# Estimation of the Regression Equation Based on the Pulp Density by "AR-31-M" XRF Spectrometer

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In 2014, a wavelength dispersive X-ray fluorescence spectrometer AR-31-M for industrial technological control was installed in the X-Ray laboratory, Erdenet Mining Corporation which is one of the biggest mining industries in Asia. In this work estimation of registration equation based on pulp density by the XRF spectrometer, is presented.

Азийн хамгийн том уул уурхайн үйлдвэрүүдийн нэг Эрдэнэт уулын баяжуулах үйлдвэрийн Рентген лабораторид 2014 онд үйлдвэрийн технологийн процессыг хянах долгионы уртаар ялгадаг рентген-флуоресценцийн AR-31-M спектрометрийг суурилуулсан. Энэ ажилд AR-31-M спектрометрээр зуурмагийн нягтад суууриласан регрессийн тэгшитгэлийг сонгосон талаар өгүүлнэ.

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## I. INTRODUCTION

Mongolian-Russian Erdenet Mining Corporation (EMC) processed 32 million tons of ore, produced 650.0 thousand tons of copper concentrate and 4.5 thousand tons of molybdenum concentrate per year.

A XRF spectrometer AR-31-M for industrial technological control was installed at the X-ray laboratory of the EMC in 2014. Fully automated analytical system (AR-31-M) with multi-purposes is designed to determine chemical composition in pulp by continuous X-ray fluorescence analysis. Mobile measuring head with fixed spectrometer channels (up to 8) and program-controlled processing of up to 15 flow cells per 30 minutes. Measurements of the intensity are performed in four channels - Cu Ka, Fe Ka, Mo Ka and incoherent scattered radiation line from anode Pd Ka.

Operation of the analyzer carried at following two basic modes:

- Cyclically mode - provides automatic measurement for all points with cyclically mode in accordance with a predetermined program

-Single command mode - provided one-time testing of user commands for the organization of the whole spectrometer.

The calibration process starts with collection of samples from the analysis point, and the total number of samples are taken at least 50 samples for each product. These samples are assayed by a chemical laboratory and then correlated with data from the analyser. Calibration equations based on this data are obtained and the analyser calculates future elemental concentrations based on the equations.

The main purpose of this study is to determine the optimal regression equation based on the density of slurry stream (pulp). Regression results are then compared and the best calibration equation is chosen based on a comparison of the RMS error, significance, correlation coefficient and the number of terms used in the equation. General form of the regression equation is written as:

For chemical elements:

$$C_i = a_o + \sum a_i I_i + I_i \sum a_{ij} I_j + I_P \sum a_{pj} I_j \qquad (1)$$

For density:

$$C_d = a_0 + \frac{a_1}{I_p} + \frac{a_2}{I_p^2} + \frac{1}{I_p} \sum b_j I_j + I_p \sum a_{pj} I_j + \sum a_j I_j \qquad (2)$$

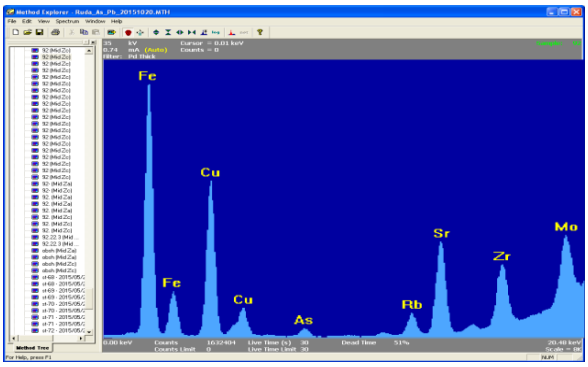


Figure 1: X-Ray spectrum of ore content of the mining plant. For grinding ore is used the steel balls

