked 3162 hours. Size analysis diagram of underscreen flow along with SAG mill feed are shown in Figure 2. Characteristics of the first sample and its comparison with plant design numbers (targets) could be observed in Table 4.

Size analysis of screen feed (output of the SAG mill), passed materials of the screen (underscreen), and remained materials over the screen (reject or overscreen) are available in Table 5.
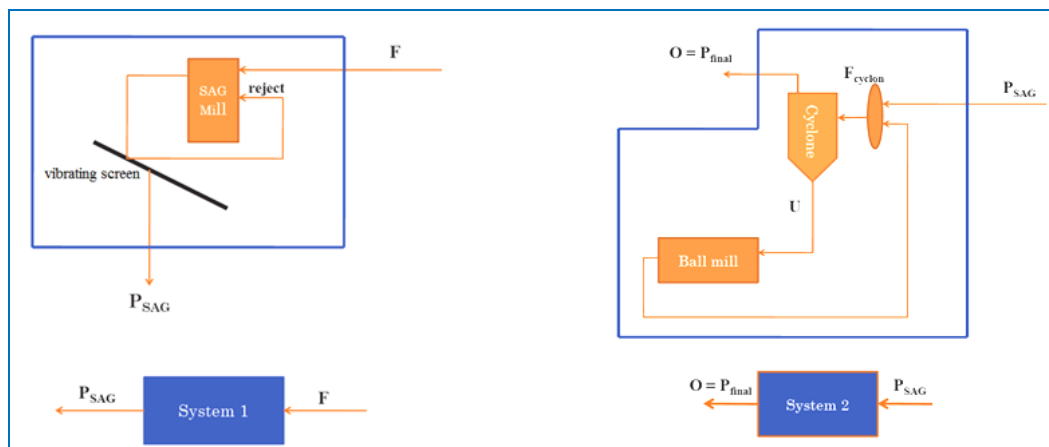
Figure 1. systems 1 and 2 of comminution circuit of the concentrator plant 2 of the Sarcheshmeh copper complex
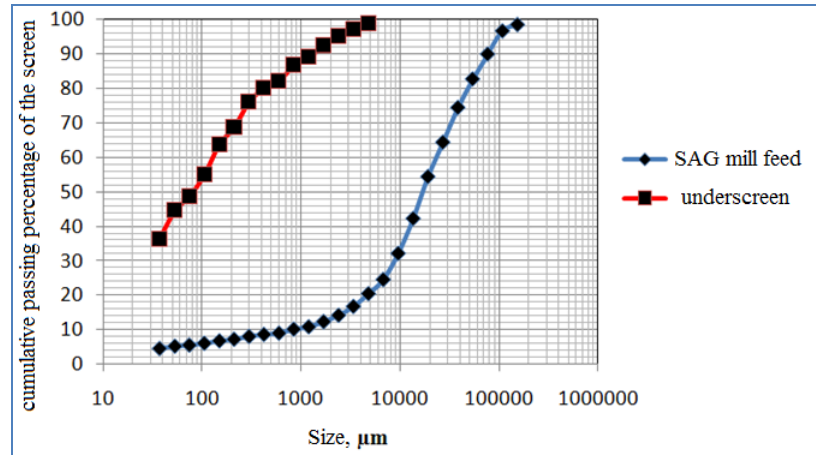
Figure 2. Size analysis of SAG mill feed and underscreen for the first sample

Table 4. Characteristics of the first sample and its comparison with plant design numbers (targets)

	The first sample	Circuit design numbers [7]
Size of the largest particles (mm)	200	250
K80 of SAG mill feed (mm)	48	38
K80 of underscreen (mm)	0.415	0.505
Amount of particles finer than 25 mm (%)	62.0	-
Comminution ratio	115.7	75.2

Table 5. Parameters related to working condition of the vibrating screen at the first sampling

