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Vesna Ljubojev, Vesna Marjanović*, Dragan Milanović*, Suzana Stanković**

MINERALOGICAL CHARACTERISTICS OF SLAG (FROM THE FLOTATION PLANT OF RTB BOR) GRANULATED IN THE LABORATORY CONDITIONS**

Abstract

A sample of slag from the Flotation Bor, RTB Bor, was mineralogical tested after granulation in the laboratory conditions. Minerals contained in the sample of granulated slag are: fayalite and ferrite that form the basis with rarely sprayed fine particles of magnetite, pyrite, chalcopyrite, bornite, copper matte and elemental - native copper [6, 7]. Granulation of slag was conducted in the laboratory conditions on the device specially designed for this purpose.

Keywords: *smelter slag, copper minerals, fayalite, mineralogical testing*

INTRODUCTION

The copper smelter slag is produced as a by-product during the pyrometallurgical copper smelting. The composition and concentration of elements in slag depends on the composition of ore concentrate which is processed and technological processing methods. Slag represents the complex systems of a number of components, which occur at high smelting temperature, such as non-metallic inclusions and newlyformed oxides [1].

Many years metallurgical processing of copper concentrate in the industrial complex of RTB Bor has created a dump slag, which is used as the secondary raw material, as it contains significant amounts of valuable metals. Total amount of slag in the "Depot - Slag 1" amounts to about 9,190,940 tons with the medium content of Cu - 0.715%, Au – 0.282 g/t, Ag - 4.5 g/t and Mo 0.0413% [2].

In the Flotation Plant Bor, the section C was originally designed for flotation of ore, and later adapted for flotation of slag [3]. The process of slag comminution in the plant consists of crushing and grinding.

However, the ore is suitable for comminution from the standpoint of consumption the energy, linings and grinding bodies of slag and to explore the possibility of energy saving and reducing the wear of linings and grinding bodies in the process of grinding; heating of slag was carried out in the laboratory conditions to the melting point and its cooling by a jet of water to form the granules of slag. It would consider the possibility of expulsion the process of comminution in the industrial conditions, and enabled the saving of energy and raw material [4].

SAMPLE AND EXPERIMENTAL METHOD

A sample of smelting slag was taken from the crushing process in the Flotation Plant in Bor [4].

* *Mining and Metallurgy Institute Bor*

** *This work is the result of the Project TR33023 "Development of Technologies for Flotation Processing the Copper Ore and Precious Metals to Achieve Better Technological Results" funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia*

Upon completion the natural drying, sampling was performed according to the standard method of sampling and a representative sample was formed that was physically and chemically analyzed. The chemical composition of the sample is given in Table 1.

Table 1 *Chemical content of sample and granulated slag [5]*

Content (%) compound – chemical element	Sample	Analytical method
Cu	0.33	ASS
Fe_3O_4	3.41	A- Fe_3O_4
CaO	19.60	V
S	0.20	G
Fe	27.92	V
SiO_2	46.72	G
Al_2O_3	4.52	ICP-AES

The term granulation involves rapidly cooling the liquid-hot slag under the pressurized cold water and obtaining the slag in the form of irregular granules. The quality of granules depends on the chemical composition of slag, slag temperature before spillage, rate of slag spillage, pressure and the amount of cooling water [4].

Previously dried and analyzed slag was subjected to melting in an induction furnace for smelting, power of 100 kWh, in a pot volume V = 10 h, manufacturer ELING - Loznica. During the experiment, 25 kg of slag was melt at the temperature of spillage of T = 1,250^{o}C [8].

Granulation of slag in the laboratory conditions was performed on a specially designed granulator which is mobile and allows rapidly cooling of slag by jets, which are located on the front side of the tank, just behind a roller of granulator, which has one part immersed in cooling water. Below the roller is a carrying basket with a perforated bottom that accepts the resulting granules and that after discharging the total amount of slag from furnace is removed by a crane after draining, left in a basket for granulated slag [4].

Copper and slag are insoluble in each other and due to this they are separated from each other in the furnace precipitator. Copper matte drops are denser than the slag and under the influence of gravity pass through the slag and form a separate layer at the bottom of the furnace. Less dense layer of slag floats on a layer of copper matte. In the furnace precipitator, blister and slag layers are formed separately in two separate layers. The basic components of slag during melting of copper concentrate are SiO_2, FeO, Fe_2O_3 and MgO, and slag often contains Fe_3O_4, Al_2O_3, Cu_2S, and smaller quantities fine droplets of mechanically affected copper. Copper content in the slag of flame furnace should be from 0.15 to 0.25%. However, due to significant presence of mechanically included copper matte in the slag, and due to the chemical bound copper in the form of copper oxide, copper content in the slag is higher [1].

Compound FeO in slag is most commonly found in the form of fayalite, Fe_2SiO_4, in which an excess of iron oxide can be dissolved, as it is the case in base slag.

MINERALOGICAL TESTING OF GRANULATES SLAG

Determination of mineral composition and structural-textural characteristics of minerals was made on a representative sample [6, 7].

The samples poured into acrylic resin are made of the obtained representative sample of granulated slag. Determination of slag samples was done on a microscope for transmitted and reflected light, the brand AXIOSKOP 40, with the device for microphoto. The chemical analysis on Niton was also carried out.

Qualitative mineralogical analysis was carried out under the polarization microscope for reflected light in the air for the purpose of identification the ore and non-ore minerals. Quantitative mineralogical analysis was carried out by the method of parallel sections, with spacing of 1 mm. The distance between the examined fields and sections were moved by hand. Determination of slag samples was done on the microscope for transmitted and reflected light, the brand AXIOSCOPE 40, with the device for microphoto.

Based on the qualitative mineralogical analyses the following mineral composition of slag was determined: solid sulfide melt (Cu-Fe), chalcocite, pyrite, copper, chalcopyrite, bornite, magnetite and gangue minerals. Gangue minerals were presented with a glass with occurrence a variety of eutectic dendrites (fayalite and others) that were not particularly determined.

Structural characteristics of samples can be divided into:

1. Simple mesogen present the investigated mineral that is easily adhered to one mineral or only gangue-double mesogens.
2. Complex mesogen presents the investigated mineral that is adhered to more minerals and gangues – multiple mesogens.

Macroscopic description of granulated slag

Granulated slag has various coarseness with visible larger pieces. The spheroids of different sizes, smooth surfaces can be observed in a sample of granulated slag, Figure 1, as well as large number of very sharp glassy particles of slag, Figure 2. The sample is dark gray to black.

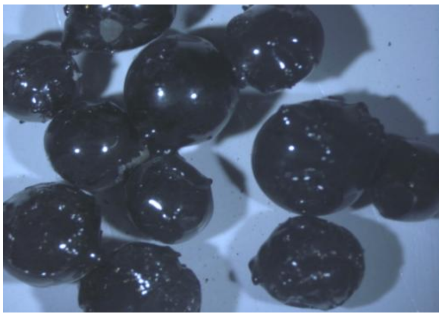

Figure 1 *Spherical grains in granulated slag, binocular, magnification 6.5 x*

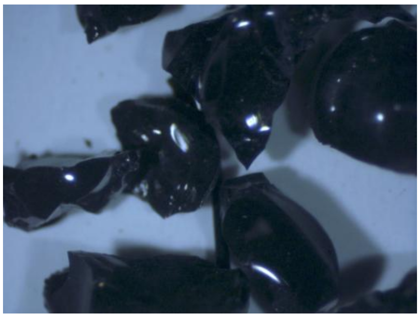

Figure 2 *Grains of granulated slag (sharo edges), binocular, magnification 2.0 x*

Microscopic description

Microscopic analysis has showed that the granulated slag is mainly built of fayalite and ferrite that build the basis in which fine particles of magnetite, pyrite, chalcopyrite, chalcocite, bornite, copper matte and elemental (native) copper are rarely sprayed, Figure 3.

Fayalite (iron silicate) is represented in the form of poke crystals, which indicates the product of smelting - slag. Ferrites (various iron oxides), also indicate the product of ore smelting. They are represented in the form of skeletal crystals (dendrites), Figure 9.

Magnetite occurs predominantly independent, in the form of cube and radial radiating aggregates. It rarely occurs in irregular shapes, Figures 7 and 8.

Pyrite is the most common of all sulfide minerals and occurs in the form of hypidiomorfic grains, mostly independent (free grain).

Since copper minerals occur chalcopyrite, chalcocite and bornite, in Figure 6.

Chalcopyrite occurs in irregular, relatively small, fields, rarely adhered to chalcocite, while some grains are permeated with chalcocite.

Chalcocite is less frequent in fine grains; it is free or is adhered to chalcopyrite and gangue mineral.

Elemental (native) copper occurs in the form of fine spherical shapes and small veins, Figures 4, 5 and 10.

Microphotos of slag

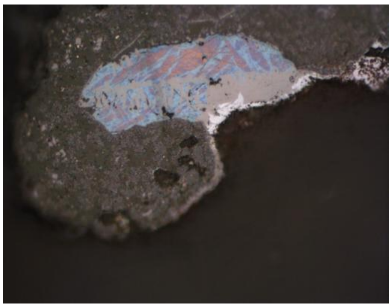

Figure 3 *Copper matte, bornite and chalcopyrite, magnification 500 x II N*

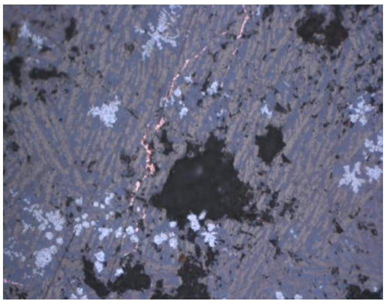

Figure 4 *Veins of elemental copper in fayalite basis, magnification 500 x II N*

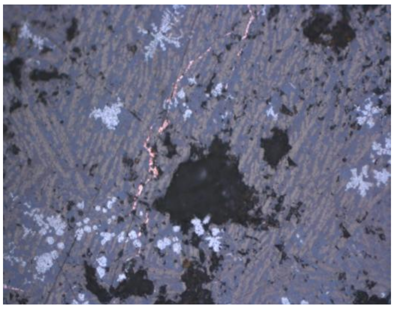

Figure 5 *Veins of elemental copper, magnification 500 x II N*

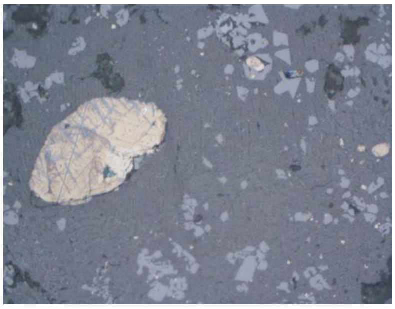

Figure 6 *Chalcopyrite grains in fayalite basis, permeated with chalcocite, magnification 500 x II N*

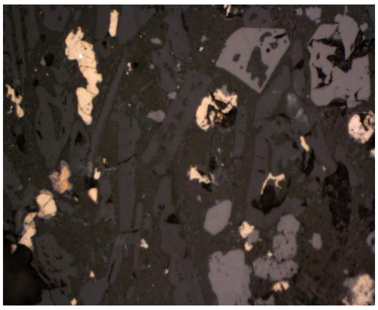

Figure 7 *Magnetite in the form of cube, chalcopyrite, magnification 500 x II N*

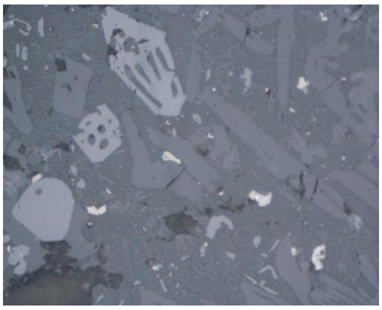

Figure 8 *Magnetite in various forms, magnification 500 x II N*

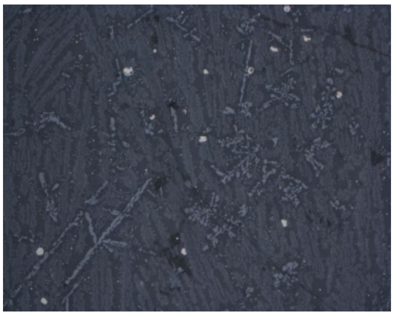

Figure 9 *Fayalite dendrites, magnification 500 x II N*

Figure 10 *Veins of elemental copper, magnification 500 x II N*

Chemical analysis of samples of granulated slag was done on apparatus NITON XL-L3t-900 from which it can be concluded that iron is the most common of 25.791%. This indicates a large content of iron minerals, which after thermal oxidation treatment transfer into Fe_2O_3 and Fe_3O_4. The copper content is 0.156%. The obtained results are shown in Table 2 and Figure 11.

Table 2 *Chemical analysis obtained by recording on X-ray NITON XL-3t-90*

Compounds – Chemical elements	Cu	S	Fe	Si	Ca	Al	Zn
Content, %	0.156	1.117	25.791	21.639	11.082	2.588	0.121

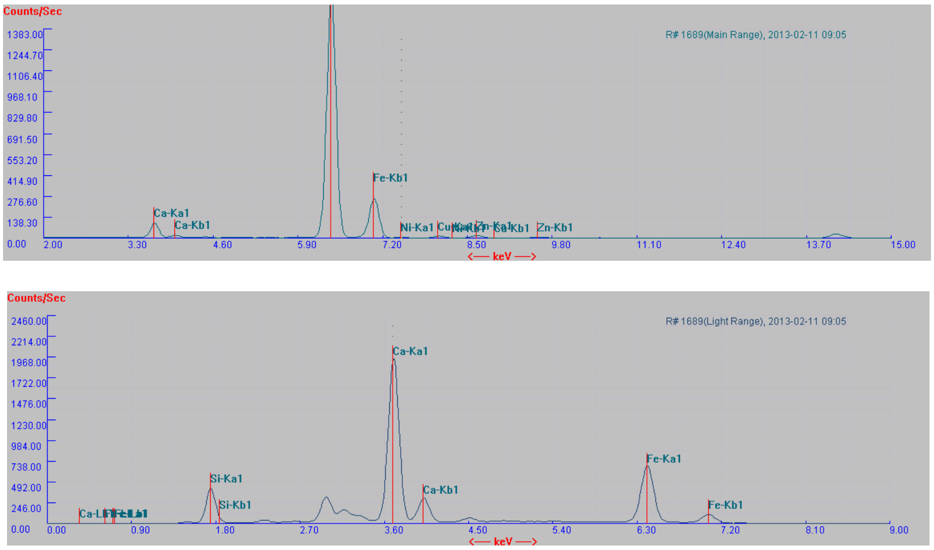

Figure 11 *Chemical analysis obtained by recording on X-ray NITON XL-3t-90*

CONCLUSION

Granulated slag from the process of pyrometallurgical smelting of copper is in the form of spherical grains and grains with sharp edges. Slag mainly contains oxide species and several species of sulfide minerals. The main component is the fayalite basis in which copper, chalcopyrite, magnetite and copper matte are permeated. Copper is in the form of copper matte and elemental copper in the form of veins in the fayalite basis. Magnetite is in the form of cube and other various forms.

REFERENCES

[1] Morales A., Cruells M., Roca A., Bergo R., Treatment of Copper Flash Smelter Dusts for Copper and Zinc Extraction and Arsenic Stabilization, Hydrometallurgy 105(2010), p. 148-154.

[2] Mitrović Z., et al., Main Mining Project for Slag Excavation from Technogenic Deposit "Depot Slag 1", Verification the Technological Process of Concentrate Obtaining and Superelevation of the Flotation Tailing Dump "RTH" in Bor to K +378 for Annual Production of 1,200,000 t Slag; Copper Institute Bor, 2006;

[3] http://rtb.rs/rtb-bor-doo/rudnik-bakra-bor/flotacija-bor/

[4] Magdalinović S., Milanović D., Čađenović B., Marjanović V., Technological Method of Slag Granulation to Reduce Grain-size at the Inlet into Flotation, Mining Engineering 3(2011), p. 101-110;

[5] Čađenović B., Marjanović V., Ljubojev V., Milanović D., Possibilities of Use the Copper Matte From Smelter Slag in its Direct in its Direct Discharge from Furnace, Mining Engineering, 2(2012), p. 143-148;

[6] Ljubojev V., Petrović J., Krstić S., Mineralogical Characteristics of Smelting Slag in the Technogenic Deposit "Depot 1" (Bor, Serbia). The Geology in digital Age: Proceedings of the Meeting of the Association of European Geological Societies (MAEGS 17), Belgrade (2011), p. 237-240;

[7] Ljubojev V., Repost on Microscope Testing of Granulatedd Slag, MMI Bor, May, 2013.

[8] Čadjenović B. Drobnjaković B., Milanović D., Magdalinović S., New Laboratory Plant for Granulation Using the Changed Technological Process of Smelter Slag Discharging, R. radovi 4(2011), p. 99-104.

[9] Požega E., Gomidželović L., Copper Smelters with Reverbatory and ISASMELT Furnace, Bakar 2(2010), p. 25-32.

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Vesna Ljubojev, Vesna Marjanović*, Dragan Milanović*, Suzana Stanković**

MINERALOŠKE OSOBINE ŠLJAKE (IZ POGONA „FLOTACIJE“ RTB BOR) GRANULISANE U LABORATORIJSKIM USLOVIMA**

Izvod

Uzorak šljake iz pogona „Flotacije“ Bor, RTB-a Bor je minerološki ispitivan posle granulacije u laboratorijskim uslovima. Minerali koji se nalaze u uzorku granulisane šljake su: fajalit i ferit koji čine osnovu, u koju su retko uprskane sitne čestice magnetita, pirita, halkopirita, bornita, bakrenca i elementarnog – samorodnog bakra [6, 7]. Granulisanje šljake je vršeno u laboratorijskim uslovima na uređaju specijalno konstruisanom za tu namenu.

Ključne reči: *topionička šljaka, minerali bakra, fajalit, minerološko ispitivanje*

UVOD

U topionicama bakra šljaka nastaje kao nus-proizvod u toku pirometalurškog topljenja bakra. Sastav i koncentracija elemenata u šljaci zavisi od sastava koncentrata rude koja je prerađena i tehnoloških postupaka prerade. Šljaka predstavlja složene sisteme većeg broja komponenata, koji nastaju na visokoj temperaturi topljenja, kao što su nemetalični uključci i novonastali oksidi [1].

U industrijskom kompleksu RTB Bor višegodišnja metalurška prerada koncentrata bakra stvorila je deponiju šljake, a koja se koristiti kao sekundarna sirovina, jer sadrži značajne količine korisnih metala. Ukupne količine šljake u „Depo - šljake 1“ iznose oko 9.190.940 t sa srednjim sadržajem Cu - 0,715%, Au – 0,282 g/t, Ag – 4,5 g/t i Mo 0,0413% [2].

U pogonu „Flotacije Bor“, sekcija C je prvobitno projektovana za flotaciju rude, a kasnije je prilagođena za flotaciju šljake [3]. Proces usitnjavanja šljake u pogonu se sastoji od drobljenja i mlevenja.

Međutim, ruda je pogodnija za usitnjavanje sa stanovišta potrošnje energije, obloga i meljućih tela od šljake i da bi se istražila mogućnost uštede energije i smanjenje habanja obloga i meljućih tela u procesu usitnjavanja, u laboratorijskim uslovima izvršeno je zagrevanje šljake do tačke topljenja i njeno hlađenje mlazom vode radi formiranja granula šljake. Time bi se razmotrila mogućnost izbacivanja procesa drobljenja u industriskim uslovima, i omogućila ušteda energije i repro materijala [4].

UZORAK I EKSPERIMENTALNA PROCEDURA

Uzorak topioničke šljake uzet je iz procesa drobljenja u pogonu „Flotacije“ u Boru [4].

* *Institut za rudarstvo i metalurgiju Bor*

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Po završetku prirodnog sušenja izvršeno je uzorkovanje prema standardnoj metodi i formiran je reprezentativan uzorak koji je fizički i hemijski analiziran. Hemijski sastav uzorka dat je u tabeli 1.

Tabela 1. *Hemijski sastav uzorka i granulisane šljake [5]*

Sadržaj (%) jedinjenjenja - hemijskog elementa	Uzorak	Analitička metoda
Cu	0,33	ASS
Fe_3O_4	3,41	A- Fe_3O_4
CaO	19,60	V
S	0,20	G
Fe	27,92	V
SiO_2	46,72	G
Al_2O_3	4,52	ICP-AES

Pod pojmom granulacije podrazumeva se naglo hlađenje tečne usijane šljake pod pritiskom hladne vode i dobijanje šljake u vidu nepravilnih granula. Kvalitet granula zavisi od hemijskog sastava šljake, temperature šljake pre izlivanja, brzine izlivanja šljake, pritiska i količine rashladne vode [4].

Prethodno osušena i analizirana šljaka je podvrgnuta topljenju u indukcionoj peći za topljenje, snage 100 kWh, u loncu zapremine V=10 L, proizvođača ELING - Loznica. Prilikom eksperimenta istopljeno je 25 kg šljake, temperatura pri kojoj je šljaka izlivena je bila T=1.250^{o}C. [8]

Granuliranje šljake u laboratorijskim uslovima je izvršeno na specijalno konstruisanom granulatoru koji je mobilan i omogućava, da se šljaka naglo hladi mlaznicama, koje se nalaze na čeonoj prednjoj strani rezervoara, odmah iza valjka granulatora, kome je jedan deo potopljen u rashladnu vodu. Ispod valjka je prihvatni koš sa perforiranim dnom, koji prihvata nastale granule i koji se nakon izlivanja celokupne količine šljake iz peći vadi uz pomoć dizalice i nakon ceđenja, odlaže u korpu za granulisanu šljaku [4].

Bakrenac i šljaka su nerastvorljivi jedan u drugo i zbog toga oni se odvajaju jedno od drugog u pećnom taložniku. Kapljice bakrenca su gušće od šljake i pod uticajem gravitacije prolaze kroz šljaku i na dnu peći formiraju poseban sloj. Manje gušći sloj šljake pluta na sloju bakrenca. U pećnom taložniku, slojevi blistera i šljake formiraju se odvojeno u dva posebna sloja. Osnovne komponente šljake prilikom topljenja bakarnog koncentrata su SiO_2, FeO, Fe_2O_3 i MgO, a šljaka često sadrži i Fe_3O_4, Al_2O_3, Cu_2S, i u manim količinama sitne kapljice mehanički zahvaćenog bakrenca. Sadržaj bakra u šljaci plamene peći trebao bi da bude od 0,15 do 0,25 %. Međutim, zbog značajnog prisustva mehanički uključenog bakrenca u šljaci i zbog hemijski vezanog bakra u obliku oksida sadržaj bakra u šljaci je veći [1].

Jedinjenje FeO u šljaci se najčešće nalazi u obliku fajalita, Fe_2SiO_4, u kome može biti rastvoren i višak gvožđe-oksida, kao što je slučaj u baznim šljakama.

MINERALOŠKO ISPITIVANJE GRANULISANE ŠLJAKE

Na reprezentativnom uzorku izvršena je determinacija mineralnog sastava i određivanje strukturno-teksturnih karakteristika minerala [6, 7].

Od dobijenog reprezentativnog uzorka granulisane šljake urađeni su preparati uliveni u akrilnu smolu. Determinacja uzoraka šljake rađena je mikroskopom za propuštenu i odbijenu svetlost, marke AXIOSKOP 40, sa uređajem za mikrofotografiju. Takođe, urađena je hemijska analiza na Nitonu.

Kvalitativna mineraloška analiza rađena je pod polarizacionim mikroskopom za odbijenu svetlost u vazduhu u cilju indentifikacije rudnih i nerudnih minerala. Kvantitativna mineraloška analiza rađena je metodom paralelnih profila, sa rastojanjem od 1 mm. Rastojanje između ispitivanih polja i profila pomerana su ručno. Determinacja uzoraka šljake rađena je mikroskopom za propuštenu i odbijenu svetlost, marke AXIOSKOP 40, sa uređajem za mikrofotografiju.

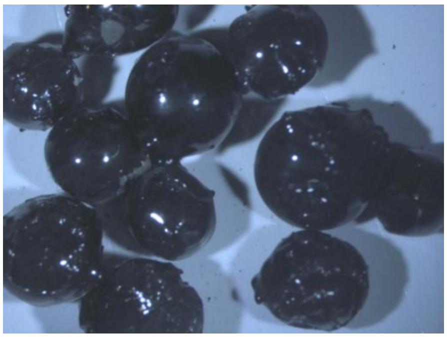
Na osnovu kvalitativnih mineraloških analiza utvrđen je sledeći mineralni sastav šljake: čvrsti sulfidni rastop (Cu-Fe), halkozin, pirit, bakar, halkopirit, bornit, magnetit i minerali jalovine. Minerali jalovine predstavljeni su staklom sa pojavom različitih eutektičkih dendrita (fajalit i dr.) koji nisu posebno određivani.

Strukturne karakteristike uzoraka možemo podeliti na :

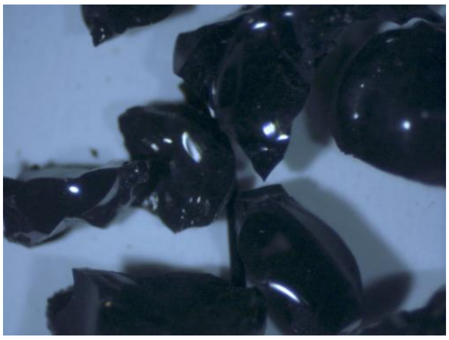
1. Prosti sraslac, predstavlja ispitivani mineral koji je jednostavno srastao sa jednim mineralom ili samo jalovinom - dvojni sraslaci.
2. Složeni sraslac, predstavlja ispitivani mineral koji je srastao sa više minerala i jalovinom višebrojni sraslaci.

Makroskopski opis granulisane šljake:

Granulisana šljaka je različite krupnoće sa vidljivim većim komadima. U uzorku granulisane šljake mogu se zapaziti sferični oblici različite veličine, glatkih površina, slika 1., kao i veliki broj veoma oštrih staklastih čestica šljake, slika 2. Uzorak je tamnosive do crne boje.



Sl. 1. *Sferična zrna u granulisanoj šljaci, binokular, uvećanje 6,5 x*



Sl. 2. *Zrna granulisane šljake (oštrih ivica), binokular, uvećanje 2,0 x*

Mikroskopski opis

Mikroskopskim ispitivanjem utvrđeno je da je granulisana šljaka pretežno izgrađena od fajalita i ferita koji grade osnovu u koju su retko uprskane sitne čestice magnetita, pirita, halkopirita, halkozina, bornita, bakrenca i elementarnog (samorodnog) bakra, slika 3.

Fajalit (silikati gvožđa) su zastupljeni u vidu pritkastih kristalića, što ukazuje na proizvod topljenja rude – šljaka. Feriti (razni oksidi gvožđa), takođe ukazuju na proizvod topljenja rude. Zastupljeni su u vidu skeletnih kristala (dendrita), slika 9.

Magnetit se javlja pretežno samostalan, u formi kocke i radialno zrakastih agregata. Ređe se javlja u nepravilnim oblicima, slika 7 i 8.

Od svih sulfidnih minerala pirit je najzastupljeniji i javlja se u vidu hipidiomorfnih zrna, uglavnom samostalan (slobodna zrna).

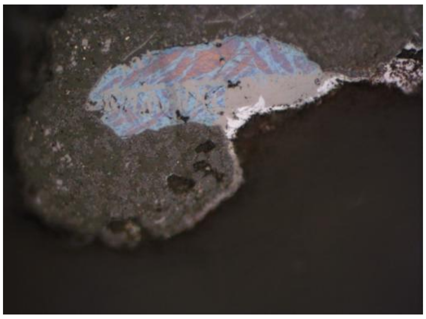
Od minerala bakra javljaju se halkopirit, halkozin i bornit, slika 6.

Halkopirit se javlja u nepravilnim, relativno sitnim, poljima, retko srastao sa halkozinom, dok su pojedina zrna prožeta halkozinom.

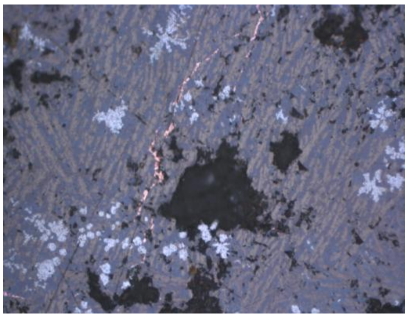
Halkozin se ređe javlja u sitnim zrnima slobodan ili je srastao za halkopirit i jalovinu.

Elementarni (samorodni) bakar se javlja u vidu sitnih sferičnih oblika kao i sitnih žilica, slike 4, 5 i 10.

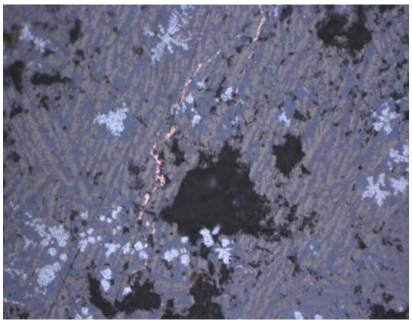
Mikrofotografije šljake



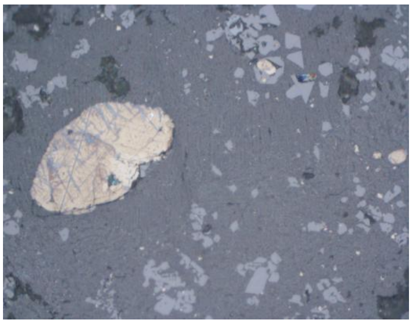
Sl. 3. *Bakrenac, bornit i halkopirit, uvećanje 500 x II N*



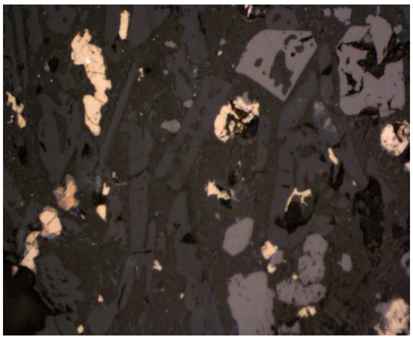
Sl. 4. *Žilice elementarnog bakra u fajalitskoj osnovi, uvećanje 500 x II N*



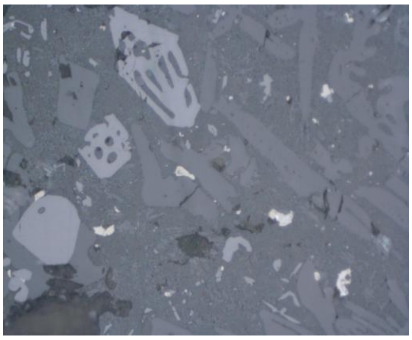
Sl. 5. *Žilice elementarnog bakra u bakrencu, uvećanje 500 x II N*



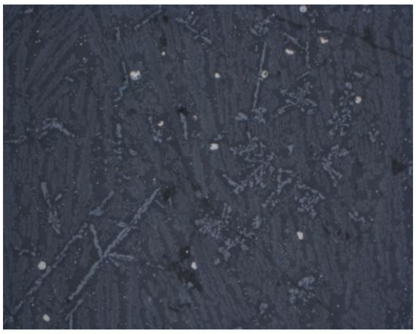
Sl. 6. *Zrno halkopirita u fajalitskoj osnovi, prožeto halkozinom, uvećanje 500 x II N*



Sl. 7. *Magnetit u formi kocke, halkopirit, uvećanje 500 x II N*



Sl. 8. *Magnetit u različitim formama, uvećanje 500 x II N*



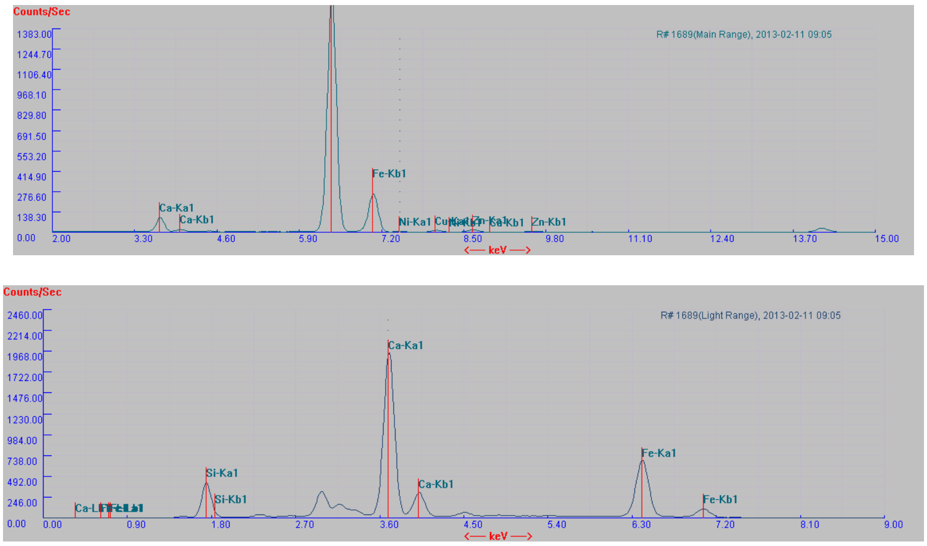
Sl. 9. *Dendriti fajalita, uvećanje 500 x II N*

Sl. 10. *Žilice elementarnog bakra, uvećanje 500 x II N*

Hemijska analiza uzoraka granulisane šljake urađena je na aparatu NITON XL-L3t-900 iz koje se može konstatovati da je gvožđe najzastupljenije 25,791%. To ukazuje na veliki sadržaj minerala gvožđa, koji nakon termičkog tretmana oksidacijom prelaze u Fe_2O_3 i Fe_3O_4. Sadržaj bakra je 0,156%. Dobijeni rezultati su prikazani na u tabeli 2 i na slici 11.

Tabela 2. *Hemijska analiza dobijena snimanjem na rengenu NITON XL-3t-90*

Jedinjenja - hemijski elementi	Cu	S	Fe	Si	Ca	Al	Zn
Sadržaj, %	0,156	1,117	25,791	21,639	11,082	2,588	0,121



Sl. 11. *Hemijska analiza dobijena snimanjem na rengenu NITON XL-3t-90*

ZAKLJUČAK

Granulisana šljaka iz procesa pirometalurškog topljenja bakra je u obliku sferičnih zrna i zrna oštrih ivica. Šljaka sadrži uglavnom oksidne vrste i nekoliko sulfidnih vrsta minerala. Glavna komponenta je fajalitska osnova u koju je prožet bakar, halkopirit, magnetit i bakrenac. Bakar se nalazi u obliku bakrenca i elementarnog bakra u obliku žilica u fajalitskoj osnovi. Magnetit se nalazi u formi kocke i drugim različitim formama.

LITERATURA

[1] Morales A., Cruells M., Roca A., Bergo R., Treatment of Copper Flash Smelter Dusts for Copper and Zinc Extraction and Arsenic Stabilization, Hydrometallurgy 105(2010), p. 148-154.

[2] Mitrović Z., i dr., Glavni rudarski projekat otkopavanja šljake iz tehnogenog ležišta „Depo Šljake 1", verifikacija tehnološkog procesa dobijanja koncentrata i nadvišenje flotacijskog jalovišta „RTH" u Boru do K +378 za godišnju proizvodnju od 1.200.000 t šljake; Institut za bakar Bor, 2006.

[3] http://rtb.rs/rtb-bor-doo/rudnik-bakra-bor/flotacija-bor/

[4] Magdalinović S., Milanović D., Čađenović B., Marjanović V., Tehnološki postupak granuliranja šljake radi sniženja krupnoće na ulazu u flotaciju, Rudarski radovi 3(2011), str. 101-110

[5] Čađenović B., Marjanović V., Ljubojev V., Milanović D., Mogućnost iskorišćenja bakrenca iz topioničke šljake kod njenog direktnog izlivanja iz peći, R. Radovi, 2(2012), str. 137-142.

[6] Ljubojev V., Petrović J., Krstić S., Mineralogical characteristics of smelting slag in the technogenic deposit "Depo 1" (Bor, Serbia). The Geology in digital Age: Proceedings of the Meeting of the Association of European Geological Societies (MAEGS 17), Belgrade (2011), p. 237-240.

[7] Ljubojev V., Izveštaj o mikroskopskom ispitivanju granulirane šljake, IRM Bor, Maj, 2013.

[8] Čadjenović B. Drobnjaković B., Milanović D., Magdalinović S., Novo laboratorijsko postrojenje za granuliranje izmenjenim tehnološkim postupkom izlivanja topioničke šljake, R. radovi 4(2011) str. 93-98

[9] Požega E., Gomidželović L., Topionice bakra sa plamenom i ISASMELT peći, Bakar 2(2010), str. 25-32.

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CONVERSION OF FLOTATION PROCESSING USING THE HEAP LEACHING METHOD IN THE MINE CEMENTACIJA – KRAKU BUGARESKU IN THE COPPER MINE BOR***

Abstract

RTB Bor is planning to expand the capacity of mining and processing at the Cementacija Kraku Bugaresku site from the current 2.5 million tons per year to 5.5 million. The current processing technology - the classic flotation of the entire excavated ore, without the separation of oxide and sulfide ores, due to the low copper recovery from oxide ore, has achieved the modest financial results. This article discusses an alternative method of copper obtaining using the hydrometallurgical heap leaching and SX / EW extraction method from leach solutions, in terms of economics, i.e. comparative analysis of cash flow and discounted cash flow for both cases (scenarios). The analysis is performed in a software for strategic planning and design in mining - Whittle Fx , with the input techno-economic data for both cases [7].

Due to the frequent breakdowns and causing the accidental situations on the current infrastructure installations of the processing plants, pipeline for pulp-hydro transport from the site to the flotation plant, in conclusion, to emphasize the comparative advantages of hydrometallurgical processing are emphasized in the conclusion not only in terms of the economy but also the environmental protection. In the world, the world's largest copper producers have a tendency to make, besides copper is necessary and valuable metal, also the "green" metal.

***Keywords**: heap leaching, hydrometallurgy, oxide ore, sulfide ore, long-term dynamics of production, cash flow, discounted cash flow*

1 INTRODUCTION

The deposit Cementacija Kraku Bugaresku has begun the exploitation in 1990 by the investment works in stripping the deposit at the site Cementacija 1. The name of the ore body and complex of ore bodies consisting of Cementacija 1, 2, 3 and 4 talks about the nature of theses ore bodies. It is a cementation zone of secondary enrichment with about 40% of oxide ore, mostly at levels near the surface, which is relatively poor to the flotation process. Flotation copper recovery from the ore has shown in the previous work a slightly higher level than 50%. Combining the processing methods - flotation of sulfide ore with maximum 10% of oxide (considered not have a negative effect on the recovery coefficient in the flotation) will achieve a significantly better economic effects [1], but the problem is in the possibility of selective excavation and separation of the aforementioned types of ore - sulphide and oxide.

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2 DESCRIPTION OF THE PROBLEM

The major problem is in fact that the flotation processing on the deposit is only to the level of pulp obtaining, i.e. grinding and then concentration, and then thepulp is transported by hydrotransport for further processing in the Flotation Plant Veliki Krivelj. In addition to the increased costs of flotation process, this processing method is also very unfavorable from the aspect of environmental protection due to the frequent accidents on the pipeline and consequences for the environment. (The last one happened in mid-April 2014).

As with the opening of mine, the manner and type of processing were influenced by a lobby for "environmental protection" The decision on the processing method was so made without the expert analyses, not taking into account the nature of the deposit (content over 40% of oxide ore). According to the leaching method, not only due to its potential impact on the environment, but without a detailed knowledge of these matters, an animosity was created even to mention the acid, or cyanide, which are, by their nature, toxic. During the current exploitation a part of deposit, it was proved that the adopted and applied method does not give good economic effects, but also is a major polluter of the environment.

One example of the total conversion of pyrometallurgical process - flotation method of concentration and classical smelting of concentrate with electrolytic anode dissociation, hydrometallurgical process, i.e. heap leaching in combination with the "in situ" leaching assisted by bacterial leaching was applied to the mine Morenci of the Phelps Dodge company, Arizona [7] in early 2001. The existing facilities for concentration were put into a "stand by" condition while the smelter was previously relocated to a place Chino, Mexico.

In addition to this example, where the daily processing is about 75,000 tons of ore (about 360,000 tons of copper a year), the examples of total conversion of pyrometallurgical process are are in Cerro Verde, (1993 - 15,000 t/d), Zaldivar (1992 - 20,000 t/d) in Peru, and Kuebrada Blanca (1,993 to 17,300 t/d) in Chile, and many other mines.

The benefits are multiple, the significant energy savings through reducing the total cost of production per tone of copper, whose purity is 99.99%, to the "clear sky" or environmental protection. It is also a way that the activities of copper exploitation and production leave behind them waste as less as possible.

3 COMPARATIVE ANALYSIS OF THE ECONOMIC EFFICIENCY OF CLASSICAL METHOD AND LEACHING METHOD WITH SX/EW EXTRACTION MODE

The analysis was carried out based on the literature techno-economic data for the "heap leaching" method and hydrometallurgical extraction process SX/EW, but bearing in mind the specificity of the cementation deposit Kraku Bugaresku both from the aspect of ore mineralogy in the deposit and the possibility of using this method, and from the aspect of a comparative cost data in relation to the classical processing method for which the relevant (known) data were used.

The following Table presents the techno-economic data with which the analysis was carried out in software for strategic planning in mining, Whittle Fx, whose working principle is based on the Lerch Grosmmann algorithm.

Table 1 *Input techno-economic parameters of exploitation for the optimization process*

Parameter	Unit	Values
Excavation capacity - excavations	t/year	12 Mt from 3rd year 17 Mt
Capacity of flotation processing – Sulfide ore with max. 10% oxide	t/year	2.5 Mt from 3rd year 5.5 Mt
Capacity of heap leaching – Oxide ore with over 10% of oxide content	t/year	2.5 Mt
Copper price	$/t cathode	5,000.00
Gold price	$/kg	40,000.00
Silver price	$/kg	500.00
Excavation costs	$/t	2,3.
Costs of flotation processing	$/t	4,00
Processing costs of heap leaching	$/t ore	1.00
Costs of metallurgical copper treatment	$/t cathode	450.00
Costs of metallurgical gold treatment	$/kg	150.00
Costs of metallurgical silver treatment	$/kg	15.00
Costs of hydrometallurgical processing (SXEW)	$/t cathode	100.0
Initial capital costs of leaching and SXEW	$	20,000,000
Total copper recovery (flot,and metallurgy)	%	0.788
Total gold recovery (flot,and metallurgy)	%	0.50
Silver recovery (flot,and metallurgy)	%	0.40
Copper recovery from oxide ore with over 10% of oxide content	%	0.54
Copper recovery by leaching from sulfide ore		0.55
Discount rate	%	10.0

3.1 Scenario 1

The obtained results by Scenario 1, or the current processing process, i.e. total ore undergoes to the flotation, without selective excavation and separation on two types of ore - sulphide and oxide. For this purpose, a block model was modified and the aforementioned types of ore were separated, as well as rock types only theoretical due to the demands in the software, but essentially the whole ore undergoes to the flotation process (mill). Table below shows the long-term dynamics of excavation with the economic indicators - cash flow, undiscounted and discounted. The analysis was done for the whole process of ore processing, both flotation and metallurgical, with the revenue of cathode copper and precious metals.

Table 2 *Long-term dynamics of excavation by Scenario 1, analyzed in the software Whittle Fx*

					SCENARIO 1_ SHEDULE GRAPPH										
	PB: 19, 26,3														
Period	tonne input	Waste tonne	Strip ratio	tonne input RSUL	Units input RSUL CU x 100	Grade input CUS	tonne input ROXD	Units input ROXD CU x100	Grade input CUOX	Grade input CU	Grade input PRCU	Grade input AU	Grade input AG	Open pit cashflow $	Open pit cashflow $ disc
1	2,497,779	9,502,221	3.8	601,834	241,726	0.2449	1,895,945	462,625	0.0413	0.282	15.4797	0.0753	1.1065	-9,847,862	-8,952,602
2	2,499,693	9,500,307	3.8	917,321	451,536	0.3076	1,582,372	426,201	0.0484	0.3511	15.7806	0.0802	1.0753	-3,387,689	-2,799,743
3	5,495,999	11,504,001	2.09	1,769,556	816,733	0.2808	3,726,443	952,774	0.0458	0.322	16.0559	0.0718	1.0124	6,867,290	5,159,496
4	5,499,999	6,315,358	1.15	1,462,051	427,596	0.2038	4,037,947	887,950	0.0393	0.2392	16.1273	0.0693	1.1278	3,452,064	2,357,806
5	5,500,000	3,586,533	0.65	1,785,345	533,392	0.2303	3,714,655	929,696	0.0397	0.266	14.6026	0.0791	1.1537	15,477,799	9,610,495
6	5,500,000	2,599,697	0.47	2,570,586	823,796	0.2542	2,929,414	753,057	0.0361	0.2867	13.4667	0.0727	1.0313	20,814,587	11,749,292
7	5,500,000	1,403,682	0.26	3,146,090	1,044,249	0.2634	2,353,910	553,530	0.0301	0.2905	11.1239	0.0848	1.0792	28,194,533	14,468,253
8	5,499,999	1,557,531	0.28	4,021,808	1,109,667	0.2397	1,478,191	300,803	0.0186	0.2564	7.6091	0.0862	1.0487	23,064,615	10,759,813
9	5,500,000	1,263,215	0.23	5,082,426	1,282,422	0.2367	417,573	85,504	0.0133	0.2487	5.3879	0.0827	1.031	21,474,074	9,107,104
10	5,500,000	605,505	0.11	4,879,546	1,326,078	0.252	620,454	125,263	0.0133	0.2639	5.2266	0.0996	1.2105	27,995,708	10,793,557
11	5,500,000	271,792	0.05	5,017,944	1,395,811	0.2582	482,056	88,229	0.0129	0.2698	5.0344	0.0848	1.3015	28,542,461	10,003,959
12	2,969,102	34,036	0.01	2,916,661	803,531	0.2654	52,440	12,601	0.0105	0.2749	3.7942	0.0994	1.3529	17,194,580	5,724,357
	57,462,571	48,143,878		34,171,168			23,291,400							179,842,160	77,981,787

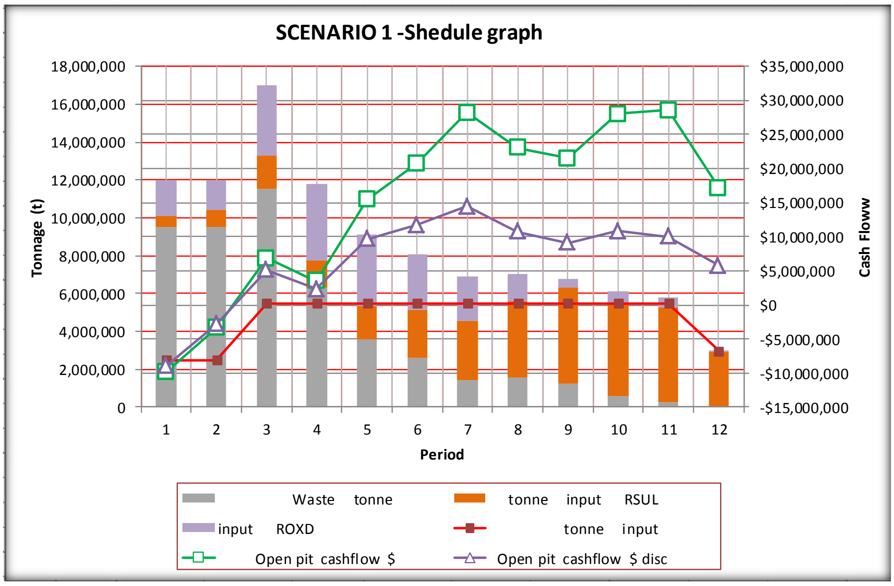

Figure 1 *Graphical presentation of the long-term dynamics of excavation by Scenario 1 – flotation processing*

3.2 Scenario 2

According to the second Scenario, due to the above given facts and plans of RTB Bor Group – Copper Mine Bor, which owns the concerned mine, to increase the capacity of excavation at this site for the flotation processing to 5,500,000 t, is the use of leaching method for processing of these amounts [7]. The oxide ore with oxide content of up to 10% during leaching was considered with the recovery coefficient of 0.7, while leaching of sulphide ore was discussed with the recovery coefficient of 0.55 (Table 1.).

The input costs have also included the rehandling costs from the stock pile (0.2 $/t ore), and also the estimated investment costs of $ 20,000,000 for the construction of infrastructure facilities and installations for hydrometallurgical processing method at the start of production (in the first year).

Table 3 *Long-term dynamics of excavation by Scenario 2, analyzed in the software Whittle Fx*

	Push backs: 19, 26,36						Long Term Shedule -Method Heap Leachig									
							RSUL tonne				ROXD tonne				cashflow	
Period	tonne input	Waste tonne	Strip ratio	Grade input CU	Grade input AU	Grade input AG	From mine input LCH1 RSUL	to stockpile SP1 - Rsulf	From stockpile to LCH1-RSUL	TOTAL RSULF LCH1	From mine input LCH2 ROXD	to stockpile SP2-Roxd	From stockpile to LCH2-ROXD	TOTAL ROKSD LCH1	Open pit cashflow $	Open pit cashflow $ disc
year	tonne	tonne	ratio	%	g/t	g/t	t	t	t	TOTAL t	t	t	t	TOTAL t	$	$
1	7,637,874	9,362,127	1.23	0.1274	0.0329	0.6228	23,404	736,892	0	23,404	3,000,000	3,877,578	0	3,000,000	-26,688,274	-24,262,067
2	6,729,443	10,270,557	1.53	0.2579	0.06	0.9707	839,606	747,903	736,892	1,576,498	3,000,000	2,141,934	0	3,000,000	-3,444,904	-2,847,028
3	14,115,539	6,884,461	0.49	0.3268	0.0801	1.0017	4,755,686	2,835,617	744,314	5,500,000	5,500,000	1,024,236	0	5,500,000	53,796,117	40,417,819
4	13,206,031	7,793,969	0.59	0.2378	0.071	1.0775	4,389,920	859,446	1,110,080	5,500,000	5,500,000	2,456,665	0	5,500,000	20,641,477	14,098,406
5	18,683,273	2,316,727	0.12	0.2285	0.0724	0.9961	4,102,604	7,296,895	1,397,396	5,500,000	5,500,000	1,783,774	0	5,500,000	19,923,823	12,371,126
6	15,363,156	5,636,844	0.37	0.19	0.0647	1.0937	2,494,353	2,731,602	3,005,647	5,500,000	5,500,000	4,637,201	0	5,500,000	9,514,108	5,370,466
7	9,816,632	49,502	0.01	0.1982	0.0603	0.8397	5,500,000	3,365,802	0	5,500,000	695,769	255,061	4,804,231	5,500,000	25,672,382	13,173,991
8	0	0	#DIV/0!	0	0	0	0	0	5,500,000	5,500,000	0	0	5,500,000	5,500,000	55,174,611	25,739,363
9	0	0	#DIV/0!	0	0	0	0	0	5,500,000	5,500,000	0	0	5,500,000	5,500,000	55,174,611	23,399,421
10	0	0	#DIV/0!	0	0	0	0	0	579,829	579,829	0	0	372,218	372,218	4,575,773	1,921,174
	85,551,948	42,314,187	0.49				22,105,573	18,574,157	18,574,158	40,679,731	28,695,769	16,176,449	16,176,449	44,872,218	214,339,724	109,382,671

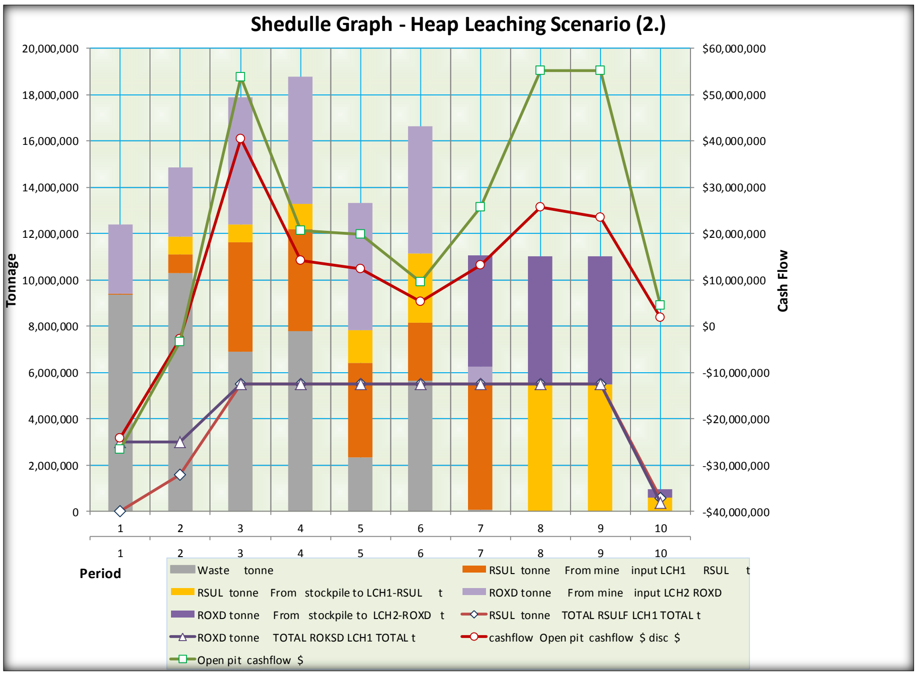

Figure 2 *Graphical presentation of the long-term dynamics and cash flows per years by Scenario 2 – total conversion of flotation process by the leaching method*

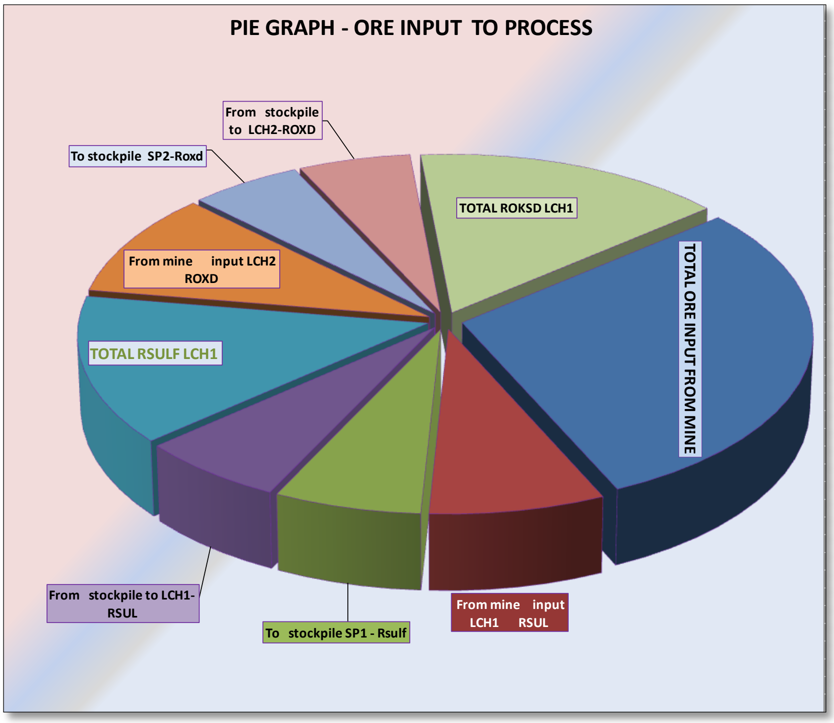

Figure 3 *Pie graph of sulphide and oxide ore participation in the leaching process*

The obtained results by Scenario 2 are with the use of storage technology (stock pile), which serve as a buffer for the planned processing capacity, but also have the option of conducting the leaching time and shortening the period of total exploitation of the planned long-term dynamics. It is important to note that in recent years, when practically the excavation at the open pit was completed, the leaching time and leaching capacity can be adapted to the needs. Therefore, whether the ore from the stock pile will be processed for the time provided for the long-term plan or shorter, depending on the input of particle size distribution of ore, or from the surface of openness of mineral grains and thereby the leaching rate.

4 CONCLUSION

It can be seen from the following Figure 3, Tables and Graphs of the comparative analysis results by Scenation 1 or Scenatio 2, as well as from Tables 2 and 3 and Graphs 1 and 2 that:

1. Calculated Cash flow by the second scenario is higher than by the first (by which any capital costs are not included for the capacity expansion);
2. That the exploitation period at the open pit (mining period) by the second scenario is almost half shorter than the first. The extended years of the second scenario is the processing of already excavated ore from the stock pile. It certainly brings savings that can be seen from the comparison with the economy by scenario 1;

3. As it was noted in the previous section, the amount of excavated ore could be processed in a shorter time than it was presented in a long term scheduling increasing the time of leaching, i.e. with conducting the size of input ore to the leaching heaps or with selection the degree of crushing fragmentation;

Discounted cash flow in scenario 2 is higher, and among other things, as the leaching operation includes the overall mineralization within the open pit limits, without the use of cutoff grade as a boundary factor of ore and waste materials. Thus, the new processing process produces not only more high purity copper for human use, but also removes the uneconomic waste material from the environment.

Period	SCENARIO1		SCENARIO 2	
	Undiscounted Open pit cashflow	Disconted Open pit cashflow	Undiscounted Open pit cashflow	Disconted Open pit cashflow
Years	$	$ disc	$	$ disc
1	-9,847,862	-8,952,602	-32,606,782	-29,642,530
2	-3,387,689	-2,799,743	-10,813,488	-8,936,767
3	6,867,290	5,159,496	25,224,785	18,951,754
4	3,452,064	2,357,806	10,821,471	7,391,211
5	15,477,799	9,610,495	2,643,834	1,641,613
6	20,814,587	11,749,292	-931,255	-525,669
7	28,194,533	14,468,253	26,226,231	13,458,203
8	23,064,615	10,759,813	44,544,958	20,780,552
9	21,474,074	9,107,104	44,544,958	18,891,411
10	27,995,708	10,793,557	44,544,958	17,174,010
11	28,542,461	10,003,959	44,544,958	15,612,736
12	17,194,580	5,724,357	44,544,958	14,193,396
13	0	0	42,905,512	12,428,199
14	0	0	18,521,234	4,877,220
15	0	0	18,521,234	4,433,836
16	0	0	5,280,764	1,230,282
SUMM	179,842,160	77,981,787	328,518,330	111,959,457

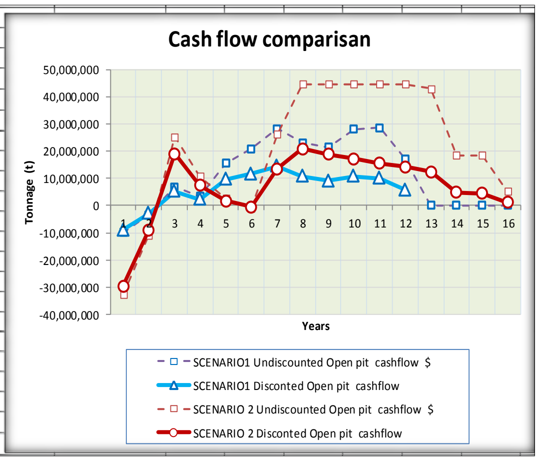

Figure 4 *Comparative analysis of cash flow Graphics for a wide variety of scenarios, processing and extraction of metals from ore per years*

4. Heap leaching process, which is in the case here, has much higher level of security in terms of environmental protection than the flotation process;
5. Hydro-metallurgical method of copper extraction as opposed to the conventional pyro-metallurgical method eliminates SO_2 and other harmful impurities from the air in the area of the town of Bor, where the Smelting plant is located and its environment. In the considered case the recommendation is the SX/EW process instead of the current classic pyrometallurgy process. The SX/EW plant requires much less capital investments.
6. Due to these facts and previous experience with accidental situations to the environmental protection, it is necessary to make an effort in the education of staff, as well as to introduce population with the bad and good aspects of this method for metal obtaining, also with a reduced risk of accidents.

REFERENCES

[1] Z. Vaduvesković, N. Vušović, D. Kržanović: Analysis the Possibilities for Improvement the Economic Indicators for Exploitation the Deposit Cementacija Kraku Bugaresku – Ore Field Cerovo, Mining and Metallurgy Engineering, Bor, 1(2014), 13-24. http://www.irmbor.co.rs

[2] William H. Dreshe: How Hydrometallurgy and the SX/EW Process Made Copper the "Green" Metal, Copper Applications in Mining & Metallurgy http://www.copper.org/publications/newsletters,innovations, A copper Alliance member.