## II. EXPERIMENTAL

Figure 2: AR-31-M Spectrometer

Figure 3: View of the control stand

Table 1. AP-31-M Spectrometer Technical Specifications

| | |
|---|---|
| X-Ray tube | Pd |
| Detector | Scintillation counting |
| Correction | Intensity correction |
| Range defined chemical elements | From Ca (20) to U (92) |
| Determining a chemical element at same time | 8 |
| Total number of analysis point (sample) | 15 |
| Technique error ,% | 0.4 |
| Detection limit, % by weight. in - solution:<br>-slurries and suspensions: | $1.10^{-3}$ ... $1.10^{-4}$<br>$5.10^{-2}$ ... $1.10^{-3}$ |
| Total power consumption, kW, not more | 5 |
| Mean time analysis of each sample, sec | 40 |
| Weight, kg | 1500 |
| Volume of the transported samples, liter | 6 |
| Pressure compressed air, kPa | 400-600 |
| Power supply system, V | 380 |

## A. Sample preparation and calibration

The calibration process starts with collection of samples from the analysis stream pulp. Option to stream more than approximately 50 samples should be collected. Turn pump each sample. Adjustment depending on the capacity of the pump once used to turn liquid sample size is different. (In our case, 4-5 l) according to the following chart prepared calibration samples analyzed.

Table 2. Condition

| | | | | | |
|---|---|---|---|---|---|
| 1 | Tube voltage | 40kV | 6 | Product type | Ore feed, tail, copper concentrate, molybdenum concentrate, CuMo tail, copper bulk concentrate. |
| 2 | Tube current | 30 mA | | | |
| 3 | Exposure | 40 sec | | | |
| 4 | Energy line | Kα | | | |
| 5 | Chemical element | Cu, Mo, Fe | | | |

## B. Method of study to choice the best regression equations

The calibration results were included in the database configuration file.

Table 3. Chemical elements in copper concentrate

| № | Cu | Mo | Fe | Ag |
|---|---|---|---|---|
| **1** | 22.82 | 0.079 | 27.24 | 23.25 |
| **2** | 24.8 | 0.23 | 26.56 | 23.67 |
| **3** | 24.13 | 0.105 | 27.18 | 22.76 |
| **4** | 24.12 | 0.34 | 27.16 | 22.72 |
| **5** | 22.86 | 0.1 | 27.2 | 22 |
| **6** | 25.05 | 0.12 | 27.13 | 25 |
| **7** | 24.32 | 0.37 | 27.07 | 24 |
| **8** | 21.27 | 0.18 | 27.38 | 23.29 |
| **9** | 23.83 | 0.15 | 27.25 | 23.03 |
| **10** | 20.15 | 0.17 | 27.29 | 20 |
| **11** | 22.61 | 0.25 | 27.12 | 23 |
| **12** | 20.74 | 0.069 | 27.5 | 20 |
| **13** | 20.2 | 0.076 | 26.24 | 20.36 |
| **14** | 24.02 | 0.077 | 27.45 | 23.96 |
| **15** | 21.1 | 0.059 | 27.5 | 22 |
| **16** | 21.89 | 0.052 | 27.15 | 21.5 |
| **17** | 26.84 | 0.049 | 24.86 | 27.01 |
| **18** | 27.81 | 0.04 | 25.51 | 28 |
| **19** | 25.08 | 0.099 | 27.42 | 24.9 |
| **20** | 19.58 | 0.12 | 27.3 | 19.94 |
| **21** | 24.2 | 0.084 | 27.35 | 25.86 |
| **22** | 23.35 | 0.081 | 27.1 | 23.1 |
| **23** | 25.53 | 0.092 | 27.36 | 17.5 |
| **24** | 23.44 | 0.07 | 27.4 | 23.01 |
| **25** | 24.8 | 0.13 | 27.19 | 24.41 |
| **26** | 24.4 | 0.15 | 27.21 | 24.29 |
| **27** | 25 | 0.27 | 27.21 | 25.01 |

**Method 1:** Choice the equation based on the following criteria F (Fisher) and P criteria. F criteria to allow for the impact of all the independent variables elements. If F> $F_{kr}$ (2.96) the equation if significant. P statistical assumptions used to verify the results of the sample function. If P = <α the regression equation if significant. The chemical elements in copper concentrate is shown in the following table. 4

