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Applicability of Statistical Process Control for Flotation of Metals Complex

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Statistical process control (SPC) can be assisted flotation plants to obtain good quality and standard products. The aims of this study was the determination of the lower control limit (LCL), upper control limits (UCL) and process capability indexes (CP) of the results for complex lead-zinc ores obtained from Beroner Mining Co. in North-Eastern of Turkey. The statistical determinations with moving range (MR) method were used for showing differences between in the quality of the concentrates and recovery ratios. The variability of grade values relative to contract specifications was compared with the tailings grades and recovery ratios. Afterwards, the variation in the revenue of the lead-zinc producer resulting from the premium or penalty application was analyzed. The weaknesses of flotation plant were determined and operational solutions to minimise unwanted anomalies or fluctuations for grades of concentrate and grades of tailings were fixed to find optimum products.

Key Words: Statistical process control, Moving range, Flotation method, Capability index.

INTRODUCTION

Statistical process control (SPC) techniques have been recognized by the mining industry and can be utilized for reaching maximum productivity. With the help of control charts (CC), which is a tool of SPC, it can be determined whether coal and other minerals are within the acceptable limits. Some different techniques of SPC in mineral processing were given by Elevli[1] and Ipek *et al.*[2]. Statistical process control aims at examining whether a process proceeds in a normal way or not. If there is any abnormality in a process, then it aims at determining the reasons for this abnormality and eliminating these sources[3]. Quality or fitness for use is determined through the interaction of quality of design and quality of conformance. By quality of conformance, we mean the systematic reduction of variability and elimination of defects until every unit produced is identical and defect-free.

Quality improvement means the systematic elimination of waste. A successful quality-improvement effort can eliminate much of this waste and lead to lower costs, higher productivity, increased customer satisfaction, increased business reputation, higher market share and ultimately higher profits for the company. Statistical methods play a vital role in quality improvement. Some applications can be used to compare different materials, components or ingredients and to determine the capability of a manufacturing process. Statistical process control can also be used to improve a process by reducing fluctuations systematically. These efforts can be directed for qualified yields and lower manufacturing costs and can lead to new designs that have longer useful lives and lower operating and maintenance costs. It is essential that engineers, scientists and managers to have an in-depth understanding of these statistical tools in any industry or business[4,5].

Selective flotation can be used to achieve specific separation from complex ores such as lead-zinc, copper zinc, *etc*. Froth flotation method can be utilized to distinguish in physico-chemical surface properties of particles of various minerals[6]. A lot of companies processing complex lead-zinc such as Oreks Mining Co., Kalkim Mining Co. Dedeman Mining Co., Gesom Co., Ezzacibasi Co., Beroner Mining Co. have had problems of efficiency in Turkey. Because of increasing demands of some importer countries, mainly China and Germany, production potentials of these companies have been aimed to reach maximum capacities since 2004. Onal *et al.*[7] investigated the difficulties in the flotation plant of Dedeman Mining Co. which was processing a complex Zn-Pb ore to reach optimum recovery rate. In this study, the flotation plant of Beroner Mining Co. conducted with rougher cells and cleaner cells as two stages using ground minerals (< 0.200 mm) was investigated. The used reagents of the plant are as follow: a) KAX (350 g/t) for lead and Aero 242 (400 g/t) for zinc were collectors. b) Na_2S (750 g/t) for oxidized lead and $CuSO_4$ (3000 g/t) for zinc were activating reagents. c) $ZnSO_4$ (2000 g/t) was depressant for zinc. e) Butyl glycol (250 g/t) for lead and diethyl hexanol (500 g/t) for zinc were frothers.