[3] J. Peacey, GUO Xian-Jian, E. Robles: Copper Hydrometallurgy-Current Status, Preliminary Economics, Future Direction and Positioning Versus Smelting, Hatch Associates Ltd., 2800 Speakman Drive, Mississauga, Ontario L5K 2R7,Canada; Hatch Ingenierosy Consultores Ltd., San Sebastian 283, Piso 9, Los Condes, Santiago 6760226, Chile.
http://www. d.wanfangdata.com.cn

[4] J. F. Lupo: Design and Operation of Heap Leach Pads by, Ph.D.Golder Asociates. The Jornal of the Soutern Institute of Mining and Metallurgy, Decembar, 2012, Vol. 112.
www.ausimm.com.au/co
.

[5] Carlos Avendaño Varas: Review on Heap Leaching of Copper Ores, LX Users Conferencea Chile, La Serena, Junio 2004. Chemical Engenieer, Sociedad Terral S.A.

[6] R. Denis, M. Marcotte:1,7 Million Square Meters PVC Heap Leach Pad Case History, Solmax International Inc., Varennes, Qc., Canada, Genivar, Montreal, Draft paper submitted for publication GeoAfrica 2009.

[7] Phelps Dodge Morenci Has Converted All Copper Production to Mine-for-Leach, Copper Applications in Mining & MetallurgyBy William H. Dresher, Ph.D.,.E.P.E.
http://www.copper.org/publications/newsletters,innovations.

[8] Whittle Strategic Mine Planning, Gemcom Whittle™ Copyright © 2012 Gemcom Software International Inc.

[9] G. Hovanec, Review the Basic Economic Aspects of Copper Production by the Process of Acid Leaching, Research Associate for mineral processing materials in the Mining Institute, Belgrade.

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KONVERZIJA FLOTACIJSKE PRERADE POSTUPKOM LUŽENJA NA GOMILI NA RUDNIKU CEMENTACIJA – KRAKU BUGARESKU U RUDNIKU BAKRA BOR[***]

Izvod

RTB Bor planira proširenje kapaciteta otkopavanja i prerade na ležištu Cementacija Kraku Bugaresku sa sadašnjih 2,5 miliona tona godišnje, na 5,5 miliona. Postojećom tehnologijom prerade, klasičnim flotiranjem celokupne otkopane rude, bez selektivnog otkopavanja i razdvanja sulfidne od oksidne, zbog niskog iskorišćenja metala iz rude, postižu se skromni finansijski efekti. Rad razmatra ***kompletnu*** *konverziju sadašnjeg načina eksploatacije, hidrometalurškim dobijanjem bakra luženjem na gomili i SX/EW metodom ekstrakcije iz lužnog rastvora, sa aspekta ekonomije, uporednom analizom novčanog i diskontovanog novčanog toka za oba slučaja (scenarija - sadašnji način flotiranjem i alternativni - luženjem). Analiza je urađena u softveru za strateško planiranje u rudarstvu-Whittle Fx, sa ulaznim tehnoekonomskim podacima za jedan i drugi slučaj [7].*

Zbog učestalih havarija i izazivanja akcedentnih situacija na postojećim infrastrukturnim instalacijama postrojenja prerade, cevovodu za hidrotransport pulpe, u zaključku se ističu i komparativne prednosti hidrometalurške prerade ne samo sa aspekta ekonomije nego i zaštite životne sredine. U svetu, kod najvećih svetskih proizvođača bakra, tendencija je da se bakar učini pored skupocenog i "zelenim" metalom.

Ključne reči*: luženje na gomili, hidrometalurgija, oksidna ruda, sulfidna ruda, dugoročna dinamika proizvodnje, novčani tok, diskontovani novčani tok*

1. UVOD

Ležište Cementacija Kraku Bugaresku je započelo sa eksploatacijom 1990. godine, investicionim radovima na raskrivanju ležištu, na lokaciji Cementacija 1. Sam naziv rudnog tela i kompleksa rudnih tela koji se sastoji od Cementacije 1, 2, 3 i 4, govori o prirodi ovih rudnih tela. Radi se o cementacionoj zoni sekundarnog obogaćenja, sa oko 40% oksidne rude, najviše na nivoima bližim površini, koja se relativno slabo flotira. Flotacijsko iskorišćenje bakra iz rude je, pokazalo se u dosadašnjem radu, nivoa nešto većeg od 50%. Kombinacijom metoda prerade - flotiranjem sulfidne rude sa maksimalno 10% oksidne (smatra se da se pri tome ne utiče negativno na koeficijent iskorišćenja u flotaciji) postigli bi se znatno bolji ekonomski efekti [1], međutim problem je u mogućnostima selektivnog otkopavanja i izdvajanju pomenutih tipova rude – sulfidne i oksidne.

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2. OPIS PROBLEMATIKE

Veliki problem je i što je na samom ležištu flotacijska prerada samo do nivoa dobijanja *pulpe*, tj. mlevenja i nakon toga zgušnjavanja, a zatim se hidrotransportom pulpa transportuje na dalju preradu u flotaciju Veliki Krivelj. Osim povećanih troškova flotiranja, ovakav način prerade je vrlo nepovoljan i sa aspekta zaštite životne sredine zbog čestih akcidenata na cevovodu i posledica po okolinu. (Poslednji takav desio se polovinom aprila 2014. godine).

Kao i prilikom otvaranja rudnika, na način i vrstu prerade veliki uticaj je imao lobi za "zaštitu životne sredine" Odluka o metodi prerade je tako donešena bez stručnih analiza, ne vodeći računa o prirodi ležišta (sadržaj preko 40% oksidne rude). Prema metodi luženja, ne samo zbog njenog eventualnog uticaja na životnu sredinu, ali bez detaljnog poznavanja ove problematike, stvoren je animozitet čak zbog same pomene kiseline, odnosno cijanida koji su, po svojoj prirodi, otrovni. Tokom dosadašnje eksploatacije dela ležišta, pokazalo se da usvojena i primenjena metoda ne samo da ne daje dobre ekonomske efekte, nego je i veliki zagađivač okoline.

Jedan od primera totalne konverzije pirometalurškog procesa – flotacijske metode koncentracije i klasičnog topljenja koncentrata sa elektrolitičkom disocijacijom anode, hidrometalurškim procesom tj. luženjem na gomili u kombinaciji sa "*in situ"* luženjem potpomognutim bakterijskim luženjem, primenjen je na rudniku, *Morenci* kompanije *Phelps Dodge*, Arizona [7], početkom 2001. godine. Postojeći objekti za koncentraciju su stavljeni u stanje "*stand by*", dok je topionica prethodno izmeštena u mesto Chino, u Meksiku.

Osim ovog primera, gde se dnevno prerađuje o ko 75.000 t rude (oko 360.000 t bakra godišnje), primeri totalne konverzije pirometalurškog procesa su još u Cerro Verde (1993 - 15.000 t/d), Zaldivar (1992 - ~ 20.000 t/d) u Peru-u, i Kuebrada Blanka (1993 - 17.300 t/d) u Čileu, i mnogi drugi rudnici.

Koristi su višestruke, od značajne uštede energije, preko smanjenja ukupnih troškova proizvodnje po toni bakra, čija je čistoća 99,99%, do "*čistog neba*" odnosno zaštite životne sredine. To je takođe način da aktivnosti eksploatacije i dobijanja bakra, iza sebe ostavljaju što manje otpada.

3. UPOREDNA ANALIZA EKONOMSKE EFIKASNOSTI KLASIČNE METODE I METODE LUŽENJA SA SX/EW NAČINOM EKSTRAKCIJE

Analiza je sprovedena na bazi literaturnih tehnoekonomskih podataka za metodu "Heap Leaching" i hidrometalurški proces ekstrakcije SX/EW, ali imajući u vidu specifičnosti ležišta cementacija Kraku Bugaresku, kako sa aspekta mineralogije rude u ležištu i mogućnosti primene ove metode, tako i sa aspekta uporednih troškovnih podataka u odnosu na klasičan način prerade, za koji su korišćeni relevantni (poznati) podaci.

U sledećoj tabeli prikazani su tehnoekonomski podaci sa kojima je analiza urađena u softveru za strateško planiranje u rudarstvu, Whittle Fx, čiji je princip rada na osnovu Lerch Grosmmann algoritma.

Tabela 1. *Ulazni tehnoekonomski parametri eksploatacije za proces optimizacije (in put)*

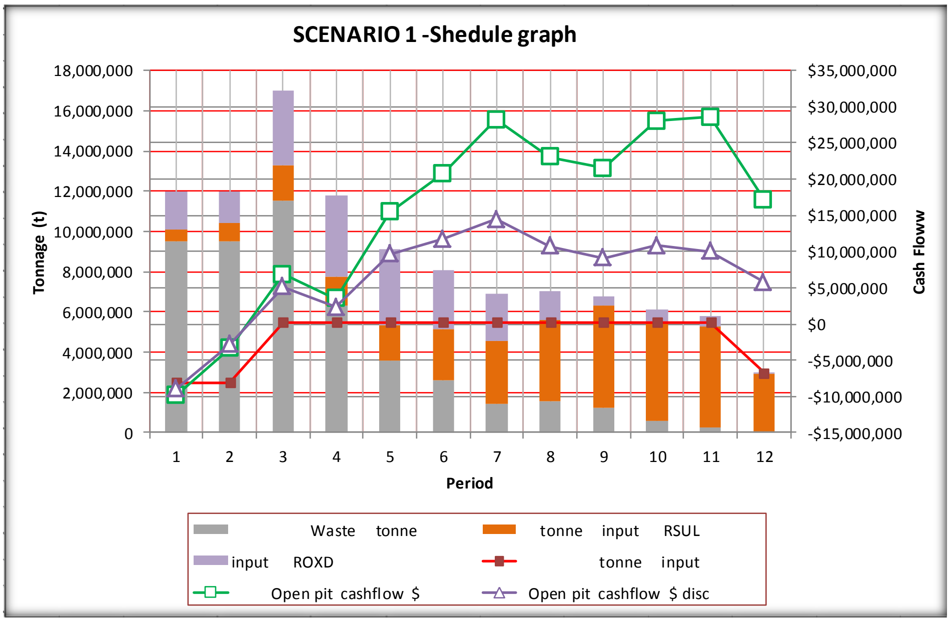
Parametar	Jedinica	Vrednosti
Kapacitet otkopavanja - iskopine	t/god	12 Mt od 3. godine 17 Mt
Kapacitet flotacijske prerade - Sulfidna ruda sa max. 10% oksidne	t/god	2,5 Mt od 3. godine 5,5 Mt
Kapacitet luženja na gomili – Oksidna ruda sa preko 10% sadržajem oksida	t/god	2.5 Mt
Cena bakra	$/tkatode	5,000.00
Cena zlata	$/kg	40,000.00
Cena srebra	$/kg	500.00
Troškovi otkopavanja	$/t	2,3.
Troškovi flotacijske prerade	$/t	4,00
Troškovi prerade luženjem na gomili	$/t rude	1.00
Troškovi metalurške prerade bakra	$/t katode	450.00
Troškovi metalurške prerade zlata	$/kg	150.00
Troškovi metalurške prerade srebra	$/kg	15.00
Troškovi hidrometalurške prerade (SXEW)	$/t katode	100.0
Inicijalni kapitalni troškovi luženja i SXEW	$	20,000,000
Ukupno iskorišćenje bakra (flot i metal)	%	0,788
Ukupno iskorišćenje zlata (flot i metal)	%	0,50
Iskorišćenje srebra (flot i metal)	%	0,40
Iskorišćenje bakra iz oksidne rude sa preko 10% sadržajem oksida	%	0,54
Iskorišćenje bakra luženjem iz sulfidnih ruda		0,55
Diskontna stopa	%	10.0

3.1. Scenario 1

Dobijeni rezultati po scenariju 1, odnosno postupkom kojim se sada vrši prerada, a to je da ukupna ruda ide na flotiranje, bez selektivnog otkopavanja i razdvajanja na dva tipa rude – sulfidnu i oksidnu. Za ove potrebe je modifikovan blok model i izvršeno razdvajanje pomenutih vrsta rude, kao tipova stena (Rock Types), samo teoretski zbog zahteva u softveru, ali suštinski celokupna ruda ide na process flotiranja (MILL). U narednoj tabeli je prikazana dugoročna dinamika otkopavanja sa ekonomskim pokazateljima - novčanim tokom, nediskontovanim i diskontovanim. Analiza je urađena za ceo process prerade rude, kako flotacijskog, tako i metalurškog, sa prihodom od katodnog bakra i plemenitih metala.

Tabela 2. *Dugoročna dinamika otkopavanja po scenariju 1, anlizirana u softveru Whittle Fx*

					SCENARIO 1_ SHEDULE GRAPPH										
	PB: 19, 26,3														
Period	tonne input	Waste tonne	Strip ratio	tonne input RSUL	Units input RSUL CU	Grade input CUS	tonne input ROXD	Units input ROXD CU	Grade input CUOX	Grade input CU	Grade input PRCU	Grade input AU	Grade input AG	Open pit cashflow $	Open pit cashflow $ disc
					x 100			x100							
1	2,497,779	9,502,221	3.8	601,834	241,726	0.2449	1,895,945	462,625	0.0413	0.282	15.4797	0.0753	1.1065	-9,847,862	-8,952,602
2	2,499,693	9,500,307	3.8	917,321	451,536	0.3076	1,582,372	426,201	0.0484	0.3511	15.7806	0.0802	1.0753	-3,387,689	-2,799,743
3	5,495,999	11,504,001	2.09	1,769,556	816,733	0.2808	3,726,443	952,774	0.0458	0.322	16.0559	0.0718	1.0124	6,867,290	5,159,496
4	5,499,999	6,315,358	1.15	1,462,051	427,596	0.2038	4,037,947	887,950	0.0393	0.2392	16.1273	0.0693	1.1278	3,452,064	2,357,806
5	5,500,000	3,586,533	0.65	1,785,345	533,392	0.2303	3,714,655	929,696	0.0397	0.266	14.6026	0.0791	1.1537	15,477,799	9,610,495
6	5,500,000	2,599,697	0.47	2,570,586	823,796	0.2542	2,929,414	753,057	0.0361	0.2867	13.4667	0.0727	1.0313	20,814,587	11,749,292
7	5,500,000	1,403,682	0.26	3,146,090	1,044,249	0.2634	2,353,910	553,530	0.0301	0.2905	11.1239	0.0848	1.0792	28,194,533	14,468,253
8	5,499,999	1,557,531	0.28	4,021,808	1,109,667	0.2397	1,478,191	300,803	0.0186	0.2564	7.6091	0.0862	1.0487	23,064,615	10,759,813
9	5,500,000	1,263,215	0.23	5,082,426	1,282,422	0.2367	417,573	85,504	0.0133	0.2487	5.3879	0.0827	1.031	21,474,074	9,107,104
10	5,500,000	605,505	0.11	4,879,546	1,326,078	0.252	620,454	125,263	0.0133	0.2639	5.2266	0.0996	1.2105	27,995,708	10,793,557
11	5,500,000	271,792	0.05	5,017,944	1,395,811	0.2582	482,056	88,229	0.0129	0.2698	5.0344	0.0848	1.3015	28,542,461	10,003,959
12	2,969,102	34,036	0.01	2,916,661	803,531	0.2654	52,440	12,601	0.0105	0.2749	3.7942	0.0994	1.3529	17,194,580	5,724,357
	57,462,571	48,143,878		34,171,168			23,291,400							179,842,160	77,981,787



Sl. 1. *Grafički prikaz dugoročne dinamike otkopavanja po Scenariju 1 – flotacijka prerada*

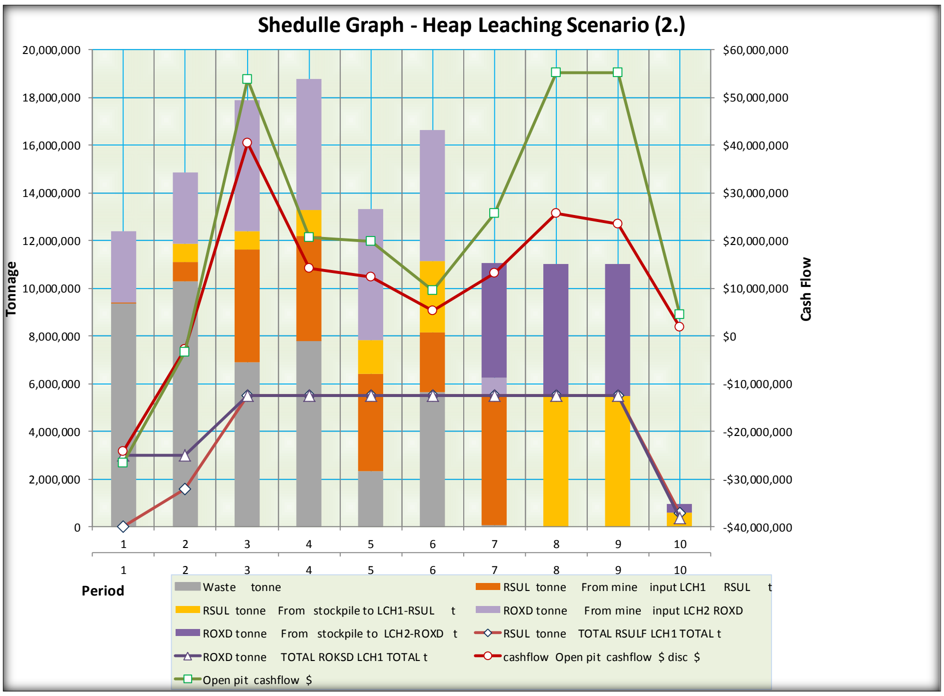
3.2. Scenario 2

Prema drugom scenariju, zbog navedenih činjenica i planova RTB Bor Grupe – Rudnika Bakra Bor u čijem je vlasništvu predmetni rudnik, o povećanju kapaciteta otkopavanja na ovom lokalitetu za flotacijsku preradu na 5.500.000 t, jeste da se te količine prerade luženjem [7]. Oksidna ruda sa sadržajem oksida do 10% prilikom luženja razmatrana je sa jednim koeficijentom iskorišćenja (0,7), dok je luženje sulfidne rude razmatrano sa koeficijentom iskorišćenja od 0,55 (Tabela 1.).

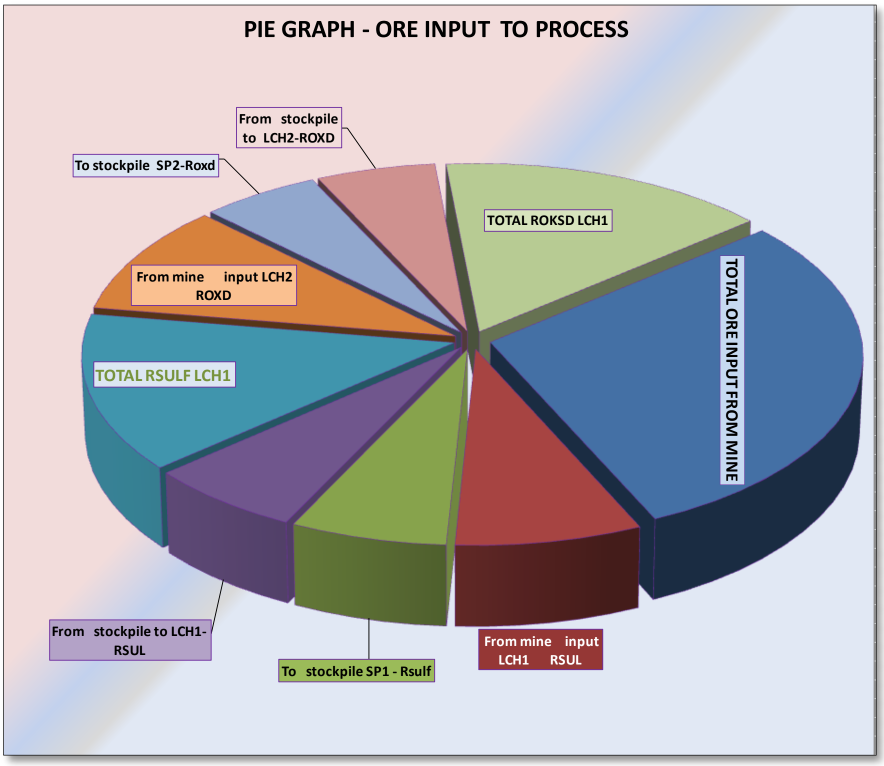
U ulazne troškove uračunati su i *re-handling* troškovi sa skladišta (0,2 $/t rude), a uzeti su u obzir i procenjeni investicioni troškovi od 20.000.000 $ za izgradnju infrastrukturnih objekata i instalacija za hidrometaluršku metodu prerade, i to na samom startu proizvodnje (u prvoj godini).

Tabela 3. *Dugoročna dinamika otkopavanja po scenariju 2, anlizirana u softveru Whittle Fx*

	Push backs: 19, 26,36						Long Term Shedule -Method Heap Leachig									
							RSUL tonne				ROXD tonne				cashflow	
				Grade	Grade	Grade	From mine	to	From	TOTAL	From mine	to	From	TOTAL	Open pit	Open pit
	tonne	Waste	Strip	input	input	input	input LCH1	stockpile	stockpile to	RSULF	input LCH2	stockpile	stockpile to	ROKSD	cashflow	cashflow
Period	input	tonne	ratio	CU	AU	AG	RSUL	SP1 - Rsulf	LCH1-RSUL	LCH1	ROXD	SP2-Roxd	LCH2-ROXD	LCH1	$	$ disc
year	tonne	tonne	ratio	%	g/t	g/t	t	t	t	TOTAL t	t	t	t	TOTAL t	$	$
1	7,637,874	9,362,127	1.23	0.1274	0.0329	0.6228	23,404	736,892	0	23,404	3,000,000	3,877,578	0	3,000,000	-26,688,274	-24,262,067
2	6,729,443	10,270,557	1.53	0.2579	0.06	0.9707	839,606	747,903	736,892	1,576,498	3,000,000	2,141,934	0	3,000,000	-3,444,904	-2,847,028
3	14,115,539	6,884,461	0.49	0.3268	0.0801	1.0017	4,755,686	2,835,617	744,314	5,500,000	5,500,000	1,024,236	0	5,500,000	53,796,117	40,417,819
4	13,206,031	7,793,969	0.59	0.2378	0.071	1.0775	4,389,920	859,446	1,110,080	5,500,000	5,500,000	2,456,665	0	5,500,000	20,641,477	14,098,406
5	18,683,273	2,316,727	0.12	0.2285	0.0724	0.9961	4,102,604	7,296,895	1,397,396	5,500,000	5,500,000	1,783,774	0	5,500,000	19,923,823	12,371,126
6	15,363,156	5,636,844	0.37	0.19	0.0647	1.0937	2,494,353	2,731,602	3,005,647	5,500,000	5,500,000	4,637,201	0	5,500,000	9,514,108	5,370,466
7	9,816,632	49,502	0.01	0.1982	0.0603	0.8397	5,500,000	3,365,802	0	5,500,000	695,769	255,061	4,804,231	5,500,000	25,672,382	13,173,991
8	0	0	#DIV/0!	0	0	0	0	0	5,500,000	5,500,000	0	0	5,500,000	5,500,000	55,174,611	25,739,363
9	0	0	#DIV/0!	0	0	0	0	0	5,500,000	5,500,000	0	0	5,500,000	5,500,000	55,174,611	23,399,421
10	0	0	#DIV/0!	0	0	0	0	0	579,829	579,829	0	0	372,218	372,218	4,575,773	1,921,174
	85,551,948	42,314,187	0.49				22,105,573	18,574,157	18,574,158	40,679,731	28,695,769	16,176,449	16,176,449	44,872,218	214,339,724	109,382,671



Sl. 2. *Grafik dugoročne dinamike i novčanih tokova po godinama po Scenariju 2. - totalna konverzija flotiranja metodom luženja*



Sl. 3. *Pie grafik učešća sulfidne i oksidne rude rude u procesu luženja*

Dobijeni rezultati po Scenariju 2 su sa tehnologijom korišćenja skladišta (Stock pile), koji služe kao bafer za planirani kapacitet prerade, ali stoji i mogućnost dirigovanja vremenom luženja i skraćenjem perioda ukupne eksploatacije predviđenog dugoročnom dinamikom. Bitno je napomenuti i da se u poslednjim godinama, kada je praktično otkopavanje na kopu završeno može vreme luženja, time i kapacitet luženja prilagoditi potrebama. Dakle, da li će se ruda sa skladišta prerađivati za vreme predviđeno dugoročnim planom ili kraće, zavisi od ulaznog granulometrijskog sastava rude, odnosno od površine otvorenosti mineralnih zrna i time brzine izluživanja.

ZAKLJUČAK

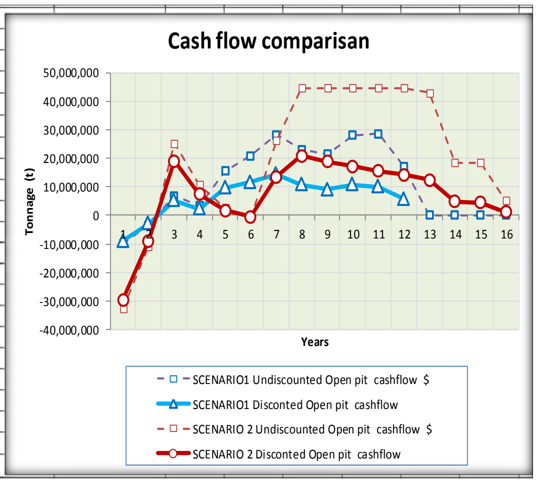
Na sledećoj slici 4 – *Tabela i dijagram uporednih rezultata analize po jednom i drugom scenariju*, kao i iz Tabela 2 i 3, odnosno grafika 1 i 2, vidi se:

1. Sračunati Cash flow po drugom scenariju je veći nego po prvom (po kome nisu uračunati nikakvi investicioni troškovi za povećanje kapaciteta);
2. Da je vek eksploatacije na kopu (otkopavanja) po drugom scenariju upola kraći nego po prvom. Preostalih godina po drugom scenariju je prerada sa već otkopanom rudom – rudom sa skladišta. To svakako donosi uštede koje se vide iz upoređenja sa ekonomijom po scenariju 1.

3. Kao sto je u prethodnom poglavlju napomenuto, otkopana ruda se može preraditi i ukraćem vremenu nego što je predstavljeno u dugoročnoj dinamici, smanjujući potrebno vreme izluživanja po osnovu veličine ulazne granulacije rudena gomile za luženje, odnosno izborom stepena drobljenja;

Diskontovani novčani tok po scenariju 2. je veći pored ostalog, izbog toga što se procesom luženja zahvata celokupna mineralizacija u granicama kopa, bez korišćenja graničnog sadržaja kao faktora razgraničenja rude i jalovine. Dakle, novi proces prerade stvara ne samo više bakra visoke čistoće za ljudsku upotrebu, već takođe uklanja neekonomični otpad iz životne sredine.

Period	SCENARIO1		SCENARIO 2	
	Undiscounted Open pit cashflow	Disconted Open pit cashflow	Undiscounted Open pit cashflow	Disconted Open pit cashflow
Years	$	$ disc	$	$ disc
1	-9,847,862	-8,952,602	-32,606,782	-29,642,530
2	-3,387,689	-2,799,743	-10,813,488	-8,936,767
3	6,867,290	5,159,496	25,224,785	18,951,754
4	3,452,064	2,357,806	10,821,471	7,391,211
5	15,477,799	9,610,495	2,643,834	1,641,613
6	20,814,587	11,749,292	-931,255	-525,669
7	28,194,533	14,468,253	26,226,231	13,458,203
8	23,064,615	10,759,813	44,544,958	20,780,552
9	21,474,074	9,107,104	44,544,958	18,891,411
10	27,995,708	10,793,557	44,544,958	17,174,010
11	28,542,461	10,003,959	44,544,958	15,612,736
12	17,194,580	5,724,357	44,544,958	14,193,396
13	0	0	42,905,512	12,428,199
14	0	0	18,521,234	4,877,220
15	0	0	18,521,234	4,433,836
16	0	0	5,280,764	1,230,282
SUMM	179,842,160	77,981,787	328,518,330	111,959,457



Sl. 4. *Grafik uporedne analize novčanih tokova za različite scenarije prerade i ekstrakcije metala iz rude, po godinama*

4. Proces luženja na gomili, o kome se ovde radi, je sa mnogo većim stepenom sigurnosti sa aspekta zaštite životne sredine nego što je process flotiranaja;
5. Prerada ove rude za razliku od klasične prerade topljenjem, eliminiše SO_2 i druge štetne primese iz vazduha na području topionice, odnosno grada Bora i okoline. Ovde se umesto klasičnog pirometaluršog procesa, primenjuje SX/EW process. Postrojenje zahteva mnogo i manja kapitalna ulaganja.
6. Zbog navedenih činjenica, i dosadašnjih iskustava saakcedentnim situacijamapo zaštitu životne sredine, potrebno je uložiti napor kako u edukaciju kadrova, tako i u upoznavanje stanovništva sa lošim i dobrim stranama ovakve metode dobijanja metala, takođe sa smanjenim rizikom od akcidenata.

LITERATURA

[1] Z. Vaduvesković, N. Vušović, D. Kržanović: Analiza mogućnosti poboljšanja ekonomskih pokazatelja eksploatacije ležišta Cementacija Kraku Bugaresku–rudno polje Cerovo, Mining and Metallurgy Engineering Bor, 1/2014, str. 25-36, http://www.irmbor.co.rs

[2] William H. Dresher: How Hydrometallurgy and the SX/EW Process Made Copper the "Green" Metal, Copper Applications in Mining & Metallurgy http://www.copper.org/publications/newsletters, innovations, A copper Alliance member

[3] J. Peacey, GUO Xian-Jian, E. Robles: Copper hydrometallurgy-currentstatus, preliminary economics, future direction and positioning versus smelting,. Hatch Associates Ltd., 2800 Speakman Drive, Mississauaga, Ontario L5K 2R7, Canada; 2Hatch Ingenierosy Consultores Ltda., San Sebastian 283, Piso 9, Los Condes, Santiago 6760226, Chile.
http://www. d.wanfangdata.com.cn

[4] J. F. Lupo: Design and Operation of Heap Leach Pads, By Ph.D. Golder Asociates. The Jornal of The Soutern Institute of Mining and Metallurgy, Decembar, 2012. Vol. 112.

[5] Carlos Avendaño Varas: Review on heap leaching of copper ores, LX Users Conferencea Chile, La Serena, Junio 2004., Sociedad Terral S.A

[6] R. Denis, M. Marcotte: 1,7 Million Square Meters PVC Heap Leach Pad Case History, Solmax International Inc., Varennes, Qc., Canada, Genivar, Montreal, Qc., Canada, Draft paper submitted for publication GeoAfrica 2009;

[7] William H. Dresher: Phelps Dodge Morenci Has Converted All Copper Production to Mine-for-Leach, Copper Applications in Mining & Metallurgy, http://www.copper.org/publications/newsletters,innovations

[8] Whittle Strategic Mine Planning, Gemcom Whittle™ Copyright © 2012 Gemcom Software International Inc.

[9] G. Hovanec: Osvrt na osnovne ekonomske aspekte proizvodnje bakra primenom postupka kiselinskog luženja, Rudarski institut Beograd.

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FORECAST THE BEHAVIOUR OF ROCK MASS BEFORE TAKING UP THE EXCAVATION AT DEEPER LAYERS OF THE ORE BODY BORSKA REKA[****]

Abstract

This paper presents one possible approach for resolving some important issues related to the stability of underground rock structures at higher depths. The analysis is focused on forecast the behavior of rock mass before performing the mining excavation at deeper levels of the ore body "Borska Reka".

Regardless of extensive previous research of the ore body "Borska reka" and necessary parameters obtained for modeling of stress and strain that occur under the influence of mining excavation, additionally the estimation state of stress in the rock massif is also done. The stability analysis is shown for the roadway at the level XVII and forecast their stability for deeper level. As the result, it is expected that the level of uncertainty and risk associated with many identified geomechanical risks with management of rock massif will be reduced.

Keywords: *forecast, behaviour of rock mass, roadway stability, ore body Borska reka*

INTRODUCTION

The mining works and roadways construction in deep mines causes instability which may occur as the result of roof falls, wall failures or combination of both. Thus, in order to safety come first when performing the mining operations, the stability of such roadways is very important. The prime concern in excavations is the control of displacements in the rock surrounding the excavation. In each excavation, the design objective is to ensure that displacements of the rock do not interfere with the specified engineering activities.

Computer modeling for strata control in rock mechanics has significantly developed in recent years. There are various numerical methods and codes available for stability analysis of underground openings. Despite the significant advances that have been made, it must be recognized that the successful application of numerical methods in rock engineering design analyses depends to a

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[****] *This work is the result of the Project 33021 "Investigation and Monitoring the Changes of Stress-strain State in the Rock Mass "In-situ" around the Underground Rooms with Development a Model with Special Reference on the Tunel of the Krivelj River and Jama Bor", funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.*

great extent on geomechanical models and boundary conditions developed from the site characterization data. Duew to a difficulty in defining some of the input data, the deterministically, probabilistic or stochastic methods are often used to represent mechanical properties of rocks and rock masses, and in the analyses themselves.

Underground mine design requires an iterative process which is often approached in different ways. Initially, the possible mining methods are selected, likely production capacities determined and indicative cut-offs derived. Preferred mining methods are selected followed by more refined ore definition. The primary infrastructure options are then established and the analysis taken through to the global extraction sequencing. Much evaluation has to be done before design commences.

When the primary infrastructures - roadways have to be designed, one of the first questions often put to the rock mechanic & mining engineers is "What is the maximum stable opening?" However, it is often too early and there is rarely anything like enough data available on which to base an informed decision.

Serious consideration of geomechanics problems, associated with deep and high stress mining, began before the advent of modern high-speed digital computers and numerical modelling methods.

In this computer era, a wide range of computer software has been used in numerical analyses of the rock mass behavior. They include the range of displacement discontinuity and related programs, as well as **FEM**[*] ***(Phase2)***, BEM[†], FDM[‡] and DEM[§] codes. [1]

Despite the availability of computer techniques and software and applicable engineering procedures, the geomechanical analysis is even more of an art than real modelling of rock mass.

Obviously, it will never be possible to do enough geomechanical exploration to enable geomechanics risks of this wide range of types to be fully accounted in the planning stages of mining project. However, as the project proceeds through the various stages from concept to detailed design and implementation, the level of uncertainty and risk associated with many sources of geomechanics risk identified previously can be expected to be reduced.

Applicability of standard strength criteria

Most of numerical analyses, currently used for evaluation the stability of underground excavations, are based on the linear Mohr–Coulomb strength criterion. However, the experimental data and experience of the field engineering showed that the strength of nearly all types of rock mass is followed by the non-linear Hoek–Brown strength criterion.The Hoek–Brown strength criterion for rock mass is widely accepted and applied in a large number of engineering in the world.

The classic Mohr-Coulomb strength criterion consisting of two independent cohesive and frictional components does not provide a realistic representation of progressive fracture and breakdown of rock under stress. The Hoek-Brown criterion is widely applied to jointed rock masses, but may also be applied to intact rock. In fact, much more data

[*] *Finite Element (**FEM**) and related methods (Beck et al., 2009, 2010; Goodman et al., 1968; Wittke, 1977, 1990; Zienkiewicz, 1977)*

[†] *Boundary Element Methods (**BEM**) (Beer and Watson, 1992; Brady, 1979, 1987; Crouch and Starfield, 1983)*

[‡] *Finite Difference Methods (**FDM**) (Hart et al., 2008; Itasca, 2011; Sainsbury et al., 2011)*

[§] *Discrete Element Methods (**DEM**) (Jing and Stephansson, 2007)* for intact rock than for rock masses were used in its original development by Hoek and Brown (1980) and later. [2]

CASE STUDY OF ORE DEPOSIT "BORSKA REKA"

For purposes of this paper, this analysis will be mainly focused on forecast the behaviour of rock mass in particular case of ore deposit (body) "Borska Reka" in the underground mine "Jama" in Bor.

This deposit has a length of about 1,000 m and a thickness about 500 m, dipping to the west at an angle of 45° to 55°, according with dipping of Bor conglomerates and sandstones, and it is separated by the Bor fault from hydrothermal zone. Exploration works on the ore body "Borska Reka" deposit have been carring out in the period from 1976 until these days with a large volume of research works. Detailed exploration works were carried out to the level -155 m and it is assumed that the deposit is dipping to elevate at the lavel of -800 m and even deeper. Part of the deposit above the XIX level K-235, is opened by the transport system for the ore bodies "Tilva Roš" and "P2A".

Mining operations are carried out on the basis of mining project for exploitation of copper ore above the XIX level (K-235). After many years of determination the mineral reserves in the ore body "Borska Reka", additional explorations and prepared documentations, this ore body is still waiting for exploitation. There are plans to increase the mine production using mining excavation methods with preserving the surface and all constructed facilities, infrastructures and mining works above the ore deposit "Borska Reka", starting with excavation from the level XIX. The deeper layers will be considered for exploitation in the further steps.

This is certainly a serious challenge in managing the rock massif and geomechanical risks. Therefore, the results of this analysis, on one hand, referred to the need for forecasts the behavior of rock mass before taking up the excavation at deeper layer, and on the other hand, the excavation of deeper layer of the ore body "Borska Reka" requests to carry out all necessary geomechanical testings in order to obtain reliable information as a basis for decision-making.

PREVIOUS EXPLORATIONS AND MODELING OF STRESS-STRAIN STATE

Previous explorations

In order to determine the geomechanical characteristics of working environment, the current technical documentations of geological, geotechnical and hydrogeological investigations and design analysis were reviewed concerning the ore body "Borska Reka" in the underground mine "Jama" Bor. Based on this, it can be generally concluded that much was done and a lot of work and effort and money were invested.

Here, some of the years will only be mentioned when the subject explorations were carried out starting from 1997, 1999, 2007 and 2014 by the Mining and Metallurgy Institute Bor. [3]

So far, according to the carried out analyses within the latest explorations, it was found out that the data show partially lower values of physical and mechanical properties of rock in relation to the previous explorations, Table 1.

Table 1 *Physical-mechanical parameters obtained by laboratory tests on samples of rock mass from the ore body "Borska reka"*

Geotechnical environment	γ [kN/m^3]	σ_c [MPa]	σ_i [MPa]	E_t [MPa]	E_s [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
Pelytes *2014	25.4	49	4.95	5600	3730	0.34	36.0	24	12.13	54	
Andesites *2014	25.9	52	5.37	6927	4633	0.31	36.8	26	12.90	66	
Kaolinizated Andesites *2014	27.0	25	3.04	5490	3672	0.37	30.4	20	7.53	34	
Silicified Andesites *2014	27.7	67	7.57	10790	7127	0.32	37.4	28	16.70	51	
(level XVII) K-155	γ [kN/m^3]	σc [MPa]	σi [MPa]	E [MPa]	Ed [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
Silicified Andesites *1999	28.2	63.39	6.71	40490	33255	0.216	41.6	15.09	18.9	73	65

Modeling of stress-strain state

Apart from the standard laboratory tests and "in situ" observations and measurements, the laboratory test procedures were carried out for testing the strength parameters and deformable characteristics of working environment using the triaxial compression. Triaxial experiment is aimed to simulate the conditions that may occur in the rocks surrounding the underground infrastructures – roadways and facilities and these openings could be exposed to the limit pressure and shearing stress. [4]

Based on the previous results of conducted laboratory tests on samples of rock massif and core from exploration drill holes, with taking into account the state of rock massif, degree of representativeness of samples, effect of samples size, mechanical strength, deformation characteristics and quality assessment of rock mass, the laboratory values are obtained for parameters of rock mass at the level XVII in the ore body "Borska Reka".[5]

The rock stability analysis was carried out on a standard cross-section of roadway which is designed and constructed in the underground mine "Jama" Bor (4x3.5m), with a scope of confirmation the relevance of data collected from previous explorations and studies mentioned above.

State of stress in the ore body "Borska Reka" is not measured previously, therefore this data was not available. Due to the lack of knowledge on the stress state of rock massif, the field of stress will be defined through the gravitational component - γH. Stress was measured in the nearest ore body "Tilva Ros" and given the proximity indicating on relations between the principal stresses (Fig. 1). The ratio is between 0.7 ± 0.05. This assessment could be also accepted for the ore body "Borska Reka" and XVII level (K -155). [6]

It should be noted that the stress measurements were made more than twenty years ago and only on the roadway contour. It can be assumed that the actual values are higher if the stress was measured deeper into the rock massif. That means the shortage of precise stress values for a specific level of depth in the ore body "Borska Reka" indicate the first problem in accuracy of executed certain calculations and conclusions.

Instead of qualitative rock mass stability analysis, the empirical analysis can be performed based on estimations and assumptions in order to meet the required range of values, but it may be wrong in that required range. [7]

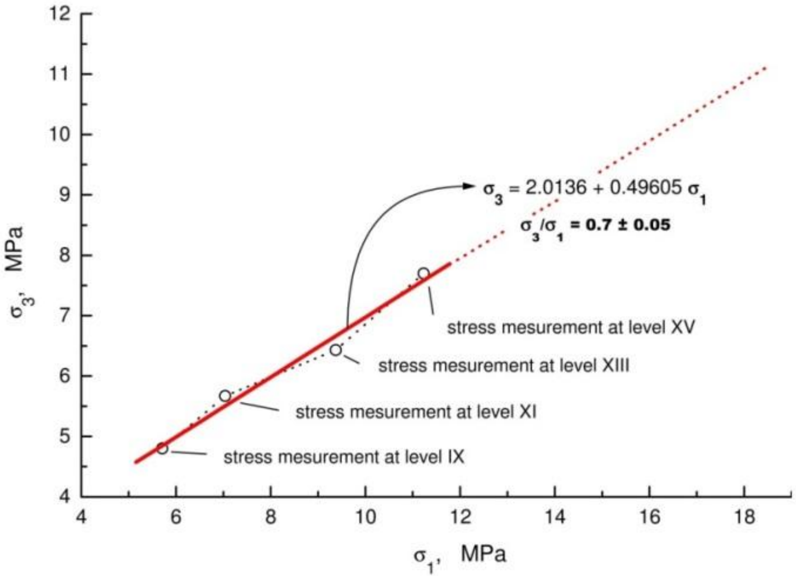


Figure 1 *Linear function of stress measured variations by depth of principal stresses for the ore body "Tilva Ros" in the underground mine "Jama" Bor*

Determined value of stresses taken from the (Fig. 1) for level XVII is for $\sigma_1 = \sigma_v$ = 14 MPa, and for σ_3 = 9.5 MPa.

Model design

Boundary conditions are defined so that the stress on model will be only under the influence of gravitational component, and the model external boundary is fixed so it cannot move in the X and Y axis direction.

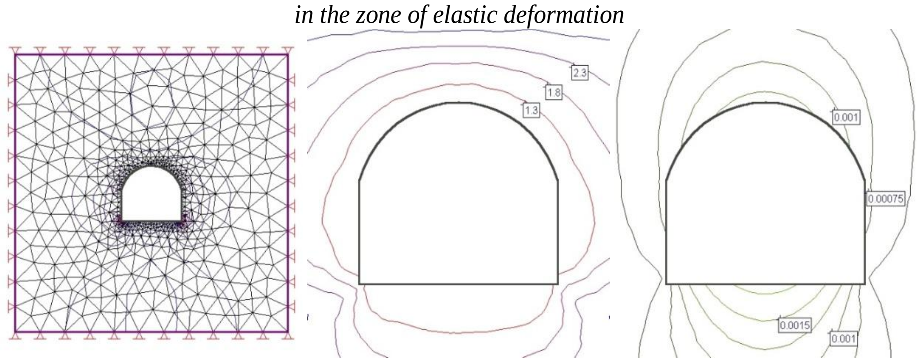
The required density of points (nodes) of which depends the number of finite elements density is determined by the model discretization. A density of 75 points (nodes) on contour profile was chosen in this case. This can show what extent the density of finite element affects the accuracy of results and the interpolation accuracy, i.e. drawing the contours of stress and strain. The finite element grid is composed of triangles and is shown in any figure of result interpretation.

Result interpretation and stability assesment

For designed roadway cross section modeling, the finite element mesh is generated with total of 1404 elements and 729 nodes. Data entry for each case only differs in direction of principal stresses. Interpretation of results and stability assessment is given for both defined cases. Calculation results are interpreted with contour lines of safety factor, total displacement and principal stress. Deformation grid is also presented, deformation on model contour lines with the direction of displacement (which is mag-nified 100 times) as well as the plasticity zone marked with markers. Markers in the form of crosses (x) mark fracture occur due to shear stress, and in the form of circles (o) mark fracture caused by tension stress. (Fig. 2).

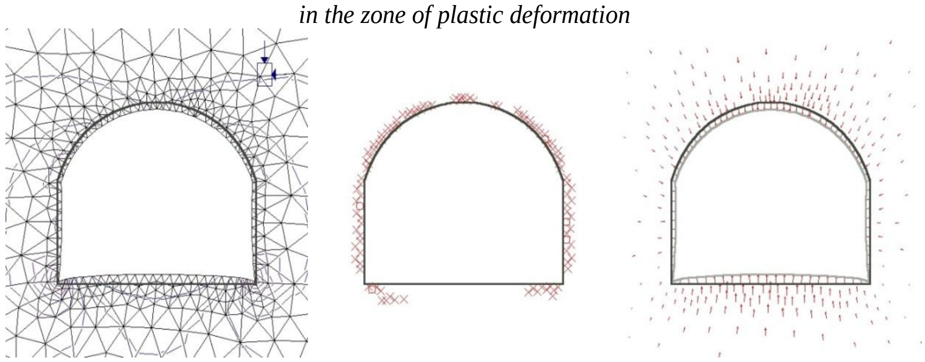
Designed - constructed object (roadway) on the level XVII - 4x3.5 m

in the zone of elastic deformation



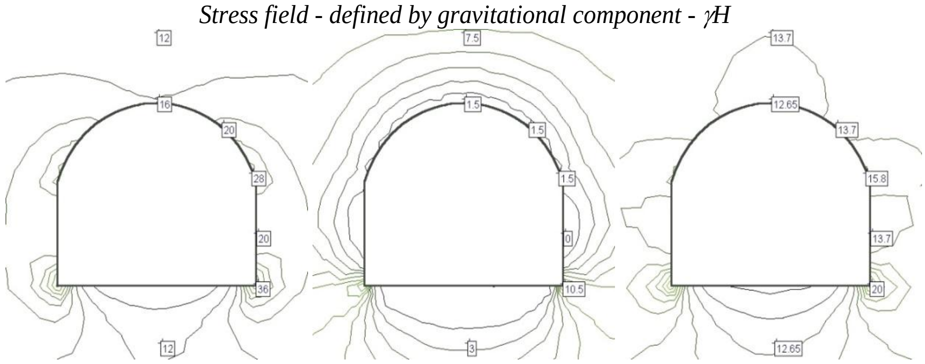
a) contour conditions b) safety factor - Fs c) total displacement - XY

in the zone of plastic deformation



d) grid deformation e) zone of plasticity f) contour deformation

Stress field - defined by gravitational component - γH



g) σ_1 h) σ_3 i) σ_v

Figure 2 *Stress-strain analyses in case the stress field under the influence of gravitational component -* $\boldsymbol{\gamma H}$

If the rock mass around given premises located in the zone of elastic deformation, so long that zone will be stable to the apportionment factors of safety as it is shown in Fig. 2b. Contour line of the safety factor of 1.3 meets the set criterion of stability. But it is seen that the sides of roadway that line is further from the contours and that consequently this area becomes susceptible to transition from the elastic zones into the zone of plastic deformation. The total displacement along the contour is 1.8 mm (Fig. 2c).

In the parts around the roadway cross-section with plastic deformation (Fig. 2e), the plastic zone due to shear stress (x) will occur in the roadway arch, and the complex plastic zone due to shear and tension stress (x and o) occurs on the sides of roadway.

It can be concluded that in this case the roadway is stable. However, the appearance of plastic deformation, which is manifested as a sporadic rock fragmentation in the form of flaking and falling down of small pieces, could be appropriately protected with the same roof support system to secure the site from future spread of damage. [8]

FORECAST THE BEHAVIOUR OF ROCK MASS

To take an advantage of modeling research which allows forecasting the behaviour of rock mass before taking up the excavation at deeper layers, the stability analysis of deeper levels of the level XVII will be used in this section.

Depth selection was taken at the level of XIX (K –235), XXI (K –315), XXIII (K –395) and XXV (K –475) and they represent a depth value of about 630 m, 710 m, 790 m and 870 m under surface.

Based on that, it can be said that the chosen levels for stability analyses, XVII and XIX level are included in the new mine design. It can be useful, because the newly constructed facilities at the levels, with the appropriate observations can be useful to demonstrate the validity of this stability analysis assessment. Other three levels are analyzed in order to predict what can be expected at deeper levels at a later stage and will be the subject of further elaboration. [9]

Interpretation of stability assessment results are done as well as stability analysis for level XVII and it might be easier to compare the results.

The values of the principal stress were obtained on the basis of the gravity component $\sigma_v = \gamma H$, and the ratio of principal stresses σ_1 and σ_3 obtained from the analytical equation from the graph in Figure 1.

Table 2 *Prognostic value of the principal streses for selected depth*

Level	Ground level	Depth m	γH MPa	σ_1 MPa	σ_3 MPa	σ_3/σ_1
XVII	-155	550	14	14	9.5	0.70±0.05
XIX	-235	630	17	17	10.5	0.65±0.05
XXI	-315	710	19.2	19.2	11.5	0.60±0.05
XXIII	-395	790	21.3	21.3	12.6	0.55±0.05
XXV	-475	870	23.5	23.5	13.5	0.55±0.05

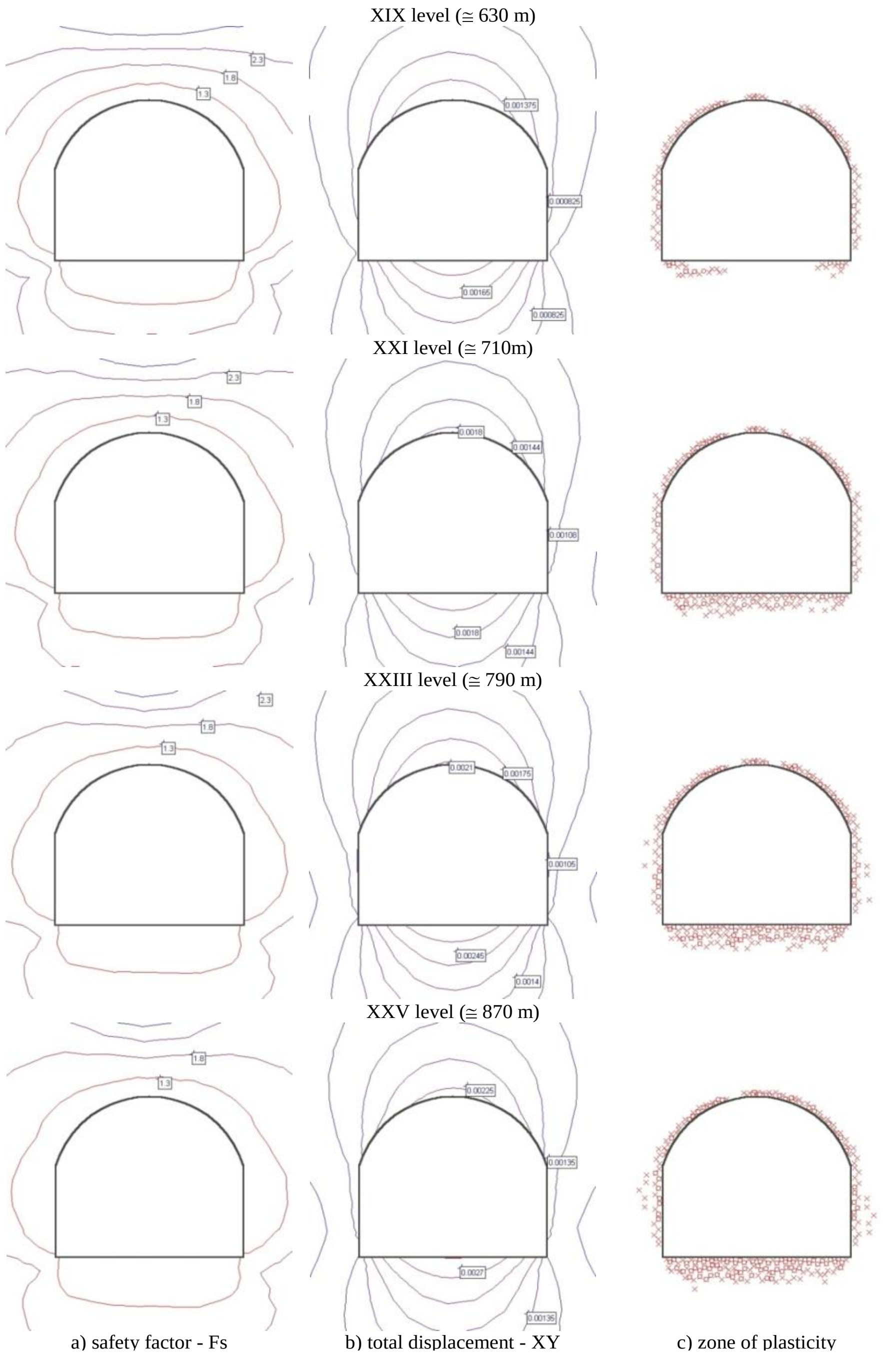


Figure 3 *Stress-strain analyses for deeper levels in case the stress field under the influence of gravitational component -* γH

Forecast the stability model at depth below the level XVII

The results of model analysis are made for the stress field determined by the gravitational component - γH. The finite element grid is used for modeling as in the previous analysis.

To define rock mass parameters for the analysis, the fracture criterion and parameters of the rock mass obtained from the parameters at the XVII level were used. It was necessary to simulate those depths for assessment the stability by increase the lateral sample using the triaxial tests, which determined the deformable characteristics of the rock mass at the level XVII. These tests were not carried out and deformable characteristics of the rock mass at the XVII level were used for these analyses.

The stress-strain analysis of rock mass at the levels XIX, XXI, XXII and XXV are shown in Figure 3.

Looking at the results of stability analysis by levels, it can be concluded that the stability of the rodway decreases linearly with increasing depth and it was expected.

Considering that maximum displacements on the model grow with the increase of depth as 2.1 mm, 2.4 mm, 2.76 mm and 3.2 mm, the rock fragmentation and rock deterioration can be expected for deeper levels than the level XXI.

The places with occurrence of plastic deformation, plastic zone on rodway will have such a character that on the roof appear the plastic zone (x), and on the sides appear plastic zone (x and o). This could be applies only for the level XIX while the deeper levels it should be expected plastic zones (x and o) all over the roadway. The size of the plastic zone influence is in the range of 18 cm, 21 cm, 28 cm and 35 cm. In the roof their value is 16 cm, 17 cm, 18 cm and 20 cm, while on the floor only the level XIX deployed in the corners and on the other levels is distributed all over the floor.

In this case of principal stress appointed, contour line of the safety factor on the side of roadway is increasingly moving away from the side. Base on that risk the stability increased due to the stress from the side of the roadway. [10]

It can be estimated that at the level XIX this roadway can stay unsupported, except on places with the plastic zone appearance and the support must be installed in these places. Forecast the stability for the same roadway at the levels XXI, XXIII and XXV indicates that it must have the adequate roof supports in some sections or on the entire length. As the result of increasing, the depth may notice a certain "calming" in plastic zone increasing around the cross-section. That requires redefining the boundary conditions on the model and estimated or measured new value of the principal stresses and their direction.

In the areas of plastic zone, the rock fragmentation is mainly induced by extensive deformation. Deformation starts immediately after excavation, and it is commonly stabilized with reaction of the installed support, reaching the equilibrium of forces, but it could be transformed into deterioration as the result of rheological behaviors of rock mass.

Rock deterioration in proximity of underground openings – roadways might occur for several reasons. The major cause is a stress concentration in immediate roof and floor rocks, as well as in sides. This concentration is generated by the initial equilibrium disturbance following the roadway development, resulting in concentration of vertical stress in sides of the roadway, while the horizontal stress is concentrated in the roof and floor. Deterioration would be manifested as a forming zone of deteriorated rock mass in the roadway roof. This is noted during previous research. In such zones, the rock is very fragmented, and the deterioration zone also continues to expand in the immediate roadway rock mass. [11]

Future research

The future research certainly should include measuring of the stress in the ore body “Borska reka” with determining the direction of principle stresses. In that case, the field of stress would be defined by the stress components σ_1, σ_3, σ_v and also taken into consideration possible influence of the Bor fault zone as well as inclination angle of the ore body "Borska reka". That could greatly change the picture of stability.

In opening every another level, the additional geomechanical investigations should be carried out. These investigations will determine the physical and mechanical parameters of the rock mass which would be used for further numerical analysis and calculations and compared with the previous laboratory tests results. Also, they would odemtofy the correlation between the physical-mechanical, structural properties and categorization of rock mass results as well as defining the behavior of rock mass by the Hoek-Brown's strength criterion. Based on this, it can carefully evaluate and determine the parameters relevant to characterize the behavior of rock mass and thereby used for further modeling of the rock mass and a new forecast for deeper levels.

CONCLUSION

This paper presents a case study forecast of behavior the rock mass for deeper levels in the ore body "Borska reka" where the field of stress is defined only by the influence of gravitational component and vertical stress direction. The principal stresses were defined by the linear function result from stress measurements in the ore body "Tilva Roš".

Based on laboratory tests on the previous results, which include the rock mass at the level XVII (K -155 m) in the ore body "Borska reka" and the accurate research and triaxial tests that were carried out on test samples taken from the rock mass, the results were analyzed by the Hoek-Brown methodology and are directly used as the input parameters for numerical modeling.

There was a limiting factor in defining values for stress, because the stress measurement for given location was not measured. Stress state is determined on the basis of the gravity component, and since the ratio of principal stresses hase been evaluated on the basis of stress measurement stress for the ore body "Tilva Roš" even 20 years ago and more.

The numerical model is based on the finite element method (FEM) and the software package PHASE^2 is used for this purpose. Analysis and interpretation of the results were carried and shown for designed and constructed roadway. The results are contained within in displacement vectors, principal stress distribution and plastic zone around the analyzed object.

Stability analysis was firstly done for the level XVII where the straingh criterion and necessary data for analyses are defined for the rock mass. Based on that, the analyses were carried out for deeper leyers in the second phase of forecast stability. The included levels are XIX (-235 K), XXI (-315 K), XXIII (-395 K) and XXV (K -475).

Results and forecast stability of the roadway at deeper layers with characteristics of the rock mass and assumed stress, showing that the stability decreases of the roadway on the analyzed model. Model applied in the analysis remains stable up to the level XIX, while at deeper levels have to be safe and secure with the roof support system or with fully support. This conclusion is based on the parameters at the level XVII which are according to the volume and estimated stress insufficient for qualitative forecasting stability, especially in the deeper levels. Due to these reasons, it is essential that for each new level the additional geomechanical investigations are needed. As the mining operations go deeper, the results of forecast for the same level would be verified or corrected with these new data, and also work out the forecast of behavior the rock mass for the next deeper level.

Certainly that one qualitative analysis such as stability analysis would be fully been worked out with no use of any estimated value as in this case for the stress value and its direction. To this end, the evaluation of stress in the ore body "Borska reka" as well as to define the parameters essential for understanding the behaviour of rock mass is necessary to complement the current geomechanical investigations with appropriate methods for stress measuring.

Synthesis of previous and proposed research would give more complex image of the ore body "Borska reka". Through appropriate models, from that aspect it would be possible to analyze all kinds of mining activities and performed work. Results of these analyzes could be more reliable applied in practice.