Table. 4

| SUMMARY OUTPUT | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Regression Statistics | | | | | ANOVA | | | | | |
| Multiple R | R Square | Adjusted R Square | Standard Error | Obser-vations | Regres-sion | *df* | *SS* | *MS* | *F* | *Signifi-canceF* |
| 0.690515 | 0.47681 | 0.4558 | 1.5007 | 27 | Residual | 1 | 51.31 | 51.31 | 22.78 | 0.0044 |
| | | | | | Total | 25 | 56.30 | 2.25 | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 26 | 107.61 | | | |
| | *Coef-ficients* | *Standard Error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* | *Lower 95.0%* | *Upper 95.0%* | | |
| Intercept | 9.28 | 2.08 | 3.11 | 0.004 | 3.13 | 15.43 | 3.13 | 15.43 | | |
| Ag | 0.61 | 0.12 | 4.77 | 0.01 | 0.35 | 0.87 | 0.35 | 0.87 | | |

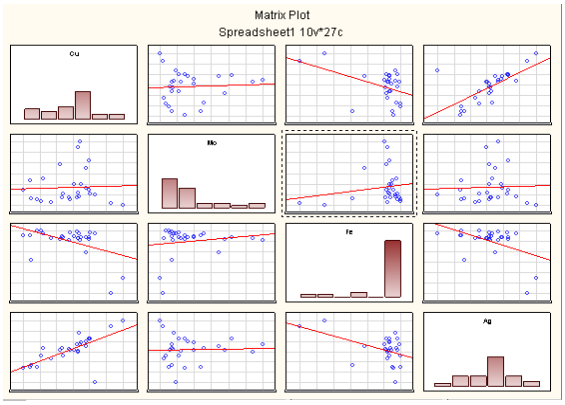


Figure 4: Matrix of the elements

It can be concluded that the copper content in the copper concentrate depends only on the density.

**Method 2:** Dependence Matrix Using program "Statistica" shows the matrix of the elements. (Figure. 4)

Matrix of the elements can be concluded that the copper content in the copper concentrate depends only on the density. According the methodology the regression equation for the copper concentrate is written as:

$$C_{Cu} = -5.88 + 24.14 * CUKA + 65.51 * CUKA * AGKA - 5.41 * AGKA \quad (3)$$
$$C_{Mo} = -0.06 + 2.86 * MOKA + 2.59 * MOKA * CUKA - 0.06 * AGKA \quad (4)$$
$$C_{Fe} = 6.49 + 13.96FEKA + 6.62FEKA * CUKA + 23.35AGKA \quad (5)$$
$$C_d = 3.55 + 1/2.71 * AGKA + 1/1.30 * AGKA * AGKA - 5.85 * AGKA * CUKA \quad (6)$$