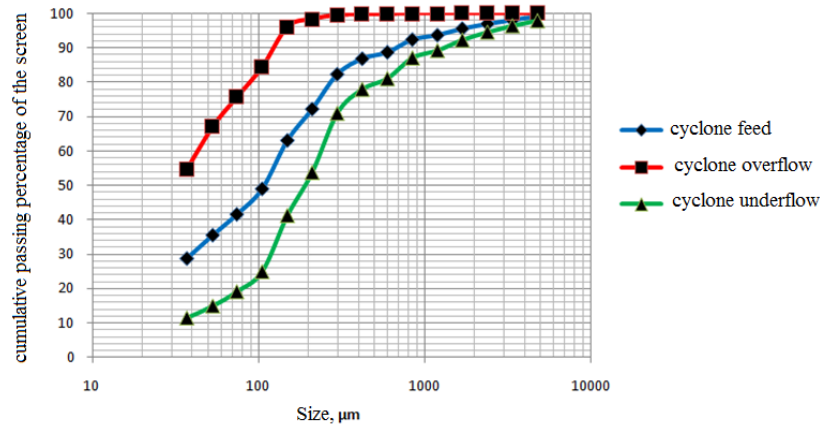|	K80 (µm)	-5 mm (%)	+25 mm (%)
Screen feed	827	91.8	2.1
Underscreen	415	98.8	-
Overscreen	25558	0.9	79.5

Figure 3. Size analysis diagram of cyclones' feed, underflow, and overflow at the time of the first sampling

Using existing numbers at Table 5, vibrating screen efficiency was obtained, which was 99.91%. At the first sampling period, 9 cyclones of 15 cyclones available at the cluster 1 were working. The average pressure of cyclones at sampling period was 83.4 kPa, which was obtained through averaging of recorded information at the plant control room during sampling. It is noteworthy to mention that

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cyclone design pressure was 93.0 kPa. In Figure 3, size analysis diagrams of cyclones' overflow, underflow, and feed flows is shown.

Solid weight percentage of cyclones' feed, underflow, and overflow at the first sampling was obtained which were 46.4%, 65.6%, and 29.0% respectively. At the first sampling, amount of d50C (corrected d50) was obtained which was 88 μm. It is noticeable that amount of d50 of circuit design was 110 μm. Also, amount of cyclone imperfection (I) was obtained which was 0.426 and cyclone separation efficiency during (first) sampling was 57.4%.

One of the examination methods of ball mill efficiency is the comparison of laboratory work index (WiL) with operational work index (WiO). To compare laboratory and operational work indices, the standard Bond work index test was performed over the underscreen sample, which in fact forms feed of the system 2, and amount of Bond's laboratory work index was obtained which was 14.66 kWh/t. To calculate ball mill's operational work index, first using recorded information at the plant control room, amount of ball mill's consumed power in terms of one ton ore was calculated which was 10.64 kWh/t. Then to calculate actual amount of consumed energy, Bond's correction coefficients was calculated and exerted (Table 6) [8].

Considering represented amounts at Table 6, Equation 4 is obtained. Finally by dividing laboratory work index by operational work index, ball mill efficiency is obtained (Equation 5).

$$Wi_O = \frac{10.64}{F_1 F_2 F_3 F_4 F_5 F_6 F_7 \times 11.02 \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right)} = 18.72 \frac{kWh}{t} \quad (4)$$

$$Efficiency_{Ball\ Mill} = \frac{Wi_L}{Wi_O} = \frac{14.66}{18.72} = 78.31\% \quad (5)$$

During the first sampling period, amount of ball mill's circulating load was obtained, 149%, which is so lower than its design amount (250%). Considering that final product of the comminution circuit (rougher cell feed) should be finer than 74 μm, determination of tonnage of particles finer than 74 μm at input and output of systems 1 and 2 is of a specific importance (Table 7).

Using recorded information at the plant control room, at time of the first sampling average consumed power of the SAG mill was 6917 kW and average consumed power of the ball mill was 7668 kW, and average amount of consumed energy to produce one ton of product finer than 74 μm was calculated, 28.91 kWh/t. With 6 times of repetition of the SPI test, the following results were obtained (Table 8).

Table 6. Bond's correction coefficients for the first sampling

Parameter	F1	F2	F3	F4	F5	F6	F7	Fo	Rr
Amount	1	1	1.053	0.824	1	1	1.039	3766.7	4.69

Table 7. Amount of particles finer than 74 microns at input and output of systems 1 and 2 at time of the first sampling

	Rate of flow (t/h)	-74 μm (%)	-74 μm (t/h)
SAG mill feed	720.64	5.66	40.79
Underscreen	720.64	48.73	351.17
Initial cyclone overflow	720.64	75.67	545.31

Table 8. Results of the SPI test for the first sample

SPI1 (min.)	SPI2 (min.)	SPI3 (min.)	SPI4 (min.)	SPI5 (min.)	SPI6 (min.)	SPIave (min.)
199	197	152	182	204	185	186.5

3.2. Results of the second sampling

Based on recorded information at the plant control room, average tonnage of dry input ore to the SAG mill during of second sampling was 751.4 t/h, which is equivalent to 69.6% of nominal capacity of the plant. Moreover, the average moisture percentage of ore was 5.3% at that time. During sampling, shell liners had worked 1376 hours and were in a good condition. Size analysis diagram of underscreen flow along with SAG mill feed is shown in Figure 4.