REFERENCES

[1] E. T. Brown, Progress and Challenges in Some Areas of Deep Mining, Deep Mining 2012, Australian Centre for Geomechanics, Perth, 2012;

[2] Boek, E., [2002]: A Brief History of the Development of the Hoek-Brown Failure Criterion.
(http://rocscience.ca/help/rocdata/webhelp/rocdata/Generalized_HoekBrown_Criterion.htm);

[3] D. Zlatanović. M. Ljubojev, L. Djurdjevac-Ignjatović, G. Stojanović: Modeling of Rock Massif in the Jama Bor with Special Focus on the Previous Explorations of the Ore Body »Borska Reka«; Journal Mining & Metallurgy Engineering 3/2014, Mining and Metallurgy Institute – Bor, pp. 17-32;

[4] V. Čebašek, N. Gojković: Rockmass Investigations for Determination of Failure Criterion, Journal Underground Mining Engineering 17, University of Belgrade - Faculty of Mining and Geology; (2010), pp. 35-47;

[5] D. Zlatanović, V. Čebašek, M. Ljubojev: Determining the Parameters of a Rock Mass Model in the Function of Fracture Criterion; The 46th International October Conference on Mining and Metallurgy 1-3 October 2014, Bor; pp. 529-532; Serbia;

[6] D. Zlatanović, M. Ljubojev, Z. Stojanović, G. Stojanović: Determining the Stress of Rock Massif, Mining & Metallurgy Engineering Bor, No. 2, 2014, pp. 33-38; Serbia;

[7] D. Zlatanović: Stability of Underground Facilities of Deep Metallic Deposits in a Case of the Ore Body – Borska reka; Master Thesis, Faculty of Mining and Geology, University of Belgrade (2000);

[8] M. Ljubojev, D. Ignjatović, L. Đurđevac-Ignjatović, D. Tašić: Probe for Measuring Stress-Strain State in Rock Massif, 45rd International October Conference on Mining and Metallurgy, Bor Lake, 16-19 October 2013, pp. 285-288;

[9] M. Ljubojev, R. Popović, D. Ignjatović, M. Jovanović; Prognosis of the Zone Size Deformations Using the Finite Element Method on the Sample of Underground Exploitation of the Ore Body “Borska reka”; The 44th International October Conference on

Mining and Metallurgy, 1-3 October 2012, Bor; pp. 249-252;
[10] M. Ljubojev, M. Avdić, L. Đurđevac Ignjatović; State around the Mine Workings; The 44th International October Conference on Mining and Metallurgy 1-3 October 2012, Bor; pp. 245-248;
[11] V. Milisavljević, I. Ristović, V. Čokorilo, N. Lilić, M. Denić: Improvement of Roadway Stability in Serbian Underground Coal Mines; Proceedings of the 4th Balkan Mining Congress, 18-20 October 2011, Ljubljana, Slovenia, (2011), pp. 533-538.

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PROGNOZA PONAŠANJA STENSKOG MASIVA PRE OTKOPAVANJA NA DUBLJIM HORIZONTIMA RUDNOG TELA BORSKA REKA****

Izvod

U ovom radu prikazan jedan od načina na koji bi moglo da se pristupi u rešavanju nekih važnih pitanja vezanih za stabilnost podzemnih objekata na većim dubinama. Analiza je fokusirana na predviđanje ponašanja stenskog masiva pre izvođenja rudarskih radova i to u konkretnom slučaju na dubljim nivoima u rudnom telu "Borska reka" u rudniku Jama u Boru.

Pored obimnog dosadašnjeg istraživanja rudog tela "Borska reka" i dobijenih parametra za modeliranje stanja napona i deformacija koji se javljaju pod uticajem rudarskih radova, dodatno je izvršena i procena naponskog stanja u masivu. Prikazana je analiza stabilnosti prostorija na nivou XVII horizonta i izvršena prognoza stabilnosti istih prostorija za dublje nivoe otvaranja. Kao rezultat se očekuje da će nivo neizvesnosti i rizika u vezi sa mnogim identifikovanim geomehaničkim rizicima u upravljanju stenskim masivom biti smanjen.

Ključne reči: *predviđanje, ponašanje stenskog masiva, stabilnost prostorije, rt Borska reka*

UVOD

Rudarski radovi i izrada prostorija u dubokim rudnicima izazivaju nestabilnost u radnoj sredini koja može nastati kao rezultat popuštanja krovine, pukotina i izboja iz bokova ili kombinacije oba. Zbog toga, stavljajući bezbednost na provom mestu prilikom izvođenja rudarskih radova, stabilnost ovakvih prostorija je veoma važna. Osnovna briga u otkopavanju je kontrola pomeranja u stenskom masivu oko izgrađene prostorije. Za svaku prostoriju, cilj projektovanja je da osigura da pomeranja oko prostorije nemaju uticaj na određene rudarske aktivnosti.

Modeliranje u kontroli ponašanja nadkopnih stena i slojeva u mehanici stena značajno je razvijan poslednjih decenija. Postoje različite numeričke metode i softveri dostupni za analizu stabilnosti podzemnih otvora. Uprkos značajnom napredku koji je

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**** *Ovaj rad je proistekao kao rezultat projekta 33021 „Istraživanje i praćenje promena naponsko deformacijskog stanja u stenskom masivu „in-situ" oko podzemnih prostorija sa izradom modela sa posebnim osvrtom na tunel Kriveljske reke i Jame Bor", koga finansira Ministarstvo prosvete, nauke i tehnološkog razvoja Republike Srbije*

napravljen, prepoznaje se da uspešna primena numeričkih metoda u projektovanju i analizi stabilnosti, zavise u velikoj meri od geomehaničkog modela i graničnih uslova razvijenih za podatke sa date lokacije. Zbog teškoća u definisanju nekih od ulaznih podataka, često se koriste stohastičke metode i verovatnoća za predstavljanje mehaničkih osobine stena i stenske mase, kao i u samim analizama.

Projekat za rudnik podzemne eksploa-

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utvrđivanje proizvodnih kapaciteta i graničnog sadržaja korisne komponente. Bira se odgovarajuća metoda prateći granice rudnog ležišta. Utvrđuje se plan razvoja osnovne infrastrukture otvaranja i analiza opšteg redosleda otkopavanja. Mnogo procena mora da se uradi pre nego što projekat započne.

Kada se projektuje osnovna infrastruktura otvaranja, jedno od prvih pitanja koja se često postavlja pred mehaniku stena tj. rudarskim inženjerima je "Koliki je maksimalni stabilan profil prostorije?". Međutim, često je prerano i retko da postoji dovoljno dostupnih i sličnih podataka

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ve modernih brzih digitalnih računara i numeričkih metoda modeliranja.

U ovoj kompijuterskoj eri, širok spektar računarskog softvera se koristi u numeričkim analizama ponašanja stenske mase. Oni uključuju različita pomeranja po diskontinuitetu i srodne programa, kao što su **FEM**[*] ***(Phase2)***, BEM[†], FDM[‡] i DEM[§].[1]

Uprkos dostupnosti računarske tehnike i

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geomehanička analiza je još uvek više umetnost nego stvarno modeliranje stenske mase.

uraditi dovoljno geomehaničkih istraživanja u fazi planiranja jednog rudarskog projekt

tipova geomehaničkog rizika bude u potpunosti uzet obzir. Međutim, kako se projekat odvija kroz razne faze od ideje do detaljnog dizajna i implementacije, nivo neizvesnosti i rizika u vezi sa mnogim izvorima geomehaničkog rizika koji su prethodno identifikovani može se očekivati da budu smanjeni.

Primena standardnih kriterijuma čvrstoće

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nutno koriste za procenu stabilnosti podzemnih prostorija se zasnivaju na linearnom Mohr–Coulomb kriterijumu čvrstoće. Međutim, eksperimentalni podaci i inženjersko iskustvo pokazalo je da čvstoća za skoro sve vrste stenske mase prati ne-linearan Hoek-Braun kriterijum čvrstoće. Hoek-Brovn kriterijum čvrstoće za stenske mase

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čajeva u svetu.

Klasični Mohr-Coulomb kriterijum čvrstoće sastoji se od dve nezavisne komponente kohezije i ugla unutrašnjeg trenja i ne daje realnu sliku o progresivnom lomu i raspadu stene pod pritiskom. Kriterijum Hoek-Braun je široko zastupljeniji za ispucalu radnu sredinu, ali takođe može da se primeni i na

[*] *Metode Konačnih Elemenata (**FEM**) (Beck et al., 2009, 2010; Goodman et al., 1968; Wittke, 1977, 1990; Zienkiewicz, 1977)*

[†] *Metode Graničnih Elemenata (**BEM**) (Beer and Watson, 1992; Brady, 1979, 1987; Crouch and Starfield, 1983)*

[‡] *Konačne Diferencijalne Metode (**FDM**) (Hart et al., 2008; Itasca, 2011; Sainsbury et al., 2011)*

[§] *Metode Diskretnih Elemenata (**DEM**) (Jing and Stephansson, 2007)* neporemećeni stenski masiv. U stvari, mno-

lnom razvoju Hoek i Brovn modela od (1980), a i kasnije. [2]

ANALIZA SLUČAJA NA PRIMERU RUDNOG TELA "BORSKA REKA"

Za svrhu ovog rada, analiza se uglavnom bazira na ponašanju stenske mase na konkretnom primeru, ležištu – rudnom telu "Borska reka" u rudniku Jama u Boru.

Ovo ležište po pružanju ima dužinu od oko 1.000 metara i moćnost oko 500 m, zaleže ka zapadu pod uglom od 45° do 55°, u skladu sa zaleganjem borskih konglomerata i peščara, a od hidrotermalne zone odvojen je borskim rasedom. Istražni radovi na rudnom telu "Borska reka" su započela u periodu od 1976. do ovih dana i to sa velikim obimom istraživačkih radova. Detaljni istražni radovi su izvedeni na nivou K-155 m, a pretpostavlja se da rudno telo zaleže do nivoa K-800 m, pa čak i dublje. Deo ležišta iznad nivoa K-235, otvoren je transportnim sistemom za rudna tela "Tilva Roš" i "P2A".

Rudarski radovi se obavljaju na osnovu rudarskog projekta eksploatacije rude bakra iznad nivoa (K-235). Nakon više godina od utvrđivanja rezervi mineralnih sirovina u rudnom telu "Borska reka", dodatnih istraži-

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vanja sa očuvanjem površine terena i svih izgrađenih objekata, infrastrukture i rudarskih radova iznad ležišta "Borska reka", počevši sa otkopavanjem od nivoa XIX

za eksploataciju u sledećoj fazi.

Ovo je svakako i ozbiljan izazov u upravljanju stenskim masivom i geomehaničkim rizicima. Dakle, rezultati ove analize, s jedne strane, odnose se na potrebu za prognozu ponašanja stenske mase pre nego što otkopavanje počne na dubljim nivoima rudnog tela "Borska reka", i sa druge strane, zahtev da se izvrše sva potrebna geomehanička ispitivanja u cilju dobijanja pouzdanih informacija kao osnova za dalje donošenje odluka.

PRETHODNA ISTRAŽIVANJA I MODELIRANJE NAPONSKO-DEFORMACIJSKOG STANJA

Prethodna istraživanja

U cilju utvrđivanja geomehaničkih karakteristika radne sredine, pregledana je sadašnja tehnička dokumentacija geoloških, geotehničkih i hidrogeoloških ispitivanja i analiza koja se odnose za rudno telo "Borska reka" u rudniku Jama Bor. Na osnovu toga, može se generalno zaključiti da je mnogo toga urađeno i da je mnogo rada, truda i novca uloženo.

Ovde će se samo pomenuti neke od godina kada su predmetna istraživanja rađena, počevši od 1997, 1999, 2007 i 2014 godine od strane Instituta za rudarstvo i metalurgiju iz Bora. [3]

Do sada, prema analizama koja su urađena u okviru najnovijih istraživanja, došlo se do podataka koji pokazuju delimično niže vrednosti koji opisuju fizičko-mehanička svojstva stenskog materijala u odnosu na prethodna istraživanja, tabela 1.

Tabela 1. *Fizičko-mehanički parametri dobijeni laboratorijskim ispitivanjima na uzorcima uzetih iz stenskog masiva rudnog tela "Borska reka"*

Geotehnička sredina	**γ [kN/m^3]**	**σ_c [MPa]**	**σ_i [MPa]**	**E_t [MPa]**	**E_s [MPa]**	**ν -**	**φ [°]**	**m_i -**	**C [MPa]**	**RMR_{89}**	**GSI**
Borski peliti *2014	25,4	49	4,95	5600	3730	0,34	36,0	24	12,13	54	
Andeziti *2014	25,9	52	5,37	6927	4633	0,31	36,8	26	12,90	66	
Andeziti kaolinisani *2014	27,0	25	3,04	5490	3672	0,37	30,4	20	7,53	34	
Andeziti silifikovani *2014	27,7	67	7,57	10790	7127	0,32	37,4	28	16,70	51	
(XVII level) K-155	γ [kN/m^3]	σc [MPa]	σi [MPa]	E [MPa]	Ed [MPa]	ν -	φ [°]	m_i -	C [MPa]	RMR_{89}	GSI
Andeziti silifikovani *1999	28.2	63.39	6.71	40490	33255	0.216	41.6	15,09	18.9	73	65

Modeliranje naponsko-deformacijskog stanja

Pored standardnih laboratorijskih testova i "in situ" opažanja i merenja, izvršeni su postupci laboratorijskih ispitivanja za testi-

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jalne kompresije. Triaksijalni eksperiment ima za cilj da simulira uslove koji se mogu pojaviti u okolnim stenama podzemne infrastrukture - hodnika i objekata i ove prostorije mogu biti izložene graničnom pritisku i naponu smicanja. [4]

Na osnovu prethodnih rezultata laboratorijskih testova sprovedenih na uzorcima stena iz masiva i jezgra istražnih bušotina, uz uzimanje u obzir stanje stenskog masiva, stepena

, deformacionih karakteristika i kvaliteta procene stenske mase, laboratorijske vrednosti su dobijene za parametre stenske mase na nivou XVII horizonta u rudnom telu "Borska reka". [5]

Analiza stabilnosti stena je izvedena na standardnom poprečnom preseku prostorije koja je projektovana i izrađena u Jami Bor (4x3,5m), sa potvrdom relevantnosti obima podataka prikupljenih iz prethodnog istraživanja i gore pomenutih istraživanja.

Stanje napona u rudnom telu "Borska reka" ranije nije mereno, zato ovi podaci nisu dostupni. Zbog nedostatka poznavanja naponskog stanja u stenskom masivu, napo-

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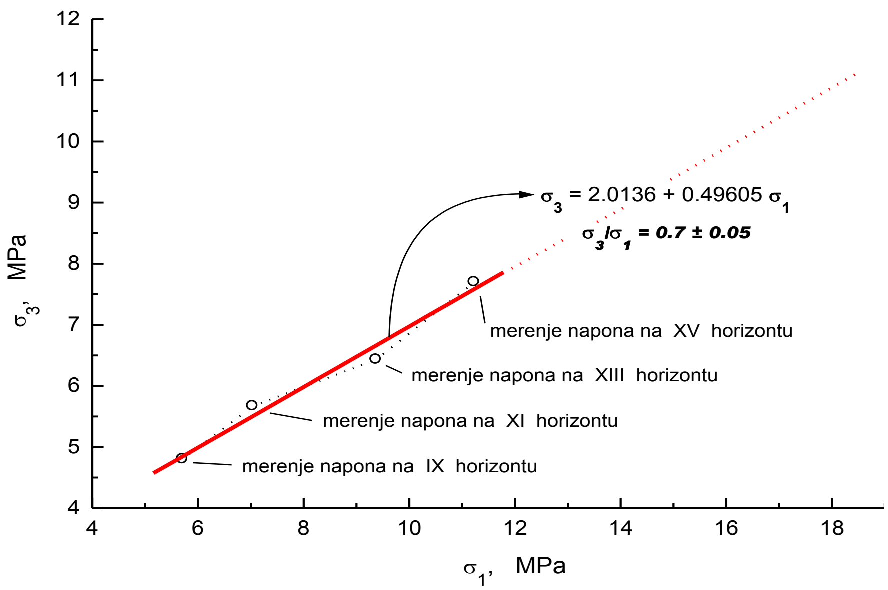
ciono komponente - γH. Napon je meren u najbližem

u vidu blizinu, ukazuje na odnose između glavnih napona. Odnos je između 0,7 ± 0,05. (Slika 1.) Ova procena će se prihvatiti i za rudno telo "Borska reka" za nivo XVII horizonta (K -155). [6]

Ovde treba napomenuti da su merenja napona urađena pre više od dvadeset godina i samo na konturi prostorije. Može se prêt-

je napon meren dublje u stenskom masivu. To znači da nedostatak preciznih vrednosti napona za određeni nivo dubine u rudnom telu "Borska reka" ukazuje na prvi problem u tačnost izvršenih određenih proračuna i zaključaka.

Umesto kvalitativne analize stabilnosti stenske mase, empirijska analiza može da se vrši na osnovu procene i pretpostavke sa namerom da se nađemo u traženom opsegu vrednosti, ali možemo i da pogrešimo. [7]



Sl. 1. *Linearna funkcija odnosa promene izmerenih glavnih napona sa dubinom za rudno telo "Tilva Ros" u rudniku Jama Bor*

Utvrđena vrednost napona uzeta je sa slike 1. Za nivo XVII horizonta je za $\sigma_1 = \sigma_v$ = 14 MPa, i za σ_3 = 9,5 MPa.

Izrada Modela

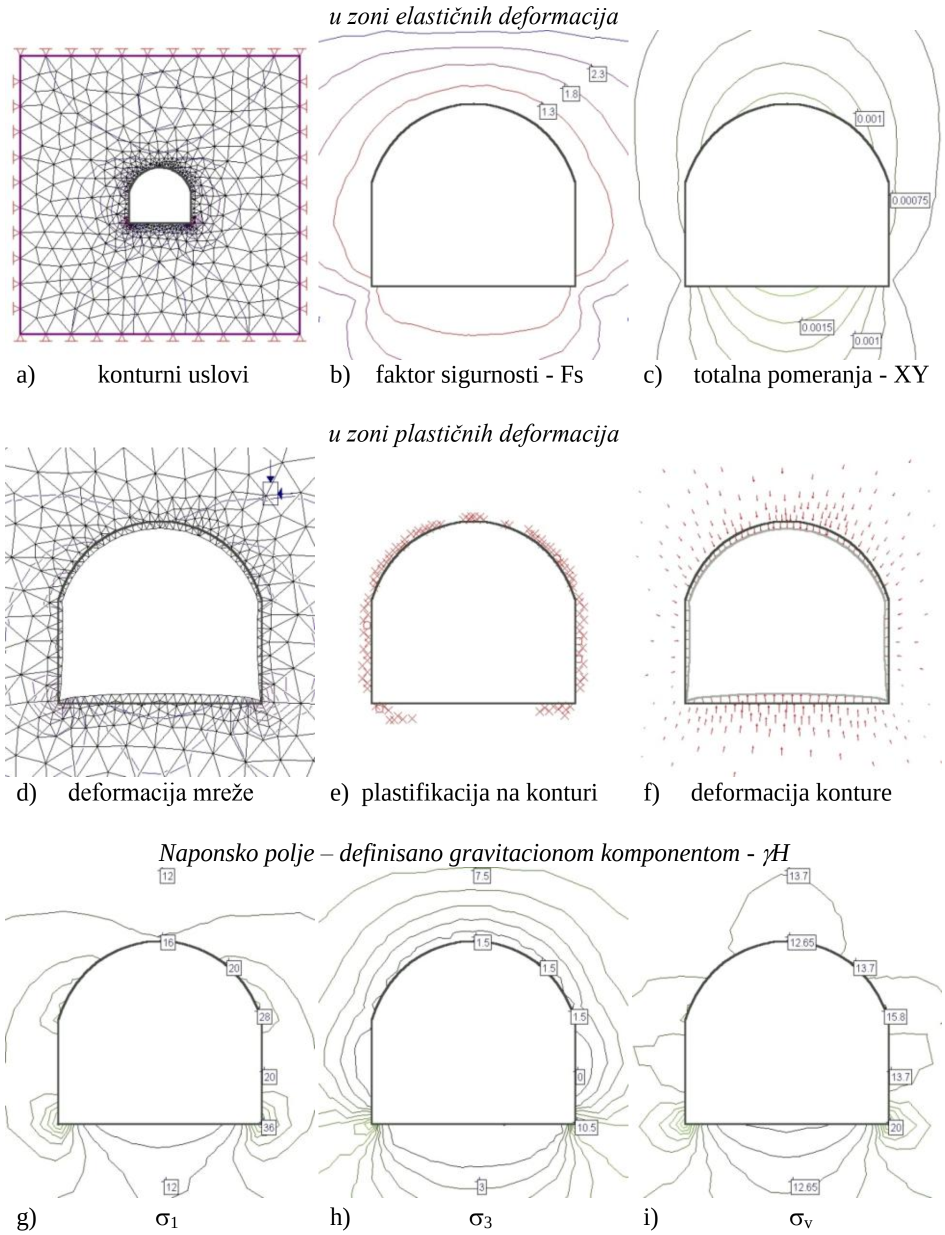
Konturni uslovi su odabrani tako da je opterećenje na modelu samo pod uticajem gravitacijske komponente, tako da je model fiksiran i da nema pomeranja u pravcu X i Y ose.

Diskretizacijom modela se određuje potrebna gustina tačaka (čvorova) na konturi profila od koje zavisi broj konačnih elemenata sa kojima će se ući u proračun. U ovom slučaju izabrana je gustina od 75 tačaka (čvorova) po konturi profila. Sa ovim se pokazuje da li i u kojoj meri gustina mreže konačnih elemenata utiče na tačnost rezultata i preciznost kod interpolacije tj. iscrtavanja izolinija napona i deformacija. Mreža konačnih elemenata je sastavljena od trouglova i prikazana je na svakoj slici kod interpretacije rezultata.

Interpretacija rezultata i ocena stabilnosti

Za modeliranje projektovanog profila prostorije generisana je mreža konačnih elemenata sa ukupno 1.404 elementa i 729 čvorova. Unos podataka se vrši za svaki model posebno, s'time što se razlikuju u pravcima delovanja glavnih napona. Interpretacija rezultata i ocena stabilnosti se prikazuje za sva oba urađena slučaja. Rezultati proračuna su interpretirani izolinijama faktora sigurnosti, totalnih pomeranja i glavnih napona. Takođe je dat prikaz deformacije mreže, deformacija konture sa smerom delovanja pomeranja (koja je uvećana 100 puta) kao i zone plastičnosti obeležene markerima. Markeri u obliku krstića (x) obeležavaju da do loma dolazi usled uticaja napona smicanja, a kružići (o) obeležavaju da do loma dolazi usled napona na zatezanje (Slika 2).

Projektovani-izvedeni objekat (prostorija) na XVII horizontu - 4x3,5 m



Sl. 2. *Naponsko-deformacijska analiza - u slučaju kada je polje napona pod uticajem gravitacione komponente - γH*

Ukoliko se stenski masiv oko date prostorije nalazi u zoni elastičnih deformacija, dotle će zona oko prostorije biti stabilna sa raspodelom faktora sigurnosti kako je to na slici 2b prikazano. Ako projektante konturna linija faktora sigurnosti od 1,3 zadovoljava postavljeni kriterijum stabilnosti, vidimo da je u bokovima prostorije ta linija udaljenija od konture i da samim tim ta oblast postaje podložna prelasku iz zone elastičnih u zonu plastičnih deformacija. Maksimalna pomeranja po konturi su 1,8 mm, slika 2c. Na slici su vrednosti totalnih pomeranja date u metrima.

Na mestima na kojima se pojave plastične deformacije, slika 2e, plastifikacija po konturi imaće takav karakter da se po svodnom delu javljaju plastične zone (x), a na bokovima se javljaju plastične zone (x i o).

Može se zaključiti da je ova prostorija stabilna, s'tim da je pojava plastičnih deformacija koje se manifestuju u vidu ljuštenja i otpadanja manjih komada iz bokova i stropa sporadična i da se na tim mestima može na odgovarajući način poduhvatiti i zaštititi prostoriju od daljeg širenja oštećenja. [8]

PROGNOZA PONAŠANJA STENSKOG MASIVA

Da bi se iskoristila prednost modelskih istraživanja koja nam omogućavaju da prognoziramo ponašanje stenskog masiva i na dubinama koje još nisu obuhvaćene rudarskim radovima, u ovom delu će se u analizama stabilnosti koristiti veće dubine od nivoa XVII horizonta.

Za izbor dubina uzeti su nivoi XIX (K –235), XXI (K –315), XXIII (K –395) i XXV (K –475) horizonta i predstavljaju vrednosti od oko 630 m, 710 m, 790 m i 870 m dubine.

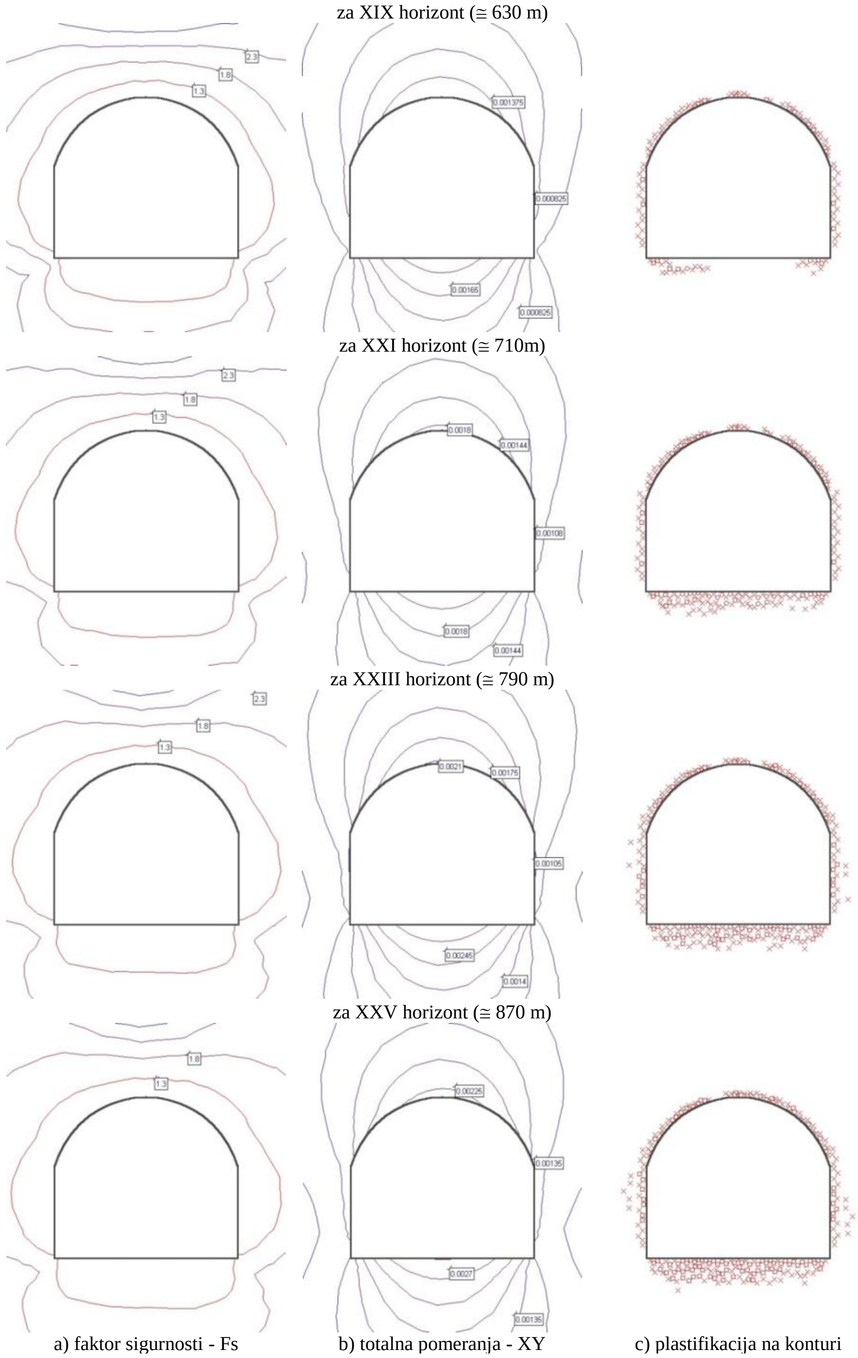
Na osnovu toga se može reći da od izabranih horizonata za procenu stabilnosti, XVII i XIX horizont su obuhvaćeni u projektovanju, što može biti od koristi, jer izgrađeni objekti na ovim horizontima, uz odgovarajuća snimanja, mogu u startu da prikažu valjanost procene ovih analiza. Ostala tri horizonta se analiziraju da bi se predvidelo šta se može očekivati na dubljim nivoima u nekoj kasnijoj fazi i sigurno će biti predmet dalje razrade. [9]

Interpretacija rezultata i ocena stabilnosti su urađeni na način kao i analiza stabilnosti na XVII horizontu da bi se moglo lakše izvršiti upoređivanje rezultata.

Vrednosti primarnih napona su dobijane na osnovu gravitacijske komponente $\sigma_v = \gamma H$, a odnos glavnih napona σ_1 *i* σ_3 je dobijen iz analitičkog izraza sa grafika na slici 1.

Tabela 2. *Prognozne vrednosti primarnih napona*

Horizont	Kota	okvirna dubina m	γH MPa	σ_1 MPa	σ_3 MPa	σ_3/σ_1
XVII	-155	550	14	14	9,5	0,70±0,05
XIX	-235	630	17	17	10,5	0,65±0,05
XXI	-315	710	19,2	19,2	11,5	0,60±0,05
XXIII	-395	790	21,3	21,3	12,6	0,55±0,05
XXV	-475	870	23,5	23,5	13,5	0,55±0,05



Sl. 3. *Naponsko-deformacijska analiza u slučaju kada je naponsko polje pod uticajem gravitacione komponente -* γH

Prognoza stabilnosti modela po dubini ispod nivoa XVII horizonta

Rezultati analize modela su dobijeni za naponsko polje koje je određeno gravitacionom komponentom - γH. Za modeliranje profila je korišćena mreža konačnih elemenata kao i kod predhodnog ispitivanja.

Za definisanje parametara radne sredine u analizama je korišćen kriterijum loma i parametri stenskog masiva dobijeni na osnovu parametara za XVII horizont. Triaksialnim ispitivanjima, kojima su određivane deformabilne karakteristike stenskog masiva na XVII horizontu, bilo je potrebno, povećanjem bočnog pritiska simulirati i one dubine za koje želimo uraditi procenu stabilnosti. Ova ispitivanja nisu rađena pa su u ovim analizama korišćene deformabilne karakteristike stenskog masiva na XVII horizontu.

Na slici 3, prikazane su naponsko-deformacijske analize stenskog masiva na XIX, XXI, XXIII i XXV horizontu.

Posmatrajući rezultate analize stabilnosti po dubini, može se zaključiti da stabilnost prostorije linearno opada sa povećanjem dubine, što je i bilo očekivano.

Obzirom da su maksimalna pomeranja po konturi u porastu sa povećanjem dubine i to 2,1 mm; 2,4 mm; 2,76 mm i 3,2 mm, a za dublje nivoe od XXI horizonta mogu se očekivati pojačana deformacija i otpadanja komada stenskog materijala iz bokova i stropa prostorije, ukoliko se prostorija ostavi nepodgrađena.

Mesta na kojima se pojavljuju plastične deformacije, plastifikacija po konturi imaće takav karakter da se po svodnom delu javljaju plastične zone (x), a na bokovima se javljaju plastične zone (x i o). Ovo važi samo na XIX horizontu dok se na dubljim horizontoma očekuju plastične zone (x i o) po celoj konturi. Veličine zone plastičnog delovanja se kreću u bokovima 18 cm, 21 cm, 28 cm i 35 cm. U stropu im je vrednost 16 cm, 17 cm, 18 cm i 20 cm, dok je u podu samo na XIX horizontu raspoređen po uglovima, a na ostalim horizontima raspoređen je po celom podu.

Ono što može narušiti stabilnost konture profila su naponi iz boka prostorije, pri ovako usvojenom odnosu glavnih napona, jer se konturna linija faktora sigurnosti u boku sve više udaljava od samog profila. [10]

Može se proceniti da na nivou XIX horizonta ta prostorija može ostati nepodgrađena osim na mestima gde se pojave plastične zone i gde se ta mesta moraju osigurati. Prognoza stabilnosti za istu prostoriju na XXI, XXIII i XXV horizontu upućuje da mora imati odgovarajuću podgradu na nekim deonicama ili celom dužinom. Kao posledica povećanja dubine može se primetiti određeno “smirivanje” u povećanju plastične zone oko konture profila što nas navodi da je potrebno redefinisati konturne uslove opterećenja na modelu sa predpostavljenim ili izmerenim novim vrednostima glavnih napona kao i nihovim pravcem delovanja.

U prostoru plastične zone rastresanje stena uglavnom je izazvana visokom deformacijom. Deformacija počinje odmah nakon iskopa i obično se stabilizuje sa ugradnjom podgrade kada dolazi do ravnoteža sila ali se može doći do pogoršanja i propadanja krovine kao rezultat reoloških ponašanja stenske mase.

Pogoršanje i propadanje krovinskih stena u podzemnim prostorijama bi moglo da se javi iz nekoliko razloga. Glavni uzrok je koncentracija napona u neposrednoj krovini i podinskim stenama, kao i u bokovima prostorije. Ova koncentracija se generiše poremećajem inicijalne ravnoteže nakon izrade prostorije, stvarajući koncentraciju vertikalnog napona u bokovima prostorije, dok je horizontalni napon koncentrisan u krovnom delu i podu. Propadanje stena bi se manifestovalo kao formiranje zone narušene stenske mase u stropu prostorije. Ovo je zabeleženo u jednom od prethodnih istraživanju. U takvim zonama stena je veoma rastresena, a zona propadanja takođe nastavlja dalje širenje u neposrednoj krovini prostorije. [11]

Buduća istraživanja

Buduća istraživanja svakako moraju uključiti merenje naponskog stanja u rudnom telu Borska reka, ali i utvrđivanjem pravca njegovog delovanja. U tom slučaju bi naponsko polje bilo definisano sa komponentama napona σ_1, σ_3, i σ_v uz uzimanje u ubzir promenu pravca delovanja napona zbog mogućeg uticaja Borske rasedne zone kao i samog ugla zaleganja rudnog tela "Borska reka", mogao u mnogome da promeni sliku o stabilnosti.

Prilikom otvaranja svakog sledećeg nivoa, izvršiti dodatna geomehanička istraživanja. Ovim istraživanjima će se odrediti fizičko-mehanički parametari stenskog masiva koji bi se koristili za dalju numeričku analizu i proračune, a ujedno bi se upoređivale sa rezultatima prethodnih laboratorijskih ispitivanja. Takođe bi se utvrdile korelacione veze između fizičko-mehaničkih, strukturnih svojstava i rezultata kategorizacije stenskih masa, kao i definisanje čvrstoće stenskog masiva po Hoek-Brown-ovom kriterijumu loma. Na osnovu toga se mogu pažljivo proceniti i odrediti parametri koji će biti relevantni da karakterišu ponašanje stenske mase i sa time ući u dalje modeliranje stenskog masiva i novu prognozu za dublje nivoe.

ZAKLJUČAK

U ovom radu prikazana je analiza slučaja prognoze ponašanja stenskog masiva za dublje nivoe u rt „Borska reka" gde je naponsko polje definisano samo sa gravitacionom silom i vertikalnim delovanjem napona, pri čemu su glavne komponente napona definisane odnosom proizašlim iz merenja napona u rt Tilva Roš.

Na osnovu prethodnih rezultata laboratorijskih ispitivanja gde je obuhvaćen stenski masiv sa XVII horizonta (K –155 m) u rudnom telu "Borska reka" i odgovarajućih istraživanja i triaksijalnih ispitivanja koja su rađena na probnim telima iz uzetih uzoraka, dobijeni rezultati obrađivani su po Hoek-ovoj metodologiji i direktno su se koristili kao ulazne veličine za numeričko modeliranje.

Ovde je bio ograničavajući faktor u proizvoljnosti uzimanja vrednosti za definisanje naponskog stanja, jer merenja napona za datu lokaciju nije bilo. Naponsko stanje je određeno na osnovu gravitacijske komponente, a dok je odnos glavnih napona procenjen na osnovu izvršenih merenja napona za rudno telo "Tilva roš" još pre 20 i više godina.

Numerički model je baziran na metodi konačnih elemenata (MKE) i za tu svrhu je korišćen programski paket PHASE^2. Analiza i interpretacija rezultata istraživanja je urađena i prikazana za projektovanu i izvedenu prostoriju. Rezultatima su obuhvaćeni vektori pomeranja, raspodela napona sa izolinijama glavnih napona kao i zone plastifikacije oko analiziranih objekata.

Analiza stabilnosti je obuhvatila prvo XVII horizont za čiju radnu sredinu imamo definisan kriterijum loma i potrebne ulazne podatke za sam tok proračuna. Na osnovu njih je u drugoj fazi vršena prognoza stabilnosti za dublje horizonte. Obuhvaćeni su nivoi XIX (K –235), XXI (K -315), XXIII (K –395) i XXV (K –475).

Rezultati i prognoza stabilnosti prostorija na dubljim horizontima sa predpostavljenim osobinama stenskog masiva i naponskog stanja, pokazuju da se stabilnost prostorija na analiziranim profilima smanjuje. Primenjeni model u analizi ostaje stabilan do nivoa XIX horizonta, dok za dublje horizonte morao bi biti osiguran i podgrađen. Ovaj zaključak se izvodi na osnovu parametara radne srednine sa XVII horizonta koji su po obimu i predpostavljenom naponskom stanju sami po sebi nedovoljni za kvalitativnu prognozu stabilnosti, a pogotovu na dubljim horizontima. Iz tih razloga je neophodno da se za svaki novi horizont urade sva potrebna geomehanička istraživanja. Kako se radovi budu spuštali na veću dubinu, sa tim podacima bi se verifikovali ili korigovali rezultati prognoza za isti nivo, a ujedno i vršila prognoza za ponašanja stenskog masiva sledećeg dubljeg nivoa.

Naravno da bi jedna kvalitativna analiza, poput analize stabilnosti, bila odrađena do kraja, ne bi smelo da u nju ulazi ni jedna procenjena vrednost, kao što je u ovom slučaju bila vrednost napona u masivu kao i njegov pravac. U tom cilju, za ocenu naponskog stanja u rudnom telu "Borska reka" kao i za definisanje parametara bitnih za sagledavanje ponašanja stenskog masiva potrebno dosadašnja geomehanička istraživanja upotpuniti i sa primenom adekvatnih metoda za merenje naponskog stanja.

Sinteza dosadašnjih i predloženih istraživanja bi dala potpuniju sliku o rudnom telu "Borska reka". Sa tog aspekta bi bilo moguće kroz odgovarajuće modele analizirati sve vrste rudarskih radova koji bi se izvodili. Rezultati tih analiza bi se mogli sa većom pouzdanošću primeniti u praksi.

LITERATURA

[1] E. T. Brown, Progress and Challenges in Some Areas of Deep Mining, Deep Mining 2012, Australian Centre for Geomechanics, Perth, 2012.

[2] Boek, E., [2002]: A Brief History of the Development of the Hoek-Brown Failure criterion (http://rocscience.ca/help/rocdata/webhelp/rocdata/Generalized_Hoek-Brown_Criterion.htm);

[3] D. Zlatanović. M. Ljubojev, L. Djurdjevac-Ignjatović, G. Stojanović: Modeliranje stenskog masiva u Jami Bor sa posebnim osvrtom na dosadašnja istraživanja rudnog tela "Borska Reka", Mining and Metallurgy Engineering Bor, 3/2014, str. 25-32;

[4] V. Čebašek, N. Gojković: Rockmass Investigations for Determination of Failure Criterion, Journal „Underground Mining Engineering 17", University of Belgrade - Faculty of Mining and Geology; (2010), str. 35-47;

[5] D. Zlatanović, V. Čebašek, M. Ljubojev: Determining the Parameters of a Rock Mass Model in the Function of Fracture Criterion; The 46th International October Conference on Mining and Metallurgy 1-3 October 2014, Bor; str. 529-532; Serbia

[6] D. Zlatanović, M. Ljubojev, Z. Stojanović, G. Stojanović: Odredjivanje napona stenskog masiva, Mining and Metallurgy Engineering Bor, 2 (2014), str. 39-44;

[7] D. Zlatanović: Stabilnost podzemnih objekata dubokih metaličnih ležišta na primeru rudnog tela - Borska reka; Magistarska teza, Rudarsko-geološki fakultet, Univerzitet u Beogradu (2000);

[8] M. Ljubojev, D. Ignjatović, L. Đurđevac-Ignjatović, D. Tašić: Probe for Measuring Stress-strain State in Rock Massif, 45rd International October Conference on Mining and Metallurgy. Bor Lake, 16-19 October 2013, str. 285-288;

[9] M. Ljubojev, R. Popović, D. Ignjatović, M. Jovanović; Prognosis of the Zone Size Deformations Using the Finite Element Method on the Sample of Underground Exploitation of the Ore Body "Borska reka"; The 44th International October Conference on Mining and Metallurgy 1-3 October 2012, Bor; str. 249-252;

[10] M. Ljubojev, M. Avdić, L. Đurđevac Ignjatović; State around the Mine Workings; The 44th International October Conference on Mining and Metallurgy 1-3 October 2012, Bor; str. 245-248;

[11] V. Milisavljević, I. Ristović, V. Čokorilo, N. Lilić, M. Denić: Improvement of Roadway Stability in Serbian Underground Coal Mines; Proceedings of the 4th Balkan Mining Congress, 18-20 October 2011, Ljubljana, Slovenia, (2011), str. 533-538.

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DETERMINATION THE NECESSARY STRENGHT OF STOPE FILLINGS AT TOTAL LAYER EXCAVATION**

Abstract

The basic aims of layer excavation by filling methods are: increasing or total layer spending without ore impoverishment, layer excavation in complex mining and geological conditions, environmental factors preservation, improvement of ergonomic and safety work conditions and recirculation the waste material.

For achievement of these aims, it is necessary to put in the stope the filling material of appropriate physical and mechanical characteristics, especially the pressure strength. This work presents a discussion of procedure of filling material selection with necessary strength, and application of filling stoping methods at complete layer excavation and protection of the earth surface and objects on it from damages.

Keywords: *total excavation, filling of the stopes, stoping strength*

1 INTRODUCTION

Complete excavation of the mineral ore layer without depletion of mineral ore and with preservation the environmental faction in the exploitation field can be only realized by the mining method with filling the cavities in ascending or descending order of excavation and filling [1]. Depending on the objectives of full deposit excavation with filling the cavities, the required strength of backfill can be determined and selection the type of filling material with which that the strength can be achieved [2].

This can be achieved by applying of solidifying backfill [3].

Completely obtaining of layers without getting ore dilution can be carried by the following groups of excavation methods [4]:

1. The central excavation of corridors, steep ore veins and lenses is a) from bottom to top, standing of equipment on the back fill, b) from top to bottom, under backfill, when the equipment is at a solid rock (ore).

2. Single-or multi-layer excavation of powerful ore deposits; a) vertically layered

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excavation from bottom to top (equipment moves on the backfill), b) horizontal layered excavation from top to bottom and beneath concrete slab (equipment is moving on solid ground).

3. Sublevel excavation of ore deposits with subsequent excavation back filling; a) curing over burden with movement of the excavation front from bottom to top, b) under concrete slabs, by excavation back filling with curing over burden (excavation fronts are moving from top to bottom.

4. Chamber pillar ore deposits excavation with ore storage, filling of stope by solidifying backfill and subsequent obtaining the protective ore pillars in filling by the same stoping method. It can be applied as: a) panel and b) cross-excavation of chambers.

Depending on the order of mining, construction and excavation geometry, objectives, implementation costs of excavation methods, physical and mechanical characteristics of the deposit and associated rocks, as well as the depth of the deposit, the necessary strength of backfill will be determined.

2 RELATIONS BETWEEN ASSOCIATED DEPOSITS ROCKS AND FILLED EXCAVATED AREAS IN THE DEPOSIT

Strength of solidifying backfill is satisfactory (normative) if it is possible to secure the opening of the artificial, (backfilling) massive of designed mining areas and excavation, and if the earth's surface and objects above the deposits can be maintained from deformation. The gravitational and tectonic (static) and blasting (dynamic) powers have effect on massive from backfilling material. Mass of backfilled excavation may be subjected to deformation under pressure, stretching, shearing, bending in uniaxial, biaxial and volume of stressed state. Strength of filling material shall be selected to suit the strength of the uniaxial pressure For choice and control the necessary strength of filling materials considering the role to be met, regardless of the character of the load. The required strength of filling material is determined by one or more factors:

a) stability (holding) of vertical open sides,
b) horizontally open ceilings,
c) the allowable deformation of the earth's surface,
d) the ability to move of equipment on the backfill surface, etc.

Mass from the filling material and surrounding rocks, in certain circumstances, form a complex spatial system backfill-rock. The main structural elements of such system roof and floor rocks and filling space are very different.

Calculation of strength of backfill is based on the knowledge of the stress-deformation characteristics of natural and artificial rock, (from backfill), mass in the excavation area, character of their interaction and is reduced to solution of three tasks.

1. Finding a load to the mass of backfilled excavation,
2. Determination of stresses in the backfill as an integral element of the system of rocks (rocks backfilled area),
3. Determining the necessary strength of backfill, resulting in the required ratio of manifestation (safety) for a given stress state, with the impact of other technological factors in the excavation of deposits.

Load to an artificially massive backfill of excavation depends on: the physical-mechanical characteristics of surrounding rocks, stress in them, backfilled excavation geometry, (size, depth and slope) and physical-mechanical characteristics of backfill, as well as the role of construction of backfilling materials fulfill during the further exploitation and termination of deposit exploitation.

In total deposit excavation (excavation by prior filling), the roof of deposit, near the excavation area, forms a zone of reduced pressure (loading), and in mineral massif in front of the zone of advancement occurs a zone of high support pressure, Fig. 1 With the increase in width of excavated space and backfilled space, the roofing rocks and backfill in the space filled, behave like the surrounding rocks and permissive support units, until backfill receives the entire burden of roofing rocks pillar. Load on the excavation comes from roofing rock slab, which is partly supported on the backfilled part of excavation area, and partially on the ore massif. Dimensions of unloading zones are proportional to the deformation characteristics of the backfill, ε. Deformation characteristics of backfill depend on the type of backfill and installation. At ε ≤ 3% moving of leaning rocks is performed by folding without cracking and fragmentation. At ε ≥ 3% in the roof occurs cracking and layering of rocks. The value of stress concentration coefficient in the ore massif is determined by the width of excavated space L and the stress concentration in the ore massif, by the formula:

$$K_k = 2.1 - 1.1\ e^{-(L/80)^{1..5}}$$

$$K_k = (0.8\ l_e \cdot n + 14)H^{-0.33}$$

where:

e - base of natural logarithm

L - width of excavated space m, $L = n \cdot l_e$

l_e - excavation width (tape, layer) in getting (the equivalent pillar width of the excavation ceiling)

n - number of tracks in simultaneous getting to achievement the critical width $l_k = n \cdot l_e$

H - depth of works for which stresses in the roof are related ;

$\tau = \rho g H$, (Pa)

Tests have shown that maximum pressure of support at width of excavation space L=30-40 m is (1.5 – 1.6) ρgH. Maximum is at 15 - 20 m from the forehead of excavation front , and the width of stressed zone is about 50 m. Backfill material suffers loading only at width of excavated space 40 - 60 m.

During excavation of backfill below deposits, backfill material plays the role of artificial roofing below which the unloading zone is also formed in the area of excavation and zone of support pressure on the sides in front of excavation forehead and in the backfilled space. The load depends of backfill weight and roofing rocks pressure, if they already have the suffered deformations.

3 REQUIRED BACKFILL STRENGHT AT CHAMBERS EXCAVATION WITH BACKFILL

Economical massive excavation of the low-grade (low value) ore deposits applying excavation method with filling the cavities, can only be performed by the use of highly productive excavation methods. The chamber pillar excavation method can be one of them with ore storage, with chamber backfilling after ore discharge by curing backfill and subsequent obtaining of protective pillars of ore using the same stoping method, for which an analysis of required backfill strength have to be carried out (Fig. 2). The required backfill strength can be viewed for three stages where a pillar of backfill material can be found in excavation area.

1. When the chamber is located between the protective pillars from ore (stage I),
2. When the chamber is located between the pillar of ore and the pillar from hardened backfill adjacent to the excavated chamber (stage II) or backfilled space,
3. When the chamber is located between the protective pillars from hardened backfill.

1. In the first stage backfill in the chamber will not be burdened by any vertical load of more lying rocks, except its own mass. Lateral load in the pillar of backfill may occur due to deformations the sides of chamber. The stable range of chamber ceiling (l_e) is determined from strict conditions of stability the mine premises and excavation and chamber ceiling. Stability of the undermined ceiling to critical deformation is determined from the condition.

$g_r > g_d$

where:

g_d - allowable deformation of ceilings at which the ceiling of chamber is stable,

g_r - relative deformation of chamber ceiling. It is determined by the formula:

$g_r = 1/[1+(H_R/le)^f]$

H_R - reduced for monolithic mass requirements, depth of chamber ceiling

$H_R=(1-K_g)\ H_k$

H_k - thickness of the roofing sediments at the surface to the plane of ceiling chamber.

K_g - stability loss coefficient of ceiling due to cracking and structural properties of rocks (depend of RQD characteristics). Its value can be determined based on the percentage of the extracted core.

$K_g = 0.84 + 0.01\ Nj – 0.0002\ Nj^2$

where:

Nj - percentage of extracted core (often showing a high value),

f - coefficient of rocks strength by Protogakonov,

l_e - equivalent stable range of chamber cavity (width).

Equivalent stable range (width) of chamber can be determined, if adopted boundary conditions, and solved explicitly by the formula l_e.

g < 0.001 - stable range of chamber,

g = (0.001-0.04) - state between stability and complete caving in,

g ≤ 0.04 - complete collapse of leaning roofing

$$l_e = \sqrt[f]{\frac{gH_R{}^f}{1-g}} = H_R\sqrt[f]{\frac{g}{1-g}}\text{ , (m)}$$

Stresses will be concentrated in the sides of chamber as shown in Fig. 1.

They will not be transferred to the backfill in the chamber, or more chambers. While undermined cavity beneath the roofing reaches a critical range (talking about the cavity because at excavation filling it will never completely include roofing materials).

$$l_k = H_k\ \sqrt[f]{\frac{g}{1-g}}\text{ , (m) at } g > 0.04$$

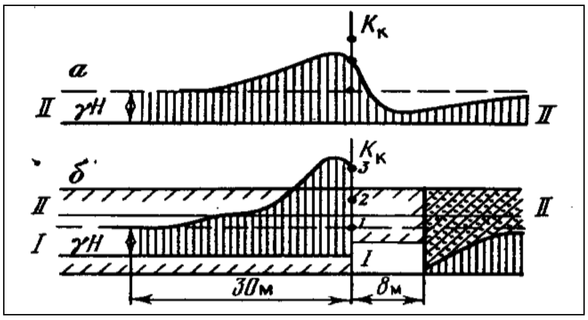

Figure 1 *Chart of changes of the stress concentration in the ore and massif of the backfill*

2 The second stage of chamber position in the excavation and backfilled space is the most common. The exploitation of large steep ore bodies, critical range of excavated areas where the roof caving occurs, is less than the length of excavation front. Blocks of caved rocks will load the backfilled space if the backfill is compressible (plastic) that will result in larger deformations in the roof, and even to the deformations of the earth's surface (in shallower deposits). Yet the filled space represents the relief zone. At the moving of excavation front from the periphery of the ore body to the opening premises, the following cases of stress can be logged:

a) Above the first of excavated chambers at width of excavated space $L = nl_e < l_k$ (stable equivalent widths), the clamping stresses appeared in the excavation roof and the comprehensive stresses are concentrated on the sides of excavation and undisturbed rocks, depending on the width of excavated space. Coefficient of power concentration is determined by formula K_k, and vertical stress in the massif is:

$$\sigma_p = K_k \rho_s g H, \text{ (Pa)}$$

Horizontal stress σ_y on the chamber side according to Fig. 2 is:

$$\sigma_y = \frac{\mu}{1-\mu} K_k \rho_s g H \text{ , (Pa)}$$

where:

μ - is the Pauson coefficient $\mu=(0.4\div0.6)$ (coefficient of side load).

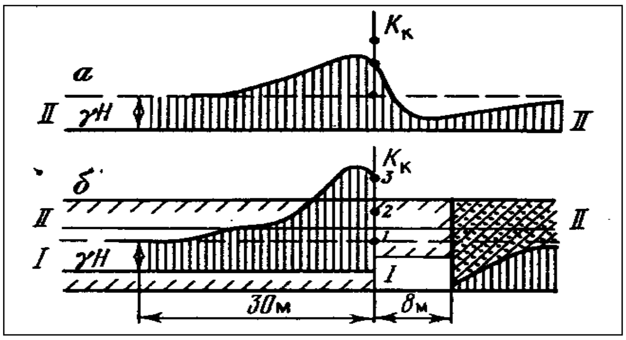

Figure 2 *Scheme for calculation the stress of protective pillars on backfill in the chamber*

Concentration of stress coefficient as in front of the forehead excavation front in the mine, and as in the final pillars of the backfill will increase with each subsequent excavation chamber, until the range of the excavated space does not exceed the critical width $L>l_k$.

b) When it excavated more chambers, so that the range of excavated space L becomes unstable or crashes, it will cause occurrence vertical stress in the backfill massif. Size of the vertical stress, which can occur in artificial pillars of the backfill, is calculated using the principle of simultaneous deformation of combined supports, pillars of the ores and pillars of backfill by the formula:

$$\sigma_1 = \frac{K_a \rho_s g H S_k}{10^6 (S_z + 0{,}77 S_p \frac{E_s}{E_z})} + 10^{-6} \rho_z g h_z$$

where:

ρ_s; ρ_z - density of rock material and backfill material

H - depth of excavated ceiling space

Sk; Sz - surface of ore pillars and pillars of the backfill

Es; Ez - deformation modulus of ore deposit and backfill material

K_a – impact coefficient of the deposit inclination angle to the load of backfill

$K_a=\cos^2\alpha-\eta\sin^2\alpha$; $\eta = \mu/(1 - \mu)$

h_z - height of backfill pillar (height of excavated and backfilled space)

α - deposit inclination angle (slope of filled cavity).

Strength of backfill in the excavated area must be greater than vertical stress that occurs in the backfill to prevent loosening and compacting of backfill and further deformation of roofing.

$\sigma_z > \sigma_1$

In deep thin deposit, a compacting of backfill may be allowed to a certain height, at which the illicit deformations of the earth's surface will not occur and the reduction of safety coefficient K [4].

c) The final event of the second stage occurs at the movement of excavation front so that the getting of chambers is performed between the massive of ore and massive of backfill. The roof is based on excavated ore front, with console of not supported roofing on backfill of length l < l ; l < n· l_e and part of the roofing which is caved under more lying masses. Chamber of excavation is located under the console, where the vertical stresses are reduced. Maximum vertical stress is in front of excavation front in ore massif. And in the excavation chamber at a distance $l < l_k$ there is a zone of reduced vertical stress. At a distance $L > l_k$, the massive and backfill are under concentrated vertical stress, the same as in the ore massif. For finding the necessary strength of backfill to preserve the earth's surface from deformation, it is necessary to take into account the possible allowed backfill compression at which there will be no damage to the earth's surface.

For blind isolated deposits with proper form, influence of size (height) of excavated areas and backfilled area to deformation (settlement) of the earth's surface, depending on the compression properties of backfill, is evaluated based on the safety coefficient whose value should be greater than are permitted by Table 1 [5].

$Ks > Kd = H / \Delta P$

The vertical acceptable size of deformation of backfilled space ΔP is determined by the formula:

$\Delta P = \varepsilon_o h_z (1-e)\sigma_1/\sigma_z$, (m)

where:

ΔP - decrease of height of pillars by backfill under load σ_1, (m)

σ_1 - acting vertical stress, (Pa)

ε_o - deformation characteristics of certain type of backfill

h_z - thickness (height) of backfill pillar

σ_z - strength of backfill to the pressure

K_s - safety coefficient which evaluates the stability of roofing.

The necessary or sufficient strength of backfill σ_z for thin deep deposits can be calculated from the above formula, where due to roofing load backfill will be overloaded and partially compressed. Permitted backfill compression will be ΔP = H/Kd, and the necessary strength of backfill σ_z:

$$\sigma_z = \frac{\sigma_1 \ln \cdot \varepsilon_o h_z}{\ln(\Delta P)}, \text{ (Pa)}$$

3. The stage of performing excavation of protective pillar or chamber which is located between the pillars of hardened protective backfill (in the backfill) is the most dangerous, because the stress concentrations occur in the pillars on both sides from excavated areas. Stresses are added, and can be calculated by equations for σ_p and σ_y. The manifestation of dynamic phenomena and rock bursts can occur in the preparation rooms. Rock bursts will not occur if the rock of pillars is not prone to the accumulation of elastic deformations energy and if concentrated stresses are less than rock hardness to the pressure $\sigma_p < \sigma_{cs}$.

Rock bursts will not occur if the backfill in filled space has a corresponding compressive strength, so that can perform stiffening of ore pillar and ensure the stability of excavation chamber during the excavation. Normative compressive strength backfill in the process of obtaining of chambers between the pillars of backfill materials shall be as follows:

$$\sigma_z = \frac{\sigma_s K_z}{K_f \cdot K_o}$$

where:

σ_s - stress in backfill pillars,

$\sigma_s = K_a K_{h\rho} gH \cdot L_s / 10^6 L_z$,

K_z -coefficient of safety K_z=(1.5-3),

K_f - coefficient of pillar form (given the influence of shape and dimensions of pillar on supporting ability [$K_f=(a/h_s)^{0.5}$ at a>h_s] or [K_f=0.6+0.4 a/h_s at a> h_s];

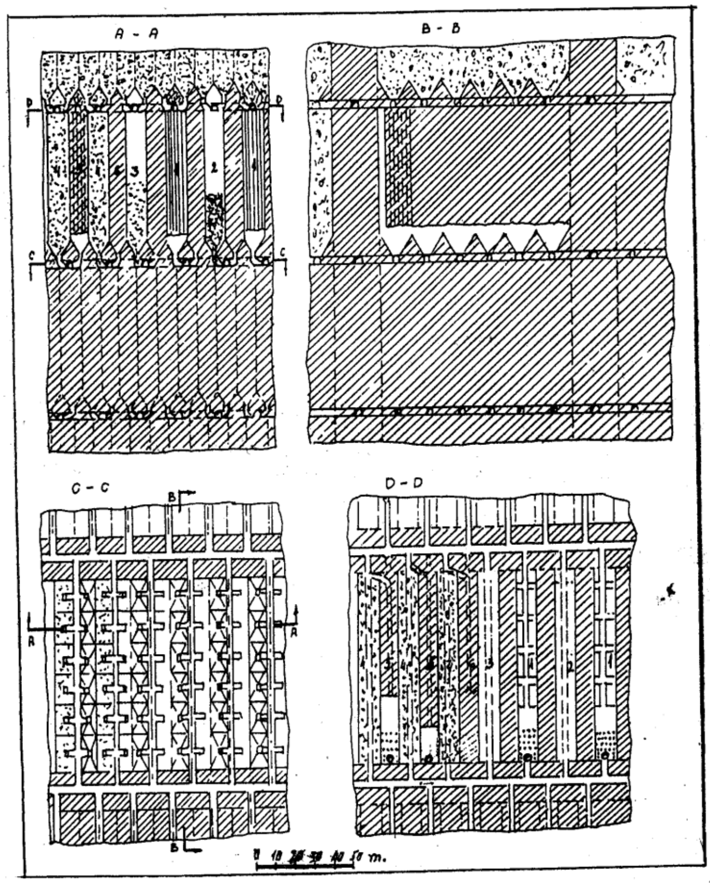

Figure 3 *Stoping with backfilling of chambers and subsequent obtaining of columns*

Table 1 *Safety coefficients*

Object category on surface	Permitted horizontal deformations (mm/m)	K_d - for layers	
		Ore	Coal
I	2.0	150	300
II	3.5	100	200
III	5.5	50	100

a - backfill pillar width,

h_s - height of the pillar from curing backfill),

K_o - coefficient that takes into account the increasing of strength pillars at pressure due to compression; $K_o=\sigma_k/\sigma_o$, H - depth of the upper surface of the pillar,

K_h - coefficient that takes into account the degree of load of backfill pillar by caved rocks from roofing,

L_p - width of the panel block (chamber) in the backfill,

L_z - width of the panel of artificial pillars of backfill.

For the unexplored "in situ" conditions $K_h = 0.5$ and for chambers between the pillars of backfill which are not backfilled $K_h = L / h < 1$, where L - chamber width (undermined pillar).