Table 5. Chemical and laboratory assays for the calibration

| № | Cu (chemical) | Cu (calculation) | Mo (chemical) | Mo (calculation) | Fe (chemical) | Fe (calculation) | Ag (chemical) | Ag (calculation) |
|---|---|---|---|---|---|---|---|---|
| 1 | 22.82 | 23.11 | 0.079 | 0.077 | 27.24 | 26.95 | 25.25 | 23.63 |
| 2 | 24.8 | 25.2 | 0.23 | 0.24 | 26.56 | 26.50 | 23.67 | 23.31 |
| 3 | 24.13 | 23.72 | 0.105 | 0.109 | 27.18 | 27.13 | 22.76 | 22.67 |
| 4 | 24.12 | 23.91 | 0.34 | 0.345 | 27.16 | 26.93 | 22.72 | 23.63 |
| 5 | 22.86 | 23.09 | 0.1 | 0.10 | 27.2 | 26.58 | 16.01 | 15.64 |
| 6 | 25.05 | 24.42 | 0.12 | 0.13 | 27.13 | 26.70 | 15 | 15.45 |
| 7 | 24.32 | 23.92 | 0.37 | 0.356 | 27.07 | 26.53 | 14.91 | 15.08 |
| 8 | 21.27 | 21.41 | 0.18 | 0.18 | 27.38 | 27.03 | 23.29 | 23.74 |
| 9 | 23.83 | 23.23 | 0.15 | 0.15 | 27.25 | 26.93 | 23.03 | 23.42 |
| 10 | 20.15 | 19.82 | 0.17 | 0.15 | 27.29 | 27.09 | 27.06 | 26.60 |
| 11 | 20.74 | 20.27 | 0.069 | 0.067 | 27.5 | 26.89 | 24 | 23.63 |
| 12 | 20.2 | 21.01 | 0.076 | 0.074 | 26.24 | 27.62 | 35 | 34.91 |
| 13 | 24.02 | 23.32 | 0.077 | 0.086 | 27.45 | 26.32 | 16.78 | 17.69 |
| 14 | 21.1 | 20.83 | 0.059 | 0.062 | 27.5 | 26.89 | 32.5 | 32.38 |
| 15 | 21.89 | 22.77 | 0.052 | 0.058 | 27.15 | 27.80 | 34.73 | 34.91 |
| 16 | 27.81 | 28.37 | 0.04 | 0.038 | 25.51 | 25.90 | 29 | 28.66 |
| 17 | 19.58 | 20.21 | 0.12 | 0.12 | 27.3 | 27.03 | 14.94 | 14.48 |
| 18 | 23.35 | 22.94 | 0.081 | 0.067 | 27.1 | 27.31 | 23.1 | 23.09 |
| 19 | 25.53 | 24.35 | 0.092 | 0.070 | 27.36 | 27.22 | 17.5 | 17.63 |
| 20 | 23.44 | 23.41 | 0.07 | 0.065 | 27.4 | 27.10 | 19.08 | 18.35 |
| 21 | 24.8 | 24.67 | 0.13 | 0.12 | 27.19 | 27.13 | 12.41 | 14.15 |
| 22 | 25 | 25.21 | 0.27 | 0.27 | 27.21 | 27.46 | 15 | 15.13 |

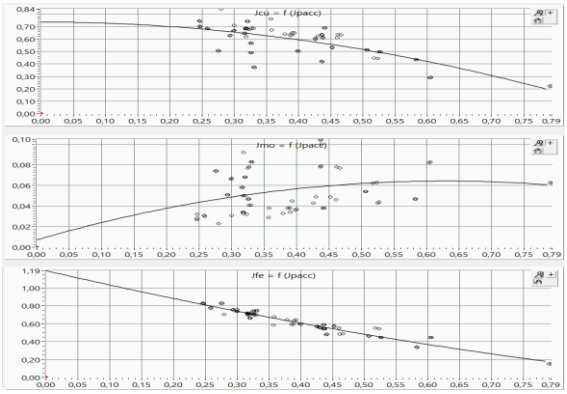

Figure 5: Dependence of the intensities of analyzed elements of the scattering intensity

The function J=f(Jscatt) allows to evaluate the dependence of the intensities of the analyzed elements on the intensity of the scattered radiation.

## III. RESULTS AND DISCUSSION

The results of the AR-31-M were compared with results of the chemical analysis and the Quant'X, can be seen in Table 6. The results of AR-31-M spectrometer were obtained by the regression equations are shown in the histogram (Figure 6-7).

Table 6. Results of the Cu in copper concentrate (01-15 April 2015)