Characteristics of the second sample and its comparison with plant design numbers (targets)

could be observed in Table 9. Size analysis of screen feed, passed materials of the screen, and remained materials over the screen are available in Table 10. Using existing numbers of Table 10, vibrating screen efficiency was obtained, which was 99.81%. During the second sampling, 14 cyclones of 15 cyclones available at the cluster 1, were working. Average pressure of cyclones at sampling time was 69.1 kPa. In Figure 5, size analysis diagrams of cyclones' overflow, underflow, and feed flows are presented.

Solid weight percentage of cyclones' feed, underflow, and overflow at the second sampling was obtained which were 54.0%, 58.9%, and 31.4% respectively. At the second sampling, amount of d50C was obtained which was 99 µm. Also, amount of cyclone imperfection was estimated which was 0.316 and cyclone separation efficiency in second sampling was 68.4%. Amount of Bond's laboratory work index for the second sample was obtained, 15.04 kWh/t. To calculate ball mill's operational work index, first recorded consumed energy in terms of one ton ore for the second sample was obtained which was 10.52 kWh/t. To calculate the actual amount of consumed energy, Bond's correction coefficients was calculated and exerted (Table 11) [8]. Just like the first sample, the operational work index for the second sample was equal to 25.34 kWh/t, using Table 11 values. Finally, with dividing laboratory work index by operational work index, ball mill efficiency was 59.35% for the second sample.

During the second sampling, amount of ball mill's circulating load was obtained, 747%, which was much higher than its design amount (250%). In Table 12, amount of particles finer than 74 µm at input and output of black box systems within the second sampling is shown.

Using recorded information from plant control room, during the second sampling average consumed power of the SAG mill was 6754 kW and average consumed power of the ball mill was 7904 kW, and average amount of consumed energy to produce one ton of product finer than 74 µm was 29.82 kWh/t. With 5 times of repetition of the SPI test, the following results were obtained (Table 13). Average SPI value for the second sample was 155.4 min., which is lower than the first sample (186.5 min.). Therefore, the second sample was softer than the first one.

3.3. Results of the third sampling

Based on recorded information from plant control room, average tonnage of dry input ore to the SAG mill during third sampling was 968.2 t/h, which is equivalent to 89.6% of plant nominal capacity. Meanwhile, ore's average moisture percentage at that time was 5.3%. During sampling, shell liners had worked 3440 hours. Size analysis diagram of underscreen stream along with SAG mill feed is showed in Figure 6.

Table 9. Characteristics of the second sample and its comparison with plant design numbers (targets)

	The second sample	Circuit design numbers[7]
Size of the largest particles (mm)	200	250
K80 of SAG mill feed (mm)	101	38
K80 of underscreen (mm)	0.604	0.505
Amount of particles finer than 25 mm (%)	30.7	-
Comminution ratio	167.2	75.2

Table 10. Parameters related to working condition of the vibrating screen at the second sampling

	K80 (µm)	-5 mm (%)	+25 mm (%)
Screen feed	807	93.5	4.9
Underscreen	604	100.0	-
Overscreen	28232	2.66	26.7

Table 11. Bond's correction coefficients for the second sampling

Parameter	F1	F2	F3	F4	F5	F6	F7	Fo	Rr
Amount	1	1	0.803	0.824	1	1	1.031	3718.8	5.56

Table 12. Amount of particles finer than 74 μm at input and output of black box systems at time of the second sampling

	Rate of flow (t/h)	-74 μm (%)	-74 μm (t/h)
SAG mill feed	751.4	2.79	20.96
Underscreen	751.4	41.12	308.98
Initial cyclone overflow	751.4	68.21	512.53