EXPERIMENTAL

Control charts and moving range: SPC is a set of problem-solving tools may be applied to any process. The major tools of SPC are histograms, pareto charts, cause and effect diagrams, defect concentration diagram, control chart, scatter diagram and check sheet. The main aim of SPC is to find and solve the problems that occur because of determinable factors. According to chart principles, if random factors play a role in a process, any variable creates a normal distribution. CC is used for measurable and immeasurable variables. Measurable quality characteristics *i.e.*, length, volume and weight can be measured by an instrument. Immeasurable quality characteristics observed by sense organs and stated numerically. Main quality features of flotation process such as grade % and recovery % can be described quantitatively. Control chart using moving range method is essential for special situations. Some of them are as follow: a) Automated inspections and measurement technology is used and every unit manufactured is analyzed. b) Production rate is very slow and it is inconvenient to allow samples size $n > 1$ to accumulate before analysis. c) Repeat measure-ments on the process differ only because of analysis error. d) Some parametrical measurements such as coating thickness, grade or recovery rate are too small[8,9]. The variability of a process is unavoidable and considered to be due to either assignable causes or random causes. An assignable cause is an influence considered to be significant and capable of being removed from the process. Such causes may be due to operational errors, defective raw materials and im-properly adjusted machines. A process that is operating in the presence of random causes is said to be in SPC. Random causes, an inherent part of the process, are smaller and uncontrollable influences that cannot be removed from the process without fundamental changes in the process itself[4,5,8]. Fig. 1 shows in control and out of control situations for CC. The measurable features are; mean ($\overline{X}$), moving range (MR) and standard deviation (s). Mean chart can be used for $\overline{X}$ and MR chart separately. $\overline{X}$ is the average result of measurements. MR is computed by subtraction of the minimum value from the maximum value. $\overline{MR}$ is an average value of the MR values (eqns. 1-3). If all points plot inside the control limits and no systematic behaviour is evident, then it is concluded that the process was in control in the past and the trial limits are suitable for controlling current. In establishing CC, $\overline{X}$ and MR charts, the following three basic elements should be calculated: central line (CL), upper control limit (UCL) and lower control limit (LCL)[9-11]. The formulas of the control limits are shown in eqns. 4 and 5.

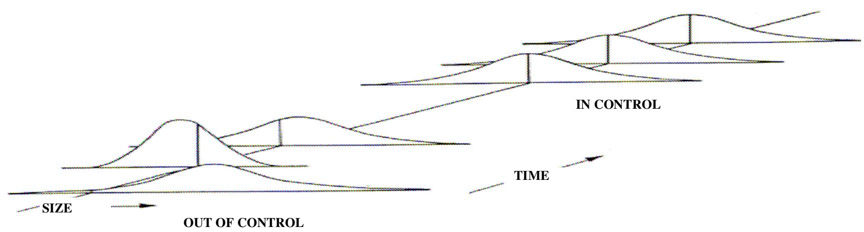

Fig. 1. Process control and variations[3]

In this study, the days that the plant was working was taken as the group and the daily shift number was taken as the sub-group size. It is desirable that the subgroups should be as small as possible. As a result, it can be examined if the process is under control in terms of mean and moving range. When X chart or MR chart shows the deviations from the average value, these deviations may result from equipment corrosion, changes due to pH, grades, reagent types, run of mine characteristics distribution of grain size and the decreasing attention of workers.

$$\overline{X} = \frac{X_1 + X_2 + X_3 + ... + X_n}{n} = \frac{1}{n}\sum X \tag{1}$$

$$MR_1 = |X_2 - X_1| \text{ and } MR_n = |X_n - X_{n-1}| \tag{2}$$

$$\overline{MR} = \frac{MR_1 + MR_2 + MR_3 + ... + MR_m}{m} = \frac{\sum_{i=1}^{m} MR_i}{m} \tag{3}$$

$$UCL_X = \overline{X} + 3\frac{\overline{MR}}{d_2},\ CL = \overline{X},\ LCL_X = \overline{X} - 3\frac{\overline{MR}}{d_2} \tag{4}$$

$$UCL_R = D_4.\overline{MR},\ CL = \overline{MR},\ LCL_R = D_3.\overline{MR} \tag{5}$$

Following steps require in setting up a CC: Choosing the characteristic to be charted, choosing the type of CC, deciding the central line to be used and the basis of calculating the limits, choosing the 'rational sub-group'. Each point on a CC represents a sub-group consisting of several units of product, providing a system for collecting the data, calculating the control limits and providing specific instructions on the interpretation of the results and the actions that various production personnel are to take, plotting the data and interpreting the results[11].