Strength of backfill materials for ensuring the stability of horizontal rooms respectively, projected span of rooms in the fill is determined by the formula:

$$\sigma_e = K_z [0,49 \rho g H_z \cos \alpha(0.95\text{-}e^{-0.06a})\text{-}1.76], \text{ Pa}$$

Selection of dimensions of chambers and pillars and their arrangement at excavation, strength of backfill of chamber and pillar mining method with storage of ore and subsequent back filling of stopes by curing backfill, if more horizons are dug, should be done by equations ΔP and $\sigma_z = f(\Delta P)$. In them, there will be a change of values $H_z = Nh_H$; H_z- height of backfilled space depends on the N height of excavated horizons h_H. Allowable deformation of backfilling area $\Delta P' = (\Delta_1 + \Delta_2 + \Delta_3)N$ does not depend on the elastic deformation (10 mm) of roofing of each horizon $\Delta 1$ incomplete filling of chambers about 1% Δ_2, and backfill compression due to load $\Delta_3 = \varepsilon_o h_H$, and changes in vertical stress σ_1.

$$\sigma_1 = K\alpha K_v \rho g H_s$$

$$\Delta_p' = H_{sr}/K_d$$

$$\sigma_z = \sigma_1' \cdot \ln\varepsilon_o \cdot N_H h_H / \ln\Delta P'$$

Besides the well-known marks K_v - coefficient which takes the stress change in the fill, depending on the ratio of ore body width and the depth of deposit $K_v = (A_R/H_s) + 0.61$; A_R- size of ore body by stretching or declining.

From this formula it is evident that protection of the earth's surface from deformation besides strength of backfill, its compressibility is an important parameter, because the strength of backfill on pressure may be less than the vertical stress. Pri $\Delta P' = \varepsilon_o N_h h_H$; $\sigma_z = \sigma'$.

CONCLUSION

For the known geometry of layer, physical and mechanical properties of deposit rocks and accompanying rocks of roofing and bottom, and objectives to be achieved, using the chamber pillar mining method with storage of ore and filling the excavated chambers after discharge of ore, curing backfill, in order to obtain the remaining protective pillars from backfill, according to Fig. 3. It is possible on the basis of considered mutual work of deposit rocks and backfill, in chambers filled, to choose the best dynamics of deposit excavation, arrangement of excavation, backfill material of adequate strength and compressibility, etc.

REFERENCES

[1] D. M. Broninkov et al., Backfill Works in the Mines Nedra, Moscow, Russia 1989, p. 146, (In Russian);

[2] V. I. Homyakov, Foreign Experience Tab in the Mines Nedra, Moscow, Russia, 1984, p. 143, (In Russian);

[3] V. R. Imenitov, V. F. Abramov, V. V. Popov, Localization of Emptiness in the Underground Ore Mining, Nedra, Moscow, Russin, 1983, p. 72, (In Russian);

[4] M. Miljković, R. Stanojlović, J. Soko-lović, Safety and Deformation Characteristics of Stopping Materials in Mines, Mining Engineering, Bor, 2(2012), pp. 13-28;

[5] V. Jovičić, M. Miljković, J. Nujić, H. Uljić, M. Vukić, Security Systems in Mining Industry, Tuzla, Univerzal, 1987, p. 423.

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ODREĐIVANJE POTREBNE ČVRSTOĆE ZASIPA PRI POTPUNOM OTKOPAVANJU LEŽIŠTA**

Izvod

Osnovni ciljevi otkopavanja ležišta metodama sa zapunjavanjem otkopanih prostora su: povećanje ili potpuno iskorišćenje ležišta bez osiromašenja rude, otkopavanje ležišta u složenim rudarsko-geološkim uslovima, očuvanje ekoloških faktora u životnoj okolini, poboljšanje ergonomsko sigurnosnih uslova rada i recirkulacija otpadne jalovine.

Za postizanje ovih ciljeva potrebno je u otkope ugrađivati zasipni materijal odgovarajućih fizičko mehaničkih karakteristika, a posebno u pogledu čvrstoće na pritisak. U radu je razmatran postupak izbora zasipnog materijala potrebne čvrstoće pri primeni otkopnih metoda sa zapunjavanjem otkopnih prostora pri potpunom dobijanju ležišta i zaštiti zemljine površine i objekata od oštećenja.

***Ključne reči**: potpuno otkopavanje ležišta, zapunjavanje otkopa, čvrstoća zasipa*

1. UVOD

Potpuno otkopavanje ležišta mineralne sirovine bez osiromašenja rude uz očuvanje ekoloških faktora u eksploatacionom polju može da se realizuje samo otkopnim metodama sa zapunjavanjem otkopanih prostora u uzlaznom ili silaznom poretku otkopavanja i zapunjavanja [1]. Zavisno od ciljeva potpunog otkopavanja ležišta sa zapunjavanjem otkopanih prostora, određuje se potrebna čvrstoća zasipa i bira se vrsta zasipnog materijala kojim se ta čvrstoća može postići [2]. Čvrstoća zasipa naziva se normativnom ako je moguće njime obezbediti sigurno držanje potrebnih otvorenih prostora. To se može postići primenom očvršćavajućeg zasipa [3].

Potpuno dobijanje ležišta bez osiromašenja rude može se realizovati sledećim grupama otkopnih metoda [4]:

1. Etažno otkopavanje hodnicima, strmih rudnih žica i sočiva; a) odozdo na gore, stajanjem opreme na zasipu, b) odozgo na dole, ispod zasipa, kada oprema stoji na čvrstoj steni (rudi).

2. Jednoslojno ili višeslojno otkopavanje moćnih rudnih ležišta; a) vertikalno slojno otkopavanje odozdo na gore, (oprema se kreće po zasipu), b) horizontalno slojno

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** *im proizvodnim sistemima Rudnik bakra Bor i Rudnika bakra Majdanpek" i TR 33038 "Usavršavanje tehnologije eksploatacije i prerade rude bakra sa monitoringom životnog i radnog okruženja u RTB Bor Grupi", koje je finansiralo Ministarstvo za obrazovanje, nauku i tehnološki razvoj Republike Srbije. Autori se zahvaljuju Ministarstvu za finansijsku podršku.*

otkopavanje odozgo na dole, ispod betonske ploče (oprema se kreće po čvrstom podu).

3. Podetažno otkopavanje ležišta sa naknadnim zapunjavanjem otkopa; a) očvršćavajućim zasipom sa kretanjem otkopnog fronta odozdo na gore, b) ispod betonske ploče, sa zapunjavanjem otkopa očvršćavajućim zasipom (kretanjem otkopnog fronta odozgo na dole.

4. Komorno stubno otkopavanje ležišta sa magazioniranjem rude, zapunjavanjem otkopa po istakanju rude očvršćavajućim zasipom i naknadnim dobijanjem zaštitnih stubova rude u zasipu istom otkopnom metodom. Tu se može primeniti: a) panelno i b) unakrsno otkopavanje komora.

U zavisnosti od poretka otkopavanja, konstrukcije i geometrije otkopa, ciljeva, troškova primene otkopne metode, fizičko-mehaničkih karakteristika ležišta i pratećih stena, kao i dubine ležišta, vrši se određivanje potrebne čvrstoće zasipa.

2. ODNOSI PRATEĆIH STENA LEŽIŠTA I ZAPUNJENIH OTKOPANIH PROSTORA U LEŽIŠTU

Čvrstoća stvrdnjavajućeg zasipa je zadovoljavajuća (normativna) ako je moguće sigurno otvaranje veštačkog, (zasipnog), masiva projektovanim rudničkim prostorijama i otkopima, i ako obezbeđuje očuvanje zemljine površine i objekata iznad ležišta od deformacija. Na masiv od zasipnog materijala deluju gravitacione i tektonske (statičke) i od minerskih radova (dinamičke) sile. Masa zapunjenog otkopa može biti podvrgnuta deformacijama usled pritiska, rastezanja, smicanja, izuvijanja u uslovima jednoosnog, dvoosnog i zapreminskog napregnutog stanja. Za izbor i kontrolu potrebne čvrstoće zasipnog materijala, s obzirom na uloge koje treba da zadovolji, nezavisno od karaktera opterećenja, čvrstoća zasipnog materijala bira se prema potrebnoj čvrstoći na jednoosni pritisak.

Potrebna čvrstoća zasipnog materijala određuje se po jednom ili više faktora:

a) stabilnosti (držanja) vertikalnih otvorenih bokova
b) horizontalno otvorenih plafona,
c) dopuštenih deformacija zemljine površine,
d) mogućnosti kretanja opreme po površini zasipa itd.

Masa od zasipnog materijala i okolne stene, u određenim uslovima obrazuju složeni prostorni sistem zasip - stene. Glavni strukturni elementi takvog sistema - stene krovine i podine i zasipnog prostora, veoma se razlikuju.

Proračun potrebne čvrstoće zasipa bazira se na znanjima o naponsko - deformacionim karakteristikama prirodnog stenskog i veštačkog, (od zasipa), masiva u zoni otkopavanja, karaktera njihovog uzajamnog delovanja i svodi se na rešavanje triju zadataka.

1. Nalaženja opterećenja na masu zasipanog otkopa
2. Određivanja napona u zasipu kao sastavnom elementu sistema stene, (stena zasipani prostor).
3. Utvrđivanja neophodne čvrstoće zasipa, koja proističe iz potrebnog koeficijenta pokazanosti, (sigurnosti), za određeno naponsko stanje, uz uticaj ostalih tehnoloških faktora pri otkopavanju ležišta.

Opterećenje na veštački masiv zasipa u otkopu zavisi: od fizičko-mehaničkih karakteristika okolnih stena, napona u njima, geometrije zapunjenog otkopa, (veličine, dubine i nagiba), i fizičko-mehaničkih karakteristika zasipa, kao i od uloge koju konstrukcija od zasipnog materijala ispunjava u toku dalje eksploatacije i po završetku eksploatacije ležišta.

Pri potpunom otkopavanju ležišta (otkop uz predhodni zapunjeni otkop), u krovini ležišta, u blizini otkopa, obrazuje se zona smanjenog pritiska (rasterećenja), a u rudnom masivu ispred fronta napredovanja otkopa pojavljuje se zona povišenog oslonačkog pritiska sl. 1. Sa povećanjem širine otkopanog prostora i zapunjenog prostora, stene krovine i zasip u zapunjenom prostoru ponašaju se kao okolne stene i popustljiva podgrada, dok zasip ne primi celokupno opterećenje stuba krovinskih stena. Opterećenje na otkopu potiče od ploče stena krovine, koja se jednim delom oslanja na zasipani deo otkopa, a drugim delom na rudni masiv. Dimenzije zone rasterećenja su proporcionalne deformacionim karakteristikama zasipa ε. Deformaciona karakteristika zasipa zavisi od vrste zasipa i načina ugradnje. Pri $\varepsilon \leq 3\%$ pomeranje nalegajućih stena vrši se povijanjem bez pucanja i komadanja. Pri $\varepsilon \geq 3\%$ u krovini dolazi do pucanja i raslojavanja stena.

Vrednost koeficijenta koncentracije napona u rudnom masivu određuje se na osnovu širine otkopanog prostora L i koncentracije napona u rudnom masivu, po obrascima:

$$K_k = 2,1 - 1,1\ e^{-(L/80)^{1,5}}$$

$$K_k = (0,8\ l_e \cdot n+14)H^{-0,33}$$

gde su:

e - osnova prirodnog logaritma

L - širina otkopanog prostora m, $L = n \cdot l_e$

l_e - širina otkopa (trake, sloja) u dobijanju (ekvivalentna stubna širina plafona otkopa)

n - broj traka u jednovremenom dobijanju do postizanja kritične širine $l_k= n \cdot l_e$

H - dubina izvođenja radova za koju su vezani naponi u krovu;

$\tau = \rho g H$, (Pa)

Ispitivanja su pokazala da maksimalni oslonački pritisak, pri širini otkopnog prostora L = 30 - 40 m iznosi (1,5 - 1,6)ρgH. Maksimum se nalazi na 15-20 m od čela otkopnog fronta, a širina opterećene zone iznosi oko 50 m. Zasipni materijal trpi opterećenje tek pri širini otkopanog prostora 40 - 60 m.

Pri otkopavanju ležišta ispod zasipa, zasipni materijal igra ulogu veštačke krovine, ispod koje se takođe obrazuje zona rasterećenja u zoni otkopa i zone oslonačkog pritiska na bokove ispred čela otkopnog fronta i u zapunjenom prostoru. Opterećenje zavisi od sopstvene težine zasipa i pritisku krovinskih stena, ako su već pretrpele deformacije.

3. POTREBNA ČVRSTOĆA ZASIPA PRI OTKOPAVANJU KOMORA ZA ZAPUNJAVANJEM

Ekonomično otkopavanje masivnih siromašnih (niske vrednosti) rudnih ležišta primenom otkopnih metoda sa zapunjavanjem otkopanih prostora, može da se izvrši samo primenom visoko produktivnih otkopnih metoda. Jedna od njih može biti komorno stubna otkopna metoda sa magazioniranjem rude, zapunjavanjem komora po istakanju rude očvršćavajućim zasipom i naknadnim dobijanjem zaštitnih stubova rude istom otkopnom metodom, za koju treba izvršiti analizu potrebne čvrstoće zasipa (sl. 2.).

Potrebna čvrstoća zasipa može se posmatrati za tri stadijuma u kojima se može naći stub od zasipnog materijala u otkopnom prostoru.

1. Kada se komora nalazi između za-štitnih stubova od rude (I stadijum).
2. Kada se komora nalazi između stuba od rude i stuba očvrslog zasipa susedne otkopane komore (II stadijum) ili zapunjenog prostora.
3. Kada se komora nalazi između zaštitnih stubova od očvrslog zasipa.

1. U prvom stadijumu zasip u komori neće biti opterećen nikakvim vertikalnim opterećenjem više ležećih stena, osim sopstvenom masom. Bočno opterećenje u stubu zasipa može se pojaviti usled deformacija bokova komore. Stabilni raspon plafona komore (l_e) određuje se iz strogih uslova stabilnosti rudničkih prostorija i otkopa, odnosno plafona komora.

Stabilnost potkopanog plafona prema ktiričnim deformacijama određuje se iz uslova.

$g_r > g_d$

gde su:

g_d - dopuštena deformacija plafona, pri kojoj je plafon komore stabilan.

g_r - relativna deformacija plafona komore. Ona se određuje po formuli:

$g_r = 1/[1+(H_R/le)^f]$

H_R - redukovana za uslove monolitnog masiva, dubina plafona komore

$H_R=(1-K_g)\ H_k$

H_k - debljina krovine od nanosa na površini do ravni plafona komore

K_g - koeficijent gubitka stabilnosti plafona zbog raspucalosti i strukturnih osobina stena (zavisno od RQD karakteristike). Njegova vrednost može biti određena na osnovu procenta izvađenog jezgra

$K_g = 0{,}84 + 0{,}01\ Nj - 0{,}0002\ Nj^2$

gde su:

Nj - procenat izvađenog jezgra (često se prikazuje visoka vrednost)

f - koeficijent čvrstoće stena po Protodjakonovu

l_e - ekvivalentni stabilni raspon šupljine (širine) komore

Ekvivalentni stabilni raspon (širina) komore može biti određen, ako se usvoje granični uslovi, i formula reši eksplicitno po l_e.

g < 0,001 - stabilni raspon komore

g = (0,001-0,04) - stanje između stabilnosti i potpunog zarušavanja

g ≤ 0,04 - potpuno obrušavanje nalegajuće krovine

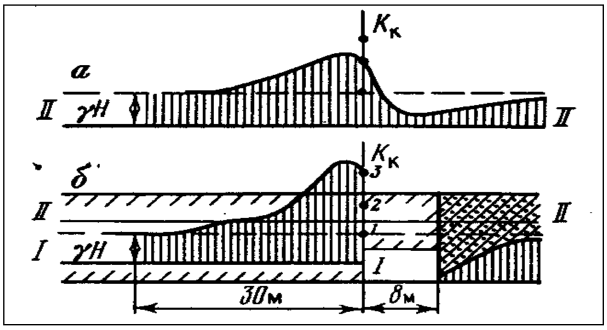
$$l_e = \sqrt[f]{\frac{gH_R{}^f}{1-g}} = H_R\sqrt[f]{\frac{g}{1-g}}\ , \quad \text{(m)}$$

Naponi će se koncentrisati u bokovima komore prema sl. 1.

Oni se neće prenositi na zasip u komori, ili čak i više komora, dok šupljina ispod podkopane krovine ne dostigne kritičan raspon (govori se o šupljini jer se pri zapunjavanju otkopa nikad neće potpuno poduhvatiti krovina).

$$l_k = H_k\ \sqrt[f]{\frac{g}{1-g}}\ , \text{(m)}$$

pri g > 0,04



Sl. 1. *Grafik promene koncentracije napona u rudnom i masivu od zasipa*

2. Drugi stadijum položaja komora u otkopavanju i zapunjenog prostora je najčešći. Pri eksploataciji velikih strmih rudnih tela, kritični raspon otkopanog prostora pri kome dolazi do zarušavanja krovine, manji je od dužine otkopnog fronta. Zarušeni blokovi stena opterećivaće zapunjeni prostor. Ako je zasip stišljiv (plastičan) doći će do većih deformacija u krovini, pa čak i do deformacija zemljine površine (kod plićih ležišta). Ipak zapunjeni prostor predstavlja zonu rasterećenja. Pri kretanju otkopnog fronta od periferije rudnog tela, prema prostorijama otvaranja, mogu se prijaviti sledeći slučajevi rasporeda napona:

a) Iznad prvih otkopanih komora pri širini otkopanog prostora L = $nl_e < l_k$ (stabilne ekvivalentne širine) u krovini otkopa pojavljuju se zatezni naponi, a nabokovima otkopa i neporemećenih stena koncentrišu se naponi pritiska, zavisno od širine otkopanog prostora. Koeficijent koncentracije napona određuje se po formuli za K_k, pa vertikalni napon u masivu iznosi:

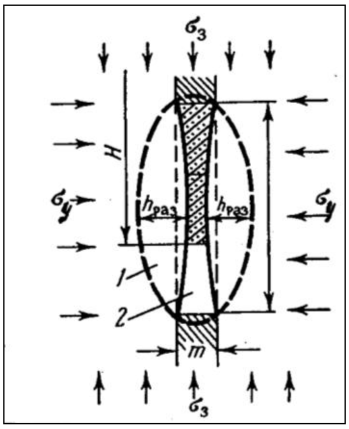
$\sigma_p = K_k \rho_s gH$, (Pa)

Horizontalni napon σ_y na boku komore prema slici 2. iznosi:

$$\sigma_y = \frac{\mu}{1-\mu} K_k \rho_s gH \text{ , (Pa)}$$

gde je:

μ - koeficijent Pausona μ = (0,4÷0,6) (koeficijent bočnog opterećenja)



Sl. 2. *Šema za proračun napona iz zaštitnih stubova na zasip u komori*

Koeficijent koncentracije napona kako ispred čela otkopnog fronta u rudniku, tako i u krajnjim stubovima od zasipa povećavaće se sa otkopavanjem svake naredne komore, dok raspon otkopanog prostora ne pređe kritičnu širinu $L > l_k$.

b) Kada bude otkopano više komora, tako da raspon otkopanog prostora L postane nestabilan ili se zaruši, doći će do pojave vertikalnog napona i u masivu od zasipa. Veličina vertikalnog napona koji se može pojaviti u veštačkim stubovima od zasipa proračunava se koristeći princip istovremene deformacije kombinovanih oslonaca, stubova od rude i stubova zasipa po formuli:

$$\sigma_1 = \frac{K_a \rho_s gHS_k}{10^6 (S_z + 0{,}77 S_p \frac{E_s}{E_z})} + 10^{-6} \rho_z gh_z$$

gde su:

ρ_s; ρ_z - gustine stenskog materijala i zasipnog materijala

H - dubina plafona otkopanog prostora

Sk; Sz - površine stubova rude i stubova od zasipa

Es; Ez - moduli deformacije stena rudnog ležišta i zasipnog materijala

K_a - koeficijent uticaja ugla nagiba ležišta na opterećenje zasipa

$K_a = \cos^2\alpha - \eta \sin^2\alpha$; $\eta = \mu/(1 - \mu)$

h_z - visina stuba od zasipa (visina otkopanog i zapunjenog prostora)

α - ugao nagiba ležišta (nagib zapunjene šupljine).

Čvrstoća zasipa u otkopanom prostoru mora biti veća od vertikalnog napona koji se pojavljuje u zasipu, da ne bi došlo do popuštanja i sabijanja zasipa i dalje deformacije krovine.

$\sigma_z > \sigma_1$

Kod dubokih tankih ležišta može se dopustiti i sabijanje zasipa do određene visine, pri kojoj neće doći do nedopuštenih deformacija zemljine površine i smanjenja koeficijenta sigurnosti K [4].

c) Krajnji slučaj drugog stadijuma pojavljuje se pri kretanju otkopnog fronta tako da se dobijanje komora vrši između masiva rude i masiva zasipa. Krovina se oslanja na otkopni front rude, sa konzolom ne oslonjene krovine na zasip dužine l < l ; l< n· l_e i dela krovine koji je popustio pod naponom višeležećih masa. Komora u otkopavanju se nalazi u zoni ispod konzole, gde su vertikalni naponi smanjeni. Maksimalni vertikalni napon se nalazi ispred otkopnog fronta u rudnom masivu. I za komore u otkopavanju na rastojanju $l < l_k$ nalazi se zona smanjenog vertikalnog napona. Na rastojanju $L > l_k$ i masiv zasipa se nalazi pod koncentrisanim vertikalnim naponom istim kao u rudnom masivu.

Za iznalaženje potrebne čvrstoće zasipa za očuvanje zemljine površine od deformacija potrebno je uzeti u obzir moguće dopušteno sabijanje zasipa pri kome neće doći do oštećenja zemljine površine.

Za slepa izolovana ležišta pravilnog oblika, uticaj dimenzija (visine) otkopanog i zapunjenog područja na deformaciju (sleganje) zemljine površine u zavisnosti od kompresionih svojstava zasipa ocenjuje se na osnovu koeficijenta sigurnosti, čija vrednost treba da bude veća od dopuštene prema tabeli 1 [5].

Ks > Kd = H / ΔP

Vertikalna prihvatljiva veličina deformacije zasipanog prostora ΔP određuje se po formuli:

$\Delta P = \varepsilon_o h_z (1\text{-}e)\sigma_1/\sigma_z$, (m)

gde su:

ΔP - smanjenje visine stuba od zasipa pod opterećenjem σ_1, (m)

σ_1 - dejstvojući vertikalni napon, (Pa)

ε_o - deformaciona karakteristika određene vrste zasipa

h_z - debljina (visina) stuba zasipa

σ_z - čvrstoća zasipa na pritisak

K_s - koeficijent sigurnosti kojim se ocenjuje stabilnost krovine

Iz prethodne formule može se izračunati potrebna ili dovoljna čvrstoća zasipa σ_z za tanka duboka ležišta, kod kojih će usled opterećenja krovine zasip biti preopterećen i delimično sabijen. Dopušteno sabijanje zasipa biće ΔP = H/Kd , a potrebna čvrstoća zasipa σ_z:

$$\sigma_z = \frac{\sigma_1 \ln \cdot \varepsilon_o h_z}{\ln(\Delta P)} \text{, (Pa)}$$

3. Stadijum kada se vrši otkopavanje zaštitnog stuba ili komore koja se nalazi između zaštitnih stubova od očvrslog zasipa (u zasipu) je najopasniji, jer u stubovima dolazi do koncentracije napona sa obe strane iz otkopanih prostora. Naponi se sabiraju, a mogu se proračunati po formulama za σ_p i σ_y. U pripremnim prostorijama može doći do ispoljavanja dinamičkih pojava i gorskih udara. Do gorskih udara neće doći ako stena stuba nije sklona akumulaciji energije elastične deformacije i ako su koncentrisani naponi manji od čvrstoće stene na pritisak $\sigma_p < \sigma_{cs}$.

Do ispoljavanja gorskih udara neće doći i ako zasip u zapunjenom prostoru ima odogovarajuću pritisnu čvrstoću, tako da može da izvrši ukrućenje stuba rude i obezbedi stabilnost otkopne komore pri otkopavanju. Normativa pritisna čvrstoća zasipa u fazi dobijanja komora između stubova od zasipnog materijala treba da iznosi:

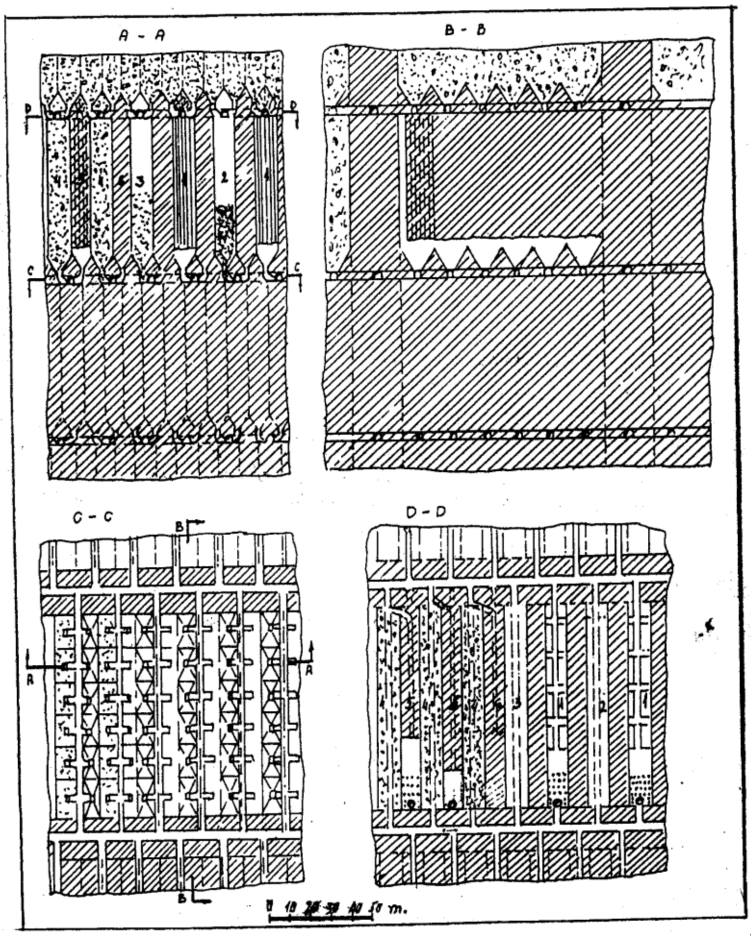
$$\sigma_z = \frac{\sigma_s K_z}{K_f \cdot K_o}$$

gde su:

$\sigma_s = K_a K_{h\rho} gH \cdot L_s / 10^6 L_z$ - napon u stubovima zasipa

K_z - koeficijent sigunosti K_z=(1,5-3)

K_f - koeficijent forme stuba. S obzirom na uticaj oblika dimenzija stuba na noseću sposobnost [$K_f=(a/h_s)^{0,5}$ pri $a>h_s$] ili [K_f=0,6+0,4 a/h_s pri $a> h_s$];



Sl. 3. *Otkopavanje sa zapunjavanjem komora i naknadnim dobijanjem stubova*

Tabela 1. *Koeficijenti sigurnosti*

Kategorija objekata na površini	Dopuštene horizontalne deformacije (mm/m)	K_d - za ležišta	
		Rudna	Ugljena
I	2,0	150	300
II	3,5	100	200
III	5,5	50	100

a - širina stuba zasipa,

h_s - visina stuba od očvršćavajućeg zasipa

K_o - koeficijent kojim se uzima u obzir povećanje čvrstoće stubova na pritisak usled sabijanja; $K_o = \sigma_k/\sigma_o$

H - dubina gornje površine stuba

K_h - koeficijent kojim se uzima u obzir stepen opterećenja stuba zasipa obrušenim stenama krovine

L_p - širina panela bloka (komore) u zasipu

L_z - širina panela veštačkih stubova od zasipa

Za neistražene "in situ" uslove K_h=0,5 $\frac{L}{H} < 1$, a za komore između stubova od zasipa koje nisu zapunjenje K_h=L / h <1, gde je L - širina komore (potkopanog stuba).

Čvrstoća zasipnog materijala za obezbeđenje stabilnosti horizontalnih prostorija odnosno, projektovanih raspona prostorija u zasipu određuje se po formuli:

$$\sigma_e = K_z\,[0{,}49\,\rho g H_z \cos\alpha(0{,}95\text{-}e^{-0{,}06a})\text{-}1{,}76]\ \text{Pa}$$

Izbor dimenzija komora i stubova i njihovog rasporeda pri otkopavanju, čvrstoće zasipa kod komorno stubne otkopne metode sa magazioniranjem rude i naknadnim zapunjavanjem odkopa očvršćavajućim zasipom, ako se otkopava više horizonata treba da se izvrši po formulama za ΔP i $\sigma_z = f(\Delta P)$. U njima će doći do izmena vrednosti veličina. $H_z = Nh_H$; H_z- visina zasipanog prostora zavisi od N visina otkopanih horizonata h_H. Dopuštena deformacija zasipnog prostora $\Delta P' = (\Delta_1 + \Delta_2 + \Delta_3)N$ ne zavisi od elastične deformacije (10 mm) krovine svakog horizonta Δ1 nepotpunog zapunjavanja komora oko 1% Δ_2, i sabijanja zasipa usled opterećenja $\Delta_3 = \varepsilon_o h_H$, kao i promene vertikalnog napona σ_1.

$$\sigma_1 = K\alpha K_v\,\rho g H_s$$

$$\Delta_p' = H_{sr}/K_d$$

$$\sigma_z = \sigma_1'\cdot\ln\varepsilon_o\cdot N_H h_H / \ln\Delta P'$$

Pored poznatih oznaka K_v - koeficijent kojim se uzima promena napona u zasipu u zavisnosti od odnosa širine rudnog tela i dubine ležišta $K_v = (A_R/H_s) + 0{,}61$; A_R-dimenzija rudnog tela po pružanju ili padu.

Iz ovih formula vidi se da je za zaštitu zemljine površine od deformacija pored čvrstoće zasipa, bitan parametar njegova stišljivost, jer čvrstoća zasipa na pritisak može biti i manja od vertikalnog napona. Pri $\Delta P' = \varepsilon_o N_h h_H$; $\sigma_z = \sigma'$.

ZAKLJUČAK

Za poznatu geometriju ležišta, fizičko-mehaničke karakteristike stena ležišta i pratećih stena krovine i podine, kao i ciljeva koji se žele postići, primenom komorno stubne otkopne metode sa magazioniranjem rude i zapunjavanja otkopanih komora nakon istakanja rude, očvršćavajućim zasipom, u cilju dobijanja zaostalih zaštitnih stubova iz zasipa, prema slici 3 moguće je na osnovu razmotrenog uzajamnog rada stena ležišta i zasipa u zapunjenim komorama odabrati najpovoljniju dinamiku otkopavanja ležišta, raspored otkopa, zasipni materijal odgovarajuće čvrstoće i stišljivosti, itd.

LITERATURA

[1] D. M. Broninkov i sarad., Backfill works in the mines Nedra, Moscow, Russia 1989, p. 146. (In Russian)

[2] V. I. Homyakov, Foreign experience tab in the mines Nedra, Moscow, Russia, 1984, p. 143. (In Russian)

[3] V. R. Imenitov, V. F. Abramov, V. V. Popov, Localization of emptiness in the underground ore mining (In Russian), Nedra, Moscow, Russin, 1983, p. 72.

[4] M. Miljković, R. Stanojlović, J. Sokolović, Sigurnosne i deformacione karakteristike zasipnih materijala u rudnicima, Rudarski radovi, Bor, 2(2012), str. 13-28.

[5] V. Jovičić, M. Miljković, J. Nujić, H. Uljić, M. Vukić, Sigurnost i tehnička zaštita u rudarstvu, Tuzla, Univerzal, 1987, p. 423.

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ANALYSIS THE LONG-TERM DEVELOPMENT OF THE OPEN PIT NORTH MINING DISTRICT MAJDANPEK FOR THE CAPACITY OF $5x10^6$ TONS OF ORE ANNUALLY[***]

Abstract

The work presents a consideration of a long-term development of the open pit North Mining District in terms of achieving maximum profit for the planned capacity of 5 million tons of copper ore annually, using the modern software Whittle for strategic planning of production. Software provides the ability to achieve a positive development of cash flow and maximum net present value by optimization the excavation limit and long-term mining dynamics. For planned technical and economic parameters, which are the input data for analysis, the boundary of the open pit is obtained for the service life of 26 years, and the value of the net present value is $ 252,591,906.

Keywords: *open pit North Mining District Majdanpek, optimization, development phase of open pit, cash flow, net present value, software Whittle*

INTRODUCTION

Within the company, Copper Mine Majdanpek, which is part of the company Mining and Smelting Basin Bor (RTB Bor), there are two open pit mines as well as the North Mining District and South Mining District. Since the deposit stripping is done at the open pit South Mining District, the holder of copper ore production in recent years is the North Mining District with a capacity of 3.5 million tons per year. The construction of a new smelter in Bor It is necessary to provide the raw material for operation the New Smelter in Bor through increasing the capacity of excavation at open pit mines operating within RTB Bor. Due to this, an analysis of possibilities for long-term mining of copper ore at the open pit North Mining District Majdanpek for a capacity of 5 million tons per year, which includes:

1) optimization the open pit and selection the optimum contour of open pit
2) defining the mining phase (pushbacks)
3) optimization the mining dynamics
4) economic analysis in the Whittle software, which is based on an analysis of trends the discounted cash flow over the mining period, or the realized net present value, and that is an indicator of achieved economic results of mining the North Mining District for the given initial conditions.

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Techno-economic analysis was carried out for the part of the copper deposits "North Mining District - Majdanpek" and deposit of polymetallic mineral resources (Zn-Pb-Cu) "Tenka - North Mining District Majdanpek" in the software Whittle.

TECHNO-ECONOMIC PARAMETERS FOR ANALYSIS

A long term development of the open pit is defined on the basis of the following initial techno-economic parameters [1].

1 Mining recoveries and dilutions

- Dilution of copper ore 4.0%
- Dilution of lead-zinc ore 6.0%
- Exploitation losses of copper ore 4.0%
- Exploitation losses of PbZn ore 6.0%

2 Flotation recoveries:

Cu ore:

- Cu recovery 82.0%
- Ag recovery 50.0%
- Au recovery 50.0%

Pb-Zn ore:

- Zn recovery 60.0%
- Pb recovery 60.0%
- Ag recovery 51.5%
- Au recovery 35.0%

3 Metallurgical recoveries:

Cu concentrate:

- Cu recovery 95.0%
- Ag recovery 90.0%
- Au recovery 90.0%

Pb-Zn concentrate:

- Zn recovery 96.5%
- Pb recovery 95.0%
- Ag recovery 90.0%
- Au recovery 90.0%

4. Selling prices of metals:

- Copper (Cu) 6,000 US $/t
- Silver (Ag) 800 US $/kg
- Gold (Au) 30,000 US $/kg
- Zinc (Zn) 1,800 US $/t
- Lead (Pb) 1,800 US $/t

5 Metal values in concentrate:

Cu concentrate:

- Copper (6.000 – 600) = 5,400 US $/t,
- Gold (30.000 – 150) = 29,850 US $/kg
- Silver (800 – 15) = 785 US $/kg

Pb-Zn concentrate:

- Zinc (1,800×0.55) = 990 US $/t
- Lead (1,800×0.55) = 990 US $/t
- Gold (30,000×0.93) = 27,900 US $/kg
- Silver (800×0.88) = 700 US $/kg
- Profit 0.55%

6 Mining costs:

- Ore and waste mining 2.0 US $/t excavation

7 Flotation costs:

- Cu flotation 4.0 US $/t ore
- Pb-Zn flotation 6.0 US $/t ore

8 Metallurgical treatment costs:

- Cu concentrate: 600 US $/t concentrate
- Pb-Zn concentrate: 0.45 %

9 Adopted discount rate 10%

CAPACITY OF MINING AND DISPOSAL

The planned value of ore mining capacity per annum is as follows:

- in the 1st year of 3,000,000 t of ore
- from the 2nd year until the end of exploitation period 5,000,000 t of ore

Capacity of waste mining is limited to 16 million tons in the first year of operation. From the second to the fourteenth year, the mining capacity of waste is 14 million tons per year, and then has steadily declined, except for the period from the eighteenth to the twentieth year when it is at the level of 12 ÷ 13 million tons (Table 3).

Figure 1 shows the landfill Mali Ujevac and West landfill. The spatial capacity of these landfills allows accommodation of the total amount of waste that is mined during the exploitation period.

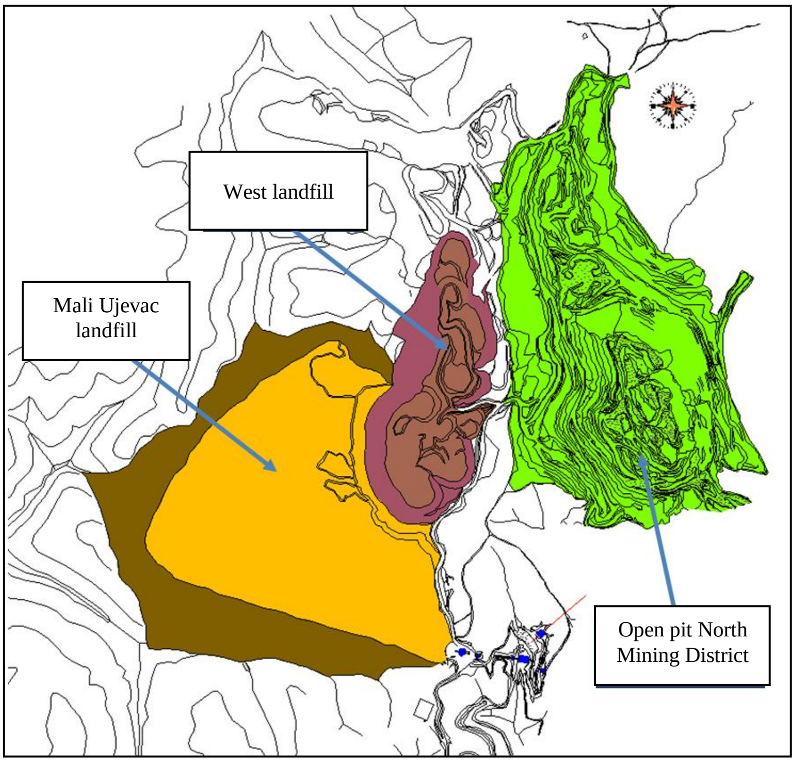

Figure 1 *View the landfill location of the open pit North Mining District*

OPTIMIZATION THE BOUNDARY OF THE OPEN PIT

An optimal boundary of open pit mining for the established techno - economic parameters was determined using the software Whittle for optimization and strategic planning of the open pits [2], [3]. The software generates several possible optimal contours of the open pits, using the revenue factor (Revenue Factor). The obtained open pits (85 open pits were generated and shown in Table 1 and Figure 2) are further analyzed and selection of optimum open pits is done according to the criteria of discounted present value. The open pit No.31 was selected for further consideration [4].

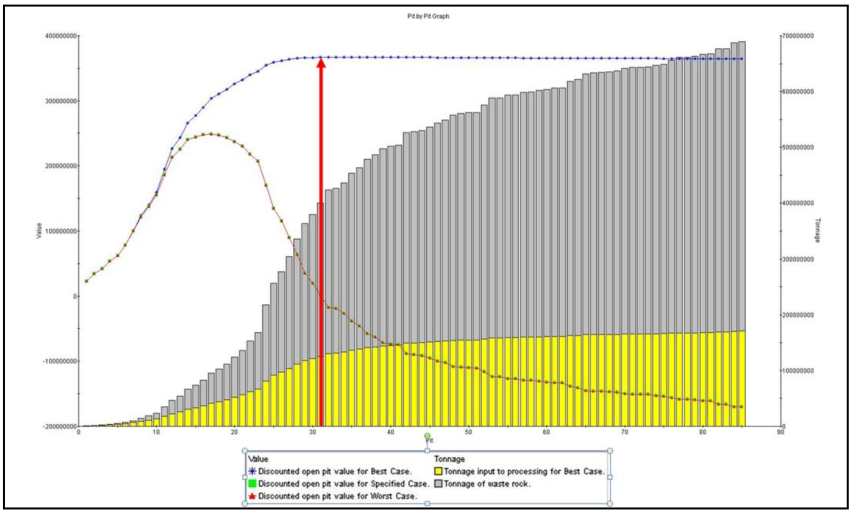

Figure 2 *Graphical presentation the optimization results of open pit and selection the optimal contour*

Table 1 *Results of open pit optimization and selection the optimal contour*

Kop	Faktor prihoda	Cena metala (Cu)	Ruda	Jalovina	Iskopine	Novčani tok best	Novčani tok specified	Novčani tok worst
		($)	(t)	(t)	(t)	($ disc)	($ disc)	($ disc)
1	0.30	1 800	968 181	203 712	1 171 893	22 584 296	22 584 296	22 584 296
2	0.32	1 920	1 623 849	450 874	2 074 723	34 312 916	34 312 916	34 312 916
3	0.34	2 040	2 123 198	606 769	2 729 967	41 789 193	41 789 193	41 789 193
4	0.36	2 160	2 929 255	1 092 474	4 021 729	53 519 286	53 519 286	53 519 286
5	0.38	2 280	3 650 220	1 318 562	4 968 782	62 533 173	62 494 501	62 494 501
6	0.40	2 400	4 902 725	2 181 611	7 084 336	78 708 554	78 355 255	78 355 255
7	0.42	2 520	7 071 396	3 160 726	10 232 122	100 864 035	99 630 269	99 630 269
8	0.44	2 640	9 286 522	5 407 075	14 693 597	123 819 279	121 872 114	121 872 114
9	0.46	2 760	11 067 156	7 406 268	18 473 424	140 301 765	137 641 992	137 641 992
10	0.48	2 880	13 157 839	10 175 045	23 332 884	159 260 909	155 303 894	155 303 894
11	0.50	3 000	17 927 373	16 712 768	34 640 141	194 754 291	186 303 811	186 303 811
12	0.52	3 120	22 711 807	23 883 135	46 594 942	226 403 804	213 021 965	213 021 965
13	0.54	3 240	25 863 252	28 182 396	54 045 648	243 162 846	226 051 272	226 051 272
14	0.56	3 360	30 724 154	35 998 077	66 722 231	266 129 304	240 625 139	240 625 139
15	0.58	3 480	33 477 175	40 271 845	73 749 020	277 057 488	244 277 282	244 277 282
16	0.60	3 600	37 192 913	45 485 293	82 678 206	289 634 825	247 798 051	247 798 051
17	0.62	3 720	41 443 508	53 842 480	95 285 988	303 274 051	248 883 219	248 883 219
18	0.64	3 840	44 205 134	58 448 831	102 653 965	310 218 420	247 430 866	247 430 866
19	0.66	3 960	47 502 042	64 495 812	111 997 854	317 462 626	243 140 799	243 140 799
20	0.68	4 080	52 113 561	71 835 689	123 949 250	325 693 173	237 056 568	237 056 568
21	0.70	4 200	56 271 861	79 412 771	135 684 632	332 198 250	230 075 464	230 075 464
22	0.72	4 320	62 083 245	90 431 004	152 514 249	339 836 560	218 071 798	218 071 798
23	0.74	4 440	66 812 254	101 754 105	168 566 359	345 104 837	207 145 863	207 145 863
24	0.76	4 560	81 051 136	136 436 453	217 487 589	354 419 784	170 356 756	170 356 756
25	0.78	4 680	91 336 065	164 736 025	256 072 090	359 366 452	134 967 260	134 967 259
26	0.80	4 800	96 781 199	180 400 615	277 181 814	361 514 656	115 608 954	115 608 954
27	0.82	4 920	103 600 175	200 782 071	304 382 246	363 567 340	89 619 201	89 619 201
28	0.84	5 040	111 265 885	223 954 422	335 220 307	365 078 953	63 384 591	63 384 592
29	0.86	5 160	117 624 186	246 149 900	363 774 086	365 958 572	34 954 332	34 954 331
30	0.88	5 280	121 256 159	258 605 230	379 861 389	366 383 339	20 018 724	20 018 724
31	0.90	5 400	125 341 356	275 079 007	400 420 363	366 729 762	2 206 940	2 206 940
32	0.92	5 520	130 350 079	293 650 437	424 000 516	366 951 984	-16 975 286	-16 975 286
33	0.94	5 640	131 114 588	295 642 962	426 757 550	366 989 137	-18 886 086	-18 886 085
34	0.96	5 760	132 767 039	303 470 052	436 237 091	367 047 835	-26 505 753	-26 505 753
35	0.98	5 880	136 322 733	317 495 007	453 817 740	367 087 144	-38 381 780	-38 381 779
36	1.00	6 000	138 161 223	324 956 295	463 117 518	367 078 291	-45 537 457	-45 537 457
37	1.02	6 120	140 999 315	337 397 231	478 396 546	367 015 651	-57 484 923	-57 484 923
38	1.04	6 240	142 503 976	344 682 084	487 186 060	366 967 239	-62 747 899	-62 747 899
39	1.06	6 360	144 045 206	353 072 457	497 117 663	366 911 456	-71 308 357	-71 308 357
40	1.08	6 480	145 132 029	356 664 572	501 796 601	366 875 490	-73 811 425	-73 811 424
41	1.10	6 600	145 473 922	358 036 674	503 510 596	366 860 881	-74 384 990	-74 384 989
42	1.12	6 720	149 261 428	377 080 767	526 342 195	366 632 022	-88 296 985	-88 296 985
43	1.14	6 840	149 466 138	378 583 793	528 049 931	366 614 915	-89 578 295	-89 578 295
44	1.16	6 960	150 016 034	379 958 771	529 974 805	366 585 864	-91 100 702	-91 100 702
45	1.18	7 080	150 850 043	385 656 957	536 507 000	366 504 709	-94 941 362	-94 941 362
46	1.20	7 200	151 819 471	391 796 162	543 615 633	366 423 017	-99 707 899	-99 707 899
47	1.22	7 320	152 797 499	395 913 378	548 710 877	366 360 418	-101 886 755	-101 886 755
48	1.24	7 440	154 095 441	404 049 312	558 144 753	366 242 969	-108 521 828	-108 521 828
49	1.26	7 560	154 593 811	405 961 093	560 554 904	366 208 247	-109 366 215	-109 366 214
50	1.28	7 680	154 781 049	407 179 922	561 960 971	366 188 588	-110 048 394	-110 048 394
51	1.30	7 800	154 934 895	407 843 052	562 777 947	366 176 200	-110 353 097	-110 353 097
52	1.32	7 920	156 991 452	419 211 707	576 203 159	365 977 282	-116 030 127	-116 030 127
53	1.34	8 040	158 440 134	429 798 959	588 239 093	365 812 883	-123 772 863	-123 772 863
54	1.36	8 160	158 496 574	429 947 801	588 444 375	365 809 317	-123 864 339	-123 864 338
55	1.38	8 280	159 556 554	434 348 748	593 905 302	365 723 291	-126 450 957	-126 450 957
56	1.40	8 400	159 595 857	434 537 270	594 133 127	365 719 666	-126 479 454	-126 479 454
57	1.42	8 520	160 056 057	437 834 259	597 890 316	365 664 818	-128 701 097	-128 701 098
58	1.44	8 640	160 324 985	439 293 394	599 618 379	365 638 059	-129 382 131	-129 382 131
59	1.46	8 760	160 579 643	441 490 045	602 069 688	365 603 014	-130 873 799	-130 873 799
60	1.48	8 880	160 755 538	442 824 454	603 579 992	365 580 228	-131 908 169	-131 908 169
61	1.50	9 000	161 049 360	445 038 006	606 087 366	365 542 337	-133 029 393	-133 029 393
62	1.52	9 120	161 058 864	445 077 723	606 136 587	365 541 347	-133 056 955	-133 056 955
63	1.54	9 240	162 575 935	455 695 298	618 271 233	365 357 635	-138 432 927	-138 432 926
64	1.56	9 360	163 095 722	458 654 209	621 749 931	365 302 145	-140 311 918	-140 311 918
65	1.58	9 480	164 216 904	467 639 247	631 856 151	365 154 330	-145 360 524	-145 360 524
66	1.60	9 600	164 397 954	468 929 719	633 327 673	365 133 146	-145 788 727	-145 788 727
67	1.62	9 720	164 519 005	469 717 084	634 236 089	365 119 229	-146 339 169	-146 339 169
68	1.64	9 840	164 640 566	470 502 220	635 142 786	365 105 246	-146 775 402	-146 775 401
69	1.66	9 960	164 855 493	472 074 991	636 930 484	365 078 343	-147 283 405	-147 283 405
70	1.68	10 080	165 335 219	476 021 343	641 356 562	365 014 381	-149 745 086	-149 745 086
71	1.70	10 200	165 542 870	478 091 662	643 634 532	364 983 174	-150 521 976	-150 521 976
72	1.72	10 320	165 547 266	478 132 427	643 679 693	364 982 500	-150 534 725	-150 534 725
73	1.74	10 440	165 624 374	478 459 438	644 083 812	364 975 915	-150 792 040	-150 792 039
74	1.76	10 560	165 805 749	480 927 794	646 733 543	364 940 505	-152 582 138	-152 582 138
75	1.78	10 680	166 131 945	482 706 428	648 838 373	364 908 502	-153 443 285	-153 443 285
76	1.80	10 800	167 027 893	489 333 476	656 361 369	364 795 419	-156 132 521	-156 132 521
77	1.82	10 920	167 433 655	493 448 141	660 881 796	364 734 158	-158 135 513	-158 135 513
78	1.84	11 040	167 442 253	493 530 673	660 972 926	364 732 931	-158 160 791	-158 160 791
79	1.88	11 280	167 746 540	495 729 794	663 476 334	364 697 624	-159 499 253	-159 499 253
80	1.90	11 400	168 322 556	498 800 288	667 122 844	364 640 649	-160 863 959	-160 863 959
81	1.92	11 520	168 349 852	498 937 026	667 286 878	364 637 998	-160 888 952	-160 888 952
82	1.94	11 640	169 216 976	507 066 195	676 283 171	364 514 195	-165 687 724	-165 687 724
83	1.96	11 760	169 277 495	507 628 162	676 905 657	364 506 058	-165 824 049	-165 824 049
84	1.98	11 880	170 327 443	516 924 107	687 251 550	364 365 855	-169 860 135	-169 860 134
85	2.00	12 000	170 560 005	518 387 985	688 947 990	364 342 172	-170 132 690	-170 132 690

DEFINING THE MINING PHASES (PUSHBACKS)

After determining the final border of mining, the next step in design process of open pits is to define the mining phases [5].

The results obtained in the software Whittle are shown in Table 2.

Table 2 *Results of defining the mining phases*

Basic exploitation parameters	Mining phases (pushbacks)		
	Phase 1 (pushback 1)	**Phase 2 (pushback 2)**	**Phase 3 (pushback 3)**
Total amount of excavations, t	46 631 341	170 986 143	183 003 754
Total amount of overburden, t	23 883 136	112 553 318	138 642 554
Amount of ore, t	22 748 205	58 432 825	44 361 200
Cut-off grade of copper in the ore, % C_u	0.100	0.100	0.100
Average copper content in the ore, % C_u	0.385	0.291	0.302
Cut-off grade of zinc in the ore, % Z_n	1.000	1.000	1.000
Average zinc content in the ore, % Z_n	1.924	1.658	1.508
Overburden coefficient, t/t	1.050	1.930	3.130

View the final contours of development phases of the open pit, resulting in the software Whittle, is shown in Figure 3.

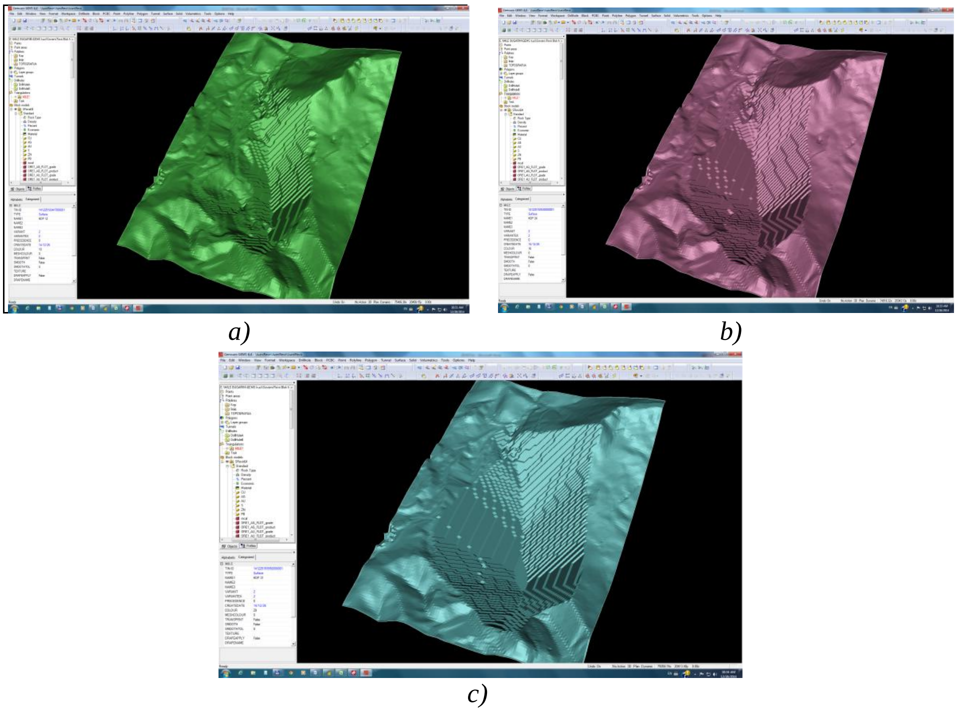

Figure 3 *View the final contours of development phases of the open pit (3D view)*
a) Phase 1, b) Phase 2, c) Phase 3

Figures 4 and 5 show the mining phases in the software Gemcom Gems where, in addition to the phase boundary, it is also noticed the block model of metal content in the ore in the deposit North Mining District.

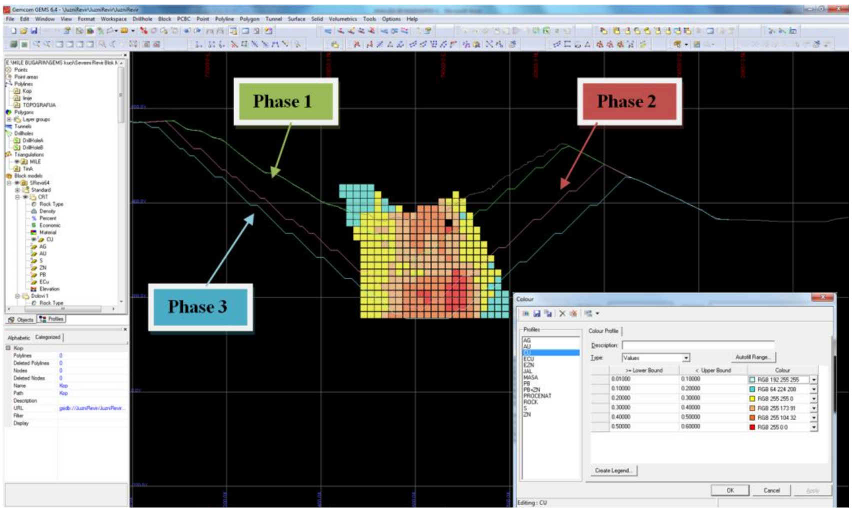

Figure 4 *Cross section of the open pit with a view of development phases of the open pit and block model of copper content (coordinates of the points X = 4973341 and Y = 7520652; X = 4974575 and Y = 7520652; azimuth ν=90°)*

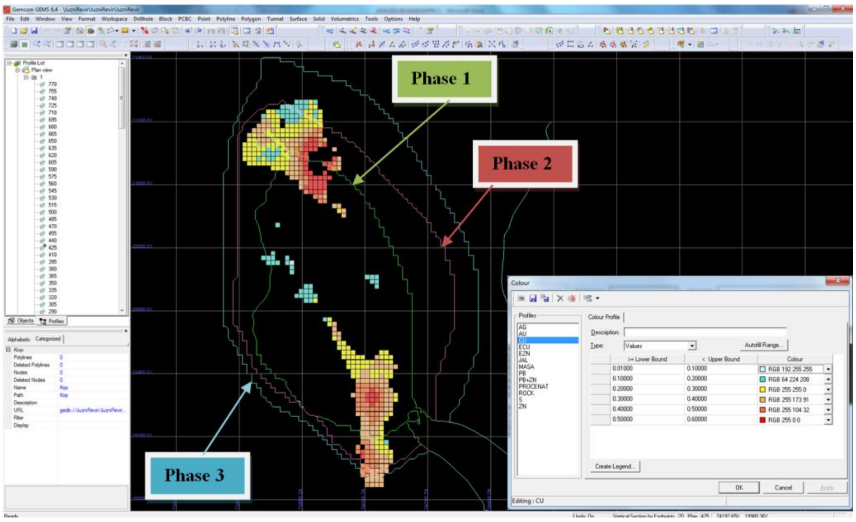

Figure 5 *View the development phase of open pit and block model of copper content in the plan (level of floor E + 425)*

OPTIMIZATION THE MINING DYNAMICS

Mining dynamics by years of exploitation was obtained in the software Whittle, in the module New Schedule Graf. To optimize the mining dynamics, the software uses the Milava algorithm, which can operate in NPV mode when maximum net present value (NPV) is required or in the balancing regime in which maximum utilization of production capacities in mining and flotation processing is required in the first years of exploitation. A balancing regime (Milawa Balanced) was used in this work.

Results of optimization the mining dynamics are shown in Table 3.

Table 3 *Mining dynamics by years of exploitation with a view of cash flow*

Year	Ore	Waste	Excavation	Overburden coefficient	Cash flow	Cash flow disc
	(t)	(t)	(t)	(t/t)	$	$
1	2 979 345	16 020 655	19 000 000	5.38	11 246 634	10 224 213
2	4 734 069	14 265 931	19 000 000	3.01	34 996 063	28 922 366
3	4 845 618	14 154 382	19 000 000	2.92	33 451 016	25 132 244
4	4 876 619	14 123 381	19 000 000	2.90	31 150 733	21 276 370
5	4 971 615	14 028 385	19 000 000	2.82	34 912 504	21 677 918
6	4 996 616	14 003 384	19 000 000	2.80	40 871 924	23 071 135
7	4 982 021	14 017 979	19 000 000	2.81	21 689 710	11 130 251
8	4 994 294	14 005 706	19 000 000	2.80	26 008 360	12 133 092
9	4 985 137	14 014 863	19 000 000	2.81	13 143 992	5 574 336
10	4 969 517	14 030 484	19 000 001	2.82	18 102 666	6 979 361
11	4 964 874	14 035 126	19 000 000	2.83	17 222 757	6 036 471
12	4 975 731	14 024 269	19 000 000	2.82	18 713 860	5 962 812
13	5 000 000	12 848 645	17 848 645	2.57	25 731 559	7 453 516
14	5 000 000	10 082 085	15 082 085	2.02	36 509 799	9 614 171
15	4 999 998	9 922 013	14 922 011	1.98	37 432 610	8 961 069
16	5 000 000	9 538 805	14 538 805	1.91	31 437 699	6 841 759
17	5 000 000	9 939 543	14 939 543	1.99	24 695 897	4 885 952
18	4 999 998	11 698 016	16 698 014	2.34	22 904 849	4 119 638
19	5 000 000	13 430 083	18 430 083	2.69	18 038 165	2 949 384
20	5 000 000	12 269 592	17 269 592	2.45	23 636 188	3 513 369
21	5 000 000	7 704 188	12 704 188	1.54	33 055 309	4 466 783
22	5 000 000	4 216 883	9 216 883	0.84	31 765 187	3 902 225
23	5 000 000	1 814 944	6 814 944	0.36	35 382 772	3 951 483
24	5 000 000	715 856	5 715 856	0.14	43 949 792	4 462 029
25	5 000 000	162 320	5 162 320	0.03	57 185 004	5 277 947
26	3 065 906	11 490	3 077 396	0.00	46 774 308	4 072 012
Total	**125 341 358**	**275 079 008**	**400 420 366**	**2.19**	**770 009 357**	**252 591 906**

Figure 6 presents the amount of ore and waste by years of exploitation with associated stripping ratio.

Figure 7 shows the changes in the amount of ore and waste by years of exploitation and development phases of open pit.