Table 13. Results of the SPI test for the second sample

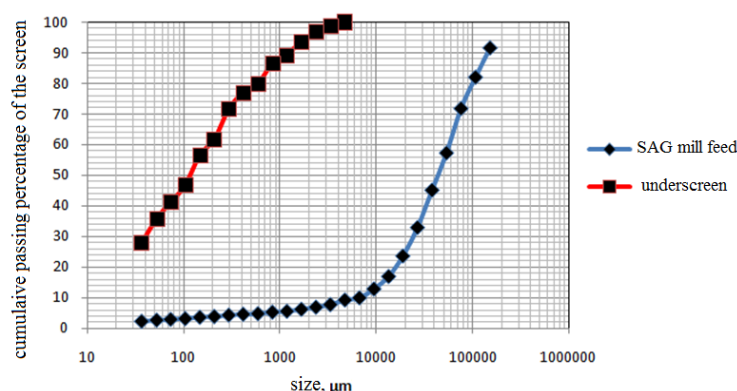| SPI1 (min.)	SPI2 (min.)	SPI3 (min.)	SPI4 (min.)	SPI5 (min.)	SPIave (min.)
146	164	149	143	175	155.4

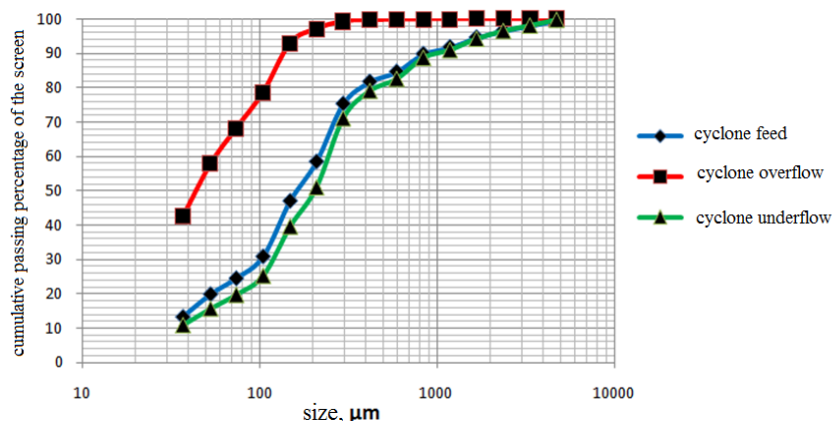**Figure 4. Size analysis of SAG mill feed and underscreen for the second sample**

Figure 5. Size analysis diagram of cyclones' feed, underflow, and overflow at time of the second sampling

Characteristics of the third sample and its comparison with plant design numbers (targets) could be observed in Table 14. Size analysis of screen feed, passed materials of the screen, and remained materials over the screen are presented in Table 15. Considering existing numbers in Table 15, vibrating screen efficiency was obtained, which was 99.96%. During the third sampling, 11 cyclones of 15 cyclones available at the cluster 2, were working. Average pressure of cyclones at sampling time was 96.8 kPa. In Figure 7, size analysis diagrams of cyclones' overflow, underflow, and feed flows are presented.

Solid weight percentage of cyclones' feed, underflow, and overflow at the third sampling was obtained which were 48.1%, 70.3%, and 28.2% respectively. At the third sampling, amount of d50C was obtained which was 134 μm.
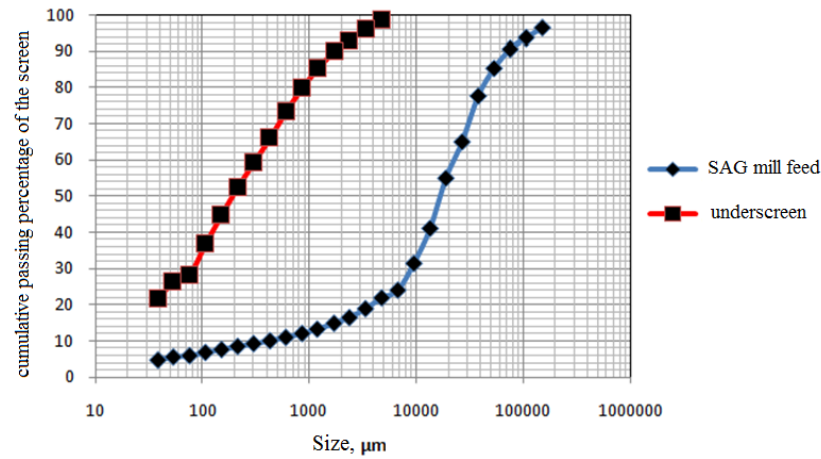
Figure 6. Size analysis of SAG mill feed and underscreen for the third sample

Table 14. Characteristics of the third sample and its comparison with plant design numbers (targets)