RESULTS AND DISCUSSION

The variation of feed grades of the flotation plant for 26 d in November of 2006 was shown in Fig. 2. Average values of the feed grades % of ores are 2.058 ± 0.53 for Pb % and 4.59 ± 0.95 for Zn %. The values of grade % for each element were changeable. The grades of raw ores particularly increased after 18 d. Therefore, fine grinding of the raw material in the beginning of grinding circuit was necessary to prevent fluctuations in the control charts.

The variations of feed grades between Zn and Pb % had a harmonious distribution examined with regression analysis method, statistically. The result of F-test showed a consistency for grade values (sign. level: 0.000). This situation was explained by two ways. One of them was the similar properties of grades of the mine deposits and the other was the mineralogical formations of the raw ores. However, optimization of the plant outputs using SPC was necessary. Thus, X and MR charts were applied for grade % or recovery % of Zn concentrate and grade % or recovery % of Pb concentrate,

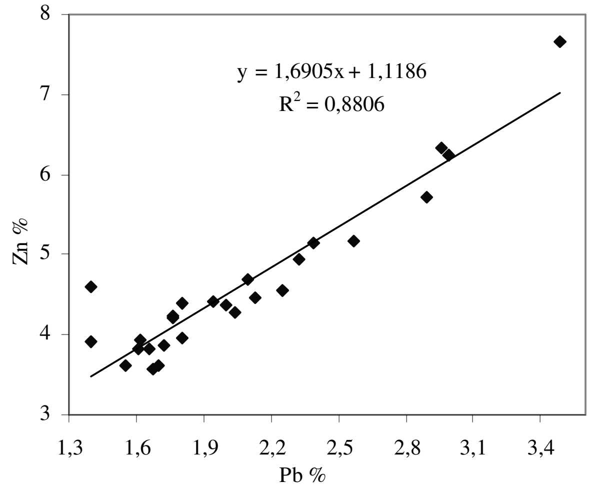

Fig. 2. Variation of the feed grades %

separately. The tailing contents were also analyzed using SPC. The Zn-Pb grades % and recovery rates were evaluated for quality changes of the final product at the process. With the help of eqns. 1-5, the X, MR, UCL, LCL and CL were determined. There were three shifts at work. Thus, sub-group number were taken n = 3. Hence, coefficients were taken from as d2 (1.693), A3 (0) and A4 (2.574)[4,5]. The following calculations for X and MR charts were made and the details were given in Table-1.