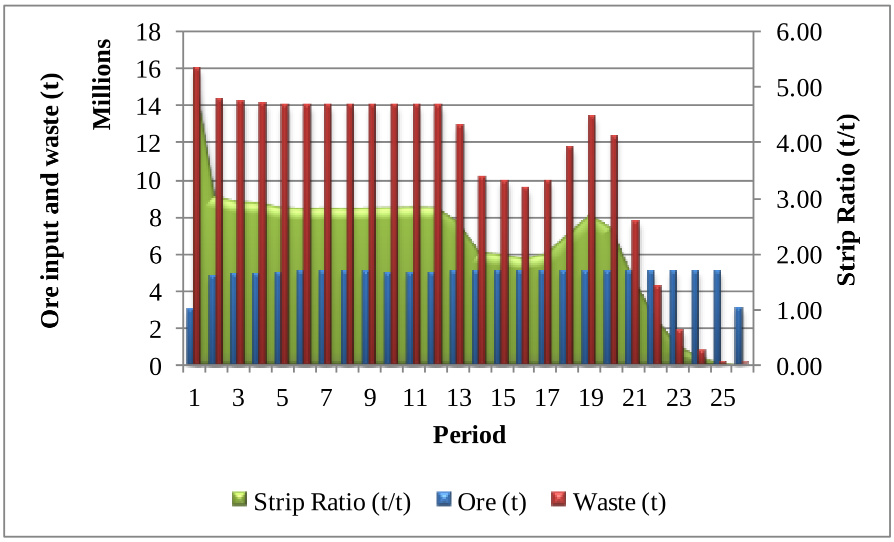

Figure 6 *Amount of ore and waste by years of exploitation with associated stripping ratio*

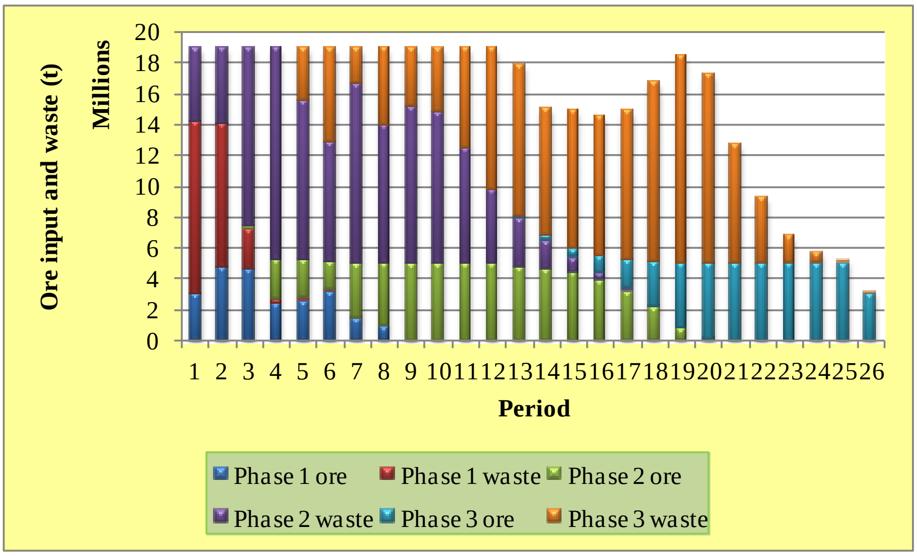

Figure 7 *Amounts of ore and waste by years of exploitation and development phases of open pit*

Change of medium content of copper, silver and gold in copper ore and stripping ratio by years of exploitation can be read from the graph in Figure 8.

Figure 9 shows the movement of discounted cash flow and amount of ore and waste by years of exploitation.

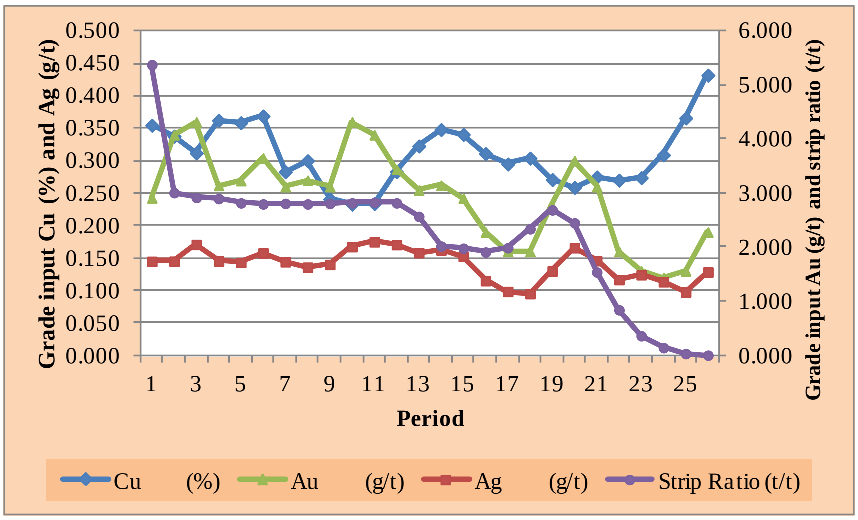

Figure 8 *Change of medium content of copper, silver and gold in copper ore and stripping ratio by years*

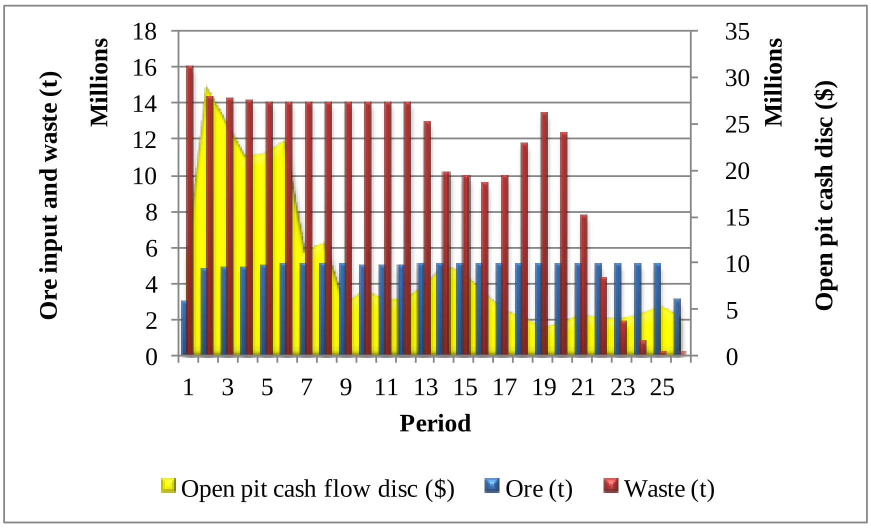

Figure 9 *Change of discounted cash flow and amount of ore and waste by years of exploitation*

CONCLUSION

Based on the carried out analysis, the following is concluded:

1) The specified capacity in copper ore mining at the open pit North Mining District Majdanpek of 5 million tons per year is achieved in the second year of operation. In the first year, the capacity is at the level of 3 million tons.
2) Service life of the open pit is 26 years.

3) The stripping ratio in the first year of exploitation is 5.38 t/t. From the second to the fourteenth year, this ratio has a value of around 2.8 t/y, and then steadily declines, except for a period from the eighteenth to the twentieth year when it is at approximately level of 2.5 t/t.
4) Movement in cash flow is positive during the whole period of exploitation.
5) The net present value is achieved in the amount of **$ 252,591,906** (calculation in the software Whittle).

REFERENCES

[1] Elaborate on reserves of the Copper Deposit "South Mining District – Majdanpek" and Deposit of Polymetallic Mineral Resources (Zn-Pb-Cu) "Tenka – North Mining District Majdanpek", Mining and Metallurgy Institute Bor, 30/06/2011;

[2] D. Kržanović, R. Rajković, M. Mikić: The Effect of Open Pit Slope Design on Net Present Value for Long Term Planning, The 46th International October Conference on Mining and Metallurgy, Bor Lake, Serbia, 2014;

[3] G. Whittle, W. Stange and N. Hanson, Optimizing Project Value and Robustness, Project Evaluation Conference, Melbourne, Vic, 19 - 20 June 2007, pp. 1-10;

[4] D. Kržanović, R. Rajković, M. Mikić: Application of Software Packages Gemcom and Whittle for Design in Mining Aimed to Rational and Cost-Effective Utilization the Copper Deposit Veliki Krivelj near Bor, Serbia, Mining Engineering, Mining and Metallurgy Institute Bor, 2012, pp. 91-98;

[5] D. Kržanović, R. Rajković, M. Mikić, M. Ljubojev: Effect of Stage Development of Mining Operations on Maximization the Net Present Value in Long-Term Planning of Open Pits, Mining and Metallurgy Engineering Bor, 4/2014, pp. 33-40.

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ANALIZA DUGOROČNOG RAZVOJA POVRŠINSKOG KOPA SEVERNI REVIR MAJDANPEK ZA KAPACITET $5x10^6$ TONA RUDE GODIŠNJE***

Izvod

U radu je izvršeno sagledavanje dugoročnog razvoja površinskog kopa Severni revir sa aspekta ostvarivanja maksimalne dobiti za planirani kapacitet od 5 miliona tona rude bakra godišnje, primenom savremenog softvera za strateško planiranje proizvodnje Whittle.

Softver pruža mogućnost da se optimizacijom granice otkopavanja i dugoročne dinamike otkopavanja ostvari pozitivno kretanje novčanog toka i maksimalna neto sadašnja vrednost.

Za planirane tehnoekonomske parametre, koji su ulazni podaci za analizu, dobijena je granica površinskog kopa za vek eksploatacije od 26 godina, a vrednost neto sadašnje vrednosti iznosi 252.591.906 $.

***Ključne reči**: površinski kop Severni revir Majdanpek, optimizacija, fazni razvoj kopa, novčani tok, neto sadašnja vrednost, softver Whittle*

UVOD

U okviru preduzeća Rudnik bakra Majdanpek, koji je deo kompanije Rudarsko topioničarski basen Bor (RTB Bor), posluju dva površinska kopa i to Severni revir i Južni revir. S obzirom da se na površinskom kopu Južni revir vrši raskrivanje ležišta, nosilac proizvodnje rude bakra poslednjih godina je kop Severni revir, sa kapacitetom oko 3,5 miliona tona godišnje. Izgradnjom nove topionice u Boru neophodno je obezbediti sirovinu za njen rad kroz povećanje kapaciteta otkopavanja na površinskim kopovima koji posluju u okviru RTB Bor. U tom cilju izvršena je analiza mogućnosti dugoročnog otkopavanja rude bakra na površinskom kopu Severni revir Majdanpek za kapacitet od 5 miliona tona godišnje, koja obuhvata:

1) optimizaciju površinskog kopa i izbor optimalne konture kopa
2) definisanje faza otkopavanja (pushbacks)
3) optimizaciju dinamike otkopavanja
4) ekonomsku analizu u softveru Whittle, koja se zasniva na analizi kretanja diskontovanog novčanog toka tokom eksploatacionog perioda, odnosno ostvarene neto sadašnje vrednosti, i koja je pokazatelj postignutih ekonomskih rezultata eksploatacije ležišta Severni revir za zadate početne uslove.

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Tehničko-ekonomska analiza izvršena je za deo ležišta bakra „Severni revir – Majdanpek“ i ležišta polimetaličnih mineralnih sirovina (Zn-Pb-Cu) „Tenka – Severni revir Majdanpek“ u sofveru Whittle.

TEHNOEKONOMSKI PARAMETRI ZA ANALIZU

Dugoročni razvoj površinskog kopa definisan je na osnovu sledećih polaznih tehnoekonomskih parametara [1].

1. Rudarska iskorišćenja i osiromašenja

- Osiromašenje rude bakra 4,0%,
- Osiromašenje olovo-cinkane rude 6,0%,
- Eksploatacioni gubici bakarne rude 4,0%,
- Eksploatacioni gubici PbZn rude 6,0%.

2. Flotacijska iskorišćenja:

Ruda Cu:

- Iskorišćenje Cu 82,0%,
- Iskorišćenje Ag 50,0%,
- Iskorišćenje Au 50,0%.

Ruda Pb-Zn:

- Iskorišćenje Zn 60,0%,
- Iskorišćenje Pb 60,0%,
- Iskorišćenje Ag 51,5%,
- Iskorišćenje Au 35,0%,

3. Metalurška iskorišćenja:

Koncentrat Cu:

- Iskorišćenje Cu 95,0%,
- Iskorišćenje Ag 90,0%,
- Iskorišćenje Au 90,0%,

Koncentrat Pb-Zn:

- Iskorišćenje Zn 96,5%,
- Iskorišćenje Pb 95,0%,
- Iskorišćenje Ag 90,0%,
- Iskorišćenje Au 90,0%.

4. Prodajne cene metala:

- Bakar (Cu) 6.000 US $/t,
- Srebro (Ag) 800 US $/kg,
- Zlato (Au) 30.000 US $/kg,
- Cink (Zn) 1.800 US $/t,
- Olovo (Pb) 1.800 US $/t,

5. Vrednost metala u koncentratu:

Koncentrat Cu:

- Bakar (6.000 – 600) = 5.400 US $/t,
- Zlato (30.000 – 150) = 29.850 US $/kg,
- Srebro (800 – 15) = 785 US $/kg.

Koncentrat Pb-Zn:

- Cink (1.800×0,55) = 990 US $/t,
- Olovo (1.800×0,55) = 990 US $/t,
- Zlato (30.000×0,93) = 27.900 US $/kg,
- Srebro (800×0,88) = 700 US $/kg,
- Dobit 0,55%.

6. Troškovi otkopavanja:

- Otkopavanje rude i jalovine 2,0 US $/t iskopa.

7. Flotacijski troškovi:

- Flotiranje Cu 4,0 US $/t rude,
- Flotiranje Pb-Zn 6,0 US $/t rude.

8. Troškovi metalurške prerade:

- Koncentrat Cu: 600 US $/t koncentrata,
- Koncentrat Pb-Zn: 0,45 %.

9. Usvojena diskontna stopa 10%.

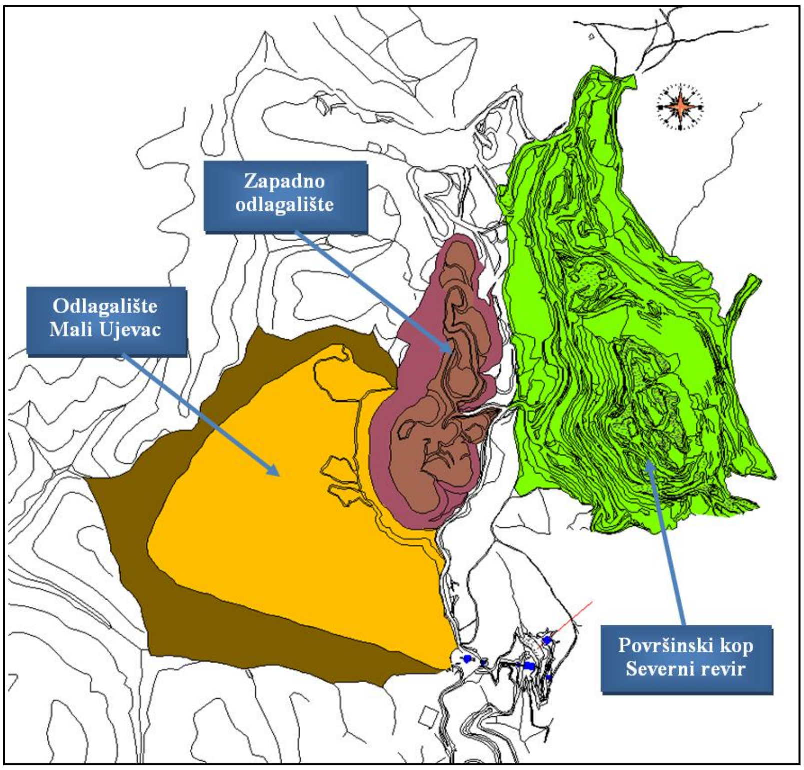
KAPACITETI OTKOPAVANJA I ODLAGANJA

Planirana vrednost kapaciteta otkopavanja rude na godišnjem nivou je sledeća

- u 1. godini 3.000.000 t rude
- od 2. godine do kraja eksploatacionog perioda 5.000.000 t rude.

Kapacitet otkopavanje jalovine ograničen je na 16 miliona tona u prvoj godini eksploatacije. Od druge do četrnaeste godine kapacitet otkopavanja na jalovini iznosi 14 miliona tona godišnje, a zatim konstantno opada, sem u periodu od osamnaeste do dvadesete godine kada je na nivou od 12÷13 miliona tona (tabela 3).

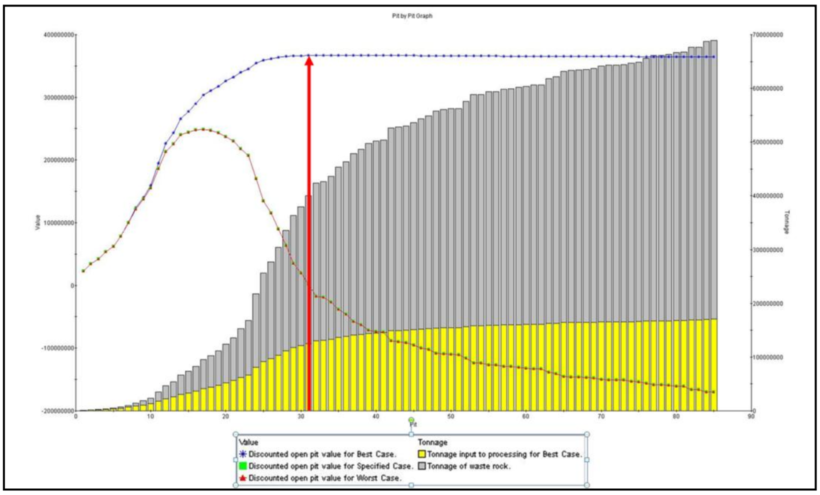
Na slici 1 prikazana su odlagališta Mali Ujevac i Zapadno odlagalište. Prostorni kapacitet navedenih odlagališta omogućava smeštaj celokupne količine jalovine koja se otkopava u toku ekploatacionog perioda.



Sl. 1. *Prikaz lokacija odlagališta površinskog kopa Severni revir*

OPTIMIZACIJA GRANICE POVRŠINSKOG KOPA

Optimalna granica otkopavanja površinskog kopa, za utvrđene tehno – ekonomski parametre određena je korišćenjem softvera za optimizaciju i strateško planiranje površinskih kopova Whittle [2], [3]. Softver generiše više mogućih optimalnih kontura kopova, primenom faktora prihoda (Revenue Factor). Dobijeni kopovi (generisano je 85 kopova koji su prikazani u tabeli 1 i na slici 2) dalje se analiziraju i vrši se izbor optimalnog kopa po kriterijumu diskontovane sadašnje vrednosti. Za dalje sagledavanje izabran je kop broj 31 [4].



Sl. 2. *Grafički prikaz rezultata optimizacije površinskog kopa i izbora optimalne konture*

Tabela 1. *Rezultati optimizacije površinskog kopa i izbor optimalne konture*

Kop	Faktor prihoda	Cena metala (Cu)	Ruda	Jalovina	Iskopine	Novčani tok best	Novčani tok specified	Novčani tok worst
		($)	(t)	(t)	(t)	($ disc)	($ disc)	($ disc)
1	0.30	1 800	968 181	203 712	1 171 893	22 584 296	22 584 296	22 584 296
2	0.32	1 920	1 623 849	450 874	2 074 723	34 312 916	34 312 916	34 312 916
3	0.34	2 040	2 123 198	606 769	2 729 967	41 789 193	41 789 193	41 789 193
4	0.36	2 160	2 929 255	1 092 474	4 021 729	53 519 286	53 519 286	53 519 286
5	0.38	2 280	3 650 220	1 318 562	4 968 782	62 533 173	62 494 501	62 494 501
6	0.40	2 400	4 902 725	2 181 611	7 084 336	78 708 554	78 355 255	78 355 255
7	0.42	2 520	7 071 396	3 160 726	10 232 122	100 864 035	99 630 269	99 630 269
8	0.44	2 640	9 286 522	5 407 075	14 693 597	123 819 279	121 872 114	121 872 114
9	0.46	2 760	11 067 156	7 406 268	18 473 424	140 301 765	137 641 992	137 641 992
10	0.48	2 880	13 157 839	10 175 045	23 332 884	159 260 909	155 303 894	155 303 894
11	0.50	3 000	17 927 373	16 712 768	34 640 141	194 754 291	186 303 811	186 303 811
12	0.52	3 120	22 711 807	23 883 135	46 594 942	226 403 804	213 021 965	213 021 965
13	0.54	3 240	25 863 252	28 182 396	54 045 648	243 162 846	226 051 272	226 051 272
14	0.56	3 360	30 724 154	35 998 077	66 722 231	266 129 304	240 625 139	240 625 139
15	0.58	3 480	33 477 175	40 271 845	73 749 020	277 057 488	244 277 282	244 277 282
16	0.60	3 600	37 192 913	45 485 293	82 678 206	289 634 825	247 798 051	247 798 051
17	0.62	3 720	41 443 508	53 842 480	95 285 988	303 274 051	248 883 219	248 883 219
18	0.64	3 840	44 205 134	58 448 831	102 653 965	310 218 420	247 430 866	247 430 866
19	0.66	3 960	47 502 042	64 495 812	111 997 854	317 462 626	243 140 799	243 140 799
20	0.68	4 080	52 113 561	71 835 689	123 949 250	325 693 173	237 056 568	237 056 568
21	0.70	4 200	56 271 861	79 412 771	135 684 632	332 198 250	230 075 464	230 075 464
22	0.72	4 320	62 083 245	90 431 004	152 514 249	339 836 560	218 071 798	218 071 798
23	0.74	4 440	66 812 254	101 754 105	168 566 359	345 104 837	207 145 863	207 145 863
24	0.76	4 560	81 051 136	136 436 453	217 487 589	354 419 784	170 356 756	170 356 756
25	0.78	4 680	91 336 065	164 736 025	256 072 090	359 366 452	134 967 260	134 967 259
26	0.80	4 800	96 781 199	180 400 615	277 181 814	361 514 656	115 608 954	115 608 954
27	0.82	4 920	103 600 175	200 782 071	304 382 246	363 567 340	89 619 201	89 619 201
28	0.84	5 040	111 265 885	223 954 422	335 220 307	365 078 953	63 384 591	63 384 592
29	0.86	5 160	117 624 186	246 149 900	363 774 086	365 958 572	34 954 332	34 954 331
30	0.88	5 280	121 256 159	258 605 230	379 861 389	366 383 339	20 018 724	20 018 724
31	0.90	5 400	125 341 356	275 079 007	400 420 363	366 729 762	2 206 940	2 206 940
32	0.92	5 520	130 350 079	293 650 437	424 000 516	366 951 984	-16 975 286	-16 975 286
33	0.94	5 640	131 114 588	295 642 962	426 757 550	366 989 137	-18 886 086	-18 886 085
34	0.96	5 760	132 767 039	303 470 052	436 237 091	367 047 835	-26 505 753	-26 505 753
35	0.98	5 880	136 322 733	317 495 007	453 817 740	367 087 144	-38 381 780	-38 381 779
36	1.00	6 000	138 161 223	324 956 295	463 117 518	367 078 291	-45 537 457	-45 537 457
37	1.02	6 120	140 999 315	337 397 231	478 396 546	367 015 651	-57 484 923	-57 484 923
38	1.04	6 240	142 503 976	344 682 084	487 186 060	366 967 239	-62 747 899	-62 747 899
39	1.06	6 360	144 045 206	353 072 457	497 117 663	366 911 456	-71 308 357	-71 308 357
40	1.08	6 480	145 132 029	356 664 572	501 796 601	366 875 490	-73 811 425	-73 811 424
41	1.10	6 600	145 473 922	358 036 674	503 510 596	366 860 881	-74 384 990	-74 384 989
42	1.12	6 720	149 261 428	377 080 767	526 342 195	366 632 022	-88 296 985	-88 296 985
43	1.14	6 840	149 466 138	378 583 793	528 049 931	366 614 915	-89 578 295	-89 578 295
44	1.16	6 960	150 016 034	379 958 771	529 974 805	366 585 864	-91 100 702	-91 100 702
45	1.18	7 080	150 850 043	385 656 957	536 507 000	366 504 709	-94 941 362	-94 941 362
46	1.20	7 200	151 819 471	391 796 162	543 615 633	366 423 017	-99 707 899	-99 707 899
47	1.22	7 320	152 797 499	395 913 378	548 710 877	366 360 418	-101 886 755	-101 886 755
48	1.24	7 440	154 095 441	404 049 312	558 144 753	366 242 969	-108 521 828	-108 521 828
49	1.26	7 560	154 593 811	405 961 093	560 554 904	366 208 247	-109 366 215	-109 366 214
50	1.28	7 680	154 781 049	407 179 922	561 960 971	366 188 588	-110 048 394	-110 048 394
51	1.30	7 800	154 934 895	407 843 052	562 777 947	366 176 200	-110 353 097	-110 353 097
52	1.32	7 920	156 991 452	419 211 707	576 203 159	365 977 282	-116 030 127	-116 030 127
53	1.34	8 040	158 440 134	429 798 959	588 239 093	365 812 883	-123 772 863	-123 772 863
54	1.36	8 160	158 496 574	429 947 801	588 444 375	365 809 317	-123 864 339	-123 864 338
55	1.38	8 280	159 556 554	434 348 748	593 905 302	365 723 291	-126 450 957	-126 450 957
56	1.40	8 400	159 595 857	434 537 270	594 133 127	365 719 666	-126 479 454	-126 479 454
57	1.42	8 520	160 056 057	437 834 259	597 890 316	365 664 818	-128 701 097	-128 701 098
58	1.44	8 640	160 324 985	439 293 394	599 618 379	365 638 059	-129 382 131	-129 382 131
59	1.46	8 760	160 579 643	441 490 045	602 069 688	365 603 014	-130 873 799	-130 873 799
60	1.48	8 880	160 755 538	442 824 454	603 579 992	365 580 228	-131 908 169	-131 908 169
61	1.50	9 000	161 049 360	445 038 006	606 087 366	365 542 337	-133 029 393	-133 029 393
62	1.52	9 120	161 058 864	445 077 723	606 136 587	365 541 347	-133 056 955	-133 056 955
63	1.54	9 240	162 575 935	455 695 298	618 271 233	365 357 635	-138 432 927	-138 432 926
64	1.56	9 360	163 095 722	458 654 209	621 749 931	365 302 145	-140 311 918	-140 311 918
65	1.58	9 480	164 216 904	467 639 247	631 856 151	365 154 330	-145 360 524	-145 360 524
66	1.60	9 600	164 397 954	468 929 719	633 327 673	365 133 146	-145 788 727	-145 788 727
67	1.62	9 720	164 519 005	469 717 084	634 236 089	365 119 229	-146 339 169	-146 339 169
68	1.64	9 840	164 640 566	470 502 220	635 142 786	365 105 246	-146 775 402	-146 775 401
69	1.66	9 960	164 855 493	472 074 991	636 930 484	365 078 343	-147 283 405	-147 283 405
70	1.68	10 080	165 335 219	476 021 343	641 356 562	365 014 381	-149 745 086	-149 745 086
71	1.70	10 200	165 542 870	478 091 662	643 634 532	364 983 174	-150 521 976	-150 521 976
72	1.72	10 320	165 547 266	478 132 427	643 679 693	364 982 500	-150 534 725	-150 534 725
73	1.74	10 440	165 624 374	478 459 438	644 083 812	364 975 915	-150 792 040	-150 792 039
74	1.76	10 560	165 805 749	480 927 794	646 733 543	364 940 505	-152 582 138	-152 582 138
75	1.78	10 680	166 131 945	482 706 428	648 838 373	364 908 502	-153 443 285	-153 443 285
76	1.80	10 800	167 027 893	489 333 476	656 361 369	364 795 419	-156 132 521	-156 132 521
77	1.82	10 920	167 433 655	493 448 141	660 881 796	364 734 158	-158 135 513	-158 135 513
78	1.84	11 040	167 442 253	493 530 673	660 972 926	364 732 931	-158 160 791	-158 160 791
79	1.88	11 280	167 746 540	495 729 794	663 476 334	364 697 624	-159 499 253	-159 499 253
80	1.90	11 400	168 322 556	498 800 288	667 122 844	364 640 649	-160 863 959	-160 863 959
81	1.92	11 520	168 349 852	498 937 026	667 286 878	364 637 998	-160 888 952	-160 888 952
82	1.94	11 640	169 216 976	507 066 195	676 283 171	364 514 195	-165 687 724	-165 687 724
83	1.96	11 760	169 277 495	507 628 162	676 905 657	364 506 058	-165 824 049	-165 824 049
84	1.98	11 880	170 327 443	516 924 107	687 251 550	364 365 855	-169 860 135	-169 860 134
85	2.00	12 000	170 560 005	518 387 985	688 947 990	364 342 172	-170 132 690	-170 132 690

DEFINISANJE FAZA OTKOPAVANJA (PUSHBACKS)

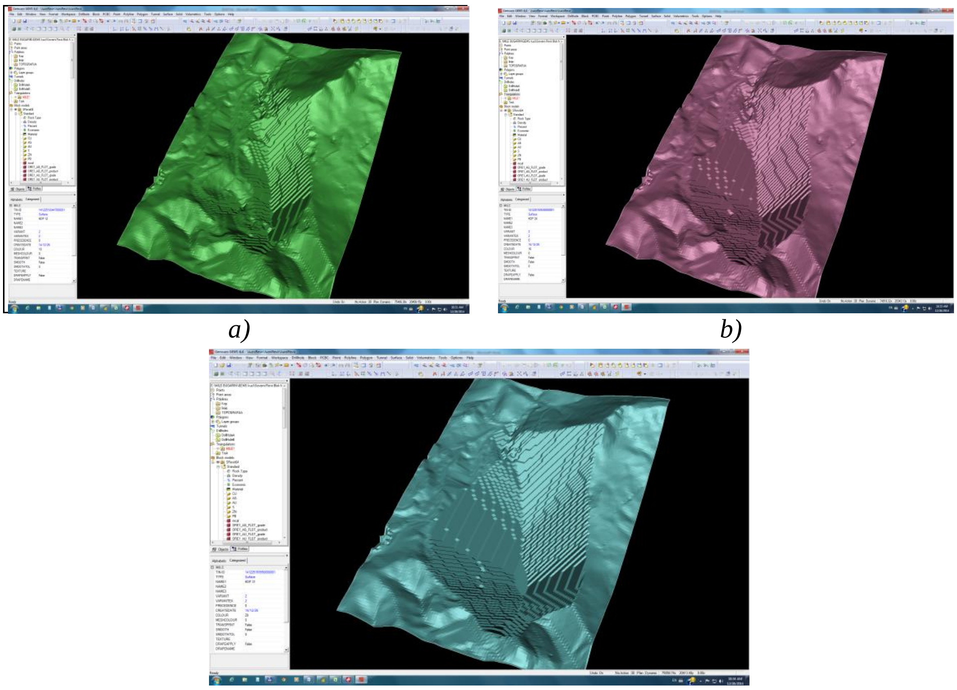
Nakon određivanja konačne granice otkopavanja, sledeći korak u procesu dizajniranja površinskih kopava jeste definisanje faza otkopavanja [5].

Dobijeni rezultati u softveru Whittle prikazani su u tabeli 2.

Tabela 2. *Rezultati definisanja faza otkopavanja*

Osnovni eksploatacioni parametri	Faze otkopavanja (pushbacks)		
	Faza 1 (pushback 1)	**Faza 2 (pushback 2)**	**Faza 3 (pushback 3)**
Ukupna količina iskopina, t	46 631 341	170 986 143	183 003 754
Ukupna količina otkrivke, t	23 883 136	112 553 318	138 642 554
Količina rude, t	22 748 205	58 432 825	44 361 200
Granični sadržaj bakra u rudi, % C_u	0,100	0,100	0,100
Prosečan sadržaj bakra u rudi, % C_u	0,385	0,291	0,302
Granični sadržaj cinka u rudi, % Z_n	1,000	1,000	1,000
Prosečan sadržaj cinka u rudi, % Z_n	1,924	1,658	1,508
Koeficijent otkrivke, t/t	1,050	1,930	3,130

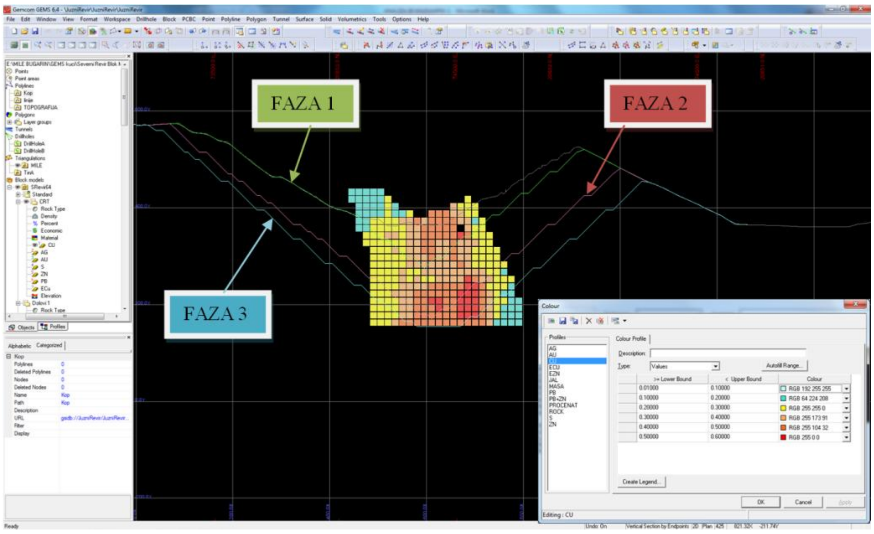
Prikaz završnih kontura Faza razvoja kopa, dobijena u softveru Whittle, dat je na sl. 3.



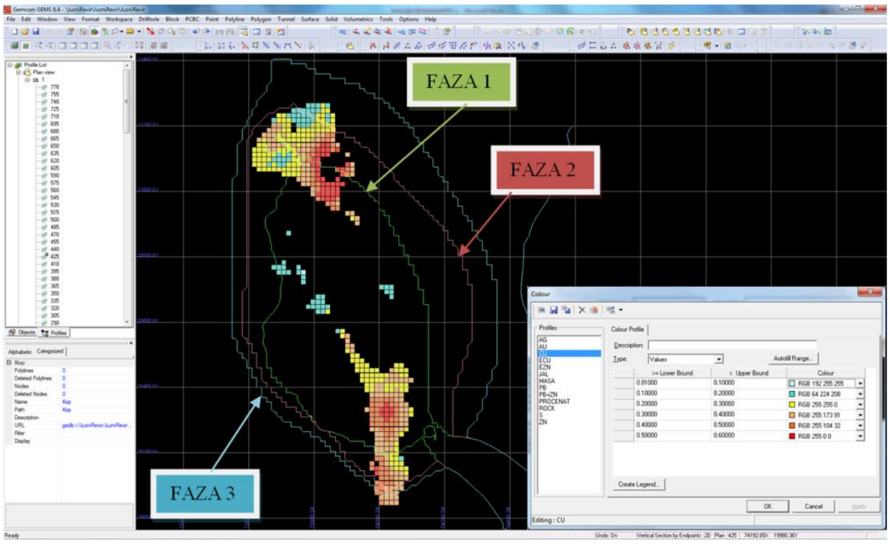
a) b) c)

Sl. 3. *Izgled završnih kontura Faza razvoja kopa(3D prikaz)*
a) faza 1, b) faza 2, c) faza 3

Na slikama 4 i 5 prikazane su Faze otkopavanja u softveru Gemcom Gems, na kojima se pored granica Faza uočava i blok model sadržaja metala u rudi u ležištu Severni revir.



Sl. 4. *Poprečni presek kopa sa prikazom Faza razvoja kopa i blok modela sadržaja bakra (koordinate tačaka X=4973341 i Y= 7520652; X=4974575 i Y= 7520652; azimut v=90°)*



Sl. 5. *Prikaz Faza razvoja kopa i blok modela sadržaja bakra u planu (nivo etaže E+425)*

OPTIMIZACIJA DINAMIKE OTKOPAVANJA

Dinamika otkopavanja po godinama eksploatacije dobijena je u softveru Whittle, u modulu New Schedule Graf. Za optimizaciju dinamike otkopavanja softver koristi Milava algoritam, koji može da radi u režimu NPV kada se traži maksimalna neto sadašnja vrednost (NSV) ili u režimu balansiranja u kome se traži da se maksimalno iskoriste proizvodni kapaciteti na otkopavanju i flotacijskoj pripremi u prvim godinama eksploatacije. U ovom radu primenjen je režim balansiranja (Milawa Balanced).

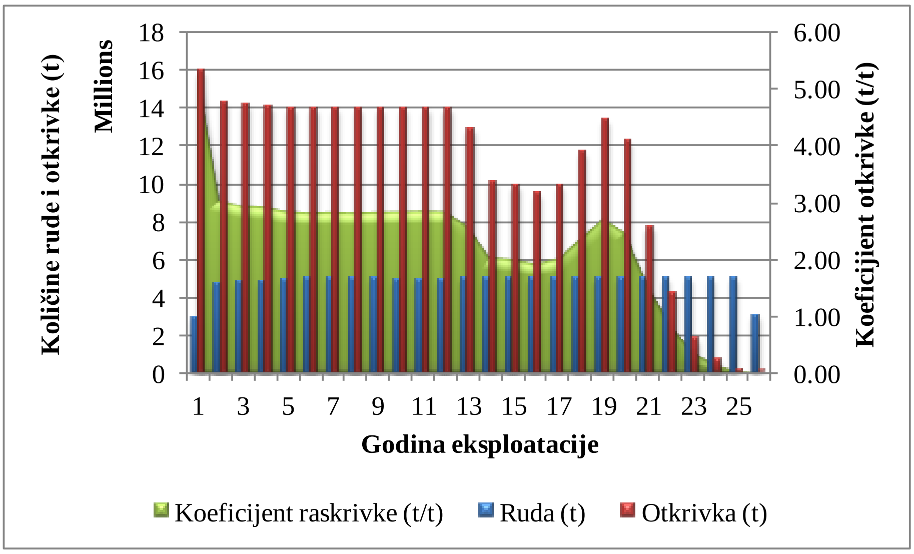
Rezultati optimizacije dinamike otkopavanja prikazani su u tabeli 3.

Tabela 3. *Dinamika otkopavanja po godinama eksploatacije sa prikazom novčanog toka*

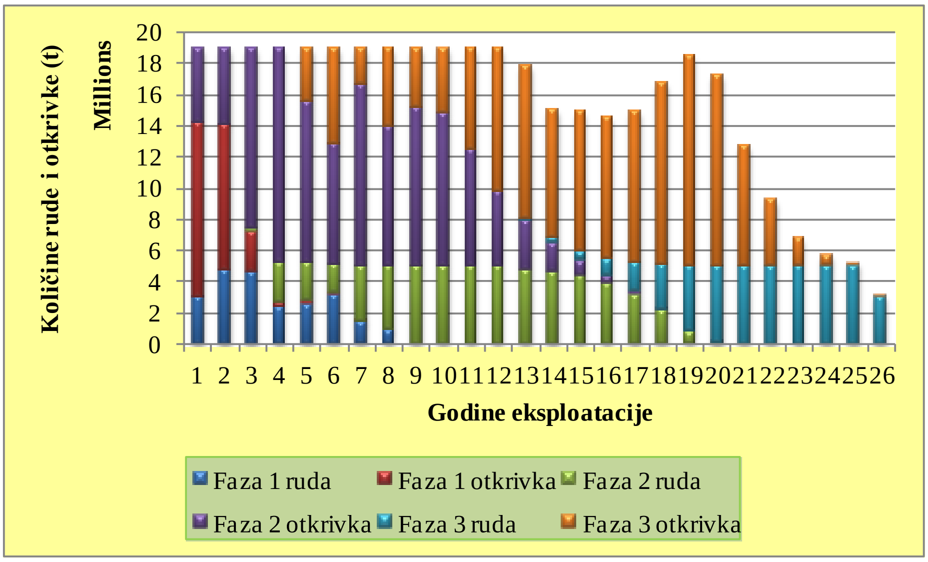
God.	Ruda	Jalovina	Iskopine	Koef. rask.	Novčani tok	Novčani tok disc
	(t)	(t)	(t)	(t/t)	$	$
1	2 979 345	16 020 655	19 000 000	5.38	11 246 634	10 224 213
2	4 734 069	14 265 931	19 000 000	3.01	34 996 063	28 922 366
3	4 845 618	14 154 382	19 000 000	2.92	33 451 016	25 132 244
4	4 876 619	14 123 381	19 000 000	2.90	31 150 733	21 276 370
5	4 971 615	14 028 385	19 000 000	2.82	34 912 504	21 677 918
6	4 996 616	14 003 384	19 000 000	2.80	40 871 924	23 071 135
7	4 982 021	14 017 979	19 000 000	2.81	21 689 710	11 130 251
8	4 994 294	14 005 706	19 000 000	2.80	26 008 360	12 133 092
9	4 985 137	14 014 863	19 000 000	2.81	13 143 992	5 574 336
10	4 969 517	14 030 484	19 000 001	2.82	18 102 666	6 979 361
11	4 964 874	14 035 126	19 000 000	2.83	17 222 757	6 036 471
12	4 975 731	14 024 269	19 000 000	2.82	18 713 860	5 962 812
13	5 000 000	12 848 645	17 848 645	2.57	25 731 559	7 453 516
14	5 000 000	10 082 085	15 082 085	2.02	36 509 799	9 614 171
15	4 999 998	9 922 013	14 922 011	1.98	37 432 610	8 961 069
16	5 000 000	9 538 805	14 538 805	1.91	31 437 699	6 841 759
17	5 000 000	9 939 543	14 939 543	1.99	24 695 897	4 885 952
18	4 999 998	11 698 016	16 698 014	2.34	22 904 849	4 119 638
19	5 000 000	13 430 083	18 430 083	2.69	18 038 165	2 949 384
20	5 000 000	12 269 592	17 269 592	2.45	23 636 188	3 513 369
21	5 000 000	7 704 188	12 704 188	1.54	33 055 309	4 466 783
22	5 000 000	4 216 883	9 216 883	0.84	31 765 187	3 902 225
23	5 000 000	1 814 944	6 814 944	0.36	35 382 772	3 951 483
24	5 000 000	715 856	5 715 856	0.14	43 949 792	4 462 029
25	5 000 000	162 320	5 162 320	0.03	57 185 004	5 277 947
26	3 065 906	11 490	3 077 396	0.00	46 774 308	4 072 012
Total	**125 341 358**	**275 079 008**	**400 420 366**	**2.19**	**770 009 357**	**252 591 906**

Na slici 6 dat je prikaz količina rude i jalovine po godinama eksploatacije sa pripadajućim koeficijentom otkrivke.

Slika 7 prikazuje promenu količina rude i jalovine po godinama eksploatacije i Fazama razvoja kopa



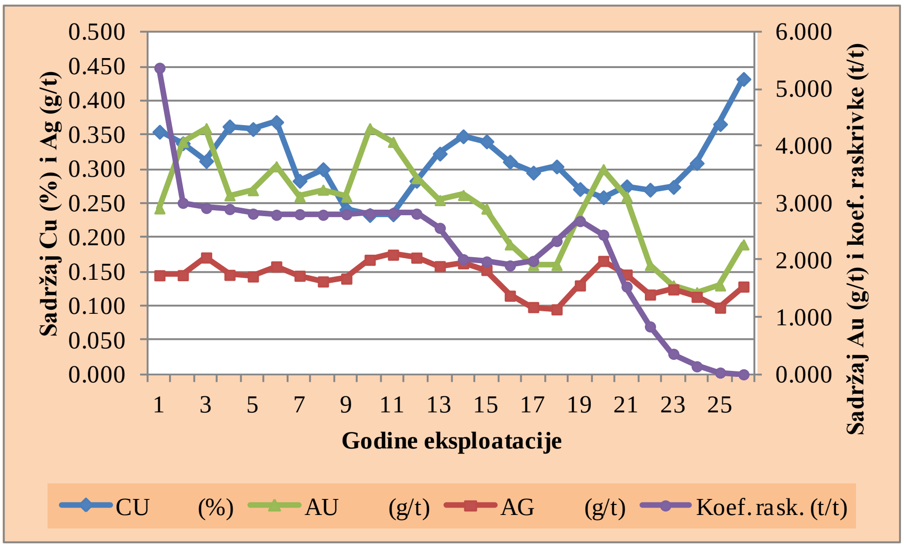
Sl. 6. *Količine rude i jalovine po godinama eksploatacije sa pripadajućim koeficijentom otkrivke*



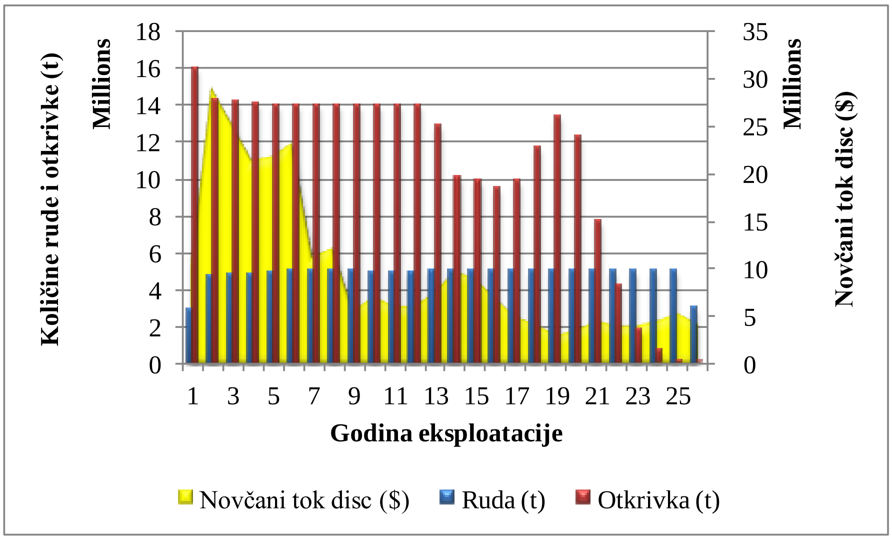
Sl. 7. *Količine rude i jalovine po godinama eksploatacije i Fazama razvoja kopa*

Promena srednjeg sadržaja bakra, srebra i zlata u rudi bakra i koeficijenta raskrivke po godinama eksploatacije može se očitati sa grafika na slici 8.

Slika 9 prikazuje kretanje diskontovanog novčanog toka i količina rude i jalovine po godinama eksploatacije.



Sl. 8. *Promena srednjeg sadržaja bakra, srebra i zlata u rudi bakra i koeficijenta raskrivke po godinama*



Sl. 9. *Promena diskontovanog novčanog toka, količina rude i jalovine po godinama eksploatacije*

ZAKLJUČAK

Na osnovu sprovedene analize zaključuje se sledeće:

1) Zadati kapacitet na otkopavanju rude bakra na površinskom kopu Severni revir Majdanpek od 5 miliona tona godišnje postiže se u drugoj godini eksploatacije. U prvoj godini kapacitet je na nivou od 3 miliona tona.
2) Vek eksploatacije kopa iznosi 26 godina.

3) Koeficijent raskrivke u prvoj godini eksploatacije iznosi 5,38 t/t. Od druge do četrnaeste godine ovaj koeficijent ima ima vrednost oko 2,8 t/t, a zatim konstantno opada, sem u periodu od osamnaeste do dvadesete godine kada je na približno na nivou od 2,5 t/t.
4) Kretanje novčanog toka je pozitivno tokom celog perioda eksploatacije.
5) Ostvaruje se neto sadašnja vrednost u iznosu od **252.591.906 $** (obračun u softveru Whittle).

LITERATURA

[1] Elaborat o rezervama ležišta bakra „Severni revir – Majdanpek“ i ležišta polimetaličnih mineralnih sirovina (Zn-Pb-Cu) „Tenka – Severni revir Majdanpek“, Institut za rudarstvo i metalurgiju Bor, 30.06.2011.

[2] D. Kržanović, R. Rajković, M. Mikić: The Effect of Open Pit Slope Design on Net Present Value for Long Term Planning, The 46th International October Conference on Mining and Metallurgy, Borsko jezero, Serbia, 2014.

[3] G. Whittle, W. Stange and N. Hanson, Optimising Project Value and Robustness, Project Evaluation Conference, Melbourne, Vic, 19 - 20 June 2007, str. 1-10.

[4] D. Kržanović, R. Rajković, M. Mikić: Primena softverskih paketa za projektovanje u rudarstvu Gemcom i Whittle u cilju racionalnog i ekonomičnog iskorišćenja ležišta bakra Veliki Krivelj kod Bora, Srbija, Rudarski radovi, Institut za rudarstvo i metalurgiju Bor, 3/2012, str. 85-90.

[5] D. Kržanović, R. Rajković, M. Mikić, M. Ljubojev: Efekat faznog razvoja rudarskih radova na maksimizaciju neto sadašnje vrednosti kod dugoročnog planiranja površinskih kopova, Mining and Metallurgy Engineering Bor, 4/2014, str. 41-48.

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Branislav Rajković, Zoran Ilić*, Daniela Urošević**

TAKE UP PULLEY SELECTION OF BELT CONVEYOR FOR THE ORE IN TERMS OF AXLE SIZING

Abstract

This work gives the methodology of take up pulley axle calculation on the example of belt conveyor for ore T 3505 designed for the needs of Majdanpek open pit with capacity of 800 t/h.

The analysis was made by calculation and represents a universal method for belt conveyor take up pulley axle calculation whose results are indispensable for reliability the check of this important part of belt conveyors.

Also, technical characteristics of all elements of the take up assembly are given, as well as their graphical representation.

Keywords*: belt conveyor for ore, take up pulley axle calculation, take up assembly*

1 INTRODUCTION

It is necessary that the conveyor belt is tense for correct operation of belt conveyors by corresponding force during the operation. Belt tensioning is made by take up pulley, while tensioning force itself is mostly obtained via screw take up device for the belt conveyors of shorter length or via counter weight for the belt conveyors of longer length.

Belt conveyor for the ore T 3505 was designed for transportation the small fraction screening product at the Majdanpek open pit from the screening facility to the belt conveyor T 3504[1].

Accordingly, it is a horizontal belt conveyor with a drive pulley on the discharge side of the conveyor and a take up pulley on the loading side of the conveyor. Considering that it is a belt conveyor of shorter length than 50 m, a screw take up device was predicted for obtaining the tensioning force by axial moving of the take up pulley what consequently tightens the belt.

Tensioning force on the take up pulley is a result of the preliminary calculation of the belt conveyor and it is an input value for the sizing of its elements.

2 TECHNICAL DESCRIPTION OF TAKE UP ASSEMBLY

The take up assembly of the belt conveyor consists of take up pulley assembly with axle and bearings, screw take up device, snub pulley assembly with axle and bearings, carrying troughing set with rollers, plow cleaner and bearing construction.

Technical characteristics of the belt conveyor itself are as follows:

- capacity: –
- material type: copper ore
- maximum lump size:
- bulk density: —

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- transport length:
- lifting of the material on belt:

- side carrying rollers inclination angle:

- belt speed: –
- belt type: 800/4 EP250 7/2
- electric motor power for belt drive:

The take up pulley (mark USF,620,950, 65,YA,RR,15; made by Rulmeca) is placed at the opposite side of the belt conveyor in relation to the drive pulley and it is equipped with the screw take up device with travel of 457,2 mm (mark TUHD-300-18; manufactured by Superior). Bearings of the take up pulley are self-adjusting (mark 22215 EK; manufactured by SKF). The snub pulley is placed in front of the take up pulley (mark USF,320,950,40,YA; manufactured by Rulmeca) with self-adjusting bearings (mark 22209 EK; manufactured by SKF). To prevent material from getting between the belt and the take up pulley the plow cleaner is predicted (mark E 4000 „V“ plough; manufactured by BMS). Within the take up assembly there is also a carrying troughing set (mark A3P/50,800,F22,H160,YA, manufactured by Rulmeca) with three carrying rollers (mark PSV4,30F,133N,323, manufactured by Rulmeca). All the elements of the take up assembly are placed on the bearing steel construction made by welding from hot rolled steel profiles.

The take up pulley dimensions with rubber lagging are as follows according to Fig. 1:

D=650 mm
B=950 mm
d=65 mm
d_1=70 mm
G=1140 mm
F=35 mm
C=1210 mm

According to the catalog data of the Rulmeca manufacturer [2] series USF pulleys with clamping units connection between the axle and hub enables the compression axle locking using a system of screws and tapered sleeves eliminating the play and eccentricity. This locking system is used mostly today having in mind the strength, simplicity of construction, easy assembly and disassembly as well as the maintenance. The advantage compared to the traditional connection between the axle and the hub by key is in the fact that there is module of resistance reduction at traditional connection due to the key groove as well as difficult alignment on the assembly and difficult disassembly of pulleys being long time in exploitation.

The take up assembly of the belt conveyor T 3505 is given in Fig. 2.

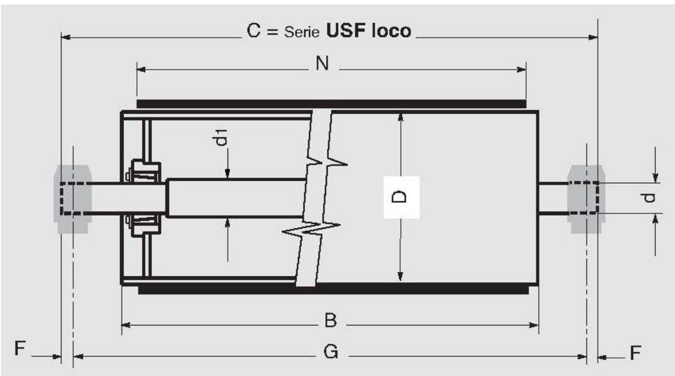

Fig. 1 *Take up pulley of belt conveyor T 3505*

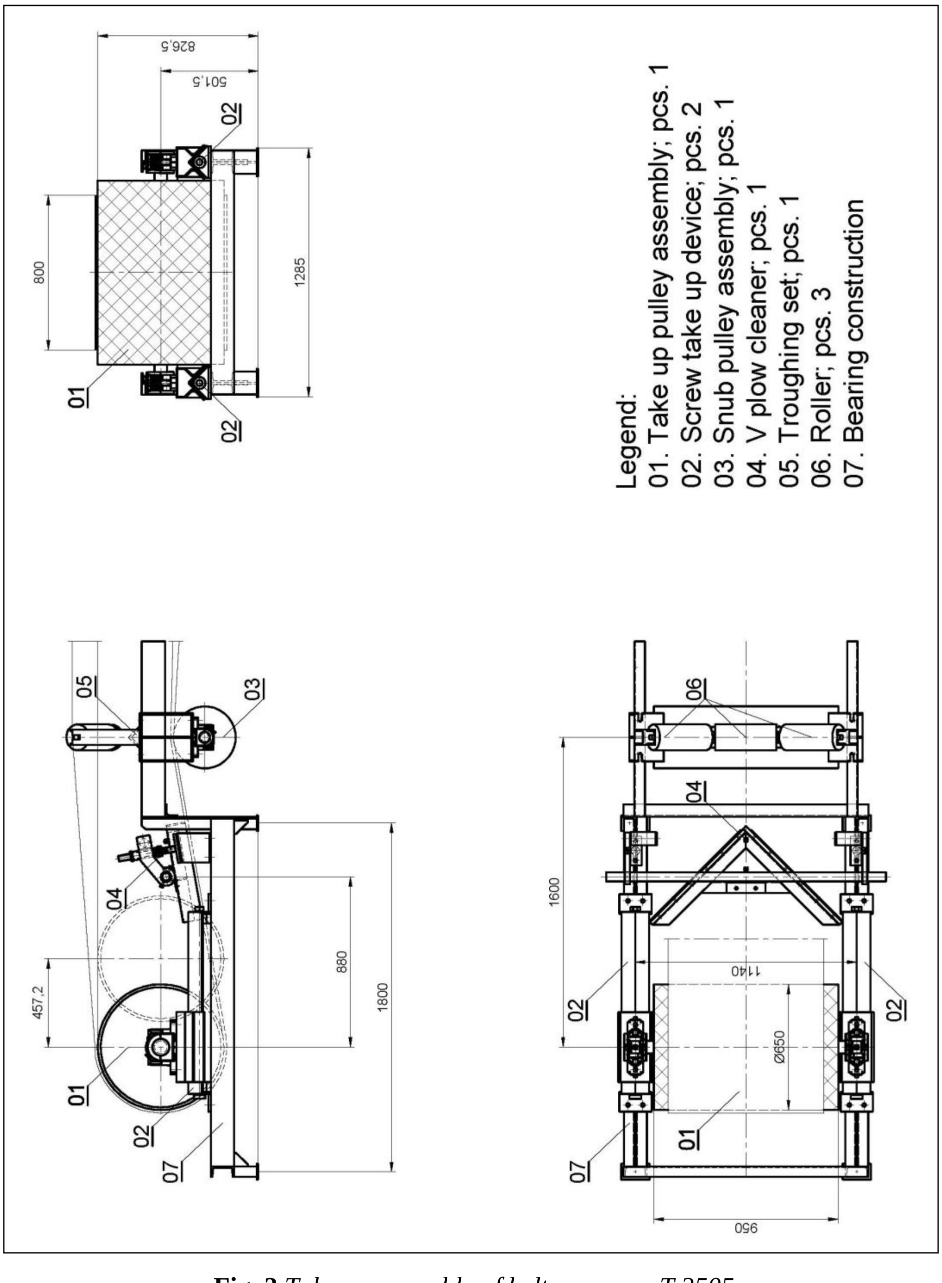

Fig. 2 *Take up assembly of belt conveyor T 3505*

3 CALCULATION OF TAKE UP PULLEY AXLE

3.1 Calculation of take up pulley axle diameter according to the stress limit

1. Calculation of take up pulley axle diameter according to the stress limit has for a purpose of determination the minimum axle diameter considering the load and admissible stress and it is given according to [2].

2. Bending moment

3. Module of resistance

4. Axle diameter

Where is:

–tension force at the pulley

–geometrical parameter

– admissible stress for material of the axle steel C40

3.2 Calculation of take up pulley axle according to the axle deflection at hub

1. Calculation of take up pulley axle according to axle deflection at hub has for a purpose the determination of deflection angle made as a result of axle elastic deformation under load considering allowable deflection and it is given according to [3] and figure 3.

2. Tangent of angle made by the deflected axle and its natural axis before bending, at the take up pulley hub

Where are:

– tension force at the pulley

– geometrical parameter

– geometrical parameter

– geometrical parameter

– modules of elasticity of steel

– area moment of inertia for diameter D

– axle diameter at hub

– area moment of inertia for diameter D2

–axle diameter inside the pulley

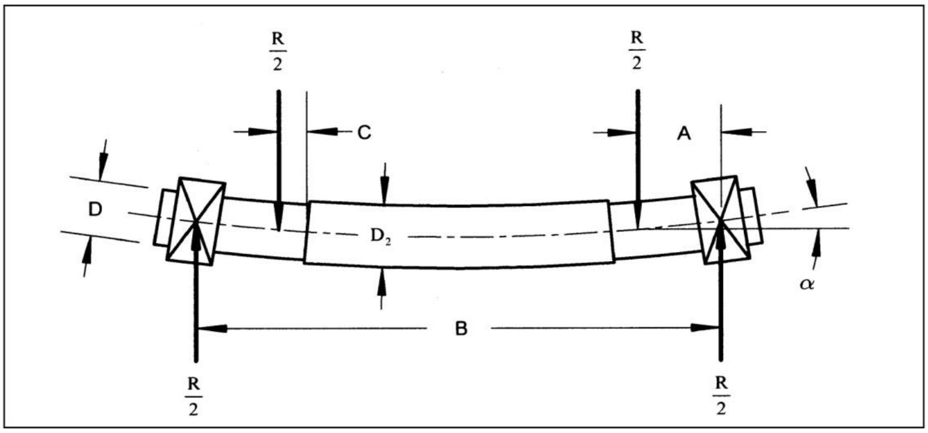

Figure 3 *Take up pulley axle deflection – geometrical parameters*

4 DISCUSSION OF CALCULATION

The take up pulley axle is symmetrically loaded in bending. Steel C40 (heat treated) was selected as the axle material from the manufacturer's catalog. The axle is calculated according to the stress limit and allowable deflection angle. Calculation of take up pulley axle diameter according to the stress limit indicates that selected axle diameter is larger than required what means that the axle is satisfactory regarding the stress limit. The axle was designed with two different diameters so that its diameter inside the pulley is larger reducing the elastic deformations of axle under load compared to the case in which the axle is designed with constant diameter. Calculation of take up pulley axle according to the axle deflection at hub indicates that the deflection angle of axle is within acceptable limits. Namely, according to data from literature [3], maximum value of this angle amounts 8' while calculated value in this particular case amounts 3.9'. Applying the above formula, it is easily shown that the axle designed with constant diameter of 65 mm would have a deflection angle of 4.7'.