	The third sample	Circuit design numbers[7]
Size of the largest particles (mm)	250	250
K80 of SAG mill feed (mm)	42	38
K80 of underscreen (mm)	0.854	0.505
Amount of particles finer than 25 mm (%)	62.9	-
Comminution ration	49.3	75.2

Table 15. Parameters related to working condition of the vibrating screen at the third sampling

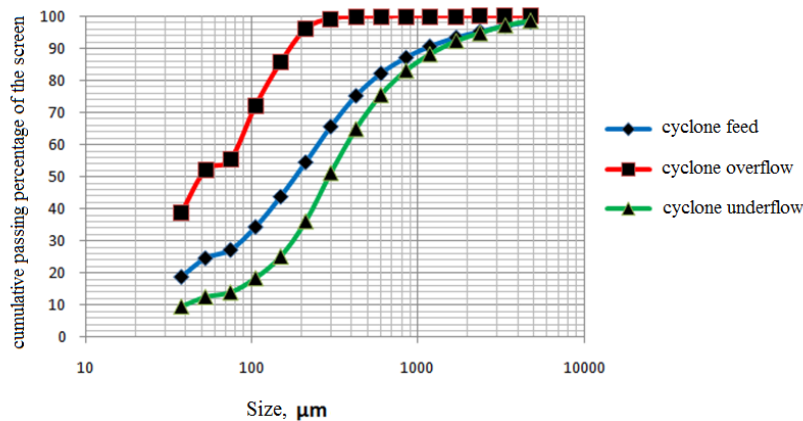|	K80 (μm)	-5 mm (%)	+25 mm (%)
Screen feed	1150	92.5	2.4
Underscreen	854	98.7	-
Overscreen	20241	0.43	9.3

Figure 7. Size analysis diagram of cyclones' feed, underflow, and overflow at time of the third sampling

Also, amount of cyclone imperfection was obtained which was 0.341 and cyclone separation efficiency during third sampling was 65.9%. Amount of Bond's laboratory work index for the third sample was obtained which was 13.07 kWh/t. To calculate ball mill's operational work index, first recorded

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consumed energy in terms of one ton ore for the third sample was obtained which was 7.96 kWh/t. To calculate actual amount of consumed energy, Bond's correction coefficients was calculated and exerted (Table 16)[8]. Again similar to the previous samples, the operational work index for the third sample was calculated, 16.09 kWh/t, using Table 16 values. Finally, by dividing laboratory work index by operational work index, ball mill efficiency was 81.23% for the third sample. It should be noticed that during the third sampling, amount of ball mill's circulating load was obtained, 223%, which was close to its design amount (250%). In Table 17, amount of particles finer than 74 μm at input and output of black box systems at time of the third sampling is showed.

Using recorded information from plant control room, during third sampling average consumed power of the SAG mill was 5234 kW and average consumed power of the ball mill was 7710 kW, and average amount of consumed energy to produce one ton of product finer than 74 μm was calculated, 27.03 kWh/t. With 8 times of repetition of the SPI test, the following results were obtained (Table 18). As it is observed, average amount of obtained SPI at the third sample (184.7 min.) is approximately equal to the resulted SPI of the first sample (186.5 min.), but it is much larger than the resulted SPI of the second sample (155.4 min.). So, the third sample has hardness approximately equal to the first sample while it is harder than the second sample. Table 19 summarizes the obtained results of all three sampling.

Considering Table 19, the following results are obtained:

- Extensive fluctuation of K80 of cyclone overflow which is the final product of comminution circuit indicates unstable condition of rougher cell feed and can influence the entire flotation operation.
- Amount of ball mill's circulating load at the second sampling seems so irrational that its reason is be attributed to cyclones' very low pressure. That is to say, cyclones' low pressure causes most of the cyclone feed in the form of short circuit to enter into the underflow and separation only is performed over the small part of feed.
- The decrease of ball mill efficiency during the second sampling is due to the increase of amount of circulating load, which causes

increase of operational work index and as a result decrease of ball mill efficiency.

- Compared with other samplings, the proportion of the SAG mill at producing particles finer than 74 μm at the third sampling is much lower. This could be due to the existence of more slime at input feed to the SAG mill at this sample in comparison with other samples.
- Ball mill's consumed energy in producing one ton of particles finer than 74 μm at the third sampling is much lower than other two samples. This could be attributed to coarser K80 of cyclone underflow at this sample in comparison with the other two samples.
- The proportion of the ball mill of the whole consumed energy at all three samplings is more than that of the SAG mill. This sounds natural, because firstly, input feed to the ball mill is much finer than input feed to the SAG mill and secondly, particles which enter the ball mill are so hard that the SAG mill had not been able to break them.