TABLE-1
LIMIT VALUES OF X AND MR CHARTS OF THE PRODUCTS

i) For grade % of Zn concentrate; $\overline{X} = \frac{1371.33}{26} = 52.74$, $\overline{MR} = \frac{42.6}{26} = 1.64$ $UCL_X = 52.74 + 3 \times (1.64/1.693) = 55.75$ $LCL_X = 52.74 - 3 \times (1.64/1.693) = 49.73$ $UCL_R = 2.57 \times 1.64 = 4.22$, $LCL_R = 0 \times 1.64 = 0$	iv) For grade % of Pb concentrate; $\overline{X} = \frac{1832.68}{26} = 70.48$, $\overline{MR} = \frac{64.32}{26} = 2.47$ $UCL_X = 70.48 + 3 \times (2.47/1.693) = 74.87$ $LCL_X = 70.48 - 3 \times (2.47/1.693) = 66.10$ $UCL_R = 2.57 \times 2.47 = 6.37$, $LCL_R = 0 \times 2.47 = 0$
ii) For recovery % of Zn Concentrate $\overline{X} = \frac{2253.10}{26} = 86.66$, $\overline{MR} = \frac{42.82}{26} = 1.65$ $UCL_X = 86.66 + 3 \times (1.65/1.693) = 89.58$ $LCL_X = 86.66 - 3 \times (1.65/1.693) = 83.74$ $UCL_R = 2.57 \times 1.65 = 4.24$, $LCL_R = 0 \times 1.65 = 0$	v) For recovery % of Pb Concentrate $\overline{X} = \frac{1718.25}{26} = 66.08$, $\overline{MR} = \frac{147.73}{26} = 5.68$ $UCL_X = 66.08 + 3 \times (5.68/1.693) = 76.15$ $LCL_X = 66.08 - 3 \times (5.68/1.693) = 56.02$ $UCL_R = 2.57 \times 5.68 = 14.63$, $LCL_R = 0 \times 5.68 = 0$
iii) For grade % of Zn tailings $\overline{X} = \frac{14.91}{26} = 0.57$, $\overline{MR} = \frac{2.74}{26} = 0.11$ $UCL_X = 0.57 + 3 \times (0.11/1.693) = 0.76$ $LCL_X = 0.57 - 3 \times (0.11/1.693) = 0.39$ $UCL_R = 2.57 \times 0.11 = 0.27$, $LCL_R = 0 \times 0.11 = 0$	vi) For grade % of Pb tailings $\overline{X} = \frac{11.05}{26} = 0.43$, $\overline{MR} = \frac{1.99}{26} = 0.08$ $UCL_X = 0.43 + 3 \times (0.08/1.693) = 0.56$ $LCL_X = 0.43 - 3 \times (0.08/1.693) = 0.29$ $UCL_R = 2.57 \times 0.08 = 0.19$, $LCL_R = 0 \times 0.08 = 0$

The X chart and MR charts of Zn products for grades of concentrate, tailings and recovery in the process were presented in Figs. 3-8, respectively. In the charts, suggested for quality features of Zn-Pb products of the flotation plant, the following points were important and considered before analyzing the data. Two thirds of the points should be on the central line or near the central line, number of points near the control limits should be minimum and points should randomly fall below or above central limits and should be balanced. For the X chart of grade % of Zn concentrate generally fluctuated very high. The fluctuations on the 5th day and on the 12th day shown in Fig. 3 exceeded limit values, but on the other days were low and high fluctuations were observed. For the MR chart of grade % of Zn concentrate, temporal patterns were resulted in higher fluctuations during the test period shown in Fig. 4. The MR value on the 13th day fluctuated very high exceeded limit values, but on the other days low and high fluctuations were observed. The daily MR values of 2, 5, 20 and 26 reached limit value (LCL_R).

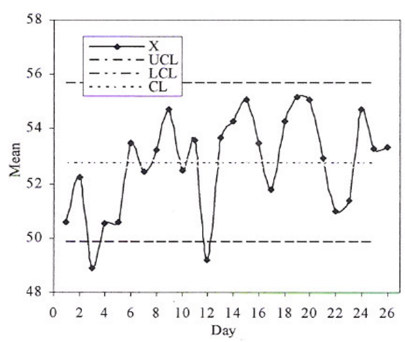

Fig. 3. X chart for grade % of Zn concentrate

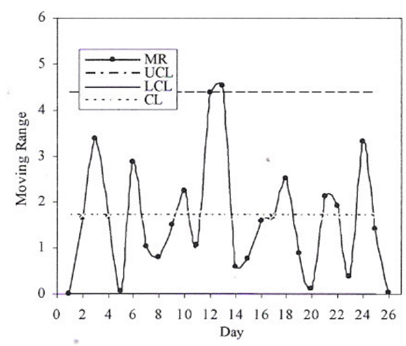

Fig. 4. MR chart for grade % of Zn concentrate

For the X chart of recovery % of Zn concentrate, low fluctuations were observed (except for 7th day, for 18th day and for 21st day) shown in Fig. 5. For the MR chart of recovery % of Zn concentrate shown in Fig. 6, low fluctuations were observed, but the recovery ratio were higher than the UCL_R limit for the 19-20 d. For the X chart for Zn % of tailings, the pattern of the fluctuation was similar to that of the MR chart for Zn % of tailings. The fluctuation level increased between the 18th day and the 25th day shown in Figs. 7 and 8.