CONCLUSION

The results obtained by calculation show that the take up pulley axle is sized correctly by both criteria, i.e. according to the stress limit and according to the allowable deflection.

Take up pulley selection is usually done from the catalog data of the manufacturers. On this occasion, it is often necessary to check how the take up pulley axle is resistant in given operating conditions, so this work may be useful in this sense.

REFERENCES

[1] Detail Design of Relocation of the Crushing Facility from the North Mining District and Construction the New Transportation System No. 3 for Ore of the South Mining District in the Copper Ming Majdanpek - Detail Mechanical Design of the Belt Conveyor for the Small Fraction Screening Product with all Transfer Points; Mining and Metallurgy Institute Bor; Section MEGA; 2013 (in Serbian);

[2] Catalog of Rulmeca Company: Rollers and Components for Bulk Handling; Rulli Rulmeca S.p.A.; 4th Edition; July 2003; pp. 65, 259;

[3] Catalog CEMA (Conveyors Equipment Manufacturer Association): Belt Conveyors for Bulk Materials“; 6th Edition; 2007, p. 227;

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IZBOR ZATEZNOG BUBNJA TRAKASTOG TRANSPORTERA ZA RUDU SA ASPEKTA DIMENZIONISANJA OSOVINE

Izvod

U ovom radu je, na primeru trakastog transportera za rudu T 3505 projektovanog za potrebe površinskog kopa u Majdanpeku sa kapacitetom 800 t/h, data metodologija proračuna osovine zateznog bubnja.

Analiza je urađena računskim putem i predstavlja univerzalni metod za proračun osovine zateznih bubnjeva trakastih transportera čiji su rezultati neophodni za proveru pouzdanosti ovog važnog dela trakastih transportera.

Takođe su date tehničke karakteristike svih elemenata zatezne grupe i njihov grafički prikaz.

***Ključne reči**: trakasti transporter za rudu, proračun osovine zateznog bubnja, zatezna grupa*

1. UVOD

Za ispravan rad trakastih transportera neophodno je da transportna traka u toku rada bude zategnuta odgovarajućom silom. Zatezanje trake ostvaruje se preko zateznog bubnja, a sama sila zatezanja najčešće se ostvaruje, za transportere manje dužine preko navojnog vretena, a za transportere veće dužine preko zateznog tega.

Trakasti transporter za rudu T 3505 projektovan je za transport podrešetnog proizvoda rude na površinskom kopu u Majdanpeku od sitare do trakastog transportera T 3504 [1].

Dakle, radi se o horizontalnom trakastom transporteru sa pogonskim bubnjem na istovarnoj strani transportera i sa zateznim bubnjem na utovarnoj strani transportera. S obzirom da se radi o transporteru manje dužine od 50 m za ostvarivanje sile zatezanja predviđeno je navojno vreteno kojim se aksijalno pomera zatezni bubanj i na taj način zateže traka.

Zatezna sila na zateznom bubnju je rezultat prethodnog proračuna transportera i predstavlja ulazni podatak za dimenzionisanje njenih elemenata.

2. TEHNIČKI OPIS ZATEZNE GRUPE

Zatezna grupa trakastog transportera sastoji se od sklopa zateznog bubnja sa osovinom i ležajima, uređaja za zatezanje trake sa navojnim vretenom, sklopa otklonskog bubnja sa osovinom i ležajima, nosećeg sloga sa valjcima, plužnog brisača i noseće konstrukcije.

Tehničke karakteristike samog transportera su sledeće:

- kapacitet: –
- vrsta materijala: ruda bakra
- krupnoća:
- nasipna gustina: —

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- dužina transporta:
- visina dizanja materijala na traci:

- ugao nagiba bočnih nosećih rolni:

- brzina trake: –
- tip trake: 800/4 EP250 7/2
- snaga elektromotora za pogon trake:

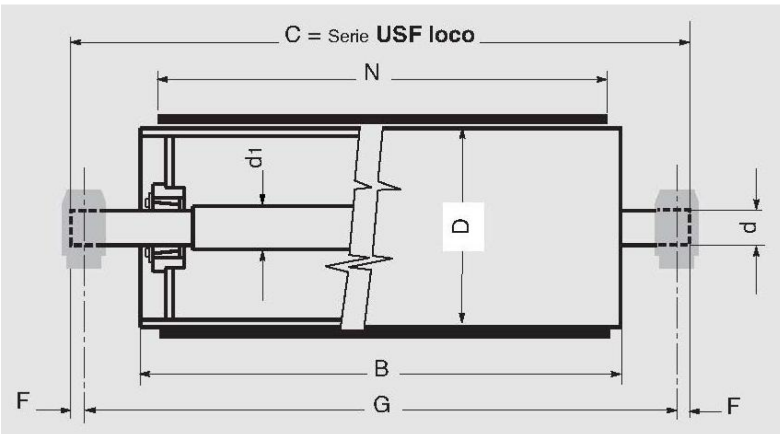
Zatezni bubanj (oznake USF,620,950,65, YA,RR,15; proizvođača Rulmeca) nalazi se na suprotnom kraju transportera u odnosu na pogonski bubanj i snabdeven je uređajem za zatezanje trake sa navojnim vretenom čiji je hod 457,2 mm (oznake TUHD-300-18; proizvođača Superior). Ležaji zateznog bubnja su samopodesivi (oznake 22215 EK; proizvođača SKF). Ispred zateznog bubnja se nalazi otklonski bubanj (oznake USF,320,950,40,YA; proizvođača Rulmeca) sa samopodesivim ležajima (oznake 22209 EK; proizvođača SKF). Za zaštitu od upadanja materijala između trake i zateznog bubnja predviđen je plužni brisač (oznake E 4000 „V“ plough; proizvođača BMS). U sastav zatezne grupe ulazi i noseći slog (oznake A3P/50,800,F22,H160,YA, proizvođača Rulmeca) sa tri noseća valjka (oznake PSV4,30F,133N,323, proizvođača Rulmeca). Svi elementi zatezne grupe smešteni su na noseću čeličnu konstrukciju izrađenu zavarivanjem od toplo valjanih čeličnih profila.

Dimenzije zateznog bubnja sa gumenom oblogom su sledeće prema slici 1.:

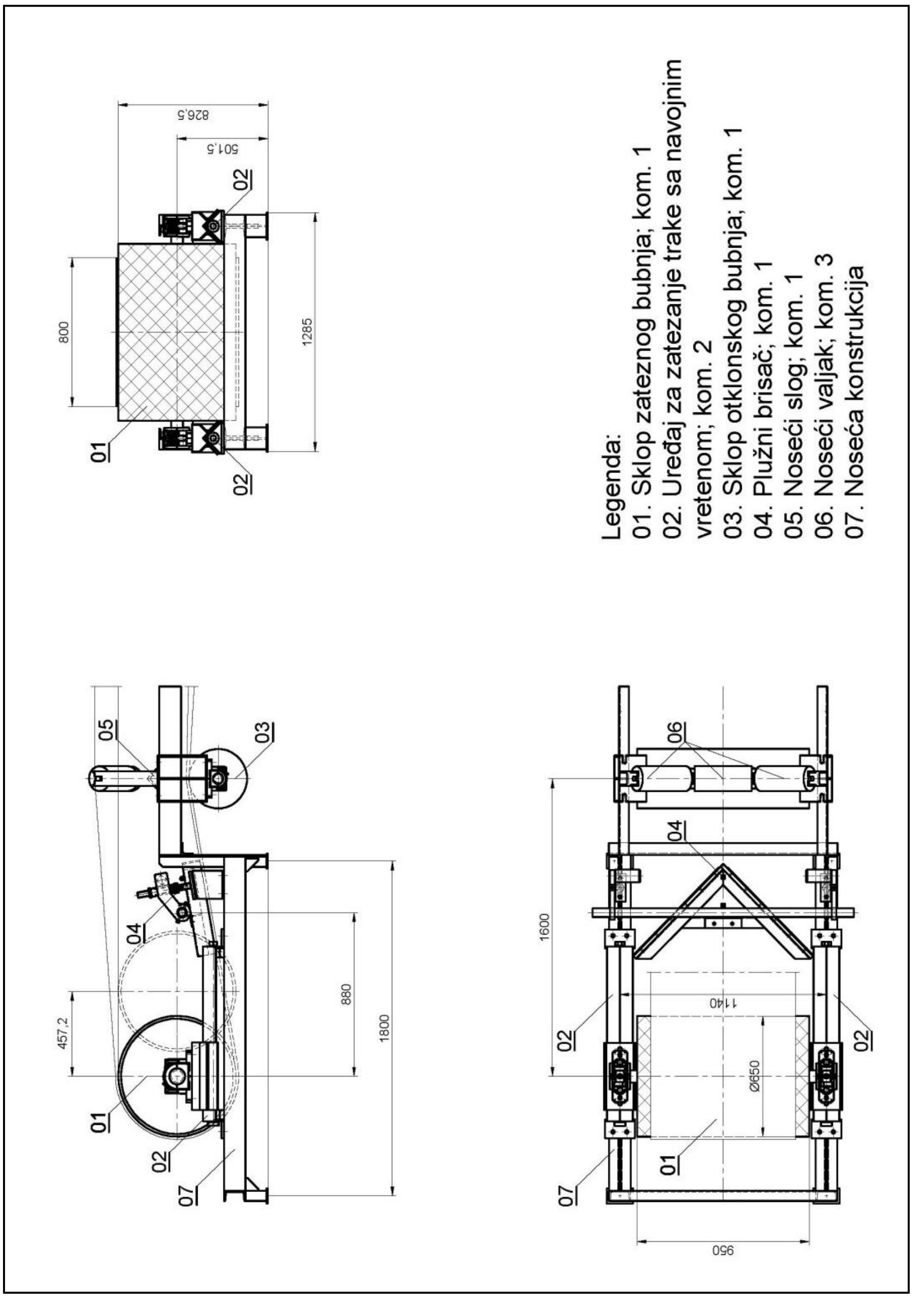
D=650 mm
B=950 mm
d=65 mm
d_1=70 mm
G=1140 mm
F=35 mm
C=1210 mm

Prema kataloškim podacima proizvođača Rulmeca [2] serija USF bubnjeva sa vezom između osovine i glavčine bubnja steznim jedinicama omogućava zabravljivanje osovine kompresijom koristeći sistem zavrtnjeva i konusnih rukavaca eliminišući mrtvi hod i ekscentricitet. Ovaj sistem zabravljivanja se danas najčešće koristi imajući u vidu jačinu, jednostavnost konstrukcije, laku montažu i demontažu, kao i održavanje. Prednost u odnosu na tradicionalnu vezu između osovine i glavčine bubnja klinom je što kod tradicionalne veze postoji smanjenja otpornog momenta osovine usled žleba za klin, kao i otežano centriranje pri montaži odnosno otežana demontaža kod bubnjeva koji su duže vreme u eksploataciji.

Prikaz zatezne grupe trakastog transportera T 3505 dat je na slici 2.



Sl. 1. *Zatezni bubanj trakastog transportera T 3505*



Sl. 2. *Zatezna grupa trakastog transportera T 3505*

3. PRORAČUN OSOVINE ZATEZNOG BUBNJA

3.1. Proračun prečnika osovine zateznog bubnja prema dozvoljenom naponu

1. Proračun prečnika osovine zateznog bubnja prema dozvoljenom naponu ima za cilj određivanje minimalnog prečnika osovine s obzirom na opterećenje i dozvoljeni napon i dat je prema [2].

2. Moment savijanja

3. Otporni moment

4. Prečnik osovine

gde su:

–zatezna sila na bubnju

–geometrijski parametar

– dozvoljeni napon za materijal osovine čelik C40

3.2. Proračun osovine zateznog bubnja prema nagibu osovine na glavčini

1. Proračun osovine zateznog bubnja prema nagibu osovine na glavčini ima za cilj određivanje ugla nagiba koji nastaje kao posledica elastične deformacije osovine pod opterećenjem s obzirom na dozvoljenu deformaciju i dat je prema [3] i slici 3.

2. Tangens ugla između deformisane osovine i njene prirodne ose pre savijanja na mestu glavčine zateznog bubnja

gde su:

– zatezna sila na bubnju

– geometrijski parametar

– geometrijski parametar

– geometrijski parametar

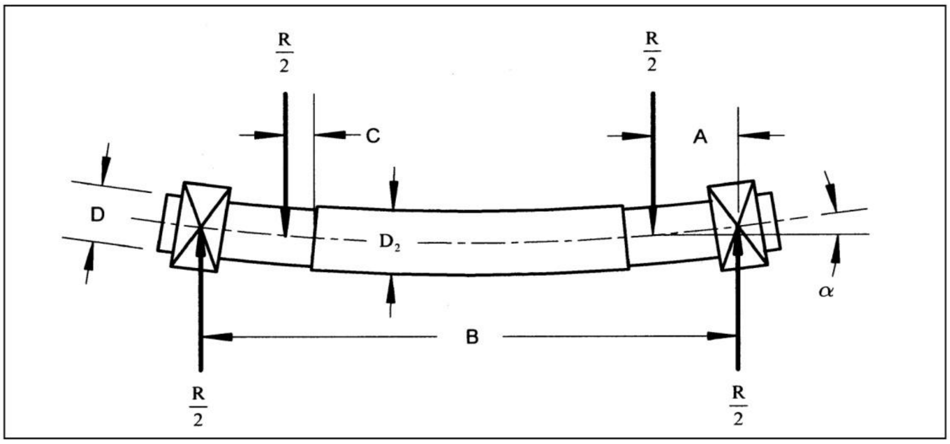
– modul elastičnosti za čelik

– moment inercije za prečnik D

–prečnik osovine na glavčini

– moment inercije za prečnik D_2

– prečnik osovine unutar bubnja



Sl 3. *Deformacija osovine zateznog bubnja-geometrijski parametri*

4. DISKUSIJA PRORAČUNA

Osovina zateznog bubnja simetrično je opterećena na savijanje. Iz kataloga proizvođača usvojen je kao materijal osovine čelik C40 (poboljšan). Osovina se proračunava prema dozvoljenom naponu i prema dozvoljenom nagibu. Proračun prečnika osovine prema dozvoljenom naponu pokazuje da je usvojeni prečnik osovine veći od potrebnog što znači da u pogledu dozvoljenog napona osovina zadovoljava. Osovina je izvedena sa dva različita prečnika tako da je njen prečnik unutar bubnja veći čime se smanjuju elastične deformacije osovine pod opterećenjem u odnosu na slučaj kada se osovina izvodi sa konstantnim prečnikom. Proračun osovine prema nagibu osovine na glavčini pokazuje da je nagib osovine u dozvoljenim granicama. Naime, prema podacima iz literature [3] maksimalna vrednost ovog nagiba iznosi 8’ dok proračunska vrednost u konkretnom slučaju iznosi 3,9’. Primenom gornje formule lako se pokazuje da bi osovina izvedena sa konstantnim prečnikom od 65 mm imala nagib od 4,7’.

ZAKLJUČAK

Proračunom dobijeni rezultati pokazuju da je osovina zateznog bubnja ispravno dimenzionisana po oba kriterijuma tj. i prema dozvoljenom naponu i prema dozvoljenoj deformaciji.

Izbor zateznih bubnjeva obično se vrši iz kataloških podataka proizvođača. Tom prilikom često je potrebno proveriti kako se ponaša osovina zateznog bubnja u datim radnim uslovima, te ovaj rad može biti koristan doprinos u tom smislu.

LITERATURA

[1] „Tehnički projekat preseljenja drobiličnog postrojenja sa Severnog revira i izgradnje novog transportnog sistema br. 3 za rudu ležišta Južni Revir u Rudniku bakra Majdanpek-Tehnički mašinski projekat transportera za podrešetni proizvod sa svim presipnim mestima”; Institut za rudarstvo i metalurgiju Bor; Odeljenje MEGA; 2013.

[2] Katalog firme Rulmeca: „Rollers and components for bulk handling"; Rulli Rulmeca S.p.A.; 4. izdanje; jul 2003.; str. 65, 259

[3] Katalog CEMA (Conveyors Equipment Manufacturer Association): „Belt conveyors for bulk materials"; 6. izdanje; 2007.; str. 227

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HYDROGEOCHEMICAL INVESTIGATION OF GROUND AND SURFACE WATER IN THE NEOGENE - QUATERNARY SEDIMENTS**

Abstract

Geochemical investigations in order to identify the mineral deposits, as well as the sources of water supply of rural settlements included in the area of Bela Crkva, between the Nera and the Karaš rivers, draining the Neogene and Quaternary sediments. During the prospecting, water samples were collected from surface water streams, springs, wells, drills, water reservoirs, as well as the samples of stream sediments and rocks. Hydrogeochemical investigations are of significance, where, in the water of Vrsac hills, elevated levels of radionuclides U, Ra and Rn, and other toxic elements were detected with values above maximum allowed concentrations for drinking water. The wells of rural households had increased levels of Fe and Mn, as well as the increased mineralization, conductivity, and nitrogen cycle. The concentration of heavy metals in water wells was increased in the most settlements around Bela Crkva, as well as in Češko Selo, Banatska Subotica, Kuštilj, Jablanka and Karaš river.

From the water accumulations formed in the Quaternary sediments southwest from Bela Crkva, samples of water, mud, overbank sediments, and A-horizon were collected. The water samles were determined on: Na, K, Ca, Mg, Fe, Mn, Al, NH_4, NO_3, SO_4, HCO_3, Cl, F, Ep, Eh, pH value, mineralization, Pb, Cd, Co, Ni, Cr, Cu, Zn, H_2S, O_2, CO_2, U, Ra, Rn, As, Hg, Br. In the solid samples, Au, Ag, Pb, Zn, and other elements, as well as the content of ^{238}U, ^{232}Th and ^{40}K were determined. Test results are presented in tables, diagrams, and hydrogeochemical maps.

Keywords: *hydrogeochemistry, prospecting, radioactivity, toxical elements, Neogene and Quaternary sediments.*

INTRODUCTION

The presence of uranium deposits in Romania (Čudanovica Dobre), located in the zone of Rešica-Moldava Nova, relatively close to the border with Serbia im posed the need for research in Vršac-Bela Crkva region, as a perspective area for discovering uranium deposits and other mineral materials (Figure 1).

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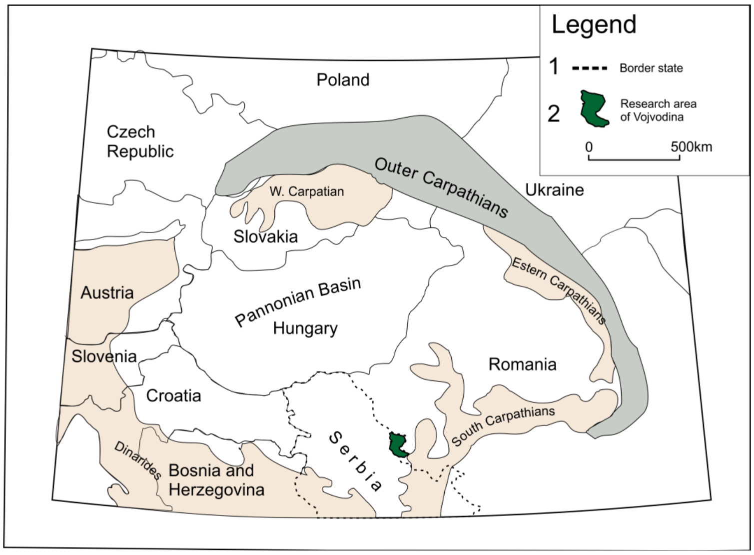

Figure 1 *Location of research area of the Pannonian Basin in Serbia*

The earliest studies dating back to the 19th century (1880-1886) [1], when the first geological map of the Vršac area, scale 1:144000, with explanation was made. The most important data of studied area were gathered during research of oil and gas which were synthesized and then used for creation of book interpreter for the map of Bela Crkva 1:100000 [2, 3]. Researches included numerous geological, hydrogeological, geophysical, geochemical investigations. For the water supplying of Bela Crkva and surrounding rural settlements, in the area of Bela Crkva, the systematic monitoring of chemical elements distribution in different environments of geosphere was carried out, which is of special significance in detecting the natural and anthropogenic influence on living environment, and for defining the ecological status as well [4]. The largest number of data was collected during the regional research of nuclear materials in the area of Vršač hills - Bela Crkva [5], during the preparation of maps geochemical-ecological atlas 1:50000 [6]. The area of Bela Crkva is located in the southeastern Banat and presents the southeast end of the Pannonian plain. In morphogenic terms, it is divided into three parts: sandstone west of the Bela Crkva, loess plateau and river lake terrace while the lowest parts of terrain are presented as the alluvial plains. An aquifer is formed in them with free level or so called the first aquifer, which is locally exploited through shallow wells for water supply or irrigation.

METHODOLOGY

Lithogeochemical, metalometric and hydrogeochemical researches of the area of Bela Crkva (Figure 1) were applied. Sampling network was adjusted to the morphological and hydrographic characteristics of the terrain. The surface flows and shallow and deeper aquifers were tested.

In all water samples, contents of U, Eh, pH and Ec were determined. In water with the increased content of uranium, and pH, Eh and Ec changes, the complete chemical analyses were conducted: anion-cation composition, content of microelements and radioactive elements U, Ra and Rn, content of gases O_2, CO_2, H_2S (Figure 2).

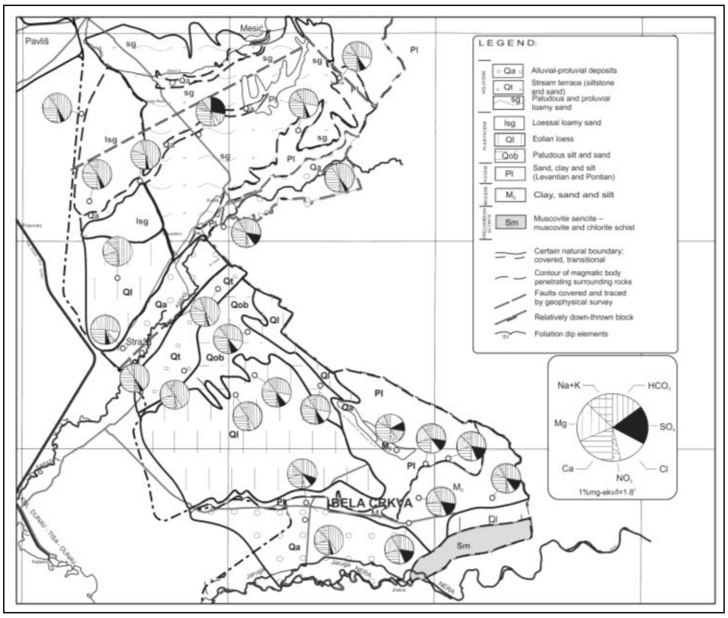

Figure 2 *Anion-Cation composition of water samples from the area of Bela Crkva*

For determining the metal content in water, Atomic Absorption Spectrophotometry was applied (AAS Perkin Elmer M-306). For other components in water solutions, colormetric, volumetric, potentiometric and turbidometric methods were used. Uranium was determined using the laser fluorimeter UA of Canadian production of Scintrex company, with fluran as the characteristic reagent. Radium concentrations were measured by radon detector RD-200 EDA, and radon concentrations were measured by radon emanometer ETR-1 Scintrex, Canada.

RESULTS AND DISCUSSION

The quaternary formations of Pleistocene and Holocene cover about 70% of total area included within regional research of uranium in the area Vršac - Bela Crkva. The terrain is made of Quaternary formations of fluvial and aeolian origin which were deposited at the time when Pannonian Basin became mainland, with rivers, lakes and puddles.

The formations are presented as puddle alevrolites (Qab), aeolian loess (Ql), and loess clays (Figure 2). These sediments were created in continental conditions, and their origin is fluvial and aeolian. The thickness of Pleistocene in the Vršac area is about 30-60 m, and in the northern and western part reaches 100 m. Holocene is developed in morphologically the lowest parts of the terrain (north and south from the Vršac hills) and along the beds of smaller or bigger rivers Nera and Karaš. The sediments have a heterogeneous composition and consist of: prolluvial suglines (Sg), debris of river terraces (alevrolites and Qz sand) and alluvial-prolluvial creations (bed facies, floods with gravels, sand and alevrolites - Qa).

In hydrogeological terms, the terrain has a complex geological structure in the northern part from Bela Crkva (Vršac hills) the terrain is composed of old rock masses: granites, gneisses, albite-muscovite schists, and on the other side of Bela Crkva area the terrain is composed of a thick strata of the Tertiary and Quaternary sediments. The position of rock masses and the character of porosity in them caused formation of different types of aquifers in that part of the terrain. In terms of structure, the structural elements are significant which extend in the NE-SW direction, and in that direction, the surface flows that drain this area are developed. In deeper parts of the terrain there are no accumulations of free underground water, so the faults which intersect the terrain do not have higher hydrogeological significance.

The underground water is mainly HCO_3-Ca-Mg type, with low mineralization (about 0,4-0,5 g/L), pH neutral and moderately hard; it is contained in an open hydrogeological structure, where there is an intense water exchange, so the contents of certain chemical components are subjected to the time changes. Free aquifer of compact type was formed on the entire expanse of alluvial-lake sediments. This aquifer was developed in the alluvial plain of the rivers Karaš and Nera, then in the sand which is locally contained at different depth [7]. Depth to groundwater is mainly 5-10 m, and on smaller expanse depth varies above and beneath this value. Hydroisopleths of the first aquifer mainly follow the isopleths of the terrain and point to the directions of underground water drainage that is towards the erosive basin of the rivers Nera and Karaš. In the area of Bela Crkva and wider (Vršac hills) in the phase of hydrogeochemical prospection, the samples of water were collected from surface flows, spring wells and lakes. According to the anioncation composition, water belongs to the hydrocarbonate type (Figure 2).

According to the presence of cations, calcium and magnesium prevail in water, which classifies it as calc-magnesium (Ca-Mg), and magnesium-calcium (Mg-Ca) type of water. Among other cations, Na+ K are present but in considerably smaller quantity. Mineralization varies within the interval of 138 mg/L - 4557 mg/L in Vršac hills. The concentration of hydrogen ions varies from 5.5 to 7.9 so this water can be classified as weakly acidic to slightly alkaline. The redox potential (Eh) was determined in every water sample. On the basis of Eh values, we can conclude that water is mostly located in oxidizing conditions. The Eh values are within the interval from -65 mV to +190 mV.

Contents of microelements vary in the interval for: Mo from 1-14 ppb, =2ppb, Li from 3-60 ppb, =5 ppb, Sr from 30 - 3250 ppb, =300 ppb, Zn from 3 - 3800 ppb, =13 ppb (Figure 3).

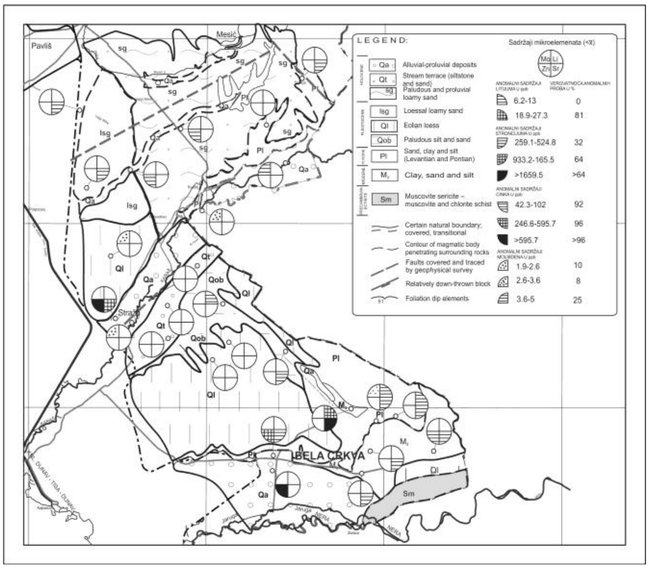

Figure 3 *Hydrogeochemical map of microelements content*

The increased contents of Li are caused by the vicinity of granite intrusion in Vršac hills, zone of fine grained gneisses with leptinolites, aplites and strings of pegmatite. Clay materials in the sediments of Bela Crkva, unlike other alkaline elements (Lithium, Rubidium, Cesium) absorb weakly Sr. Since its ion has a large radius, it cannot be absorbed into compact structure of clay minerals with the exception of multistrata structure of monmorionites. The increased content of Sr is related to hydrocarbonate water which probably originate from granite intrusion. Anomalous concentrations of U, Ra and Rn in water can be found in the Vršac hills area.

In the Bela Crkva area, inlcuding water accumulations of lakes: Vračarev Gaj, Šaran lake, Bager lake, Veliko lake, the water analysis showed that water has slightly alkaline character. Concentration of ammonium ion, according to maximum allowed concentration (MAC) of dangerous substances in water [8], has classified this water in the III/IV category and water from the lakes is classified in the I and II category. The nitrogen cycle is intense but content of nitrates does not exceed the MAC value. None of the samples detected hydrogen-sulfide as a product of anareobic decomposition, which means that there is no process of rotting and decay. This water by its composition is calcium-sulphate, and by mineralization mainly belongs to water of the I category that is the II category [9]. It is important to point out that this water by the content of heavy metals can be classified as water of the I/II category according to the mentioned regulation.

The increased content of ammonia and nitrates gives a bad bacteriological image. In most wells there is an increased content of Fe and Mn which is a characteristic of underground water in this area, so water from certain wells shown in the hydrogeochemical map (Figure 4) cannot be used for drinking [10].

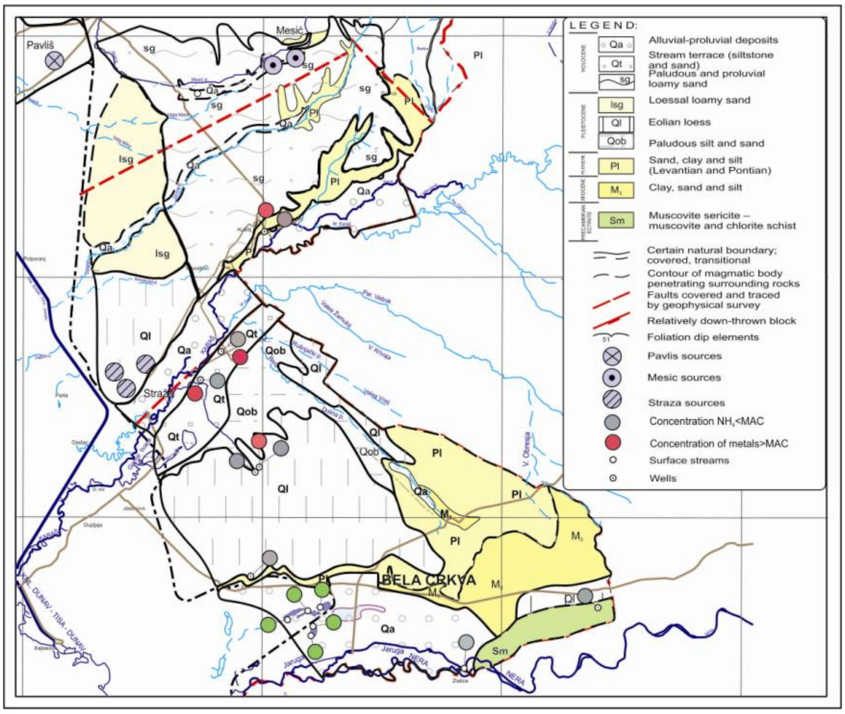

Figure 4 *Geoecological map of chemical content above maximum allowable concentration (MAC)*

CONCLUSION

In the phase of regional semi-detail and detail researches in the region of Bela Crkva and Vršac hills, the aquifer level was defined for water supply of rural settlements.

During the hydrogeochemical prospection, in every sample of water from surface flows, spring wells, and borings, complete chemical analyses were performed, which are relevant for researching the mineral materials deposits, and they present a base for the assessment of the influence of geological composition on the living environment. In the area of Bela Crkva, anomalous concentrations of elements in water of rivers Karaš and Nera and other water points are evident and they are a consequence of anthropogenic influence of excessive pollution from which the geoecological maps were done.

Presented results of chemical analyses of water, aquifer type and water quality of selected water points in rural settlements, represent a basis in spatial planning and living environment protection.

REFERENCES

[1] J. Halavats, Geological Conditions of Vršac Varoš, Journal Povesnica of free royal varoš Vršac, Pančevo, Kingdom of Yugoslavia, 1886, pp. 219-221;

[2] B. Aksin, Theoretical Problems of Classification of Oil and Gas Deposits, its Significance with Special Reference to the Deposits of Banat; Special Edition Institute for Geological and Geophysical Researches, Book 15, Belgrade, Yugoslavia, 1967;

[3] M. Rakić, Interpreter for the Geological Map of Bela Crkva 1:100000, Geological Institute, Belgrade, Yugoslavia, 1978;

[4] V. Marinković, Lj. Obradović, M. Bugarin, G. Stojanović, The Impact of Polluted Wastewater on Water Quality of the Bor River and Surrounding Groundwater, Mining and Metallurgy Engineering Bor, 3 (2014), 33-36;

[5] D. Purić, V. Gordanić, Report on Regional Studies of Nuclear Materials in the Area of Vršac Hills - Bela Crkva, Fund of Expert Documentation, Geoinstitute, Belgrade, Yugoslavia, 1981;

[6] V. Gordanić, D. Jovanović, Geochemical-geoecological Atlas 1:50000, Fund of Expert Documentation, Geoinstitute, Belgrade, Serbia, 2007;

[7] M. Vidović, V. Gordanić, Hydrogeological-Geochemical Characteristics of Groundwater in East Banat, Pannonian Basin, Serbia, Chapter 5 In: Hydrogeology – A Global Perspective, Edited by Gholam A. Kazemi, Rijeka, Croatia, InTech, 2012, pp. 161-179;

[8] Regulation on Dangerous Substances in Water, Official Gazette of the Republic of Serbia No. 31/82, Belgrade, Yugoslavia, 1982;

[9] Regulation on Water Classification, Official Gazette of the Republic of Serbia No. 5/68, 1968;

[10] Official Gazette SRY 42/98, Belgrade, Yugoslavia, 1998.

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HIDROGEOHEMIJSKA ISPITIVANJA KVALITETA PODZEMNIH I POVRŠINSKIH VODA U NEOGENIM – KVARTARNIM SEDIMENTIMA[**]

Izvod

Geološko-geohemijska istraživanja u cilju identifikacije ležišta mineralnih sirovina, kao i izvorišta za vodosnabdevanje ruralnih naselja obuhvatila su područje Bele Crkve, između reka Nere i Karaša, koje dreniraju sedimente Neogena i Kvartara. U toku prospekcije, prikupljeni su uzorci voda iz površinskih tokova, izvora, bunara, bušotina, vodenih akumulacija, potočnih sedimenata i uzorci stena. Značajna su hidrogeohemijska ispitivanja, u kojima su u vodama otkriveni povišeni sadržaji radionuklida U, Ra i Rn u području Vršačkih brda, kao i drugih toksičnih elemenata, čije su vrednosti iznad maksimalno dozvoljenih u vodi za piće. U bunarima seoskih domaćinstava povećani su sadržaji Fe, Mn, a povećani su i mineralizacija, provodljivost i azotni ciklus. Koncentracija teških metala u bunarskim vodama je povećana u većini naselja oko Bele Crkve kao i u naseljima Češko selo, Banatska Subotica, Kuštilj, Jablanka kao i reka Karaš.

Od vodenih akumulacija nastalih u kvartarnim sedimentima JZ od Bele Crkve; prikupljeni su uzorci voda muljevite komponente s dna jezera, overbank sedimenata i A-horizonta. U uzorcima voda određivani su : Na, K, Ca, Mg, Fe, Mn, Al, NH_4, NO_3, SO_4, HCO_3, Cl, F, Ep, Eh, pH, mineralizacija, Pb, Cd, Co, Ni, Cr, Cu, Zn, H_2S, O_2, CO_2, U, Ra, Rn, As, Hg, Br, u čvrstim uzorcima Au, Ag, Pb, Zn, U i dr. elementi, kao i sadržaji U, Th i ^{40}K. Rezultati ispitivanja prikazani su: tabelama dijagramima i hidrogeohemijskim kartama.

Ključne reči: *hidrogeohemija, prospekcija, radioaktivnost, toksični elementi, sedimenti neogena i kvartara*

UVOD

Prisustvo uranskih ležišta u Rumuniji (Čudanovica Dobre), koja se nalaze u zoni Rešica - Moldava Nova, na relativno bliskom rastojanju od granice sa Srbijom, nametnula su potrebu za istraživanjem regiona Vršac - Bela Crkva, kao perspektivnog područja za otkrivanja ležišta urana i drugih mineralnih sirovina (Slika 1).

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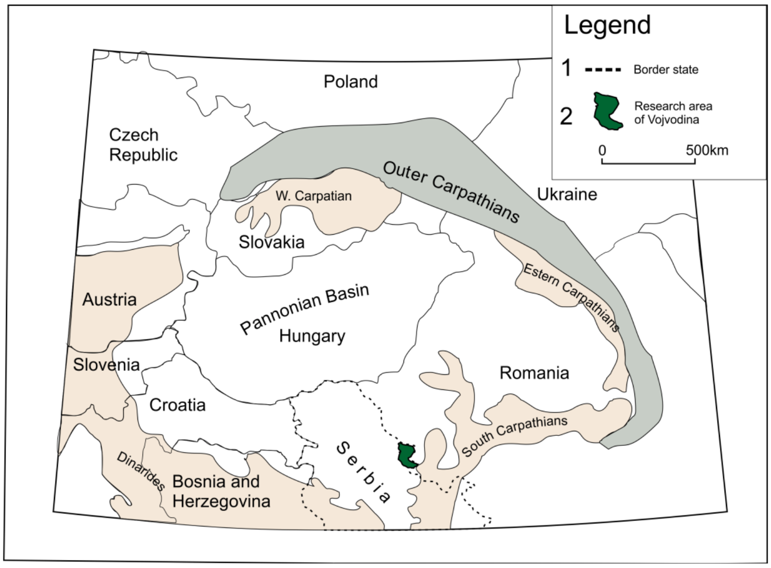
[**] *Ovaj rad je realizovan uz podršku Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije (projekat OI 176018: „Geološka i ekotoksikološka istraživanja u identifikaciji geopatogenih zona toksičnih elemenata u akumulacijama vode za piće– istraživanje metoda i postupaka smanjivanja uticaja biogeohemijskih anomalija“)*



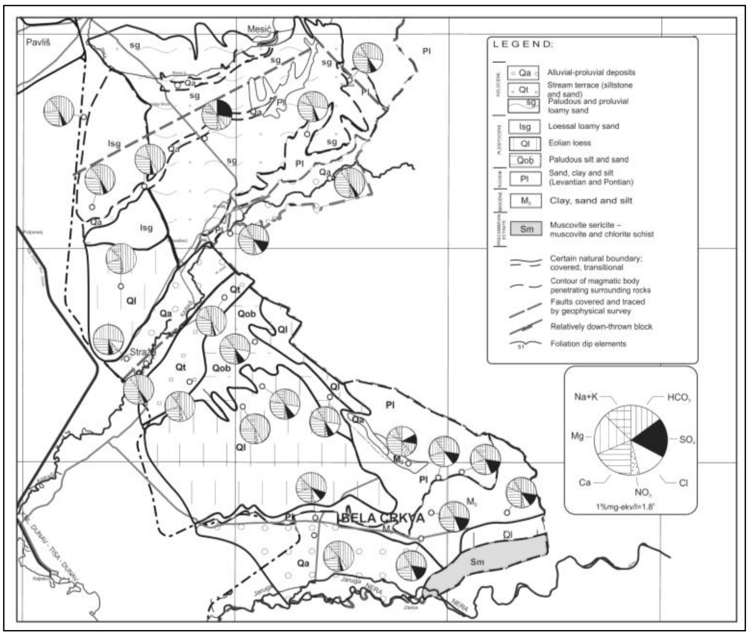
Sl. 1. *Lokacija istraživanog područja Panonskog basena u Srbiji*

Najranija istraživanja datiraju iz vremena 19. veka (1880-1886. god.), kada je urađena prva geološka karta okoline Vršca u razmeri 1:144000 sa tumačem [1]. Najvažniji podaci o ispitivanom području dobijeni su prilikom istraživanja nafte i gasa, koji su korišćeni za izradu tumača za List Bela Crkva 1:100000 [2, 3]. Istraživanjima su obuhvaćena brojna ispitivanja iz oblasti geologije, hidrogeologije, geofizike, geohemije i dr. Za potrebe vodosnabdevanja Bele Crkve i okolnih ruralnih naselja, u ovom području Bele Crkve izvršeno je sistematsko praćenje distribucije hemijskih elemenata u različitim sredinama geosfere, što je od posebnog značaja za praćenje prirodnog i antropogenog uticaja na životnu sredinu i definisanje ekološkog statusa [4]. Najveći broj podataka prikupljen je za vreme regionalnih istraživanja nuklearnih sirovina na području Vršačkih bregova-Bele Crkve [5], odnosno tokom izrade geohemijskog-ekološkog atlasa 1:50000 [6]. Područje Bele Crkve nalazi se u jugoistočnom Banatu i predstavlja krajnji jugoistočni deo Panonske nizije. U morfogenom smislu podeljeno je na tri celine: peščaru, zapadno od Bele Crkve, Lesnu zaravan i rečno jezersku terasu, a najniži delovi terena predstavljeni su aluvijalnim ravnima. U njima je formirana izdan sa slobodnim nivoom ili takozvana prva izdan, koja se lokalno eksploatiše preko plitkih kopanih bunara za vodosnabdevanje ili navodnjavanje.

METODOLOGIJA

Litogeohemijska, metalometrijska i hidrogeohemijska ispitivanja su primenjena u fazi regionalnih istraživanja na području Bele Crkve (Slika 1). Morfološkim i hidrografskim karakteristikama terena prilagođena je mreža uzorkovanja. Ispitivani su površinski tokovi plitke i dublje izdani.

U svim uzorcima voda određeni su sadržaji U i vrednosti Eh, pH i Ep. U vodama sa povišenim sadržajem urana, promenama pH, Eh i Ep urađene su kompletne emijske analize voda, i to: anjonsko-katjonski sastav vode, sadržaj mikro-elemenata i radioaktivnih elemenata U, Ra i Rn, sadržaj gasova O_2, CO_2, H_2S (Slika 2).



Sl. 2. *Anjonsko-katjonski sastav uzoraka vode sa područja Bele Crkve*

Za određivanje sadržaja metala u vodama, primenjena je Atomsko Apsorpciona spektrofotometrija (AAS Perkin Elmer M-306). Za ostale komponente, u vodenim rastvorima korišćene su kolorimetrijske, volumetrijske, potenciometrijske i turbidmetrijske metode. Uran je određivan pomoću laserskog fluorimetra UA firme Scintrex kanadske proizvodnje, sa fluranom kao karakterističnim reagensom. Koncentracije radijuma su merene pomoću radon detektora RD-200 EDA, a koncentracije radona merene su emanometrom ETR-1 Scintrex, Kanada.

REZULTATI I DISKUSIJA

Kvartarne tvorevine Pleistocena i Holocena, zahvataju oko 70% ukupne površine obuhvaćene regionalnim ispitivanjima urana područja Vršac-Bela Crkva. Teren je izgrađen od kvartarnih tvorevina, koje su fluvijalnog i eolskog porekla i taložene u vreme kada je Panonski basen postao kopno, sa rekama, jezerima i barama.

Tvorevine su predstavljene barskim alevrolitima (Qab), eolskim lesom (Ql), lesoidnim glinama (Slika 2). Ovi sedimenti su stvoreni u kontinentalnim uslovima, a porekla su fluvijalnog i eolskog. Debljina pleistocena u području Vršca je oko 30-60 m, a u severnom i zapadnom delu dostiže 100 m. Holocen je razvijen u morfološki najnižim delovima terena (severno i južno od Vršačkih brda) kao i duž korita manjih ili većih reka Nere i Karaša.

Sedimenti su heterogenog sastava i sastoje se od: barskih, proluvijalnih suglina (Sg), drobina, rečnih terasa (alevriti i peskovi Qz) i aluvijalno-proluvijalnih tvorevina (facija korita, plavina sa šljunkovima, peskovima i alevrolitima-Qa).

U hidrogeološkom smislu teren je složene geološke građe. U severnom delu od Bele Crkve (Vršačkih brda) izgrađen je od starih stenskih masa – graniti, gnajsevi, albitsko–muskovitski škriljci a sa druge strane područje Bele Crkve debelih naslaga tercijarnih i kvartarnih sedimenata. Položaj stenskih masa i karakter poroznosti u njima uslovili su da se u tom delu terena formiraju izdani različitog tipa.

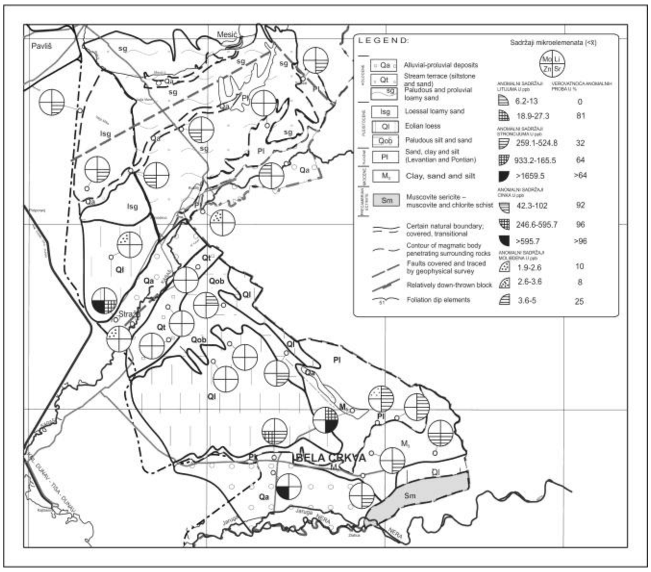
U strukturnom pogledu, značajni su strukturni elementi pravca pružanja SI-JZ, te su u tom smeru razvijeni površinski tokovi koji dreniraju ovo područje. U dubljim delovima terena nema akumulacija slobodnih podzemnih voda, pa ni rasedi koji presecaju teren nemaju veći hidrogeološki značaj.

Podzemne vode su pretežno HCO_3-Ca-Mg tipa, slabomineralizovane (oko 0,4-0,5 g/L), neutralne reakcije i umereno tvrde, koje se nalaze u otvorenoj hidrogeološkoj strukturi, gde se vrši intenzivna vodozamena, pa su i sadržaji pojedinih hemijskih komponenti podložni promenama u funkciji vremena.

Slobodna izdan zbijenog tipa formirana je na celom prostranstvu aluvijalno-jezerskih sedimenata. Ova izdan je razvijena u aluvijalnoj ravni reke Karaš i Nera, zatim u peskovima koji se lokalno nalaze na različitoj dubini [7]. Dubina do podzemne vode je pretežno 5-10 m, a na manjem prostranstvu dubina varira iznad i ispod ove vrednosti. Hidroizohipse prve izdani uglavnom prate izohipse terena i ukazuju na pravce dreniranja podzemnih voda, odnosno ka erozionom bazisu reke Nera i Karaš.

U području Bele Crkve i šire (Vršačka Brda) u fazi hidrogeohemijske prospekcije, prikupljeni su uzorci voda iz površinskih tokova izvora bunara i jezera. Prema anjonsko-katjonskom sastavu, vode pripadaju hidrokarbonatnom tipu (Slika 2). Po zastupljenosti katjona, u vodama preovlađuju kalcijum i magnezijum, što ih svrstava u kalcijsko-magnezijske (Ca-Mg), magnezijsko-kalcijske (Mg-Ca) tipove voda. Od ostalih katjona i znatno manjoj količini su Na+K. Mineralizacija se kreće u intervalu (138 mg/L do 4557 mg/L). U Vršačkim brdima koncentracija vodonikovih jona varira od 5,5 - 7,9, pa se ove vode mogu svrstati u grupu slabokiselih do slaboalkalnih voda. Oksidaciono redukcioni potencijal (Eh) određivan je u svakom uzorku vode. Na osnovu vrednosti Eh možemo zaključiti da se vode nalaze pretežno u oksidacionim uslovima. Vrednosti Eh, nalaze se u intervalu od -65 mV do +190 mV.

Sadržaji mikroelemenata variraju u intervalu za: Mo od 1-14 ppb, = 2 ppb, Li od 3-60 ppb, = 5 ppb, Sr od 30-3250 ppb, = 300 ppb, Zn od 3 ppb – 3800 ppb, = 13 ppb (Slika 3).

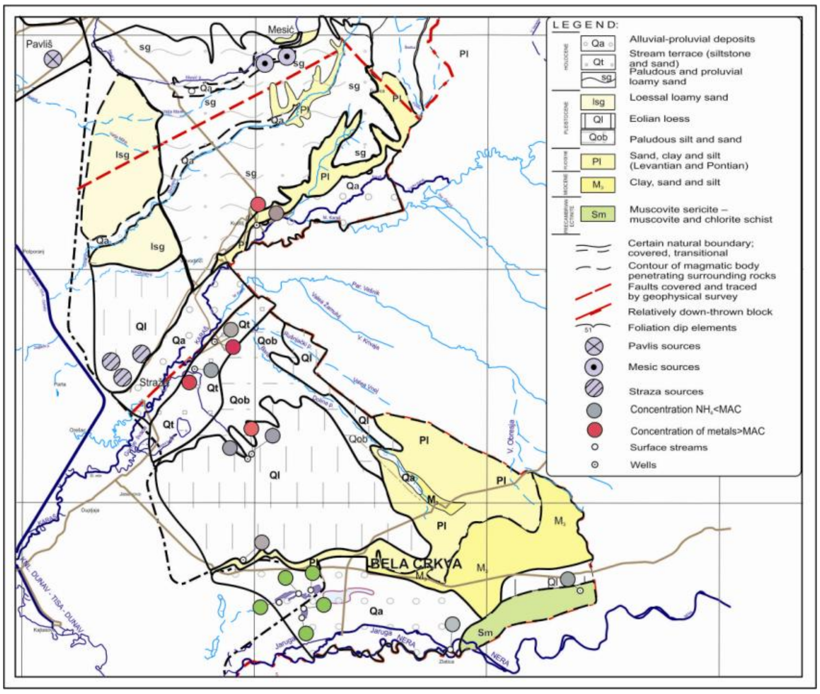


Sl. 3. *Hidrogeohemijska karta sadržaja mikroelemenata*

Povećani sadržaji Li uslovljeni su blizinom granitske intruzije u Vršačkim brdima, zone sitnozrnih gnajseva sa leptinolitima, aplitima i žicama pegmatita. Glinoviti materijali u sedimentima Bele Crkve, za razliku od drugih alkalnih elemenata (Litijum, Rubidijum, Cezijum) slabo apsorbuju Sr. Kako je njegov jon velikih razmera to ne može biti apsorbovan u zgusnutu strukturu glinovitih minerala, sa izuzetkom višeslojne strukture monmorionita. Povišeni sadržaji Sr vezani su za hidrokarbonatne vode i verovatno vode poreklo od granitskog intruziva. Anomalne koncentracije U, Ra i Rn u vodama nalaze se u području Vršačkih Brda.

U području Bele Crkve uključujući i vodene akumulacije jezera: Vračarev Gaj, Jezero, Šaransko jezero, Bagersko jezero i Veliko Jezero, analize voda su pokazale da vode imaju slabo alkalan karakter. Koncentracija amonijum jona, prema maksimalno dozvoljenoj količini opasnih materija u vodama [8] svrstava ovu vodu u kategoriju III/IV, a vode iz Jezera u I i II kategoriju. Izražen je azotni ciklus ali sadržaj nitrata ne prelazi maksimalno dozvoljenu vrednost. Ni u jednom uzorku nije detektovan vodonik-sulfid, kao proizvod anaerobnog raspadanja, što znači da nema procesa truljenja i raspadanja. Ove vode su po svom sastavu uglavnom kalcijum-sulfatne, a po mineralizaciji uglavnom pripadaju vodama I odnosno II kategorije [9]. Bitno je istaći da se, i po sadržaju teških metala mogu svrstati u I/II kategoriju voda prema navedenoj uredbi.

Povećani sadržaji amonijaka i nitrita daju lošu bakteriološku sliku. U većini bunara je povećan sadržaj Fe i Mn što je karakteristika podzemnih voda ovog područja, pa se voda iz pojedinih bunara prikazanih na hidrogeohemijskoj karti (Slika 4) ne može koristiti kao voda za piće [10].



Sl. 4. *Geoekološka karta hemijskih sadržaja preko maksimalno dozvoljene koncentracije (MDK)*

ZAKLJUČAK

U fazi regionalnih, poludetaljnih i detaljnih istraživanja, u region Bele Crkve i Vršačkih brda, definisan je nivo izdani za vodosnabdevanje ruralnih naselja.

U toku hidrogeohemijske prospekcije, u svakom uzorku vode: površinskih tokova, izvora, bunara i bušotina, urađene su hemijske analize od značaja za istraživanje ležišta mineralnih sirovina, a koje čine osnovu u proceni uticaja geološkog sastava na životnu sredinu. U području Bele Crkve, evidentne su anomalne koncentracije elemenata u vodama reke Karaš i Nere i drugih vodopunktova, koje su posledica antropogenog uticaja prekograničnog zagađenja, na osnovu čega su urađene geološke karte.

Prikazani rezultati hemijskih analiza voda, tip izdani i kvalitet voda izabranih vodopunktova u ruralnim naseljima čine osnovu u prostornom planiranju i zaštiti životne sredine.

LITERATURA

[1] J. Halavats, Geological conditions of Vršac varoš, Journal Povesnica of Free Royal Varoš Vršac, Pančevo, Kingdom of Yugoslavia, 1886, str. 219-221.

[2] B. Aksin, Theoretical Problems of Classification of Oil and Gas Deposits, its Significance with Special Reference to the Deposits of Banat; Special Edition Institute for Geological and Geophysical Researches, Book 15, Belgrade, Yugoslavia, 1967.

[3] M. Rakić, Interpreter for the Geological Map of Bela Crkva 1:100000, Geological Institute, Belgrade, Yugoslavia, 1978.

[4] V. Marinković, Lj. Obradović, M. Bugarin, G. Stojanović, Uticaj zagađenih otpadnih voda na kvalitet vode Borske reke i okolnih podzemnih voda, Mining and Metallurgy Engineering Bor, 3 (2014), 37-40.

[5] D. Purić, V. Gordanić, Report on Regional Studies of Nuclear Materials in the Area of Vršac hills - Bela Crkva, Fund of Expert Documentation, Geoinstitute, Belgrade, Yugoslavia, 1981.

[6] V. Gordanić, D. Jovanović, Geochemical-geoecological Atlas 1:50000, Fund of Expert Documentation, Geoinstitute, Belgrade, Serbia, 2007.

[7] M. Vidović, V. Gordanić, Hydrogeological-Geochemical Characteristics of Groundwater in East Banat, Pannonian Basin, Serbia, Chapter 5 In: Hydrogeology – A Global Perspective, Edited by Gholam A. Kazemi, Rijeka, Croatia, InTech, 2012, str. 161-179.

[8] Regulation on Dangerous Substances in Water, Official Gazette of the Republic of Serbia No. 31/82, Belgrade, Yugoslavia, 1982.

[9] Regulation on Water Classification, Official Gazette of the Republic of Serbia No. 5/68, 1968.

[10] Officiale gazette SRJ 42/98, Belgrade, Yugoslavia, 1998.

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Vojin Gordanić, Milka Vidović*, Ivana Trajković*, Saša Rogan**

GEOCHEMICAL MAPPING OF RIVERBANK PROFILES IN THE BASIN AREA OF THE RIVER IBAR: ROLE IN ESTABLISHING THE GEOCHEMICAL BASIS FOR THE ASSESSMENT OF ANTHROPOGENIC INFLUENCE ON THE ENVIRONMENT**

Abstract

Geochemical mapping of riverbank profiles of the basin area of the river Ibar was performed in the purpose of making regional geochemical map of Serbia 1:1000000. In this area, deposits of lead and zinc are located, and they are characterized by very complex geological composition. Sampling net at chosen locations of riverbank profiles was adjusted to the morphological and hydrographic characteristics of the terrain. At every profile, samples were collected from A-horizon, Ob-overbank sediment and S-active stream sediment, while tracking the changes of lithological members, in accordance to the WEGS methodology (Western European Geological Surveys).

The preserved geochemical track in the overbank sediment is of special significance for correlation the results of chemical elements in the surface part of (A-horizon) and active contemporary stream sediment. In the analytical process, beside determining contents of Pb, Zn, Cu, Co, Ni, Cr, Sb, V, Cd and other elements, the radiometric examinations of contents of U^{238}, Th^{232} and K^{40}, were also conducted as well as the appropriate sedimentological analyses. On the basis of geochemical prospection results, a data base was formed which represents a foundation for estimation of anthropogenic influence on the living environment of rural settlements in the basin area of the river Ibar. In accordance to the geological-structural and morphological characteristics of the terrain, the results are applicable in the research of mineral raw materials, in agriculture, forestry, geomedicine, etc.

Keywords: *overbank, strim sediments, A-horizotn, geochemical mapping, riverbank profile*

INTRODUCTION

The overbank sediment (material deposited in the alluvial plain outside of the drainage canal) is usually used in the processes of making regional geochemical maps [1]. Studies in Great Britain showed a "close link" between the mine contamination and contents of metals in the contemporary overbank sediments [2,3]. Application of OB-overbank sediment as a medium suitable for making geochemical atlas of Western Europe and defining the anthropogenic influence on the living environment was supported by Bolviken et al. [4]. For making a regional geochemical map of Serbia 1:1000000 [5], the overbank sediment was used, and for researches basin areas from 60-600 km^2 were used. The significance of overbank sediment in defining the ecological status and making regional geochemical map of Serbia is shown at locations of

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riverbank profiles (A-horizon, OB-overbank sediment and S-stream sediment) [6,7,8]. Since the riverbank sediments are used, beside in the process of making regional geochemical map, also in defining the anthropogenic influence on the living environment, the WEST methodology (Western European Geological Surveys) is usually used in researches. Due to these reasons, the basin area of the river Ibar was selected, where deposits of lead and zinc were located, which are characterized by very complex geological composition. Geochemical mapping the riverbank profiles of the river Ibar basin, included the part of the Vardar zone area and inner Dinarides. Two complexes stand out: the Volcanic zone of Kopaonik and the area of mountain Rogozna.

The volcanic zone of Kopaonik is located on the both sides of the river Ibar, in length of about 60 km and width of 35 km (direction of extending (NNW – SSE), including the area from the mouth in West Morava in the north till Leposavić in the south. It continues onto volcanogenic complex of the mines of Pb and Zn "Trepča". Volcanic activity took place in three phases: preplutonic phase - dalto-andesites, followed by larger occurrences of volcanic breccias, tuffs and tuffites; sinplutonic phasegrano-diorites, quartzmonzonites and quartzdiorites with occurrences of volcanic breccias, tuffs and tuffites and postplutonic phase - basalts and andesite basalts. Volcanics and pyroclastices of Rogozna are different from Kopaonik's by younger postplicative phases of volcanic activity. Among larger structural forms, the structural zone of Studenica is of relevance, whose system of ruptures goes along with the flow of the river Studenica (tributary of Ibar), and it is difficult to follow it in the Ibar ultramaphite complex.

MATHERIALS AND METHODS

The basin area of the river Ibar with its tributaries – rivers Ribnica, Lopatnica, Studenica, Raška, Ljudska, Jošanica, Drenska, Kozareva, Vidrenjak, covers the area of about 7000 km^2. In the phase of regional geochemical prospection, mapping of riverbank profiles of alluvial plains and river valleys in the part of southern and central Serbia was conducted. Sampling net was adjusted to the morphological and hydrographic characteristics of the terrain, in accordance to the map scale 1:1000000 (Figure 1).