3.4. Modeling Sarcheshmeh SAG mill specific consumed power

Considering performed examinations, it became known that the use of Starkey equation (Equation 3) is not possible for predicting consumed power of the SAG mill of the concentrator plant 2 of the Sarcheshmeh copper complex. Consequently a series of sampling was taken to calibrate of the mill to prediction of SAG mill's consumed power. Regarding existing operational conditions at the plant, effective factors at power consumption of the SAG mill include ore hardness, size of mill's output product, mill filling, percentage of the charged ball to the mill, and condition of installed liners inside the mill. At current conditions, SAG mills' filling cannot be exactly calculated.

However, the ratio between mill overall filling and amount of its ball charge could be attributed to average density of the load inside the mill.

In fact, at a constant filling with increase of ball amount, average density of the load increases and vice versa. Considering these issues, the only factor which would indicate changes of filling and percentage of the ball mill, at any moment is the pressure of mill trunnions. Hence, to introduce a relation for predicting SAG mill's consumed power, pressure of the free trunnion of the SAG mill was used as the agent of ball amount and also mill filling.

Table 16. Bond's correction coefficients for the third sampling

Parameter	F1	F2	F3	F4	F5	F6	F7	Fo	Rr
Amount	1	1	1.023	0.824	1	1	1	3589.9	6.53

Table 17. Amount of particles finer than 74 μm at input and output of black box systems at time of the third sampling

	Rate of flow (t/h)	-74 μm (%)	-74 μm (t/h)
SAG mill feed	968.2	6.05	58.58
Underscreen	968.2	28.29	279.00
Initial cyclone overflow	968.2	55.52	537.54

Table 18. Results of the SPI test for the third sample

SPI1 (min.)	SPI2 (min.)	SPI3 (min.)	SPI4 (min.)	SPI5 (min.)	SPI6 (min.)	SPI7 (min.)	SPI8 (min.)	SPIave (min.)
203	204	170.6	182	165	185.5	183.4	184.3	184.7

Table 19. A summary of obtained results of the first, second, and third samplings

	1st sampling	2nd sampling	3rd sampling
Tonnage of dry input ore to the SAG mill (t/h)	721.0	751.4	968.2
Time period of the shell liner function (h)	3162	1376	3440
Size of the largest particles (mm)	200	200	250
K80 of SAG mill feed (mm)	48	101	42
K80 of underscreen (mm)	0.415	0.604	0.854
K80 of screen feed (μm)	827	807	1150
K80 of overscreen (μm)	25558	28232	20241
Vibrating screen efficiency (%)	99.91	99.81	99.96
The number of working cyclones	9	14	11
Average pressure of cyclones (kPa)	83.4	69.1	96.8
K80 of cyclone feed (μm)	275	384	536
K80 of cyclone underflow (μm)	531	463	739
K80 of cyclone overflow (μm)	89	109	131
Solid weight percentage of cyclone feed	46.4	54.0	48.1
Solid weight percentage of cyclone underflow	65.6	58.9	70.3
Solid weight percentage of cyclone overflow	29.0	31.4	28.2
d50C (μm)	88	99	134
Cyclone imperfection	0.426	0.316	0.341
WiL (kWh/t)	14.66	15.04	13.07
WiO (kWh/t)	18.72	25.34	16.09
Ball mill efficiency (%)	78.31	59.35	81.23
Ball mill's circulating load (%)	149	747	223
finer than 74 μm at SAG mill feed (t/h)	40.79	20.96	58.58
finer than 74 μm at underscreen flow (t/h)	351.17	308.98	279.00
finer than 74 μm at cyclone overflow (t/h)	545.31	512.53	537.54
Consumed energy at the SAG mill to produce one ton of -74 μm (kWh/t)	22.29	23.45	23.75
Consumed energy at the ball mill to produce one ton of -74 μm (kWh/t)	39.50	38.83	29.82
The proportion of the SAG mill at producing -74 μm of final product (%)	61.52	58.59	46.02
The proportion of the ball mill at producing -74 μm of final product (%)	38.48	41.41	53.98
Average amount of consumed energy to produce one ton of -74 μm (kWh/t)	28.91	29.82	27.03
SPIave (min)	186.5	155.4	184.7