The X chart and MR charts of Pb products for grades of concentrate, tailings and recovery in the process were presented in Figs. 9-14, respectively. For the X chart of Pb concentrate, fluctuations generally were higher than X chart of Zn concentrate. The Pb % values shown in Fig. 9 were lower

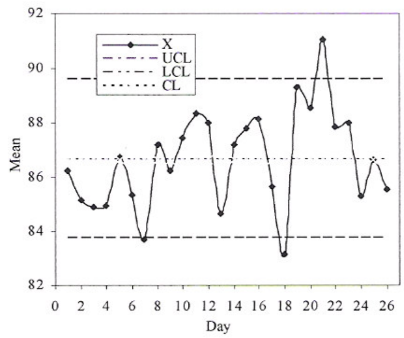

Fig. 5. X chart for recovery % of Zn concentrate

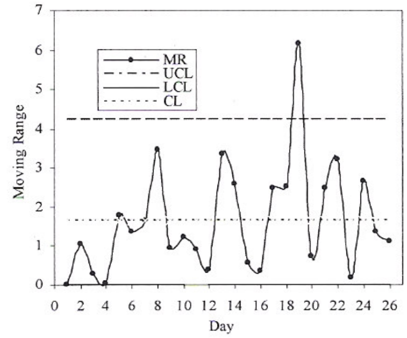

Fig. 6. MR chart for recovery % of Zn concentrate

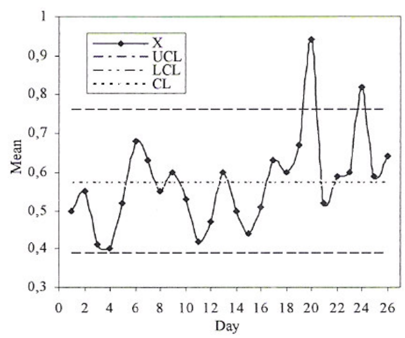

Fig. 7. X chart for Zn % of tailings

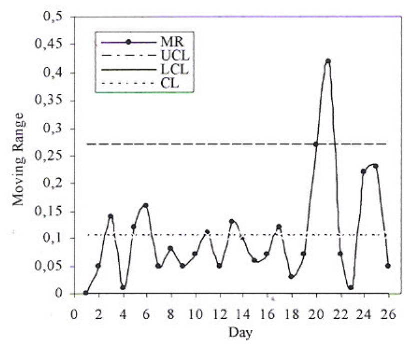

Fig. 8. MR chart for Zn % of tailings

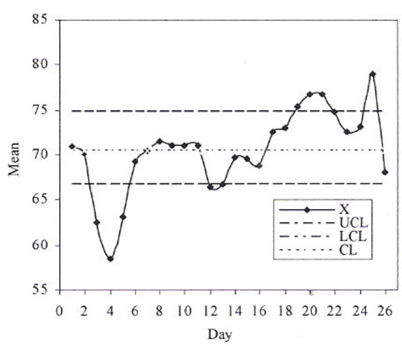

Fig. 9. X chart for grade % of Pb concentrate

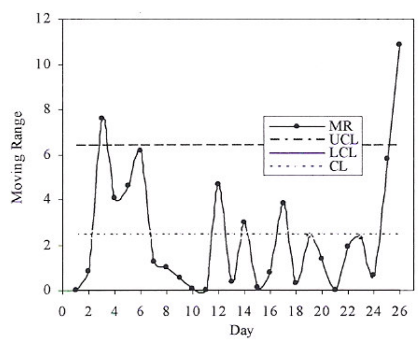

Fig. 10. MR chart for grade % of Pb concentrate

than LCL_X limit for five days and upper than UCL_X limit for four days. For the MR chart of grade% of Pb Concentrate shown in Fig. 10, the fluctuations on the 3rd day and on the 25th day were higher than UCL_R limit value. The daily MR values of 1, 10-11', 15 and 21 reached limit value (LCL_R) as critical levels. For the X chart of recovery % of Pb concentrate shown in Fig. 11, high fluctuations were observed for 5th day and for 21st day. For the MR chart of recovery % of Pb concentrate shown in Fig. 12, almost same fluctuations existed. For the X chart for Pb % of tailings, the pattern of the fluctuation was similar to that of the MR chart for Zn % of tailings (Figs. 13 and 14). The fluctuation levels were very high after the18th day of pattern for Pb % of tailings.