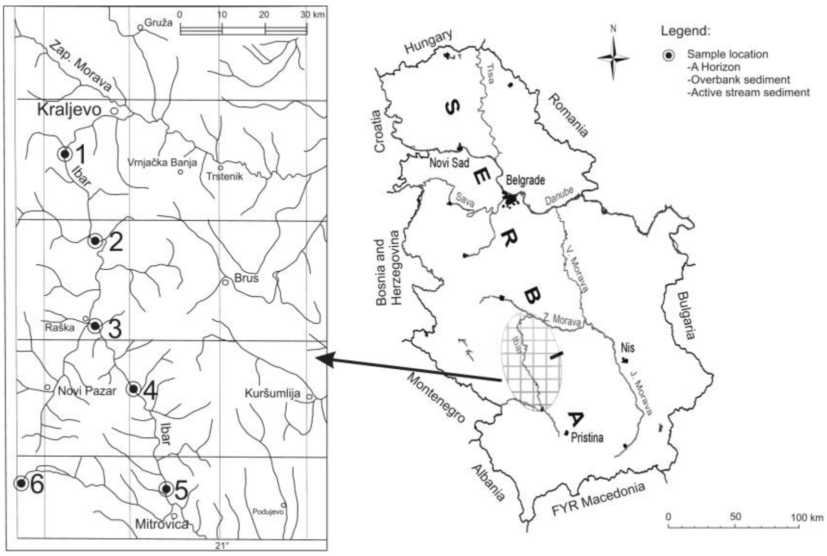

Figure 1 *Geochemical map with the sample locations*

According to the WEGS recommendation, at selected locations (shown in Figure 1), samples were collected from:

- A – horizon, at depth up to 20 cm close to surface, which is polluted by the human impact, weight 5kg;
- Subsurface material "overbank sediment" sampled at depth of 1 - 1,5 m, in accordance to the lithological changes of deposited sediments, weight 5-15 kg;
- Contemporary active stream sediment, weight 5 kg, for correlation with the results from overbank sediments, formed in the preindustrial era.

The samples were dried at temperature of 80 °C and sieved through sieves dimensions up to 2 mm; 0.5-2 mm; 0.5–0.18 mm; 0.18–0.125 mm. For fractions sma-ller than 0.125 mm, laboratory tests were conducted. Chemical analyses methods that were applied are: Atomic Absorption Spectrophotometry (AAS) and Inducted Coupled Plasma-Atomic-Emission Spectrophotometry (ICP-AES). Samples were prepared by open digestion with mineral acids: with "aqua regia" (mixture $HCl:NO_3$= 3:1) for: Ag, Au, Bi, Cd, Co, Cu, Mo, Ni, Pb, Sb, V and Zn; with "modified aqua regia" for: P and S; and separation with HF, NH3 and $HClO_4$ for: B, Ba, Be, Cr, Cs, Li, Rb and Sr.

The international geochemical standards of granite G-1 and diabase W-1 were used in the analytical process, and the samples were also checked in the other laboratories as well. In all samples sedimentological, spectrochemical, radiometric and partially mineralogical researches were performed. In collected samples with low content of U (< 50 ppm), contents of total U, ^{232}Th and ^{40}K were determined. Measurements were conducted using a scintilation detector 4'' x 4'' of Bikron company with crystal made of NaI with multiplicative analyzer (MCA; 4096 channels) type "ORTEC-7500". The analyses are based on the measurements of high energy radiations (0-3 meV). For calibration of the spectrum and calculation of natural radionuclides concentration, the standards of uranium ore (U) and thorium (Th) were used, "New Bruncvick Laboratory" (USAEC), *NBL. No.* 103 0.005%, *NBL. No.* 107 0.10% *Th.* Potassium chloride was used (r.a.) as the standard for potassium.

RESULTS AND DISCUSSION

In accordance to the geological characteristics of the terrain in the riverbank profile, the geochemical track of elements which reflect the composition of the spring material which is deposited in the fluvial plain of the basin area of the river Ibar, is preserved. On the basis of the results of granulometric examinations the collected sediments of deposit of selected locations were determined according to classification of Folk, 1954 [9] (Figure 2):

- A - horizon as: sandy alevrite, alevrite sand, sand, alevrite sandy gravel;
- OB - overbank sediment as: sandy alevrite, alevrite sand, gravelly alevrite sand, sand;
- S - stream sediment as: gravelly alevrite sand, gravelly sand, sandy gravel, coarse-grained sand, gravel.

The geochemical track of riverbank profiles at selected locations: 1, 2, 3, 4, 5, 6 is shown in Table 1 and sampling places are presented in a geochemical map (Figure 1).

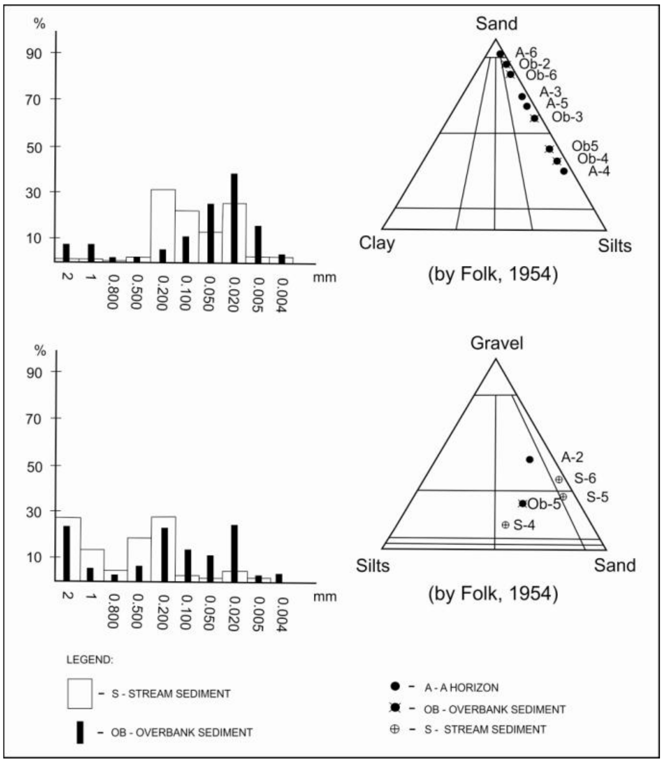

Figure 2 *Histogram-fraction distribution in profile of the river Ibar and Folk classification [9]*

Table 1 *Contents of elements in the riverbank profiles from the spring part of the river Ibar (location 6) till the mouth in the West Morava (location 1)*

River Ibar		Pb, ppm	Zn, ppm	Cu, ppm	Cd, ppm	As, ppm	Fe, ppm	Uu, ppm
Location 1	**A**	173	276	32	0.9	-	-	-
	OB	190	1333	28	3.3	-	-	-
	S	127	1220	27	3.6	-	-	-
Location 2	**A**	85	65	35	1.2	13.9	31400	4.6
	OB	95	78	35	1.3	9.8	35700	4.8
	S	90	81	35	1.3	11.6	42800	4.0
Location 3	**A**	110	81	35	0.9	8.8	22500	5.6
	OB	110	25	35	0.6	11.5	18700	9.8
	S	60	72	35	1.2	8.2	25000	18.2
Location 4	**A**	210	311	68	1	3.5	70525	3.5
	OB	390	392	61	2	7.8	72540	3.5
	S	530	712	100	4	17.4	76895	3.2
Location 5	**A**	3500	3710	345	26	78.8	150150	0.4
	OB	4000	297	491	11	36.3	241800	-
	OB	3070	4995	542	26	112	108875	4.2
	S	700	1703	79	13	7.5	80145	7.7
Location 6	**A**	85	99	68	1	10.1	59020	3.0
	OB	35	101	47	□ 1	7.0	45045	6.7
	S	100	88	44	1.0	3.2	34250	3.2

The results of contents variations of Pb, Zn, Cu, Cd, As are shown in diagrams for every riverbank profile per locations for A-horizon, OB-overbank sediment and S-stream sediment (Figures 3 - 6).

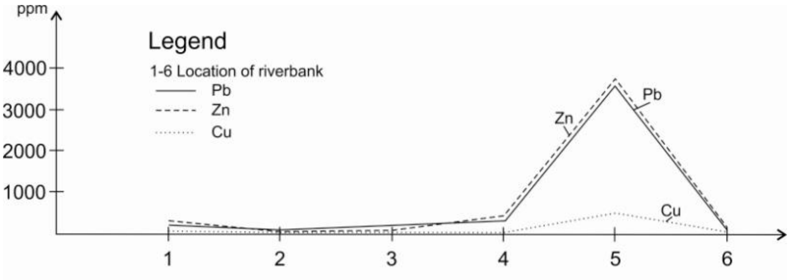

Figure 3 *Content variations of Pb, Zn and Cu in A-horizon at locations of the river Ibar*

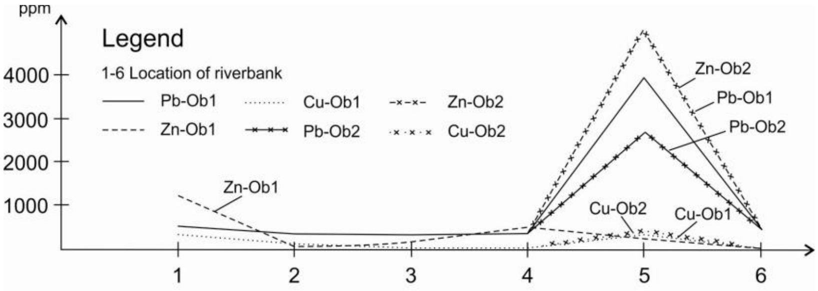

Figure 4 *Content variations of Pb, Zn and Cu in OB-overbank sediments of the river Ibar*

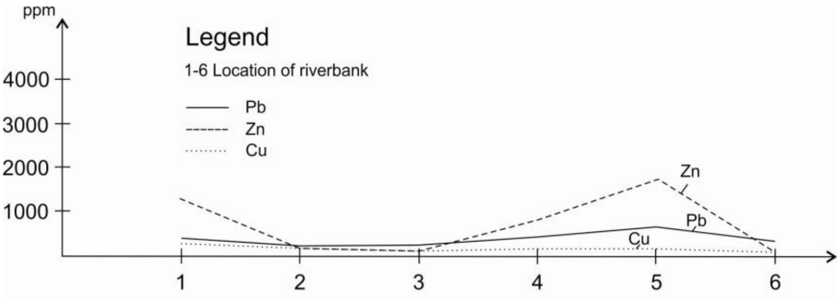

Figure 5 *Content variations of Pb, Zn and Cu in S-stream sediments of the river Ibar*

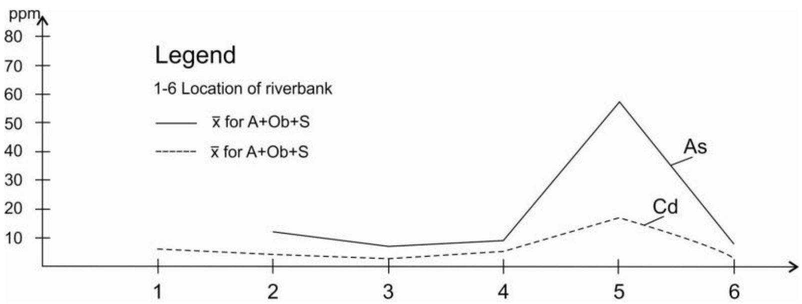

Figure 6 *Content variations of As and Cd in the riverbank profiles of the river Ibar*

Anomaly concentrations of Pb, Zn, Cu, Cd, As and Fe are of twofold origin: from rocks in which there is a fon of high values (Table 2) and elements which origi nate from ore (ore halda, old mining works), metallurgy processes, agrochemical compounds rich in metals, material for filling the roads, wastewater and other.

Table 2 *Average contrast among the metal contents in the zone without ores and in the peripheral ore*

Main metals	(A) Content in magmatic rocks, ppm	(B) Content in the ores that are being processed, ppm	Contrast ratio (B/A)
Lead, Pb	16[a]	50000[b]	3000
Zinc, Zn	80[a]	80000[b]	1000
Copper, Cu	70[a]	10000[b]	140
Chrome, Cr	2000[c]	250000[b]	125
Nickel, Ni	160[d]	15000[b]	95

[a] *[10]*
[b] *Data for Pb, Zn, Cu [11]*
[c] *Medium content in ultrabasic rocks [12]*
[d] *Medium content in gabbro [13]*

Contrasts in the metal contents between the secondary geochemical anomalies and normal fon depend on many factors: contrast between ore and surrounding rock, relative mobility of elements in scattering environment, concentration dilution by sterile material. For different types of mineral deposits, the primary contrast varies in wide limits (Table 2). The primary contrast is more sustained by immobile elements (Pb) than mobile elements (Zn, Cu and U), which are subjected to leaching, whose level is determined by decay intensity, velocity of water movement, pH value and many other factors which influence on the form of scattering. In water, contrast is also in the function of mobility [13]. The most mobile elements show the biggest contrast. Mobile elements which deposit at relatively small changes of chemical and biological conditions show the most severe contrast in hydromorphic anomalies of soil and sediments [14].

In the prospected area of the river Ibar basin, the main rocks of high fon values are located. The most distinctive is a group of ultrabasic rocks (peridotites, serpetinites) with high contents of Cr, Ni, Co and Mg, then a group of basic rocks (gabbro, basalts and diabase) with high contents of Fe, Ti and Cu. In granite, granodiorites, quartz diorites and diorite Cu, Ag, Au, Zn, Cd, Hg, Ge, Sn, Pb, As, Sb, Bi, Nb, Ta, S, Se, Te, Mo, W, U, Fe, Co and Ni are concentrated. Content of lead in magmatic rocks is changeable and depends on the character of these rocks. In the basic rocks, content of Pb is low and it rises with the acidity of magmatic rocks. So the content of Pb in granites is five times higher than the content in gabbro. Distribution of Zn in rocks of different composition is partially similar to the distribution of Fe, beginning from the basic magmatic rocks percentage of Zn rises and in granodiorites achieves the highest values. According to the level of concentration, a distinct connection of Cu with basic rocks can be observed in some magmatic rocks. The connection of As with certain magmatic rocks refers to the medium acid rocks which have an increased content of that metal. For the influence of chemical composition of riverbank profiles in the basin area of the river Ibar, beside geological composition, the area of northern part of Kosovska Mitrovica is of special significance including the mines of Pb and Zn: Crnac, Belo brdo (pit excavation) and Koporiš surface excavation, flotation in Leposavić and me-tallurgy complex which includes the chemical industry of Zn and the Factory of batteries. Anthropogenic influence is the strongest at location of riverbank profile 5 in which there are extremely high concentrations of Pb, Zn, Cu, As and Cd (Figures 3-6) and Fe in A-horizon, OB-overbank sediment and S-stream sediment and it is located down stream from Kosovska Mitrovica. The highest content of ^{238}U, ^{232}Th, ^{40}K i ^{226}Ra are found in the stream sediments at location 5, downstream from Kosovska Mitrovica (Table 3).

Table 3 *Contents of natural radionuclides ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra in the riverbank profiles from the spring part of the river Ibar (location 6) till the mouth in the West Morava (location 1)*

River Ibar		^{238}U, ppm	^{232}Th, ppm	^{40}K, %	^{226}Ra, ppm	Th/U
Location 1	**A**	2.68	6.65	1.25	0.000090	2.48
	OB	2.09	8.32	1.42	0.000071	3.98
	S	2.45	7.89	1.53	0.000083	3.22
Location 2	**A**	0.43	0.89	0.13	0.000015	2.05
	OB	1.89	7.60	1.15	0.000064	4.03
	S	2.48	7.43	1.23	0.000084	3.00
Location 3	**A**	2.28	7.75	1.50	0.000077	3.40
	OB	2.10	8.34	1.47	0.000071	3.97
	S	2.16	6.14	1.18	0.000073	2.84
Location 4	**A**	1.70	6.31	1.33	0.0000574	3.71
	OB	1.53	5.09	1.24	0.0000516	3.33
	S	2.26	6.54	1.39	0.0000763	2.89
Location 5	**A**	2.15	3.65	1.08	0.0000726	1.70
	OB	2.61	2.95	0.70	0.0000881	1.13
	OB	1.52	3.58	0.68	0.0000513	2.36
	S	6.27	18.30	2.70	0.0002117	2.92
Location 6	**A**	1.14	5.51	1.36	0.0000476	3.91
	OB	1.31	5.32	1.19	0.0000442	4.06
	S	1.13	3.53	1.26	0.0000381	3.12

The origin of anomalous concentrations of ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra can be associated with a fluvial transport of radioactive elements from Kosovo area by the river Sitnica, which flows into the river Ibar, upstream from location 5 (Figure 1). The presence of lead and zinc mines in the immediate vicinity (upstream of location 5) requires further research, but in the regional perception of the ecological status of the region, an analysis of content the chemical elements in the riverbank profile is evident and significant. Sampling methodology provides representative data in a regional sense and it is important in the selection of geopathogenic zones of influence the natural radionuclides [15] and other toxic elements.

CONCLUSION

Geochemical mapping of riverbank profiles which includes: A-horizon, OB-overbank sediment and S-stream sediment, is of significance for proper determination of scattering halos, formed depending on geological composition or anthropogenic influence. The applied sampling methodology of riverbank profiles and analytical methods are of special relevance in researching the mineral raw materials and making regional, semidetail and detail geochemical maps. Correlation of contents the chemical elements in the main rocks and defined anthropogenic influence in the riverbank profile, define the state in the living environment. By making geochemical maps in different environments of the geosphere, a data base was formed for defining the state of the living environment in the preindustrial and postindustrial period, and also monitoring was established. The research results are multipurpose, especially for marking the area of biogeochemical endemia, making of geomedicine maps, researching the mineral raw materials and the other study multidisciplinary researches.

REFERENCES

[1] R. T. Ottesen, J. Bogen, B. Bølviken, T. Volden, Overbank sediment: A Representative Sample Medium for Regional Geochemical Mapping, Journal of Geochemical Exploration, 32 (1989), 257-277.

[2] M. G. Macklin, Metal Contamination of Soils and Sediments: A Geographical Perspective. In: Newson, M.D. (Ed.), Managing the Human Impact on the Natural Environment: Patterns and Processes, London, Belhaven Press, 1992, 172-195.

[3] M. G. Macklin, J. Ridgway, D. G. Passmore, B.T. Rumsby, The Use of Overbank Sediment for Geochemical Mapping and Contamination Assessment: Results from Selected English and Welsh Floodplains, Applied Geochemistry 9 (1994), 689-700.

[4] B. Bølviken, J. Bogen, A. Demetriades, W. De Vos, J. Ebbing, R. Hindel, R.T. Ottesen, R. Salminen, O. Schermann, R. Swennen. Final Report of the Working Group on Regional Geochemical Mapping 1986-1993. Forum of European Geological Surveys (foregs), Geological Survey of Norway Open File Report, 1993, No. 93-092.

[5] V. Gordanić, D. Milovanović, M. Vidović, S. Rogan, I. Trajković, Geochemical Map of Eastern Serbia in 1:1000000 and Application in Defining the Ecological Status of Selected Areas, Proceedings of the 17th Meeting of the Association of European Geological Societies – MAEGS 17, Serbian Geological Society, Belgrade, Serbia, 2011, 187-191.

[6] V. Gordanić, A. Ćirić, D. Jovanović, The Use Overbank Sediments Data for Geochemical Mapping and Contamination Assessment: Results from Selected Floodplains of Serbia, Goldschmidt Conference Abstracts "Goldshmidt 2007", Cologne, Germany, Geochimica et Cosmochimica Acta, 71 (2007), 15, 1, A346.

[7] V. Gordanić, A. Ćirić, D. Jovanović, Regional Geochemical Mapping – Ecological Significance. Goldschmidt Conference Abstracts "Goldshmidt 2008", Vancouver, Canada, Geochimica et Cosmochimica Acta, 72 (2008), 12, A321.

[8] V. Gordanić, V. Spasić-Jokić, Geochemical indicators in identirication of geopathogenic zones of natural radioactivity. MD-Medical Data, 5 (2013), 2, 121-124.

[9] R. L. Folk, The distinction between grain size and mineral composition in sedimentary rock nomenclature. Journal of Geology 62 (1954), 4, 344-359.

[10] J. Green, Geochemical Table of the Elements for 1959, Geological Society of America Bulletin 70 (1959), 1127-1184.

[11] M. Fleischer, The Abundance and Distribution of the Chemical Elements in the Earth Crust, Journal of Chemical Education, 31 (1954), 9, 446-455;

[12] A. P. Vinogradov, Regularity of Distribution of Chemical Elements in the Earth Crust. Geochemistry, 1(1956) 1-43.

[13] R. Marković, J. Stevanović, M. Gvozdenović, J. M. Jakšić, Treatment of Waste Sulfuric Acid Copper Electrolyte, Mining and Metallurgy Engineering Bor, 3 (2014), 141-152.

[14] L. Zupunski, V. Spasic-Jokic, V. Gordanic, Chapter IX: Low Dose Exposure to Radionuclides in Soil, In: Gerada, J.G. (Ed.), Radionuclides: Sources, Properties and Hazards, New York, Nova Science Publishers, Inc., 2012, 151-170.

[15] V. Spasic-Jokic, Lj. Zupunski, Z. Mitrovic, B. Vujicic, I. Zupunski, Lj. Jankovic-Mandic, V. Gordanic, Environmental Risk of Natural Radiation Sources, 2011 IEEE International Workshop on Medical Measurements and Applications Proceedings (MeMeA), Bari, Italia, 2011, 638-641.

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Vojin Gordanić, Milka Vidović*, Ivana Trajković*, Saša Rogan**

GEOHEMIJSKO KARTIRANJE OBALSKIH PROFILA U SLIVNOM PODRUČJU REKE IBAR: ULOGA U USPOSTAVLJANJU GEOHEMIJSKE OSNOVE ZA PROCENU ANTROPOGENOG UTICAJA NA ŽIVOTNU SREDINU**

Izvod

Kartiranje obalskih profila u slivnom području reke Ibar vršeno je u cilju izrade geohemijske karte Srbije 1:1000000. U ovom području se nalaze ležišta olova i cinka, a karakteriše ga veoma složen geološki sastav. Mreža uzorkovanja na izabranim lokacijama obalskih profila prilagođena je morfološkim i hidrografskim karakteristikama terena. Na svakom profilu prikupljeni su uzorci iz A-horizonta, overbank sedimenta i aktivnog strim sedimenta, prateći promene litoloških članova, u skladu sa metodologijom WEGS (Western European Geological Surveys).

Sačuvani geohemijski zapis u overbank sedimentu je od posebnog značaja za korelaciju rezultata hemijskih elemenata u površinskom delu (A-horizont) i aktivnog savremenog strim sedimenta. U analitičkom postupku, pored određivanja sadržaja Pb, Zn, Cu, Co, Ni, Cr, Sb, V, Cd i drugih elemenata, vršena su radiometrijska ispitivanja sadržaja U^{238}, Th^{232} i K^{40}, kao i odgovarajuće sedimentološke analize. Na bazi rezultata geohemijske prospekcije formirana je baza podataka koja čini osnovu za procenu antropogenog uticaja na životnu sredinu ruralnih naselja u slivnom području reke Ibar. U skladu sa geološko-strukturnim i morfološkim karakteristikama terena, rezultati su primenjivi u istraživanju mineralnih sirovina, u poljoprivredi, šumarstvu, geomedicini i sl.

Ključne reči: *overbank, strim sedimenti, A-horizont, geohemijsko kartiranje, obalski profil*

UVOD

Overbank sediment (materijal deponovan u aluvijalnoj ravnici izvan drenažnog kanala) se obično koristi prilikom izrade regionalnih geohemijskih karata [1]. Proučavanjima u Velikoj Britaniji pokazano je da postoji „tesna veza“ između rudničke kontaminacije i sadržaja metala u savremenim overbank sedimentima [2,3]. Primenu OB-overbank sedimenta kao sredine pogodne za izradu geohemijskog atlasa zapadne Evrope i definisanje antropogenog uticaja na životnu sredinu, zastupali su Bolviken i autori [4]. Prilikom izrade regionalne geohemijske karte 1:1000000 Srbije [5], korišćen je overbank sediment, a za istraživanja su korišćene slivne površine od 60-600 km^2. Značaj overbank sedimenta u definisanju ekološkog statusa i izradi

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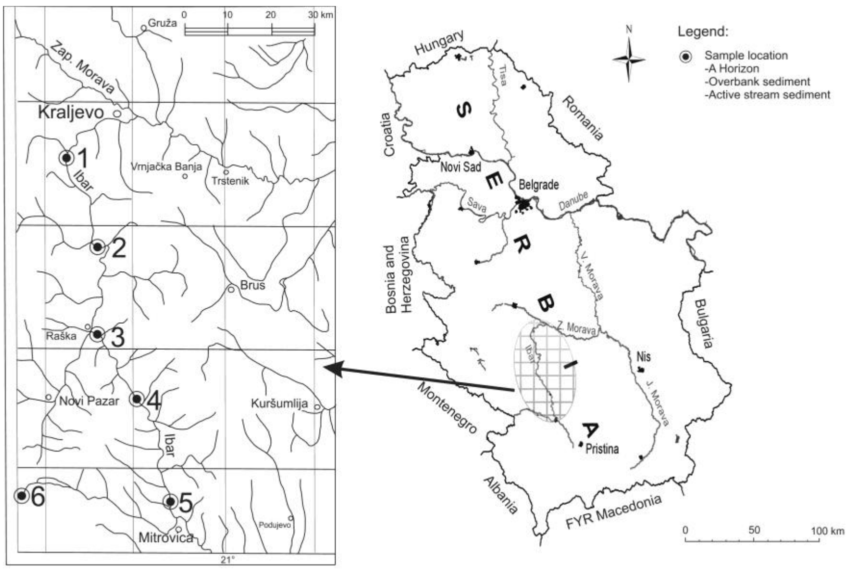
regionalne geohemijske karte Srbije prikazan je na lokacijama obalskih profila (A-horizonta, OB-overbank sedimenta i S-strim sedimenta) [6, 7, 8]. Pošto overbank sedimenti pored izrade geohemijske karte služe za definisanje stanja antropogenog uticaja na životnu sredinu, u istraživanjima se obično primenjuje metodologija WEGS (Western European Geological Surveys). Iz tih razloga izabrano je slivno područje reke Ibar u kome se nalaze ležišta olova i cinka, i koje karakteriše veoma složen geološki sastav. Geohemijsko kartiranje obalskih profila sliva reke Ibar, obuhvatilo je deo područja vardarske zone i unutrašnjih dinarida. Izdvajaju se dva kompleksa: Vulkanska zona Kopaonika i područje planine Rogozne.

Vulkanska zona Kopaonika nalazi se sa obe strane reke Ibar, u dužini oko 60 km i širine 35 km (pravca pružanja SSZ–JJI), zahvatajući prostor od ušća u zapadnu Moravu na severu do Leposavića na jugu. Ona se nastavlja na vulkanogeni kompleks rudnika Pb i Zn „Trepča“, a prošla je kroz tri faze vulkanske aktivnosti: predplutonsku fazu (dalto-andeziti, praćeni većim pojavama vulkanskih breča, tufova i tufita), sinplutonsku (granodioriti, kvarcmonconiti i kvarcdioriti sa pojavama vulkanskih breča, tufova i tufita) i postplutonsku fazu (bazalti i andezit bazalti). Vulkaniti i piroklastiti Rogozne se razlikuju od kopaoničkih samo mlađim postplikativnim fazama vulkanske aktivnosti. Od većih strukturnih formi, od značaja je strukturna zona Studenice čiji sistem razloma ide tokom reke Studenice (pritoke Ibra), a u ibarskom ultramafitskom kompleksu se teško prati.

MATERIJALI I METODE

Slivno područje reke Ibar sa svojim pritokama – rekama Ribnica, Lopatnica, Studenica, Raška, Ljudska, Jošanica, Drenska, Kozareva, Vidrenjak, obuhvata površinu od oko 7000 km^2. U fazi regionalne geohemijske prospekcije, izvršeno je kartiranje obalskih profila aluvijalnih ravnica, rečnih dolina dela južne i centralne Srbije. Mreža uzorkovanja prilagođena je morfološkim i hidrografskim karakteristikama terena, u skladu sa razmerom karte 1:1000000 (Slika 1).



Sl. 1. *Geohemijska karta sa lokacijama uzorkovanja*

Prema preporuci WEGS-a (Zapadno-Evropske Geohemijske Asocijacije), na izabranim lokacijama (prikazanim na Slici 1), prikupljeni su uzorci iz:

- A - horizonta, na dubini do 20 cm blizu površine, koji je zagađen uticajem čoveka, a težina uzorka je iznosila 5 kg;
- OB - podpovršinski materijal „overbank sediment“ uzorkovan na dubini 1-1,5 m, u skladu sa litološkim promenama deponovanih sedimenata, pri čemu je težina uzorka iznosila 5-15 kg;
- S - savremeni aktivan strim sediment, koji je uzorkovan radi korelacije sa rezultatima iz obalskih profila formiranih u preindustrijskom dobu a težina uzorka je iznosila 5 kg .

Uzorci su sušeni na temperaturi od 80°C i prosejani na sitima dimenzije do 2 mm; od 2-0,5 mm; 0,5–0,18 mm; 0,18–0,125 mm. Od frakcija manjih od 0,125 mm izvršena su laboratorijska ispitivanja. Od metoda hemijske analize, primenjene su: atomsko apsorpciona spektrofotometrija (AAS) i ICP-AES (Indukovano spregnuta plazma-atomsko-emisiona spektrofotometrija). Uzorci su pripremani otvorenom digestijom sa mineralnim kiselinama: sa „carskom vodom“ (smeša $HCl:HNO_3$= 3:1) za: Ag, Au, Bi, Cd, Co, Cu, Mo, Ni, Pb, Sb, V i Zn; sa „modifikovanom carskom vodom“ za: P i S i razlaganjem sa HF, NH_3, $HClO_4$ za: B, Ba, Be, Cr, Cs, Li, Rb i Sr.

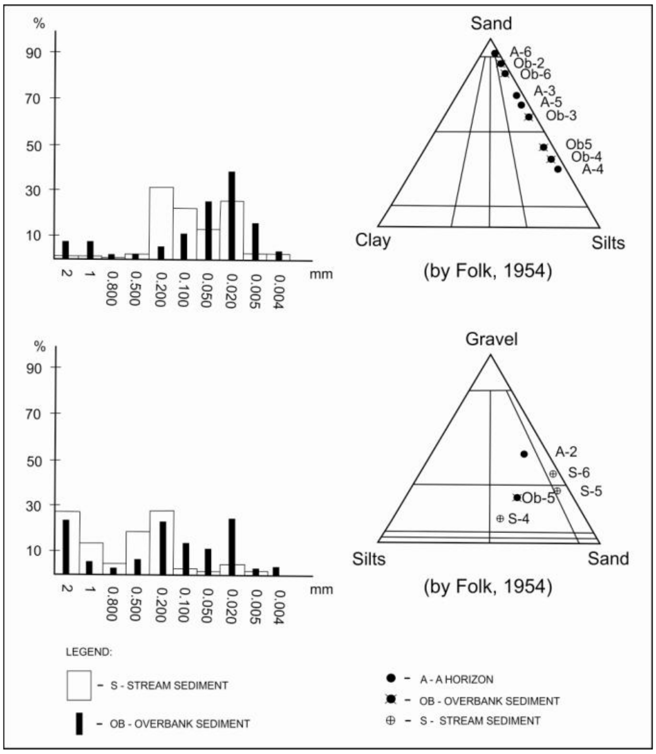
U analitičkom postupku korišćeni su međunarodni geohemijski standardi granita G-1 i dijabaza W-1, a uzorci su i proveravani u nekoliko laboratorija. U svim uzorcima vršena su sedimentološka, spektrohemijska, radiometrijska i delimično mineraloška ispitivanja. U prikupljenim uzorcima sa niskim sadržajem U (< 50 ppm), određeni su sadržaji ukupnog U, ^{232}Th i ^{40}K. Merenja su izvršena pomoću scintilacionog detektora 4’’ x 4’’, firme Bikron sa kristalom od NaI sa multiplikativnim analizatorom (MCA; 4096 kanala) tipa „ORTEC–7500“. Analize se zasnivaju na merenju zračenja visokih energija (0-3 meV). Za kalibraciju spektra i proračun koncentracije prirodnih radionuklida, korišćeni su standardi rude urana U i torijuma Th, „New Bruncvick Laboratorija“ (USAEC), *NBL. No. 103 0,005% U i NBL. No. 107 0,10% Th.* Kao standard kalijuma, upotrebljen je kalijum-hlorid (r.a.).

REZULTATI I DISKUSIJA

U skladu sa geološkim karakteristikama terena u obalskom profilu, sačuvan je geohemijski zapis elemenata koji odslikavaju sastav izvorišnog materijala, a koji je deponovan u fluvijalnoj ravni slivnog područja reke Ibar. Na osnovu rezultata granulometrijskih i hemijskih ispitivanja, prikupljeni sedimenti depozita izabranih lokacija determinisani su prema klasifikaciji Folk-1954 (Slika 2):

- A – horizont kao: peskoviti alevrit, alevritski pesak, pesak, alevritsko peskoviti šljunak;
- OB – overbank sediment kao: peskoviti alevrit, alevritski pesak, šljunkoviti alevritski pesak, pesak;
- S – strim sediment kao: šljunkovito alevritski pesak, šljunkoviti pesak, peskoviti šljunak, krupnozrni pesak, šljunak.

Geohemijski zapis obalskih profila na izabranim lokacijama: 1, 2, 3, 4, 5, 6 prikazan je u Tabeli 1, a mesta uzorkovanja su predstavljena na geohemijskoj karti (Slika 1).

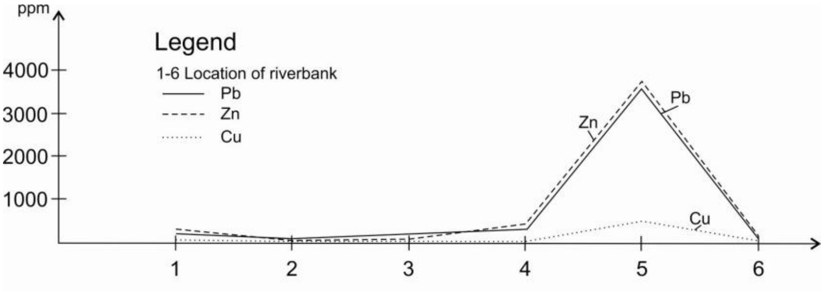


Sl. 2. *Histogram distribucija frakcija u profilu reke Ibar i klasifikacija po Folku [9]*

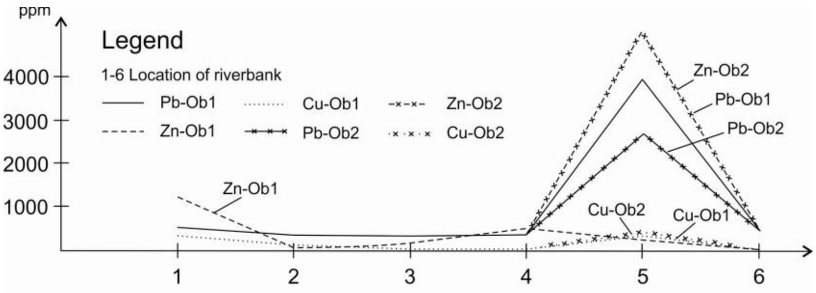
Tabela 1. *Sadržaj elemenata u obalskim profilima od izvorišnog dela reke Ibar (lokacija 6) od ušća u Zapadnu Moravu (lokacija 1).*

Reka Ibar		Pb, ppm	Zn, ppm	Cu, ppm	Cd, ppm	As, ppm	Fe, ppm	Uu, ppm
Lokacija 1	A	173	276	32	0.9	-	-	-
	OB	190	1333	28	3.3	-	-	-
	S	127	1220	27	3.6	-	-	-
Lokacija 2	A	85	65	35	1.2	13.9	31400	4.6
	OB	95	78	35	1.3	9.8	35700	4.8
	S	90	81	35	1.3	11.6	42800	4.0
Lokacija 3	A	110	81	35	0.9	8.8	22500	5.6
	OB	110	25	35	0.6	11.5	18700	9.8
	S	60	72	35	1.2	8.2	25000	18.2
Lokacija 4	A	210	311	68	1	3.5	70525	3.5
	OB	390	392	61	2	7.8	72540	3.5
	S	530	712	100	4	17.4	76895	3.2
Lokacija 5	A	3500	3710	345	26	78.8	150150	0.4
	OB	4000	297	491	11	36.3	241800	-
	OB	3070	4995	542	26	112	108875	4.2
	S	700	1703	79	13	7.5	80145	7.7
Lokacija 6	A	85	99	68	1	10.1	59020	3.0
	OB	35	101	47	□ 1	7.0	45045	6.7
	S	100	88	44	1.0	3.2	34250	3.2

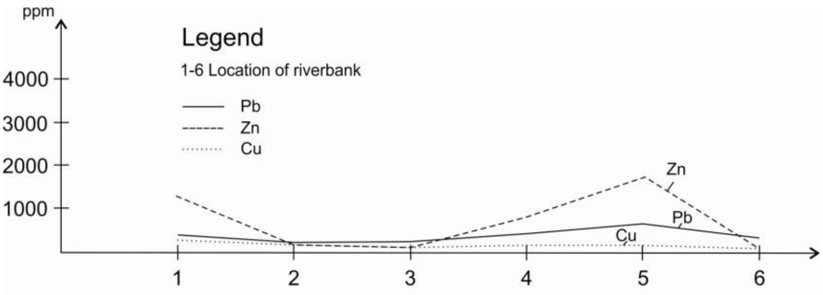
Rezultati varijacije sadržaja Pb, Zn, Cu, Cd, As prikazani su na dijagramima za svaki obalski profil po lokacijama za A - horizont, OB - overbank sedimenta i S - strim sedimenta (Slike 3-6).



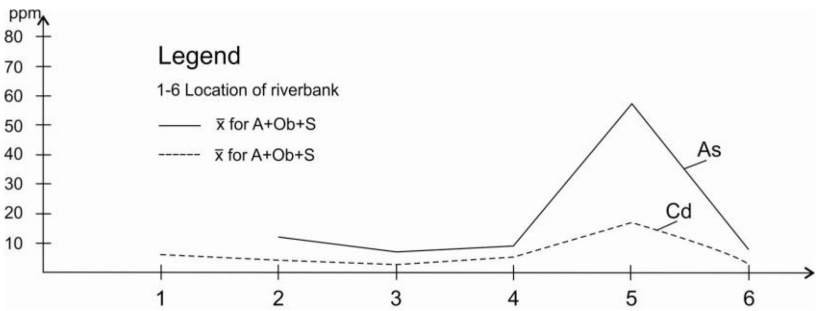
Sl. 3. *Varijacije sadržaja Pb, Zn i Cu u A-horizontu na lokacijama reke Ibar*



Sl. 4. *Varijacije sadržaja Pb, Zn i Cu u OB-overbank sedimentima reke Ibar*



Sl. 5. *Varijacije sadržaja Pb, Zn i Cu u S-strim sedimentima reke Ibar*



Sl. 6. *Varijacije sadržaja As i Cd u obalskim profilima reke Ibar*

Anomalne koncentracije Pb, Zn, Cu, Cd, As i Fe su dvojakog porekla: iz stena u kojima je fon visokih vrednosti (Tabela 2) i elemenata koji potiču od rude (rudničke halde, stari rudarski radovi), metalurški procesi, agrohemijska jedinjenja bogata metalima, materijal za nasipanje puteva, otpadne vode i dr.

Tabela 2. *Prosečan kontrast između sadržaja metala u neorudnjenoj zoni i u perifernoj rudi*

Glavni metali	(A) Sadržaj u magmatskim stenama (ppm)	(B) Sadržaj u rudama koje se obrađuju (ppm)	Kontrast odnos B/A
Olovo, Pb	16[a]	50000[b]	3000
Cink, Zn	80[a]	80000[b]	1000
Bakar, Cu	70[a]	10000[b]	140
Hrom, Cr	2000[c]	250000[b]	125
Nikl, Ni	160[d]	15000[b]	95

[a] *[10]*
[b] *Rezultati za Pb, Zn, Cu [11]*
[c] *Prosečna vrednost u ultrabaznim stenama [12]*
[d] *Prosečna vrednost u gabru [13]*

Kontrasti u sadržajima metala između sekundarnih geohemijskih anonmalija i normalnog fona je u zavisnosti od mnogih faktora: kontrasta između rude i okolne stene, relativne mobilnosti elemenata u sredini rasejavanja, razblaženjem koncentracije sterilnim materijalom. Za različite tipove mineralnih ležišta, primarni kontrast varira u širokim granicama (Tabela 2). Primarni kontrast više održavaju imobilni elementi (Pb) nego mobilni elementi (Zn, Cu i U), koji su podložni izluživanju, čiji je stepen određen intenzitetom raspadanja, brzinom kretanja vode, veličinom pH vrednosti i mnogim drugim faktorima koji utiču na oblik rasejavanja [13]. U vodi je kontrast takođe u funkciji mobilnosti. Najveći kontrast pokazuju najmobilniji elementi. Mobilni elementi koji se talože kod relativno malih promena hemijskih i bioloških uslova pokazuju najoštriji kontrast u hidromorfnim anomalijama zemljišta i sedimenata [14].

U prospektovanom području sliva reke Ibar nalaze se matične stene visokih vrednosti fona. Najizrazitija je grupa ultrabazičnih stena (peridotiti, serpentiniti) sa visokim sadržajem Cr, Ni, Co i Mg, zatim grupa bazičnih stena (gabro, bazalti i dijabazi) sa visokim sadržajem Fe, Ti i Cu. U granitu, granodioritu, kvarcdioritu i dioritu su koncentrisani: Cu, Ag, Au, Zn, Cd, Hg, Ge, Sn, Pb, As, Sb, Bi, Nb, Ta, S, Se, Te, Mo, W, U, Fe, Co i Ni. Sadržaj olova u magmatskim stenama je promenljiv i zavisi od karaktera tih stena. U bazičnim stenama, sadržaj Pb je nizak i raste sa kiselošću magmatskih stena. Tako je sadržaj Pb u granitima pet puta veći od sadržaja u gabru. Raspodela Zn u stenama različitog sastava delimično je slična raspodeli Fe, počev od bazičnih magmatskih stena udeo Zn raste i u granodioritima dostiže najveće vrednosti. Prema stepenu koncentracije u pojedinim magamatskim stenama zapaža se izrazita povezanost Cu sa bazičnim stenama. Povezanost As sa određenim magmatskim stenama odnosi se na srednje kisele stene, koje imaju povećan sadržaj tog metala. Na uticaj hemijskog sastava obalskih profila u slivnom području reke Ibar, pored geološkog sastava, od posebnog značaja je područje severnog dela Kosovske Mitrovice u kome se nalaze rudnici Pb i Zn: Crnac, Belo brdo (jamski kop) i Koporiš (površinski kop), zatim flotacija u Leposaviću i metalurški kompleks koji obuhvata hemijsku industriju Zn i fabriku akumulatora. Antropogeni uticaj najizraženiji je na lokaciji obalskog profila 5 u kome su izuzetno visoke koncentracije Pb, Zn, Cu, As i Cd (Slike 3-6) i Fe u A-horizontu, OB-overbank sedimentu i S-strim sedimentu a koji se nalaze nizvodno od Kosovske Mitrovice. Najveći sadržaji ^{238}U, ^{232}Th, ^{40}K i ^{226}Ra nalaze se u strim sedimentu na lokaciji 5 nizvodno od Kosovske Mitrovice (Tabela 3).

Tabela 3. *Uticaj prirodnih radionuklida ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra u obalskim profilima od izvorišnog dela reke Ibar (lokacija 6) od ušća u Zapadnu Moravu (lokacija 1)*

Reka Ibar		^{238}U, ppm	^{232}Th, ppm	^{40}K, %	^{226}Ra, ppm	Th/U
Lokacija 1	**A**	2.68	6.65	1.25	0.000090	2.48
	OB	2.09	8.32	1.42	0.000071	3.98
	S	2.45	7.89	1.53	0.000083	3.22
Lokacija 2	**A**	0.43	0.89	0.13	0.000015	2.05
	OB	1.89	7.60	1.15	0.000064	4.03
	S	2.48	7.43	1.23	0.000084	3.00
Lokacija 3	**A**	2.28	7.75	1.50	0.000077	3.40
	OB	2.10	8.34	1.47	0.000071	3.97
	S	2.16	6.14	1.18	0.000073	2.84
Lokacija 4	**A**	1.70	6.31	1.33	0.0000574	3.71
	OB	1.53	5.09	1.24	0.0000516	3.33
	S	2.26	6.54	1.39	0.0000763	2.89
Lokacija 5	**A**	2.15	3.65	1.08	0.0000726	1.70
	OB	2.61	2.95	0.70	0.0000881	1.13
	OB	1.52	3.58	0.68	0.0000513	2.36
	S	6.27	18.30	2.70	0.0002117	2.92
Lokacija 6	**A**	1.14	5.51	1.36	0.0000476	3.91
	OB	1.31	5.32	1.19	0.0000442	4.06
	S	1.13	3.53	1.26	0.0000381	3.12

Poreklo anomalnih koncentracija ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra može se povezati sa fluvijalnim transportom radioaktivnih elemenata sa područja Kosova rekom Sitnicom, koja se uliva u reku Ibar uzvodno od lokacije 5 (videti sliku 1). Prisustvo rudnika olova i cinka u neposrednoj blizini (uzvodno od lokacije 5) zahteva detaljnija istraživanja, ali u regionalnom sagledavanju ekološkog statusa regiona evidentna je i značajna analiza rezultata sadržaja hemijskih elemenata u obalskim profilima. Metodologija uzorkovanja obezbeđuje reprezentativne podatke u regionalnom smislu i značajna je u izdvajanju geopatogenih zona uticaja prirodnih radionuklida [15] i drugih toksičnih elemenata.

ZAKLJUČAK

Geohemijsko kartiranje obalskih profila koga čine: A-horizont, OB-overbank sediment i S-strim sediment, od značaja je za pravilnu determinaciju oreola rasejavanja, formiranih u zavisnosti od geološkog sastava ili antropogenog uticaja. Primenjena metodologija uzorkovanja obalskih profila i analitičke metode su od posebnog značaja u istraživanju mineralnih sirovina i izradi regionalnih, poludetaljnih i detaljnih geohemijskih karata. Korelacija sadržaja hemijskih elemenata u matičnim stenama i antropogeni uticaj definisan u obalskom profilu definišu stanje u životnoj sredini. Izradom geohemijskih karata u različitim sredinama geosfere, formira se osnova za praćenje definisanja stanja životne sredine u preindustrijskom i postindustrijskom periodu i uspostavljanje monitoringa. Rezultati istraživanja su višenamenskog karaktera, naročito za evidentiranje područja biogeohemijske endemije, izrade geomedicinskih karata, istraživanje mineralnih sirovina i druga studijska multidisciplinarna istraživanja.

LITERATURA

[1] R. T. Ottesen, J. Bogen, B. Bølviken, T. Volden, Overbank Sediment: A Representative Sample Medium for Regional Geochemical Mapping, Journal of Geochemical Exploration, 32 (1989), 257-277.

[2] M. G. Macklin, Metal Contamination of Soils and Sediments: A Geographical Perspective. In: Newson, M. D. (Ed.), Managing the Human Impact on the Natural Environment: Patterns and Processes, London, Belhaven Press, 1992, 172-195.

[3] M. G. Macklin, J. Ridgway, D. G. Passmore, B. T. Rumsby, The use of Overbank Sediment for Geochemical Mapping and Contamination Assessment: Results from Selected English and Welsh Floodplains, Applied Geochemistry 9 (1994), 689-700.

[4] B. Bølviken, J. Bogen, A. Demetriades, W. De Vos, J. Ebbing, R. Hindel, R.T. Ottesen, R. Salminen, O. Schermann, R. Swennen, Final Report of the Working Group on Regional Geochemical Mapping 1986-1993. Forum of European Geological Surveys (foregs), Geological Survey of Norway Open File Report, 1993, No. 93-092.

[5] V. Gordanić, D. Milovanović, M. Vidović, S. Rogan, I. Trajković, Geochemical mapp of Eastern Serbia in 1:1000000 and Application in Defining the Ecological Status of Selected Areas, Proceedings of the 17th meeting of the Association of European Geological Societies – MAEGS 17, Serbian Geological Society, Belgrade, Serbia, 2011, 187-191.

[6] V. Gordanić, A. Ćirić, D. Jovanović, The use Overbank Sediments data for Geochemical Mapping and Contamination Assessment: Results from Selected Floodplains of Serbia, Goldschmidt Conference Abstracts „Goldshmidt 2007“, Cologne, Germany, Geochimica et Cosmochimica Acta, 71 (2007), 15, 1, A346.

[7] V. Gordanić, A. Ćirić, D. Jovanović, Regional Geochemical Mapping – Ecological Significance, Goldschmidt Conference Abstracts „Goldshmidt 2008“, Vancouver, Canada, Geochimica et Cosmochimica Acta, 72 (2008), 12, A321.

[8] V. Gordanić, V. Spasić-Jokić, Geochemical Indicators in Identirication of Geopathogenic Zones of Natural Radioactivity. MD - Medical Data, 5 (2013), 2, 121-124.

[9] R. L. Folk, The Distinction Between Grain Size and Mineral Composition in Sedimentary Rock Nomenclature. Journal of Geology 62 (1954), 4, 344-359.

[10] J. Green, Geochemical Table of the Elements for 1959, Geological Society of America Bulletin 70 (1959), 1127-1184.

[11] M. Fleischer, The Abundance and Distribution of the Chemical Elements in the Earths Crust, Journal of Chemical Education, 31 (1954), 9, 446-455.

[12] A. P. Vinogradov, Regularity of Distribution of Chemical Elements in the Earth’s Crust, Geochemistry, 1 (1956), 1-43.

[13] R. Marković, J. Stevanović, M. Gvozdenović, J. M. Jakšić, Treatment of Waste Sulfuric Acid Copper Electrolyte, Mining and Metallurgy Engineering Bor, 3 (2014), 141-152.

[14] L. Zupunski, V. Spasic-Jokic, V. Gordanic, Chapter IX: Low Dose Exposure to Radionuclides in Soil, In: Gerada, J. G. (Ed.), Radionuclides: Sources, Properties and Hazards, New York, Nova Science Publishers, Inc., 2012, 151-170.

[15] V. Spasic-Jokic, Lj. Zupunski, Z. Mitrovic, B. Vujicic, I. Zupunski, Lj. Jankovic-Mandic, V. Gordanic, Environmental Risk of Natural Radiation Sources, 2011 IEEE International Workshop on Medical Measurements and Applications Proceedings (MeMeA), Bari, Italija, 2011, 638-641.

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Biserka Trumić, Aleksandra Ivanović*, Vojka Gardić**

SEGREGATION OF IMPURITIES IN PLATINUM AND PLATINUM-BASED ALLOYS**

Abstract

This work presents the research results of formation the equilibrium and non-equilibrium segregations of impurities both in pure platinum and platinum alloys. It is shown that segregations strengthen in the case when impurities, absorbed on the surface of crystals, have the same sign or similar values of range deviations regarding to the pure platinum. Equilibrium of segregations occurs as the diffusion result of impurities to the grain boundaries with creation of concentration gradient.

Non-equilibrium segregation of impurities occupies the area size of ten micrometers and is generated in the process of metal crystallization or in solid solution as the result of interaction the impurities with vacancies with formation a pair of vacancy-interstitial atom.

Segregation of impurities in the platinum alloys is conditioned by the nature of impurities, their concentration, distribution in the volume of metal, interaction with the basic and alloying components as well as the temperature - time factor.

The groups of impurities were observed in the form of foreign inclusions along with the equilibrium and non-equilibrium segregation of impurities in the platinum alloys.

Keywords: *impurities, equilibrium and non-equilibrium segregation, platinum, platinum alloys*

INTRODUCTION

The presence of chemical elements - impurities in the platinum metals and alloys is related to the composition of the starting mineral raw materials as well as the technological processes for their preparation, processing and exploitation in the industrial conditions [1-3].

The presence of impurities in the platinum metals and alloys has a major impact on their physical and mechanical properties. Due to this reason, the purity of platinum metals and alloys is one of their key characteristics [4-6].

Depending on the content and distribution of impurities in metal, their interaction also changes. With increasing the content of impurities, a probability of brittle fracture of metals during heating increases. However, technological and exploitation properties of platinum metals and alloys can be significantly modified in the presence of very small amounts of impurities (within hundredths and thousandths of percent). The risk of brittle fracture is so much higher if the increase of content of impurities does not occur in the entire volume of metal, but only in some of its parts [7,8].

Local concentration of impurities in the inter-crystal zone or boundaries within the crystal can be several times higher than the average concentrations in a volu-me of metal. Such local accumulation of impurities in

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the metal can be the result of equilibrium or non-equilibrium segregation, as well as the presence of foreign inclusions [9].

Equilibrium segregation of impurities as a rule occupies the area of one to ten nanometers, although in most cases the enrichment of impurities is limited by a monolayer segregation of atoms equal to or slightly greater than the inter-granular zone width 2-3 atomic layers [10]. Equilibrium segregation occurs as a result of diffusion of impurities to the grain boundaries with formation of a concentration gradient.

Non-equilibrium segregation of impurities takes, as a rule, the area of ten micrometers and is generated in the process of metal crystallization or in solid solution as a result of the interaction the impurities with vacancies with formation the pair of vacancy-interstitial atom.

EXPERIMENTAL TECHNIQUE

Platinum, rhodium and palladium for production the alloys are obtained as a by-product within the production of electrolytic copper of RTB, Serbia. The required purity is achieved by the additional refining. Composition of tested alloys is listed in Table 1.

Table 1 *Content of alloying elements in tested samples (mass %)*

Alloy	Rh (mass%)	Pd (mass%)	Ir (mass%)	Au (mass%)
PtRh7	7	-	-	-
PtRh25	25	-	-	-
PtIr4	-	-	4	-
PtRh20Pd10Ir0,1Au0,1	20	10	0.1	0.1

Melting of samples was carried out in the medium-frequency induction furnace. Annealing of samples was carried out in the electric furnace type LP08.

To test the mechanical properties of samples at high temperatures, a universal apparatus for tension testing of materials at high temperature, manufacturer Karl Frank, type 81221.

Chemical analysis of the materials for samples was performed in the atomic absorption spectrophotometer.

RESULTS AND DISCUSSION

Equilibrium segregation of impurities increases linearly with increasing time and temperature warming, with great absorption thereof. The most common is for systems with low solubility of impurities in the crystal lattice of metal-base, as well as in large differences in atomic diameters of impurities and base. In literature is known a dependence of inter-granular zone enriched with impurities from the solubility limit thereof in solid solution. For many studied phase systems, based on Fe, Ni and Cu, the enriched space with impurities is as large as limit of their solubility is lower. With decrease of solubility limit of the impurities to $1x10^{-3}$ % (at.), their concentration in the inter-crystal zone of metal-base may reach 10% (at.), i.e. it can be 10,000 times higher than the volume of alloys [11-15].

Based on the results of solubility of impurities in platinum, it can be assumed that practically insoluble or slightly soluble impurities like Ba, P, As, Si, Bi and Pb show a high tendency to the formation of equilibrium segregations, while, for example, Fe, Ni, Cu, Ag, Mg Zn, Al, and Sb form with platinum a steady stream of solid solutions.

Equilibrium segregation of impurities leads to decrease in strain energy of the crystal lattice in the zone of their existence, while reducing the Gibbs energy of inter-granular limits [16-22].

The impurities that accumulate at the grain boundaries can react with each other and lead to an increase or decrease in segregation of this or any other element. In the first case, with the same sign of the atomic range of disagreement between the two particles in relation to the metal – bas , the intercrystalline zone will be more enriched with atoms of impurity atoms that has a larger range of disagreement. In the latter case, at different sign of atomic disagreement and equal concentrations of two impurities there is formation of of complex atoms of these impurities and equilibrium segregation is weak.

Segregation is stronger in the case that impurities that are adsorbed on the surface of crystals have the same sign and similar values of the range of discrepancies.

In this way, it can be expected that in cases where the removal of impurities from the alloy is very difficult, their harmful effect can be minimized by introduction less harmful impurity or impurities with the opposite sign of the discrepancy range.

On the basis of the atomic diameter of platinum that is 0.139 nm, it is possible to form a range of deviations of the atomic diameters of impurities.

Size range of deviations (Δr) of the atomic diameters of platinum and impurities, in the case where diameter of platinum is higher (+ Δr) or less (-Δr) in relation to the diameters of impurities, is given in Table 2.

Table 2 *Size range of deviations (Δr) for impurities*

Element	Δr, nm	Element	Δr, nm
Zn	+0.006	As	+0.014
Si	-0.021	Sn	-0.012
P	-0.021	Mg	-0.021
Cu	+0.011	Zr	-0.020
Fe	+0.015	Sb	+0.012
Cr	+0.014	Pb	-0.036
Co	+0.014	Y	-0.039
Ni	+0.014	Bi	-0.016
Al	-0.004	Ca	-0.058
Ag	-0.005	Ba	-0.078
Ti	-0.007	K	-0.088

On the basis of the values shown in Table 1, it can be concluded that Zr decreases the equilibrium segregation and negative impact of impurities, such as Si and P in tested platinum alloys. Bismuth can somewhat neutralize the negative impact and accumulation of impurities such as Fe, Cu, Cr, Co, As and Ni.

Also, the presence of Ca, Ba and K in platinum alloys can be neutralized with different impurities with the sign of deviation range, such as Zn, Cu, As, Cr, Co, Ni, Mg.

The most severe is the form of presence the impurities with the approximate values of deviation range, and of the same sign, for example, Al and Ag, as one pair and Sb and Zn as the second pair. In these cases, the probability of equilibrium segregation of each pair of impurities increases as well as their negative impact on the technological and exploitation properties of platinum alloys.

However, in practical terms, it is difficult to predict and even harder to manage the equilibrium segregation of impurities in platinum alloys.

In real terms of formation the equilibrium segregation, ten of impurities can take part, and that process may depend heavily on their mutual effects, the effect with the metal - base and alloying element with simultaneous temperature dependence - the time factor

The question of formation the non-equilibrium segregations of impurities in solid solution with formation the pair of vacancy - interstitial atom is not sufficiently clarified. It is believed that during cooling the heated metal in the crystal lattice, a large number of vacancies occurs which diffuse to the grain boundaries in a pair with atom impurities. At the grain boundary, the pair of vacancy - interstitial atoms bump into each other to form an accumulation of atom impurities. At slower cooling of heated metal, the probability of development is more likely for the process and the area of non-equilibrium segregation of impurities becomes significant. If the higher the temperature of metal during cooling, the more significant is formation the pair of vacancy - interstitial atom, which segregate to the grain boundaries, increasing the non-equilibrium segregation of impurities, as shown in Figure 1.

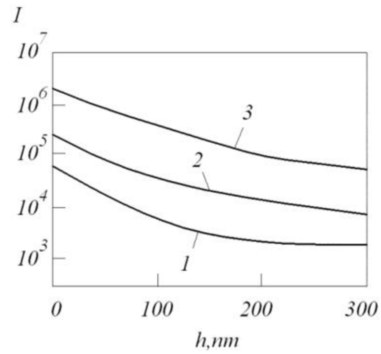

Figure 1 *Profile of Al distribution along the thickness of sample composition PtRh20Pd10Ir0,1Au0,1 in non-annealed condition (1), after annealing in the air at 1,400°C, 50 h, away from the border (2) and at the grain boundaries (3) ($j = 100\ \mu A/cm^2$, $P_{O_2}=10^{-3}$ Pa, I-size of the output secondary ions)*

Segregation of aluminum was observed during the study of secondary ions on microanalyzer, the investigated alloys using mass spectrometric method (concentration of impurities was 10^{-3} to 10^{-5}%. Based on the value of output of secondary ions (I), it can be concluded that with distance from the sample surface of non-annealed alloy, the Al concentration decreases. After annealing the platinum alloy at 1.400° C for 50 h in the air, the concentration of Al in the surface layers of sample, in the grain boundaries, is twice as higher than that of the grain.

Comparatively with equilibrium and non-equilibrium segregation of impurities in the platinum alloys, the groups of impurities were observed in the form of foreign inclusions. In these inclusions, the impurities are, as a rule, in the form of solid compounds, usually in the form of oxides. Oxide particles get into the alloy, for example, in the process of melting in ceramic pots or arise in the form of silicate inclusions in the warming process. The size of these inclusions reaches a hundredth of micrometer.

Based on numerous experiments, the possibility of formation of these inclusions was confirmed in the platinum alloys. The investigation of the alloy PtRh20Pd10Ir0,1 Au0,1 by the electron probe (after creeping at 1,400°C, at load of 5 MPa) has studied the foreign inclusions arranged along grain boundaries and within grains.

Along the grain boundaries, the inclusions reach the size of 40-50 microns and contain Si and Ti. Large inclusions of copper were discovered inside the grain. Small number of inclusions (up to 10 microns) based on Al and Si occur both in the grain boundaries and within the grains themselves.