In addition, the change at lifters' height influences SAG mill's consumed power, so that with decrease of lifters' height usually the load does not rise up to the desirable height, and as a result at time of the fall does not release enough energy to crush particles, and in addition the materials' retention time increases as well. It is remarkable that increase of retention time and decrease of particles' energy at time of collision cause more consumption of energy at the mill to crush materials. Therefore, it was decided that time period of the shell liner function is used as an effective factor at SAG mill's consumed power at time of introducing the relation of its consumed power. In addition to pressure of mill's free trunnion and time period of the shell liner function which are related to the mill's operational conditions (parameters related to the selection function), also characteristics of feed and final product of the SAG mill (parameters related to the breakage function) are effective in SAG mill's specific consumed power. Characteristics of SAG mill's feed appear in the formula as the SPI number and characteristics of SAG mill's final product appear in the formula as the underscreen K80. Then, assuming that these four parameters are independent, it was tried that the relation between specific consumed powers with each of the parameters was calculated individually. Consequently, SAG mill's specific consumed power was represented in the form of an average of predicted specific powers by these parameters. Considering amounts of Table 20, and using Excel software, the relation between SAG mill's specific consumed power (obtained of control room information) and SPI was in the form of the exponential Equation 6.

Considering amounts of Table 21 and using Excel software, the relation between SAG mill's specific consumed power and the underscreen K80 was in the form of the exponential Equation 7.

Considering amounts of Table 22 and using Excel software, the relation between SAG mill's specific consumed power and time period of the shell liner function was in the form of the linear Equation 8.

Considering plant control room information, the relation between SAG mill's free trunnion pressure and SAG mill's consumed power is illustrated in Figure 8 which is in the form of linear (Equation 9).

$$P\left(\frac{kWh}{t}\right) = gp + l, g = 5.5 \times 10^{-3}, l = -17.66, r^2 = 0.865 \quad (9)$$

where, p is SAG mill's free trunnion pressure (kPa). Considering Equations 6 to 9, the general relation is in the form of Equation 10. Numbers related to the

first, second, and third samplings are available in Table 23.

$$4\,P = [0.09\,(SPI)^{0.9}] + [8.26\,(K_{80})^{-0.2}] + \left[0.49\left(\frac{H}{1000}\right) + 7.79\right] + \left[5.50\left(\frac{p}{1000}\right) - 17.66\right], r^2 = 0.865 \quad (10)$$

As it is observed from comparison of amounts of actual and predicted specific consumed power in all three samplings, the introduced relation to predict/estimate SAG mill's specific consumed power (Equation 10) enjoys relatively high accuracy. In previous projects, in order to compare laboratory and operational work indices, the Bond's work index test was performed over the cyclones' underflow sample, which in fact forms ball mill's feed[2], while for the Bond test, the sample should be taken from fresh input feed to the ball mill. In other words, the sample should be taken from a place where there is not ball mill's circulating load. As a matter of fact, it is necessary that the sample to be provided from underscreen stream. The introduced Equation 1 suffers from this fault which with changing the SPI number from 100 to 200 min., amount of predicted power changes 0.004 kWh/t which is very little amount. Namely, compared with other parameters available in the formula, the SPI role is very few:

SPI = 100, 0.55 (SPI)0.01 = 0.5759 kWh/t
SPI = 200, 0.55 (SPI)0.01 = 0.5799 kWh/t

3.5. The SAGDesign test to predict SAG mills' consumed power

As Starkey mill was not accurate enough and the formula introduced (Equation 3) was valid only at the specific cases, in recent years, Starkey et al. have sought to find a relation for predicting SAG mills' consumed power to be applicable for all SAG mills, like Bond's work index which is valid to all ball mills. For this reason, they have tried to use the laboratory mill illustrated at the Figure 9, to solve this problem [9, 10, 11, and 12]. Feed of this mill is provided of core samples of almost 10 kg the K80 of which is 152 mm and is then crushed to reach sizes of passing 80% of 19 mm screen. Size of product of this mill is particles with sizes of passing 80% of 1.7 mm screen. Finally, SAG mill's product is used to the work index test of the standard Bond ball mill [10, 11]. Calibrated equation to the SAGDesign test is as following (Equation 11) [10]:

$$\frac{kWh}{t} = Revs \times \frac{(g + 16000)}{(447.3g)} \qquad (11)$$

where, Revs is the number of the mill revolution to grind the ore to sizes of 80% finer than 1.7 mm, g is

weight of the tested ore (g), 16000 is weight of steel balls (g), and 447.3 is the calculated coefficient of empirical tests.