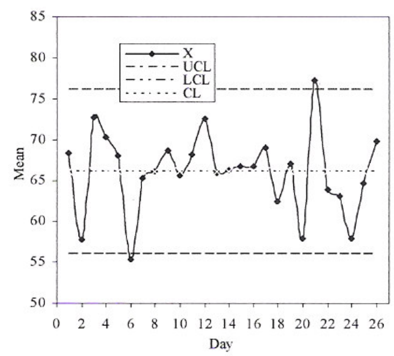

Fig. 11. X chart for recovery % of Pb concentrate

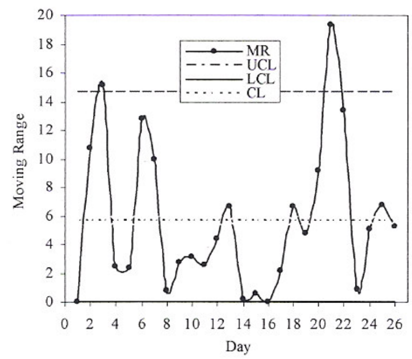

Fig. 12. MR chart for recovery % of Pb concentrate

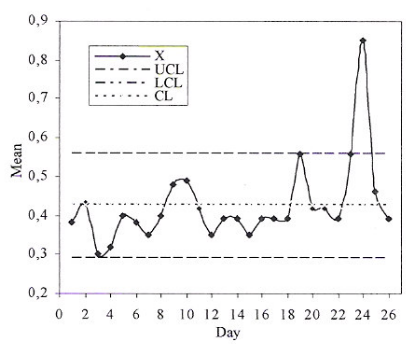

Fig. 13. X chart for Pb % of tailings

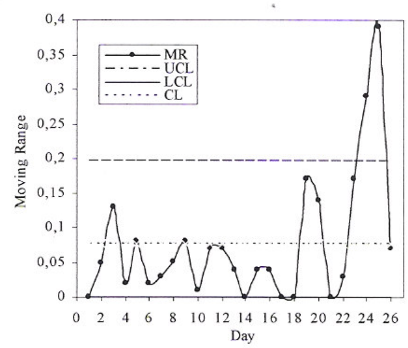

Fig. 14. MR chart for Pb % of tailings

Analysis of process capability: Process capability potential (C_p) is the ratio of the distribution curve of a quality characteristic which is required to be under control for a normal distribution curve. The numerical definitions of C_p were called Process Capability Ratios ($C_{pr(1)}$ or $C_{pr(2)}$). For determination of C_p, process capability indices is used which is given eqn. 6 and 7 with $\sigma = (\overline{MR}/d_2)$. In this method, C_p controls only the distribution of the process, but $C_{pr(1)}$ or $C_{pr(2)}$ controls both the distribution and the average. The following decisions were considered after analyzing the data. If the C_p or C_{pr} values are below 1.0, it is obvious that the process is inadequate. If the C_p and C_{pr} values higher than 1.0, the specification limits are wider than the natural tolerance and the process has the potential for meeting specifications. If the C_p and $C_{pr(1)}$ or $C_{pr(1)}$ were ≥ 1.33, the process is adequate in the most applications[11-13].