| Day | | AP-31-M | Quant'X | Chemical | AP-31-Quant'X | AP-31-M-Chemical | Quant'X-Chemical |
|---|---|---|---|---|---|---|---|
| 1 | 1 shift | 22.72 | 22.7 | 22.63 | 0.02 | 0.09 | 0.07 |
| | 2 shift | 22.94 | 22.9 | 22.67 | 0.04 | 0.27 | 0.23 |
| | 3 shift | 23.48 | 23.3 | 23.29 | 0.18 | 0.19 | 0.01 |
| 2 | 1 shift | 23.24 | 23.44 | 23.61 | -0.2 | -0.37 | -0.17 |
| | 2 shift | 23.73 | 23.94 | 24.15 | -0.21 | -0.42 | -0.21 |
| | 3 shift | 23.26 | 23.52 | 23.28 | -0.26 | -0.02 | 0.24 |
| 3 | 1 shift | 23.52 | 23.35 | 23.34 | 0.17 | 0.18 | 0.01 |
| | 2 shift | 22.86 | 23.01 | 22.63 | -0.15 | 0.23 | 0.38 |
| | 3 shift | 23.05 | 22.88 | 22.62 | 0.17 | 0.43 | 0.26 |
| 4 | 1 shift | 23.51 | 23.11 | 23.15 | 0.4 | 0.36 | -0.04 |
| | 2 shift | 22.83 | 22.65 | 22.76 | 0.18 | 0.07 | -0.11 |
| | 3 shift | 22.61 | 22.63 | 22.64 | -0.02 | -0.03 | -0.01 |
| 5 | 1 shift | 22.9 | 22.72 | 22.57 | 0.18 | 0.33 | 0.15 |
| | 2 shift | 22.94 | 22.84 | 22.88 | 0.1 | 0.06 | -0.04 |
| | 3 shift | 23.57 | 23.83 | 23.78 | -0.26 | -0.21 | 0.05 |
| 6 | 1 shift | 22.93 | 23 | 22.85 | -0.07 | 0.08 | 0.15 |
| | 2 shift | 23.02 | 22.83 | 22.9 | 0.19 | 0.12 | -0.07 |
| | 3 shift | 23.67 | 23.6 | 23.76 | 0.07 | -0.09 | -0.16 |
| 7 | 1 shift | 23.55 | 23.61 | 23.8 | -0.06 | -0.25 | -0.19 |
| | 2 shift | 23.06 | 23.18 | 23.28 | -0.12 | -0.22 | -0.1 |
| | 3 shift | 23.68 | 23.31 | 23.49 | 0.37 | 0.19 | -0.18 |
| 8 | 1 shift | 22.84 | 22.89 | 23.21 | -0.05 | -0.37 | -0.32 |
| | 2 shift | 22.8 | 22.74 | 22.75 | 0.06 | 0.05 | -0.01 |
| | 3 shift | 21.68 | 21.73 | 21.77 | -0.05 | -0.09 | -0.04 |
| 9 | 1 shift | 23.83 | 23.89 | 23.93 | -0.06 | -0.1 | -0.04 |
| | 2 shift | 23.6 | 23.8 | 23.82 | -0.2 | -0.22 | -0.02 |
| | 3 shift | 22.47 | 22.55 | 22.88 | -0.08 | -0.41 | -0.33 |
| 10 | 1 shift | 23.17 | 23.28 | 23.53 | -0.11 | -0.36 | -0.25 |
| | 2 shift | 23.24 | 23.14 | 23.53 | 0.1 | -0.29 | -0.39 |
| | 3 shift | 22.31 | 22.4 | 22.11 | -0.09 | 0.2 | 0.29 |
| 11 | 1 shift | 23.24 | 23.38 | 23.43 | -0.14 | -0.19 | -0.05 |
| | 2 shift | 23.56 | 23.6 | 23.69 | -0.04 | -0.13 | -0.09 |
| | 3 shift | 23.46 | 23.48 | 23.57 | -0.02 | -0.11 | -0.09 |
| 12 | 1 shift | 23.04 | 23.1 | 23.57 | -0.06 | -0.53 | -0.47 |
| | 2 shift | 22.5 | 22.81 | 22.72 | -0.31 | -0.22 | 0.09 |
| | 3 shift | 22.3 | 22.34 | 22.13 | -0.04 | 0.17 | 0.21 |
| 13 | 1 shift | 23.58 | 23.53 | 23.78 | 0.05 | -0.2 | -0.25 |
| | 2 shift | 24.14 | 24.21 | 24.19 | -0.07 | -0.05 | 0.02 |
| | 3 shift | 23.05 | 23.34 | 22.9 | -0.29 | 0.15 | 0.44 |
| 14 | 1 shift | 23.34 | 23.18 | 23.07 | 0.16 | 0.27 | 0.11 |
| | 2 shift | 22.86 | 22.8 | 22.61 | 0.06 | 0.25 | 0.19 |
| | 3 shift | 23.31 | 23.03 | 22.97 | 0.28 | 0.34 | 0.06 |
| 15 | 1 shift | 22.91 | 22.81 | 23.04 | 0.1 | -0.13 | -0.23 |
| | 2 shift | 22.95 | 22.83 | 22.49 | 0.12 | 0.46 | 0.34 |
| | 3 shift | 23.98 | 23.67 | 23.81 | 0.31 | 0.17 | -0.14 |