Table 20– The relation of SAG mill's specific consumed power and SPI

SPI (min.)	180	181.1	148.4	142	143	186.5
P (kWh/t)	10.15	9.46	7.26	8.27	7.81	9.60

$$P = a\,(SPI)^b, a = 0.09, b = 0.9, r^2 = 0.78 \quad (6)$$

Table 21. The relation of SAG mill's specific consumed power and the underscreen K80

K80 (mm)	0.51	0.74	1.47	0.61	1.57	0.42
P (kWh/t)	10.15	9.46	7.26	8.27	7.81	9.60

$$P = c\,(K_{80})^d, c = 8.26, d = -0.2, \quad r^2 = 0.71 \quad (7)$$

Table 22. The relation of SAG mill's specific consumed power and time period of the shell liner function

H (h)	5304.3	3019.4	116.6	149.2	50.73	3162.2
P (kWh/t)	10.15	9.46	7.26	8.27	7.81	9.60

$$P = eH + f, e = 4.9 \times 10^{-4}, f = 7.79, r^2 = 0.90 \quad (8)$$

Table 23. Numbers related to the first, second, and third samplings to predict SAG mill's consumed power

	SPI (min.)	K80 (mm)	H (h)	p (kPa)	Pactual (kWh/t)	Ppredicted (kWh/t)
1st sampling	186.5	0.415	3162	5036	9.60	9.79
2nd sampling	155.4	0.604	1376	4560	8.99	8.37
3rd sampling	184.7	0.854	3440	4436	8.41	8.65

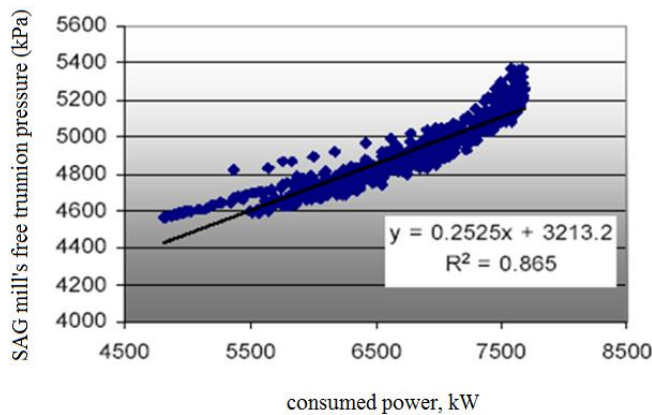**Figure 8. The relation between SAG mill's free trunnion pressure and SAG mill's consumed power [3]**

Figure 9. The SAGDesign's laboratory mill

4. Conclusion

In this research, efficiency of the comminution circuit including SAG and ball mills, and efficiency of size classification equipment of the concentrator plant 2, of SCC was studied. Three stages of sampling were performed and consumed energy was also modeled. The following conclusions were made:

- Average efficiency of the initial ball mill was obtained which was 72.96%.

- Average of the proportion of (consumed) energy by SAG and ball mills from total consumed energy at mills, was 44.65% and 55.35%, respectively. Generally, the ball

- mill consumes energy, about 10.7% more than the SAG mill.
- Average of the proportion of SAG and ball mills to produce final product (particles finer than 74 μm) was 55.38% and 44.62% respectively. Thus, the SAG mill has a role of about 10.76% more than that of the ball mill at producing final product.
- Average of consumed energy at SAG and ball mills to produce one ton of final product was 23.16 kWh/t and 36.05 kWh/t respectively. Thus, the ball mill consumes 12.89 kWh/t more energy than the SAG mill in producing the final product, which it sounds natural.
- Average of consumed energy to produce one ton of final product was 28.59 kWh/t.
- Average of cyclones' imperfection was 0.361 and therefore average efficiency of cyclones' separation was equal to 63.9% which is a relatively low number.
- Average efficiency of the vibrating screen was equal to 99.89% which sounds desirable.
- Considering the definition of systems 1 and 2, it became clear that the required sample to the Bond's work index test should not be taken from cyclone underflow, but it should be taken from underscreen stream.
- To predict SAG mill's consumed power, equation 10 could to be implemented.
- Because overflow of the initial cyclones (final product of comminution circuit) forms feed of rougher cells, cyclones' inappropriate performance can influence the whole flotation process. Consequently, increase of cyclones' separation efficiency enjoys a specific importance.

Acknowledgment

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