$$C_P = \frac{\sum \text{Tolerance}}{6\sigma} = \frac{USL_X - LSL_X}{6\sigma} \quad (6)$$

$$C_{pr(1)} = \frac{USL_X - \overline{X}}{3\sigma} \text{ and } C_{pr(2)} = \frac{X - LSL_X}{3\sigma} \quad (7)$$

The USL_X and LSL_X as expected values for calculations indexes were obtained from the management of the plant. The calculated capability indexes the products were for Zn concentrates were given in Table-2. For the grades of Zn concentrate, index values were under 1.0. For the recovery ratio of Zn concentrate, similar results were obtained (except $C_{pr(1)}$). For the grades of Zn tailings, index values were very low (C_p = 0.77). It was determined that the flotation plant was inadequate for mineral processing. The calculated capability indexes of the products for Pb concentrates were given in Table-3. For the grades of Pb concentrate, index values were lower than 1.0 (except $C_{pr(1)}$), but the Pb concentrate values were near the adequate point (1.0). For the recovery ratio of Pb concentrate (C_p = 0.50), the capability results of recovery were lower than the recovery ratio of Pb concentrate. For the grades of Pb tailings, index values were under 1.0 (C_p = 0.71, $C_{pr(1)}$ = 0.49 and $C_{pr(2)}$ = 0.92). Therefore, the flotation plant was inadequate for mineral processing. It was thought that the feed at the plant is homogenous. Instead of processing the ores produced at the pit separately, it is better to mix them and feed them to the plant as single Zn-Pb ores. The determined values here mean that the process had a larger fluctuation than defined. Because of this situation, reagent types and usage dosages of reagents should be rearranged using SPC. For decreasing of losses in tailings, fine grinding of raw ore can be used.

TABLE-2
CAPABILITY INDEXES FOR Zn GRADES OF THE PRODUCTS

%	Concentrate	Recovery	Tailings
USL_X	55.00	90.00	0.60
LSL_X	50.00	85.00	0.30
C_p	0.85	0.86	0.77
$C_{pr(1)}$	0.78	1.14	0.15
$C_{pr(2)}$	0.94	0.57	0.09

TABLE-3
CAPABILITY INDEXES FOR Pb GRADES OF THE PRODUCTS

%	Concentrate	Recovery	Tailings
USL	76.00	90.00	0.50
LSL	68.00	80.00	0.30
Cp	0.91	0.50	0.71
$C_{pr(1)}$	1.26	0.10	0.49
$C_{pr(2)}$	0.57	0.66	0.92

Conclusion

It was observed that there was a necessity to struggle quality problems or errors of the flotation circuit using statistical process control (SPC). A lot of values for grade %, recovery % and tailings % fluctuated outsides of control limits and the values of C_p, $C_{pr(1)}$ and $C_{pr(1)}$ were under 1.33 in general. It was advised that intelligent techniques could have incorporated to solve a large variety of problems. Control chart (CC) and process capability analysis using SPC should be utilized to reach at the following conclusions:

(i) The grade values of tailings and recovery rates of the Zn-Pb concentrates is very significant to export of final products to the other countries varied within the short time periods, but all of the tested parameters were not statistically stable in the measurements, and a lot of values were out of limits (Tables 2 and 3). (ii) Concentrate grades of Zn-Pb products at the plant had the worst fluctuation among them indicating no homogenous run of mine was fed into the plant during the period of testing. There were necessities of raw material homogenization and automatic control systems to permit an optimum feed for forecasting or preventing fluctuations in the plant. (iii) SPC using MR method can be applied an economic concept with powerful mini-computers. It will lead a substantial savings in cost and improved operation by comparison with traditional trials or error methods. For this reason, applications of new techniques were rather slowly included in the information systems. (iv) The optimum flotation process must be controlled by means of X-ray analyzers, automatically. A process monitor must check the metal content of the slurry using X-ray analyzer. Therefore, the monitors achieve to adjust the proportion of the chemical additive to optimize recovery of the metal using MR method, automatically. Also, Rietveld-based computational method (Siroquant™)[14] and SPC using MR method could also be applied for control machines to determine quantifications of products.

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