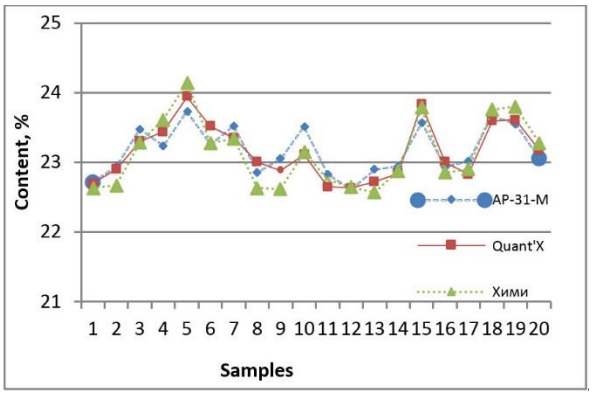


Figure.6 The molybdenum content in copper concentrate. Comparison results of the chemical, RSEL's and AP-31-M spectrometer

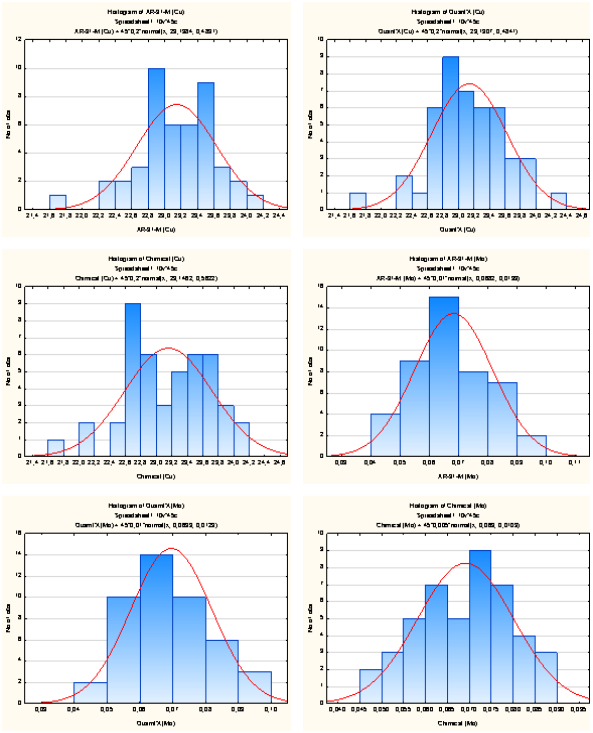

Figure. 7: Copper in copper concentrate, molybdenum histogram results

## IV. CONCLUSION

WDXRF method allows determining Cu, Mo, Fe and density contents in the all samples from ore to concentrate. X-Ray laboratory performed quantitative elemental analysis on wide range of industry technology product.

The correlation coefficient, determination coefficient, standard error and significance were calculated using the software EVIEWS-8, Statistic, Excel- ANOVA and the optimal regression equation was estimated by this method.

From this study, we have concluded that determination of elements such Cu, Mo, Fe and density in a short-time is possible by the developed method.

[1] Стандарт КОО “Предприятие Эрдэнэт” СТП-001-11 Комплексная система управления качеством продукции (КС УКП) стандарт рентгено-спектральной экспресс лаборатории (РСЭЛ)

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