The number of small inclusions containing Mg, Zn, Ni and Cr is negligible. The inclusions of complex composition, type of Al-Fe-Ti, Si-Cr-Sn and Pb-Sn, are also present.

Impurities such as Al, Mg, Si, and Fe, present in platinum alloys, after heating in the air (1400°C, 50 h), are found primarily in the oxide form, while after annealing in vacuum (1400°C, 2 h) are registered in elemental form.

By investigation the alloy of composition PtRh20Pd10Ir0,1Au0,1 it was shown that foreign inclusions contain a tenth of the percentage of S, C, P and Pb and other harmful impurities [23].

Figure 2 gives the standard view of the area of the sample composition PtRh20Pd10 Ir0,1Au0,1 with inclusions of impurities both on the grain boundaries and within the grains in characteristic radiation.

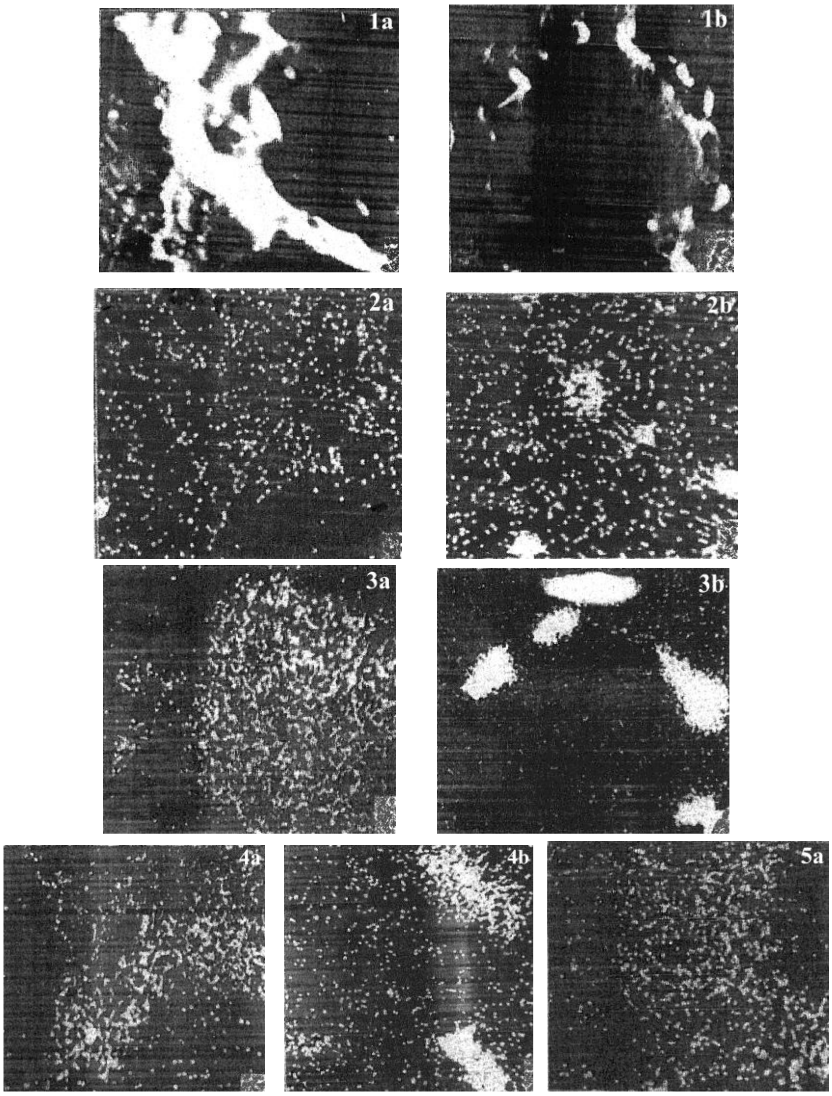

Figure 2 *Standard view the area of the sample composition PtRh20Pd10Ir0,1Au0,1 with inclusions of impurities with the secondary electrons (1a) and (1b), at the characteristic X-ray radiation FeKα (2a), AlKα (3a), BiKα (4a), SnKα (5a), SiKα (2b), TiKα (3b), CaKα (4b); Magnification: a) 800x, b) 400x*

It is obvious that, in the area where the inclusions enriched with Fe, Al, Si, Ca, Ti, Bi and Pb are present, the local concentration of impurities ranges from 5-40%.

Also, it is noticed the probability of presence in different ways resulting inclusions enriched with Si, Ca, Al, Ag, As and Pb (Figures 3-6).

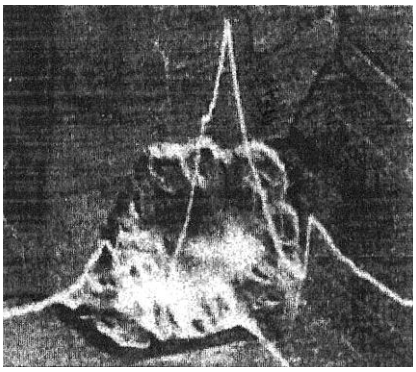

Figure 3 *Standard view the area of the sample composition with PtRh7 inclusions and line distribution of Si in it at Kα radiation*

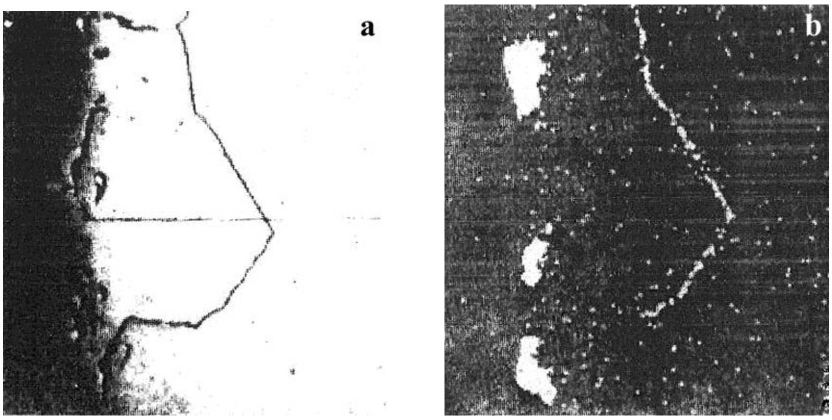

Figure 4 *Area of destruction the sample PtRh25 with inclusions, with content of Ag with the secondary electrons (a) and in X-ray separation of AgKα (b) (Magnification 360x)*

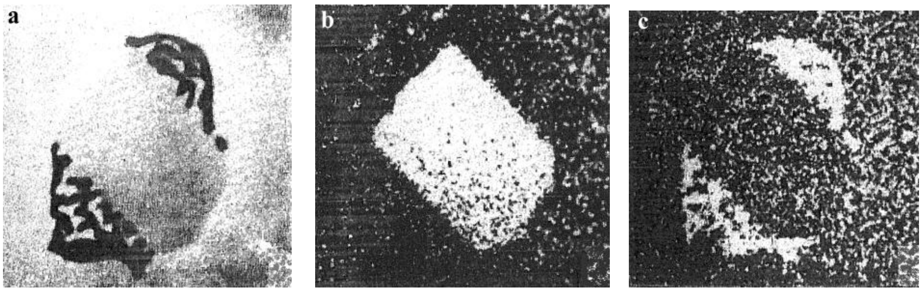

Figure 5 *View a part of platinum sample with the inclusion of secondary electrons a) and in the X-ray PbKα separation (b) and AsKα (c), (Magnification 720x)*

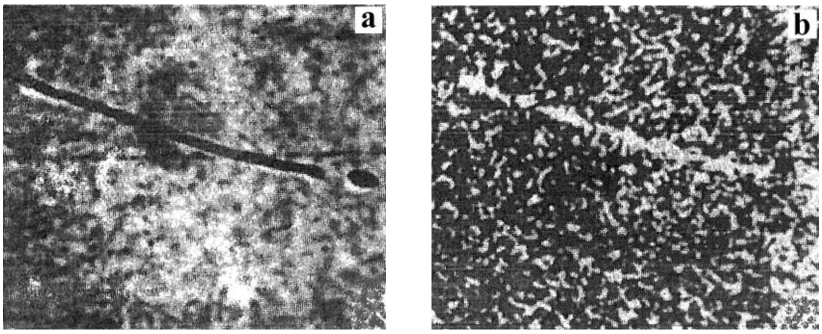

Figure 6 *View a part of alloy sample PtIr4 with the inclusions containing Pb, with secondary electrons (a) and in the X-ray PbKα separation (b) (magnification 850x)*

In most cases, the foreign inclusions in the platinum alloy can be seen under the normal light microscope, as shown in Figure 7.

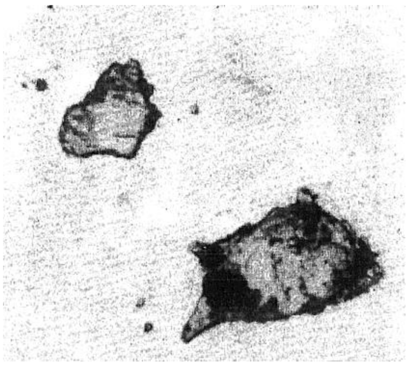

Figure 7 *Inclusion in the alloy PtRh20Pd10Ir0,1Au0,1 seen under the light microscope*

In investigation the microstructure of pure platinum after creeping at 1350°C, at stress of 13 MPa for 10 min as shown in Figure 8, the characteristic glassy separations could be observed.

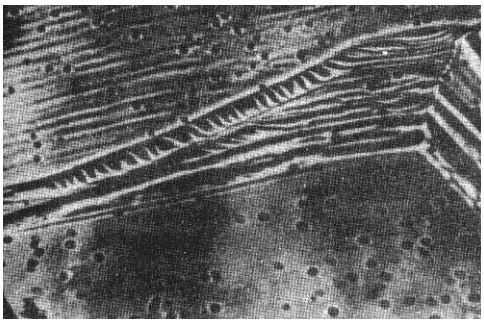

Figure 8 *Microstructure of pure platinum after creeping at 1350°C, at stress of 13 MPa for 10 min (magnification 300x)*

Similar separations were the subject of research the alloy PtIr4, where it was observed that at temperature higher than 1300°C, the sample surface is covered with many small droplets of liquid, which gradually pour forming a large transparent drops, as shown in Figure 9.

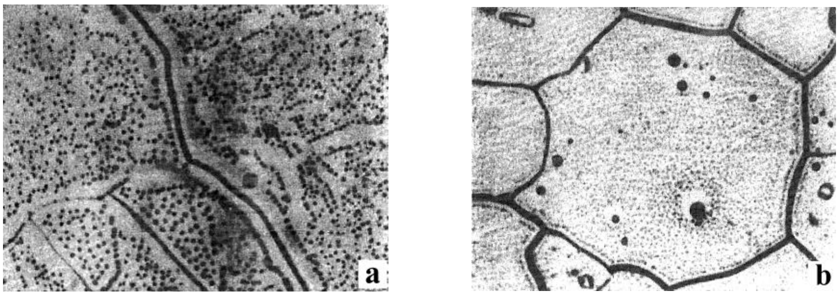

Figure 9 *Surface of the alloy PtIr4 with formation of silicate drops after annealing at 1400°C: a) 4 h, magnification 500x; b) 300 h, magnification 100x*

The limits and sub-limits occur at the same time as the zone of separation and further removal of liquid. The separated liquid makes it difficult sliding over the plane (111) within the grain, as shown in Figure 10.

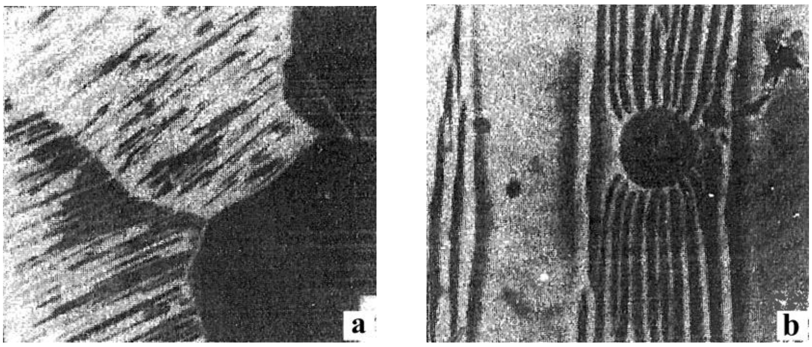

Figure 10 *Lines of sliding within the grain formed on platinum surface at heating in the air: a) up to 1.300°C, magnification 200x; b) over 1300°C, magnification 500x*

If the rate of metal heating up to 1300°C is rather large, making slipping lines is unlikely. Only in the exceptional uncontrolled cases on the surface of platinum, a small amount of slipping lines of liquid phase, as shown in Figure 10 b, can be observed inside the grain at the same time.

The absence of slipping lines in the presence of liquids (droplets) on the metal surface is associated with it, that all drops are united in a thin film of liquid which prevents the formation of a layer of adsorbed oxygen, and thus the creation of slip lines. Hardened drops of liquid did not react with hydrochloric or nitric acid, but they are excellent diluted in fluorohydrochloric acid. Microanalysis of hardened drops showed the presence of 8% Si; 10% Al; 10% Ca; 0.1% Ni; 0.1% Fe; 0.1% Mn, and 0.1% Mg. In addition to these elements, Pb and Na were present.

Spectral analysis showed that platinum heating for a period of 800 h results into a gradual reduction of content of impurities such as Si, Fe, Ni, Ca and Mg. Formation of liquid silicate phase is associated with reduction in creeping resistance of platinum and its alloys at content of some of these impurities, as the intermediate layer of molten silicates on the planes grain boundaries probably accelerates sliding.

CONCLUSION

Based on the previous results of research, it can be concluded the following:

In real conditions of formation the equilibrium segregation, ten of impurities can take part and the process is very depend on their mutual effects, the effect with the metal - base and alloying elements with simultaneous dependence temperature - time factor.

If the higher metal temperature in cooling, therefore, the creation of a pair vacancy-interstitial atom is much more important that diffuses to the grain boundaries, increasing the non-equilibrium segregation of impurities.

Along with the equilibrium and non-equilibrium segregation of impurities in the platinum alloys, the groups of impurities were observed in the form of foreign inclusions. In these inclusions, the impurities are in the form of solid compounds, usually in oxide form. Oxide particles enter the alloy in the melting process in ceramic pots or arise in the form of silicate inclusions in the heating process. The size of these inclusions reaches a hundredth part of a micrometer.

The impurities such as Al, Mg, Si, and Fe, present in the platinum alloys, after heating in the air (1400°C, 50 h), are in the oxide form, whereas after annealing in vacuum (1400°C, 2 h) are registered in the elemental form.

The investigation the alloy of composition PtRh20Pd10Ir0,1Au0,1 has shown that foreign inclusions contain a tenth of the percentage of S, C, P and Pb, and other harmful impurities.

Segregation of impurities in the platinum alloys is conditioned by the nature of impurities, their concentration, distribution in the volume of metal, interaction with the basic and alloying components as well as the temperature - time factor. It is possible to expect that as the result of interaction of harmful impurities with the platinum metals that enter the composition of the alloy, the reductions of a high-temperature resistance of the alloy and increase the possibility of brittle fracture at high temperatures are formed.

REFERENCES

[1] H. Gavin, Platinum Met. Rev. 54 (2010) 166.

[2] E. Preston, Platinum Met. Rev. 4 (1960) 48.

[3] D. F. Lupton, J. Merker, B. Fischer, R. Völkl, 24th International Precious Metals Cconference, Williamsburg, Virginia, USA, 1–14 June 2000.

[4] Y. Ning, Z. Yang, H. Zhao, Platinum Met. Rev.4 (1996) 80.

[5] N. Yuantao, Y. Zhengfen, Platinum Met. Rev. 43 (1999) 62.

[6] B. Trumić, D. Stanković, V. Trujić, J. Min. Metall., Sect. B 45 (1) B (2009) 79 – 87.

[7] B. Wu, G. Liu, , Platinum Met. Rev. 41 (1997) 81.

[8] M. Funabikia, T. Yamadaa, K. Kayanoa, Catal. Today 10 (1991) 33.

[9] T. Biggs, S.S. Taylor, E. Van der Lingen, Platinum Met. Rev. 49 (2005) 2.

[10] John C. Wright, Platinum Metals Rev., 2002, 46 (2), 66.

[11] T. Biggs, M. B. Cortie, M. J. Witcomb, L. A. Cornish, Platinum Metals Rev., 2003, 47, (4), 142.

[12] T. Biggs, M.J. Witcomb, L.A. Cornish, Materials Science and Engineering A273–275 (1999) 204.

[13] F. Xiao, F. Zhao, D. Mei, Z. Mo, B. Zeng, Biosens. Bioelectron. 24 (2009) 3481.

[14] K. T. Jacob, S. Priya, and Y. Waseda, Metall. Mater. Trans. A 29A (1998) 1545.

[15] G. Dereli, T. Cagin, M. Uludogan, M. Tomak, Philos. Mag. Lett. 75 (4) (1997) 209.

[16] P. Battaini, Platinum Met. Rev. 55 (2011) 74.

[17] J. Luyten, J. De Keyzer, P. Wollants, C. Creemers, Calphad 33 (2009) 370.

[18] B. Trumic, L. Gomidželovic, S. Marjanovic, V. Krstic, A. Ivanovic, S. Dimitrijevic, Pt - Materials Testing, 55 (2013) 38.

[19] Ритвин, Е. И., Медовој, Л.А.: Влиание физико-химическој следи на жаропрочност мераллических материалов, Москва, Наука, 1974

[20] Савицкиј, Е. М., Полјакова В. П., Горина, Н. Б., Рошан, Н. Р.: Металоведение платинових металов, Москва, Металургија, 1975.

[21] Захаров, М. В., Захаров, А. М.: Жаропрочние сплави, Москва, Металургија, 1983.

[22] Ритвин, Е. И.,: Жаропрочност платинових сплавоажв, Москва, Металургија, 1987.

[23] B. Trumić, L. Gomidželović, M. Bugarin, Mining and Metallurgy Engineering Bor, 1/2015, p. 141-148.

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SEGREGACIJA NEČISTOĆA U PLATINI I LEGURAMA NA BAZI PLATINE**

Izvod

U radu su predstavljeni rezultati ispitivanja nastanka ravnotežnih i neravnotežnih segregacija nečistoća kako u čistoj, tako i u legurama platine. Pokazano je da segregacije jačaju u slučaju kada nečistoće, apsorbovane na površini kristala imaju isti znak ili pak slične vrednosti opsega odstupanja u odnosu na čistu platinu. Ravnotežna segregacija javlja se kao rezultat difuzije nečistoća ka granicama zrna uz stvaranje koncentracionog gradijenta.

Neravnotežna segregacija nečistoća zauzima oblast veličine desetak mikrometara i nastaje u procesu kristalizacije metala ili u čvrstom rastvoru kao rezultat uzajamnog dejstva nečistoća s vakancijama uz obrazovanje para vakancija-intersticijski atom.

Segregacija nečistoća u platinskim legurama uslovljena je prirodom nečistoća, njihovom koncentracijom, raspodelom u zapremini metala, uzajamnim dejstvom sa osnovnim i legirnim komponentama, kao i temperaturno - vremenskim faktorom.

Uporedo sa ravnotežnom i neravnotežnom segregacijom nečistoća u platinskim legurama primećene su skupine nečistoća u obliku stranih uključaka.

Ključne reči: *nečistoće, ravnotežna i neravnotežna segregacija, platina, legure platine*

UVOD

Prisustvo hemijskih elemenata-nečistoća u platinskim metalima i legurama povezano je sa sastavom polaznih rudnih sirovina kao i sa tehnološkim operacijama njihovog dobijanja, prerade i eksploatacije u industrijskim uslovima [1-3].

Prisustvo nečistoća u platinskim metalima i legurama ima veliki uticaj na njihova fizička i mehanička svojstva. Iz tog razloga, čistoća platinskih metala i legura jedna je od njihovih ključnih karakteristika [4-6].

U zavisnosti od sadržaja i rasporeda nečistoća u metalu menja se i njihovo međusobno dejstvo. Sa povećanjem sadržaja nečistoća verovatnoća krtog preloma metala pri zagrevanju raste. Međutim, tehnološka i eksploataciona svojstva platinskih metala i legura mogu se bitno izmeniti u prisustvu veoma malih količina nečistoća (u granicama stotih i hiljaditih delova procenata). Opasnost od krtog preloma je utoliko veća, ukoliko do povećanja sadržaja nečistoća ne dolazi u celoj zapremini metala, već samo u pojedinim njegovim delovima [7,8].

Lokalna koncentracija nečistoća u međukristalnoj zoni ili granicama unutar kristala može biti i nekoliko puta viša od srednje koncentracije u zapremini metala. Takvo lokalno nagomilavanje nečistoća u metalu može biti rezultat ravnotežne ili

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neravnotežne segregacije, kao i prisustva stranih uključaka [9].

Ravnotežna segregacija nečistoća zauzima po pravilu područje od jednog do desetak nanometara, premda u većini slučajeva obogaćenje nečistoćama ograničeno je monoslojnom segregacijom atoma jednakom ili neznatno većom od međukristalne zone širine 2–3 atomska sloja [10]. Ravnotežna segregacija javlja se kao rezultat difuzije nečistoća ka granicama zrna uz stvaranje koncentracionog gradijenta.

Neravnotežna segregacija nečistoća zauzima, po pravilu, oblast veličine desetak mikrometara i nastaje u procesu kristalizacije metala ili u čvrstom rastvoru kao rezultat uzajamnog dejstva nečistoća s vakancijama uz obrazovanje para vakancija-intersticijski atom.

EKSPERIMENTALNA TEHNIKA

Platina, rodijum i paladijum za izradu legura su dobijeni kao sporedan proizvod u okviru proizvodnje elektrolitičkog bakra RTB, Srbija. Dodatnom rafinacijom postignuta je neophodna čistoća. Sastav ispitivanih legura je naveden u tabeli 1.

Tabela 1. *Sadržaj legirnih elemenata u ispitivanim uzorcima (maseni %)*

Legura	Rh (mas.%)	Pd (mas.%)	Ir (mas.%)	Au (mas.%)
PtRh7	7	-	-	-
PtRh25	25	-	-	-
PtIr4	-	-	4	-
PtRh20Pd10Ir0,1Au0,1	20	10	0,1	0,1

Topljenje uzoraka vršeno je u srednjefrekventnoj indukcionoj peći. Žarenje uzoraka vršeno je u elektrootpornoj peći tipa LP08.

Za ispitivanje mehaničkih karakteristika uzoraka na visokim temperaturama korišćen je univerzalni aparat za ispitivanje materijala zatezanjem na viskoim temperaturama, proizvođača Karl Frank, tip 81221.

Hemijska analiza materijala za uzorke izvršena je na atomskom apsorpcionom spektrofotometru.

REZULTATI I DISKUSIJA

Ravnotežna segregacija nečistoća linearno raste sa povećanjem vremena i temperature zagrevanja, uz veliku apsorbciju istih. Najzastupljenija je kod sistema s malom rastvorljivošću nečistoća u kristalnoj rešetki metala-osnove, kao i pri velikim razlikama u atomskim prečnicima nečistoća i osnove. U literaturi poznata je zavisnost veličine međukristalne zone obogaćene nečistoćama od granice rastvorljivosti istih u čvrstom rastvoru. Za mnoge proučavane fazne sisteme na bazi Fe, Ni i Cu prostor obogaćen nečistoćama je utoliko veći, ukoliko je manja granica njihove rastvorljivosti. Sa smanjenjem granice rastvorljivosti nečistoća do $1x10^{-3}$ % (at.), njihova koncentracija u međukristalnoj zoni metala-osnove može dostići 10% (at.), tj. može 10.000 puta biti veća u odnosu na zapreminu legure [11-15].

Na osnovu rezultata rastvorljivosti nečistoća u platini, može se pretpostaviti da praktično nerastvorne ili malo rastvorne nečistoće poput Ba, P, As, Si, Bi i Pb pokazuju veliku sklonost ka obrazovanju ravnotežnih segregacija, dok na primer Fe, Ni, Cu, Ag, Mg, Zn, Al i Sb obrazuju s platinom neprekidan niz čvrstih rastvora.

Ravnotežna segregacija nečistoća dovodi do smanjenja energije deformacije kristalne rešetke u zoni njihovog postojanja, uz istovremeno smanjenje Gibsove energije međuzrnih granica [16-22].

Nečistoće koje se nagomilavaju na granicama zrna mogu međusobno reagovati i dovesti do porasta ili smanjenja segregacije tog ili nekog drugog elementa. U prvom slučaju, pri istom znaku atomskog opsega neslaganja dvaju primesa u odnosu na metal - osnovu, međukristalna zona biće obogaćenija atomima one nečistoće koja ima veći opseg neslaganja. U drugom slučaju, pri različitom znaku atomskog neslaganja i jednakim koncentracijama dvaju primesa dolazi do obrazovanja kompleksnih atoma tih nečistoća i ravnotežna segregacija slabi.

Segregacija jača u slučaju kada nečistoće koje se apsorbuju na površini kristala imaju isti znak i slične vrednosti opsega odstupanja.

Na taj način može se očekivati da u slučajevima kada je odstranjivanje štetnih primesa iz legure veoma otežano, njihov štetni uticaj može biti sveden na minimum i uvođenjem manje štetne nečistoće ili nečistoće sa suprotnim znakom opsega odstupanja.

Na osnovu atomskog prečnika platine koji iznosi 0,139 nm, moguće je formirati niz opsega odstupanja atomskih prečnika nečistoća.

Veličina opsega odstupanja (Δr) atomskih prečnika platine i nečistoća, u slučaju kada je prečnik platine veći (+Δr) ili manji (-Δr) u onosu na prečnike nečistoća dat je u tabeli 2.

Tabela 2. *Veličina opsega odstupanja (Δr) za nečistoće*

Element	Δr, nm	Element	Δr, nm
Zn	+0,006	As	+0,014
Si	-0,021	Sn	-0,012
P	-0,021	Mg	-0,021
Cu	+0,011	Zr	-0,020
Fe	+0,015	Sb	+0,012
Cr	+0,014	Pb	-0,036
Co	+0,014	Y	-0,039
Ni	+0,014	Bi	-0,016
Al	-0,004	Ca	-0,058
Ag	-0,005	Ba	-0,078
Ti	-0,007	K	-0088

Na osnovu vrednosti prikazanih u tabeli 1 može se zaključiti da Zr smanjuje ravnotežnu segregaciju i negativan uticaj nečistoća, kao što su Si, i P u ispitivanim platinskim legurama. Bizmut donekle može neutralizovati negativan uticaj i nagomilavanje nečistoća poput Fe, Cu,Cr, Co, As i Ni.

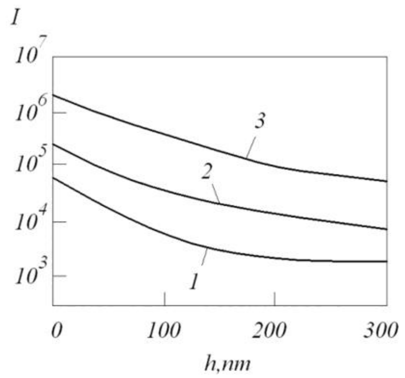
Takođe, prisustvo Ca, Ba i K u platinskim legurama može biti neutralizovano nečistoćama s različitim znakom opsega odstupanja, poput Zn, Cu, As, Cr, Co, Ni, Mg.

Najteži je oblik prisustva nečistoća s približnim vrednostima opsega odstupanja, a istog znaka, na primer Al i Ag, kao jedan par i Sb i Zn kao drugi par. U tim slučajevima, raste verovatnoća ravnotežne segregacije svakog para nečistoća kao i njihov negativan uticaj na tehnološke i eksploatacione osobine platinskih legura.

Međutim, u praktičnim uslovima teško je prognozirati a još teže upravljati procesom ravnotežne segregacije nečistoća u platinskim legurama.

U realnim uslovima u nastajanju ravnotežne segregacije može uzeti učešće desetak nečistoća i taj proces može jako zavisiti od njhovog međusobnog dejstva, dejstva s metalom - osnovom i legirnim elementima uz istovremenu zavisnost temperaturno - vremenskog faktora.

Pitanje nastanka neravnotežnih segregacija nečistoća u čvrstom rastvoru uz obrazovanje para vakancija - intersticijski atom nije dovoljno razjašnjeno. Smatra se da pri hlađenju zagrejanog metala u kristalnoj rešetki nastaje veliki broj vakancija koje difunduju ka granicama zrna u paru s atomom nečistoća. Na granici zrna par vakancija - intersticijski atom međusobno se sudaraju pri čemu nastaje nagomilavanja atoma nečistoća. Pri sporijem hlađenju zagrejanog metala veća je verovatnoća odvijanja procesa i oblast neravnotežne segregacije nečistoća postaje značajna. Ukoliko je viša temperatura metala pri hlađenju, utoliko je više i značajnije stvaranje para vakancija - intersticijski atom koji difunduje ka granicama zrna, pojačavajući neravnotežnu segregaciju nečistoća, kako je prikazano na slici 1.



Sl. 1. *Profil raspodele Al po debljini uzorka sastava PtRh20Pd10Ir0,1Au0,1 u nežarenom stanju (1), posle žarenja na vazduhu na 1.400°C, 50 h, dalje od granice (2) i na granicama zrna (3) (j = 100 μA/cm^2, $P_{O_2}=10^{-3}$ Pa, I - veličina izlaznih sekundarnih jona)*

Segregacija aliminijuma bila je zapažena pri istraživanju sekundarnih jona, na mikroanalizatoru, ispitivane legure metodom masene spektrometrije (koncentracija nečistoća iznosila je 10^{-3} do 10^{-5}%. Na osnovu vrednosti izlaznih sekundarnih jona (I) može se zaključiti da sa udaljavanjem od površine uzorka neodžarene legure koncentracija Al se smanjuje. Nakon žarenja platinske legure na 1.400°C u trajanju od 50 h na vazduhu, koncentracija Al u površinskim slojevima uzorka, u granicama zrna, duplo je veća u odnosu na samo zrno.

Uporedo sa ravnotežnom i neravnotežnom segregacijom nečistoća u platinskim legurama primećene su skupine nečistoća u obliku stranih uključaka. U tim uključcima nečistoće se nalaze, po pravilu, u obliku čvrstih jedinjenja, najčešće u obliku oksida. Čestice oksida dospevaju u leguru, na primer, u procesu topljenja u keramičkim loncima ili nastaju u vidu silikatnih uključaka u procesu zagrevanja. Veličina tih uključaka dostiže stoti deo mikrometra.

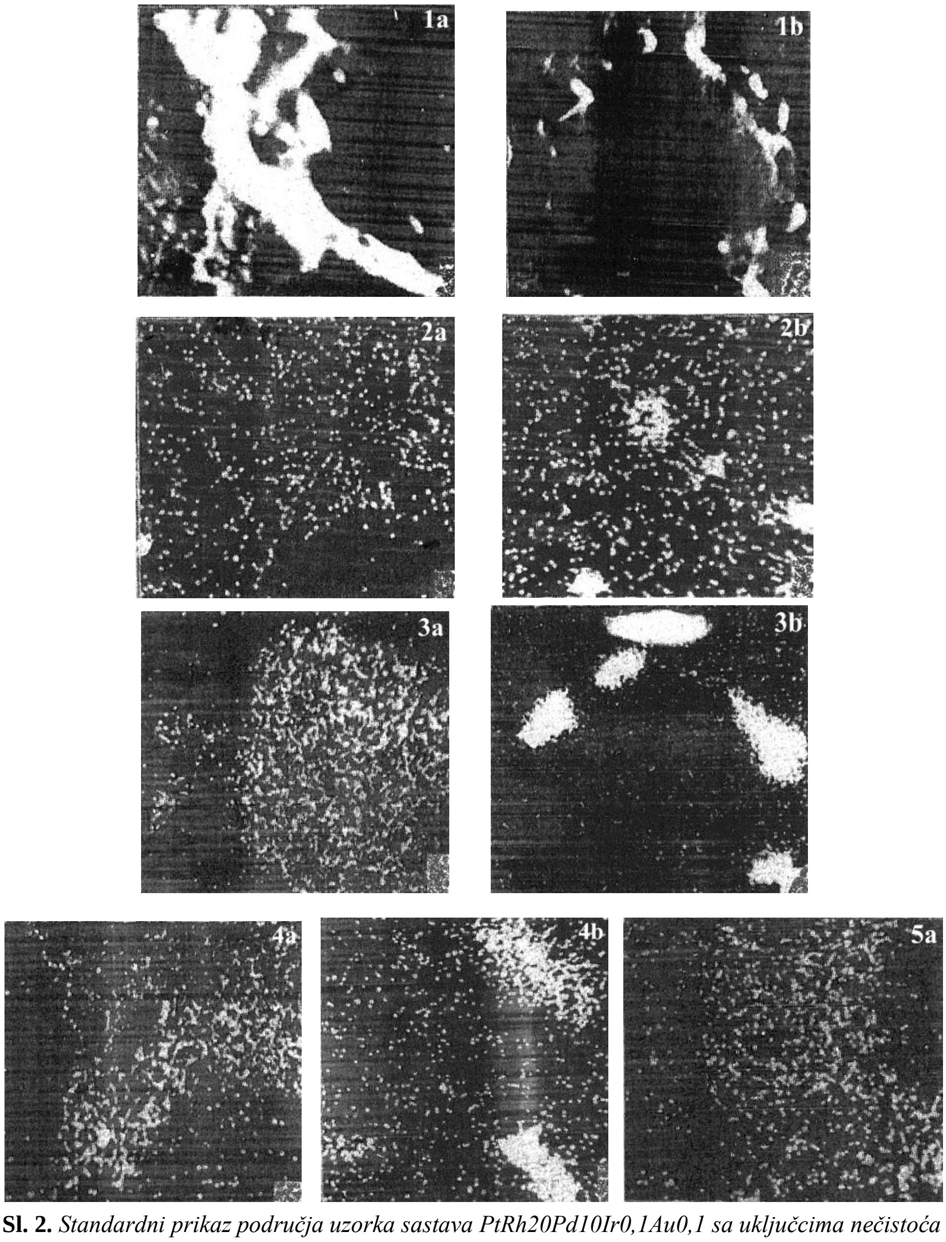
Na osnovu brojnih eksperimenata potvrđena je mogućnost obrazovanja tih uključaka u platinskim legurama. Istraživanjem legure PtRh20Pd10Ir0,1Au0,1 elektronskom sondom (nakon puzanja na 1.400°C, pri opterećenju od 5 MPa) proučavani su strani uključci raspoređeni po granicama zrna i u samim zrnima.

Po granicama zrna uključci dostižu veličinu 40–50 μm i sadrže Si i Ti. Veliki uključci bakra otkriveni su unutar zrna. Mali uključci (veličine do 10 μm) na bazi Al i Si javljaju se kako u granicama zrna tako i unutar samih zrna. Neznatan je broj malih uključaka koji sadrže Mg, Zn, Ni i Cr. Prisutni su takođe i uključci složenog sasta-va tipa Al-Fe-Ti, Si-Cr-Sn i Pb-Sn.

Nečistoće poput Al, Mg, Si i Fe, prisutne u platinskim legurama, nakon zagrevanja na vazduhu (1.400°C, 50 h), nalaze se prvenstveno u oksidnom obliku, dok se nakon žarenja u vakuumu (1.400°C, 2 h) registruju u elementarnom stanju.

Ispitivanjem legure sastava PtRh20Pd10 Ir0,1Au0,1 pokazano je da strani uključci sadrže deseti deo procenta S, C, P i Pb i drugih štetnih nečistoća [23].

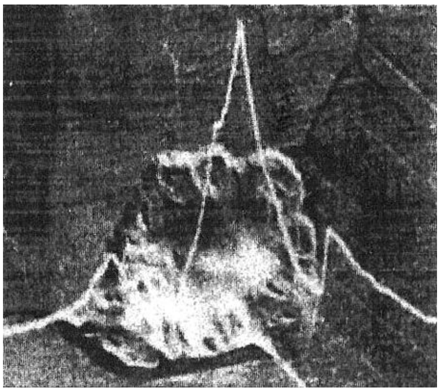
Na slici 2. dat je standardni prikaz područja uzorka sastava PtRh20Pd10Ir0,1 Au0,1 sa uključcima nečistoća kako po granicama zrna, tako i unutar zrna, pri karakterističnom zračenju.



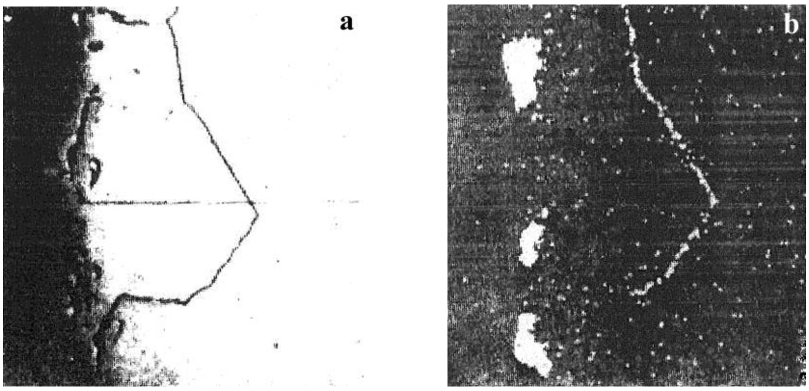
Sl. 2. *Standardni prikaz područja uzorka sastava PtRh20Pd10Ir0,1Au0,1 sa uključcima nečistoća sa sekundarnim elektronima (1a) i (1b), pri karakterističnom rentgenskom zračenju FeKα(2a), AlKα(3a), BiKα(4a), SnKα(5a), SiKα(2b), TiKα(3b), CaKα(4b); Uvećanje: a) 800x, b) 400x*

Očigledno je da, u području gde su prisutni uključci obogaćeni Fe, Al, Si, Ca, Ti, Bi i Pb lokalna koncentracija nečistoća kreće se od 5–40%.

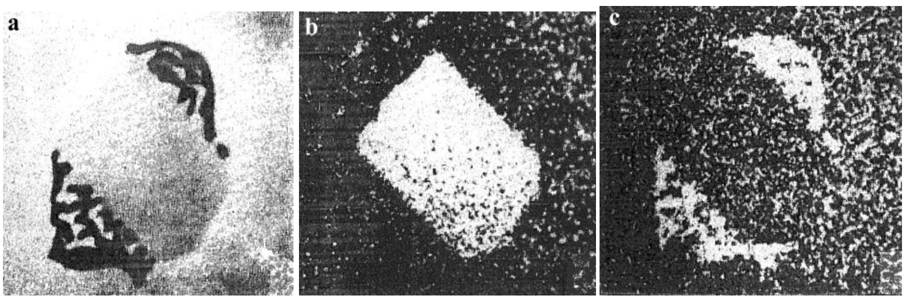
Takođe, zapažena je mogućnost prisustva, na različite načine nastale uključke obogaćene Si, Ca, Al, Ag, As i Pb. (slika 3-6).



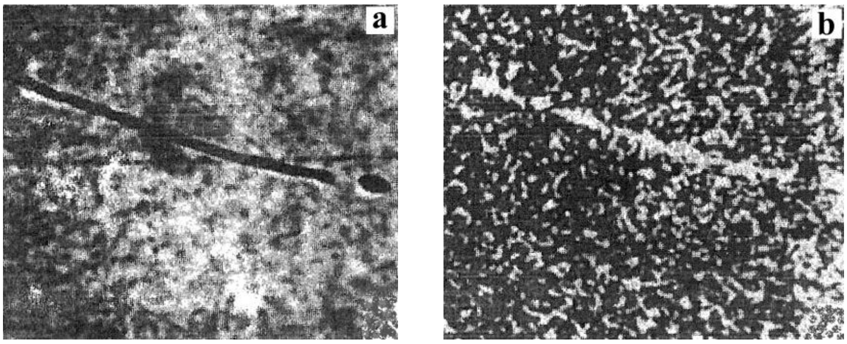
Sl. 3. *Standardni prikaz područja uzorka sastava PtRh7 sa uključcima i linijskog rasporeda Si u njemu pri Kα zračenju*



Sl. 4. *Oblast razaranja uzorka PtRh25 s uključcima, sa sadržajem Ag sa sekundarnim elektronima (a) i pri rentgenskom izdvajanju AgKα (b) (uvećanje 360x)*

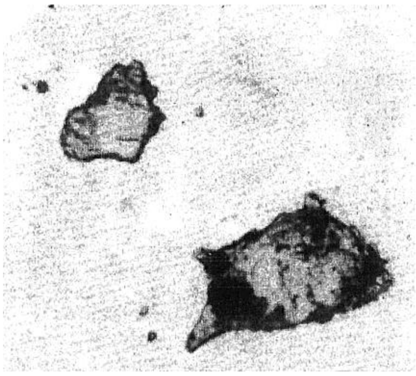


Sl. 5. *Prikaz dela uzorka platine sa uključivanjem sekundarnih elektrona a) i pri rentgenskom izdvajanju PbKα (b) i AsKα (c), (Uvećanje 720x)*



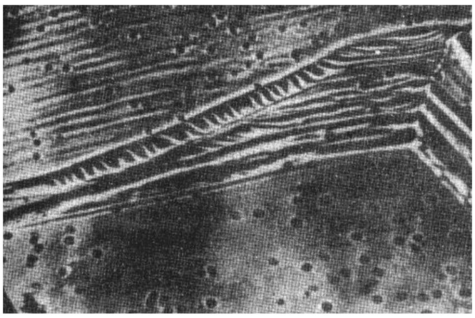
Sl. 6. *Prikaz dela uzorka legure PtIr4 sa uključcima koji sadrže Pb, sa sekundarnim elektronima (a) i pri rentgenskom izdvajanju PbKα (b) (uvećanje 850x)*

U većini slučajeva strani uključci u platinskim legurama mogu se videti pod običnim svetlosnim mikroskopom, kako je prikazano na slici 7.



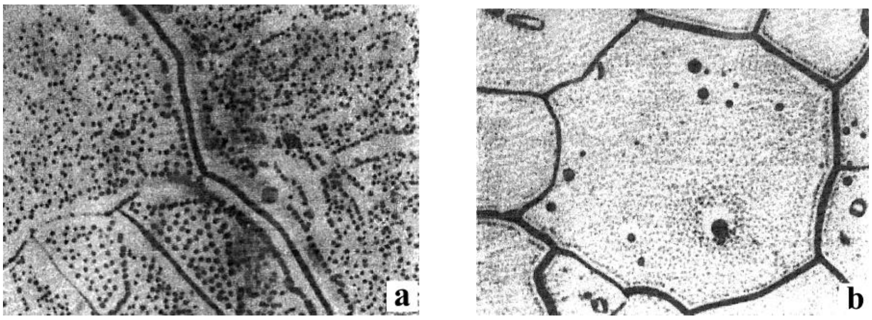
Sl. 7. *Uključak u leguri PtRh20Pd10Ir0,1Au0,1 posmatran pod svetlosnim mikroskopom*

Pri ispitivanju mikrostrukture čiste platine nakon puzanja na 1.350°C, pri naprezanju od 13 MPa u trajanju od 10 min, kako je prikazano na slici 8., mogla su se primetiti karakteristična staklasta izdvajanja.



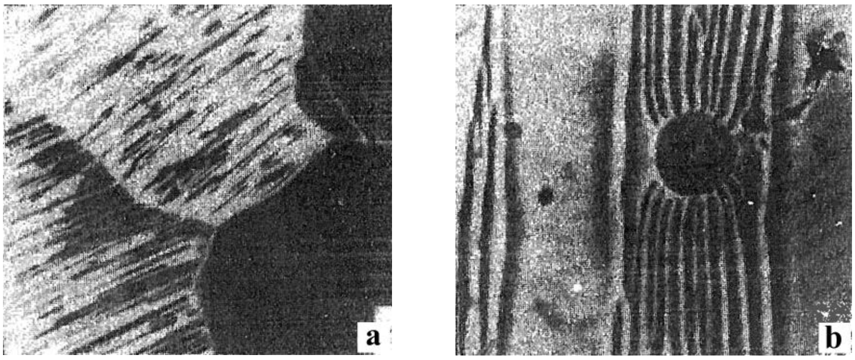
Sl. 8. *Mikrostruktura čiste platine nakon puzanja na 1.350°C, pri naprezanju od 13 MPa, u trajanju od 10 min (uvećanje 300x)*

Slična izdvajanja bila su predmet istraživanja legure PtIr4, gde je primećeno da na temperaturi višoj od 1.300°C površina uzorka pokrivena je mnogobrojnim malim tečnim kapljicama, koje se postepeno slivaju obrazujući velike providne kapi, kako je prikazano na slici 9.



Sl. 9. *Površina legure PtIr4 s obrazovanjem silikatnih kapljica nakon žarenja na 1.400°C: a) 4 h, uvećanje 500x; b) 300 h, uvećanje 100x*

Granice i subgranice javljaju se istovremeno kao zona izdvajanja i dalje, odvođenja tečnosti. Izdvojena tečnost otežava klizanje po ravni (111) unutar zrna, kako je prikazano na slici 10.



Sl. 10. *Linije klizanja unutar zrna obrazovane na površini platine pri zagrevanju na vazduhu: a) do 1.300°C, uvećanje 200x; b) preko 1.300°C, uvećanje 500x*

Ukoliko je brzina zagrevanja metala do 1.300°C prilično velika, stvaranje linija klizanja je malo verovatno. Samo u izuzetno nekontrolisanim slučajevima na površini platine, unutar zrna mogu se istovremeno opaziti mala količina linija klizanja i tečne faze, kako je prikazano na slici 10 b.

Odsustvo linija klizanja u prisustvu tečnosti (kapljica) na površini metala povezano je sa tim, da su sve kapi sjedinjene u tanak film tečnosti koji sprečava stvaranje sloja adsorbovanog kiseonika, pa samim tim i stvaranje linija klizanja. Očvrsle kapi tečnosti nisu reagovale sa sonom i azotnom kiselinom, ali su se odlično rastvarale u fluorovodoničnoj kiselini. Mikro-analiza očvrslih kapi pokazala je prisustvo: 8%Si; 10%Al; 10%Ca; 0,1%Ni; 0,1%Fe; 0,1%Mn i 0,1%Mg. Pored nabrojanih elemenata prisutni su bili Pb i Na.

Spektralna analiza pokazala je da zagrevanjem platine, u trajanju od 800 h, dolazi do postepenog smanjenja sadržaja nečistoća poput Si, Fe, Ni, Ca i Mg. Obrazovanje tečne silikatne faze povezano je sa smanjenjem otpora puzanju platine i njenih legura, pri sadržaju nekih od navedenih primesa, budući da međusloj istopljenih silikata na ravnima granica zrna verovatno ubrazava klizanje.

ZAKLJUČAK

Na osnovu dosadašnjih rezultata istraživanja, može se sledeće zaključiti:

U realnim uslovima u nastajanju ravnotežne segregacije može uzeti učešće desetak nečistoća i taj proces jako zavisi od njhovog međusobnog dejstva, dejstva s metalom - osnovom i legirnim elementima uz istovremenu zavisnost temperaturno - vremenskog faktora.

Ukoliko je viša temperatura metala pri hlađenju, utoliko je više i značajnije stvaranje para vakancija-intersticijski atom koji difunduje ka granicama zrna, pojačavajući neravnotežnu segregaciju nečistoća.

Uporedo sa ravnotežnom i neravnotežnom segregacijom nečistoća u platinskim legurama primećene su skupine nečistoća u obliku stranih uključaka. U tim uključcima nečistoće se nalaze, u obliku čvrstih jedinjenja, najčešće u obliku oksida. Čestice oksida dospevaju u leguru, u procesu topljenja u keramičkim loncima ili nastaju u vidu silikatnih uključaka u procesu zagrevanja. Veličina tih uključaka dostiže stoti deo mikrometra

Nečistoće poput Al, Mg, Si i Fe, prisutne u platinskim legurama, nakon zagrevanja na vazduhu (1.400°C, 50 h), nalaze se u oksidnom obliku, dok se nakon žarenja u vakuumu (1.400°C, 2 h) registruju u elementarnom stanju.

Ispitivanjem legure sastava PtRh20 Pd10Ir0,1Au0,1 pokazano je da strani uključci sadrže deseti deo procenta S, C, P i Pb i drugih štetnih nečistoća

Segregacija nečistoća u platinskim legurama uslovljena je prirodom nečistoća, njihovom koncentracijom, raspodelom u zapremini metala, uzajamnim dejstvom sa osnovnim i legirnim komponentama, kao i temperaturno - vremenskim faktorom. Moguće je očekivati da kao rezultat uzajamnog dejstva štetnih nečistoća s platinskim metalima koji ulaze u sastav legure, nastaju sniženja visokotemperaturne otpornosti legure i povećanje verovatnoće krtog preloma na visokim temperaturama

LITERATURA

[1] H. Gavin, Platinum Met. Rev. 54 (2010) 166.

[2] E. Preston, Platinum Met. Rev.4 (1960) 48.

[3] D. F. Lupton, J. Merker, B. Fischer, R. Völkl, 24th International Precious Metals Cconference, Williamsburg, Virginia, USA, 1–14 June 2000.

[4] Y. Ning, Z. Yang, H. Zhao, Platinum Met. Rev.4 (1996) 80.

[5] N. Yuantao, Y. Zhengfen, Platinum Met. Rev. 43 (1999) 62.

[6] B. Trumić, D. Stanković, V. Trujić, J. Min. Metall., Sect. B 45 (1) B (2009) 79 – 87.

[7] B. Wu, G. Liu, , Platinum Met. Rev. 41 (1997) 81.

[8] M. Funabikia, T. Yamadaa, K. Kayanoa, Catal. Today 10 (1991) 33.

[9] T. Biggs, S.S. Taylor, E. Van der Lingen, Platinum Met. Rev. 49 (2005) 2.

[10] John C. Wright, Platinum Metals Rev., 2002, 46 (2), 66.

[11] T. Biggs, M. B. Cortie, M. J. Witcomb, L. A. Cornish, Platinum Metals Rev., 2003, 47, (4), 142.

[12] T. Biggs, M.J. Witcomb, L.A. Cornish, Materials Science and Engineering A273–275 (1999) 204.

[13] F. Xiao, F. Zhao, D. Mei, Z. Mo, B. Zeng, Biosens. Bioelectron. 24 (2009) 3481.

[14] K. T. Jacob, S. Priya, and Y. Waseda, Metall. Mater. Trans. A 29A (1998) 1545.

[15] G. Dereli, T. Cagin, M. Uludogan, M. Tomak, Philos. Mag. Lett. 75 (4) (1997) 209.

[16] P. Battaini, Platinum Met. Rev. 55 (2011) 74.

[17] J. Luyten, J. De Keyzer, P. Wollants, C. Creemers, Calphad 33 (2009) 370.

[18] B. Trumic, L. Gomidželovic, S. Marjanovic, V. Krstic, A. Ivanovic, S. Dimitrijevic, Pt-Materials Testing, 55 (2013) 38.

[19] Ритвин, Е. И., Медовој, Л. А.: Влиание физико-химическој следи на жаропрочност мераллических материалов, Москва, Наука, 1974

[20] Савицкиј, Е. М., Полјакова В. П., Горина, Н. Б., Рошан, Н. Р.: Металоведение платинових металов, Москва, Металургија, 1975.

[21] Захаров, М. В., Захаров, А. М.: Жаропрочние сплави, Москва, Металургија, 1983.

[22] Ритвин, Е. И.,: Жаропрочност платинових сплавоажв, Москва, Металургија, 1987.

[23] B. Trumić, L. Gomidželović, M. Bugarin, Mining and Metallurgy Engineering Bor, 1/2015, str. 141-148.

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Bore Jegdić, Maja Stevanović, Aleksandar Jegdić**

CHEMICAL AND ELECTROCHEMICAL DISSOLUTION OF CHROMIUM AT ROOM AND ELEVATED TEMPERATURES**

Abstract

The influence of temperature on electrochemical and chemical dissolution of chromium was studied in the acidic sulphuric solutions. The hydrogen evolution reaction, as well as the anodic dissolution and chemical dissolution of chromium from activated surfaces in sulphuric acid solutions pH 1 follow the Arrhenius law, with the apparent activation energies of 35 kJ mol^{-1}, 58 kJ mol^{-1} and 62 kJ mol^{-1}, respectively. The higher activation energy of the chemical dissolution of chromium leads to the signifycantly noticeable chemical corrosion on elevated temperatures in comparison with the electrochemical corrosion.

Keywords: *chromium chemical corrosion, electrochemical dissolution, activation energy*

INTRODUCTION

Simultaneously with the electrochemical dissolution of chromium occurs its chemical dissolution, which does not depend on potential and that, in certain circumstances, is dominant process of dissolution, especially at elevated temperatures [1-9]. Chemical dissolution is the cause of occurrence the hydrogen evolution, which is not subjected to the laws of electrochemical kinetics.

Determination the activation energy of chemical chromium dissolution, electrochemical chromium dissolution, cathodic hydrogen evolution and temperature dependence on electrochemical corrosion rate was determined and analyzed in this paper. Also, texture of chromium was determined using the OIM method (orientation imaging microscopy). Determination of chromium concentration in solution was carried out by the atomic absorption spectroscopy (AAS). The anodic and cathodic polarization curves were recorded, and also, electrochemical corrosion rates were determined using the various electrochemical methods.

EXPERIMENTAL PART

Before testing, the surface of chromium samples was mechanically polished gradually with abrasive paper to the grade 1000. The solution for testing was 0.1 M Na_2SO_4 + H_2SO_4, pH 1, which was purified conducting through testing solution of pure nitrogen.

A three-part glass electrochemical cell with water jackets for thermostationing, with an auxiliary Pt electrode and a saturated calomel electrode (SCE) as the reference electrode were used for electrochemical tests.

The chromium electrode was cathodically activated at -0.900 V for 120 s to the aim of removal thesurface oxide layer before each test. Oxide layer is spontaneously cre

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ates on the chromium surface in contact with air. Electrochemical measurements were made using the potentiostat-galvanostat PAR 273.

RESULTS AND DISCUSION

Figure 1 shows the inverse polar image of chromium, obtained by the OIM method. The grains with the orientation (111) are marked with blue colour and it can be seen that a large number of grains on the chromium surface has exactly this orientation. The size of chromium crystal grains was also determined, which have been the small dimensions, with a high degree of in orientations. In fact, these are separate grains with their own orientation.

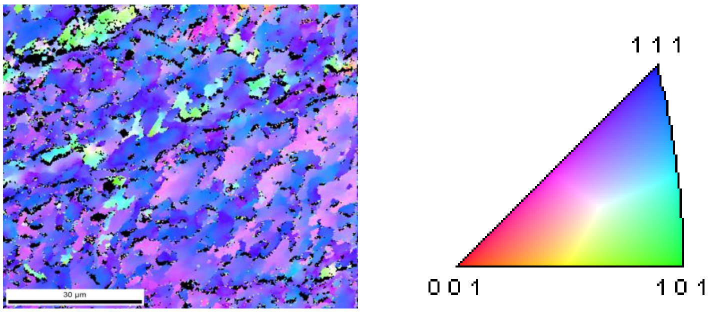

Figure 1 *Texture (111) of the chromium electrode is obtained by the OIM method. The approximate grain size can be estimated on the basis of the scale given in Figure*

The temperature influence on chemical and electrochemical chromium dissolution in temperature the range from 291 to 353 K in aqueous sulphuric acid, pH 1 was carried out.

Cathodic polarization curves, recorded at different temperatures at 291 to 343 K in sulphuric acid pH 1, are shown in Figure 2. Figure 2 shows that with an increase in temperature, the rate of hydrogen evolution increases, while the Tafel slope variation with the temperature was at theoretically expected levels. An inset in Figure 2 shows the dependence of current density logarithm as a function of reciprocal temperature for determination the apparent activation energy for hydrogen evolution at -0.860 V. The apparent activation energy 35 kJ mol^{-1} is for cathodic reaction of hydrogen evolution.

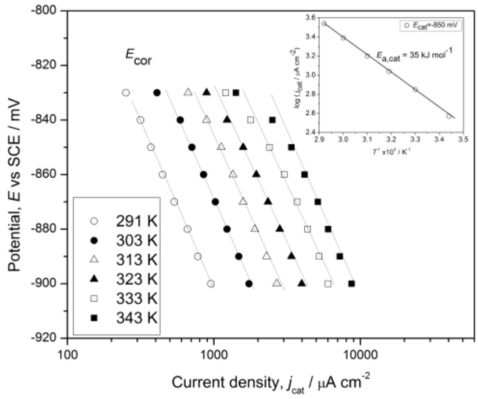

Figure 2 *Chatodic polarization curves for chromium electrode in aqueous solution of 0.1 M Na_2SO_4 + H_2SO_4, pH 1 at various temperatures*

The anodic polarization curves of chromium in the solution of sodium sulphate and sulphuric acid pH 1, recorded at different temperatures, were shown Figure 3. The shape of polarization curves is similar, except that the curves at higher temperatures are shifted towards higher current densities, as it might be expected. The Arrhenius dependence at -0.750 V is shown in inset in Figure 3. The apparent activation energy $E_{a,an}$ = 58 kJ mol^{-1} obtained for the reaction of the active anodic dissolution. This indicates that the anodic reaction is more dependent on temperature than the cathodic reaction. The corrosion potential change with temperature in a direction of more negative potentials also explains this.

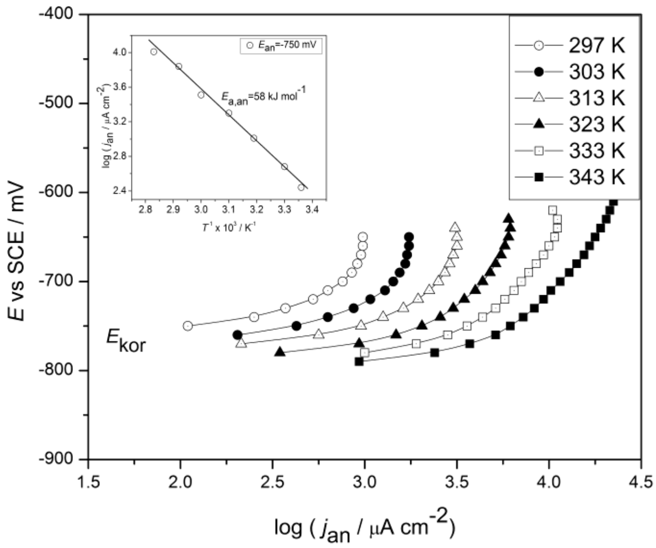

Figure 3 *Anodic polarization curves of chromium electrode in sulphuric acid solution pH 1, at various temperatures*

The electrochemical current density $j_{cor,el}$ is determined by extrapolation the Tafel slope on corrosion potential and by the Stern-Gery linear polarization method, while the total chromium dissolution rate j_{tot}, was determined analyzing the solution with atomic absorption spectrophotometry, and they are shown in Figure 4. It can be seen from Figure 4 that the overall rate of dissolution or equivalent current density with temperature is higher than the electro chemical corrosion current density. A significant part of electrochemical corrosion is the chemical corrosion of chromium at all temperatures. That difference increases with temperature as it can be seen in Figure 4. At 353 K, the total dissolution rate is about four times higher than the electrochemical corrosion rate. It means that the chemical dissolution rate at this temperature is for approximately three times higher than the electrochemical dissolution rate.

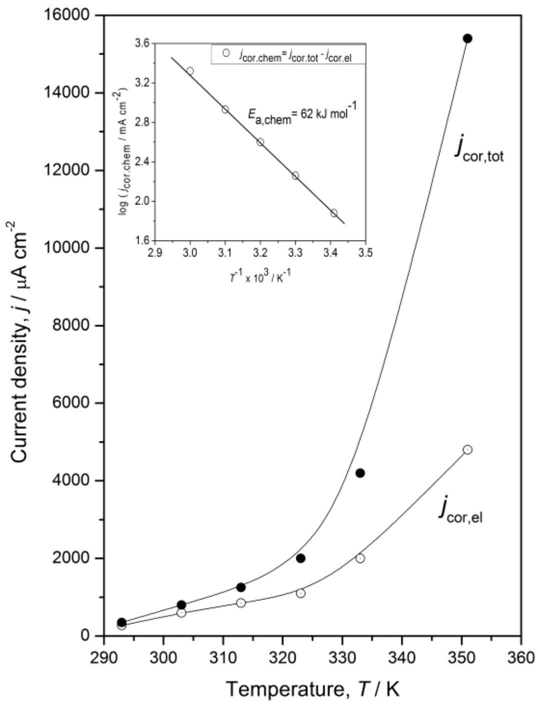

Figure 4 *Total current density obtained analytically (●) and corrosion current density obtained electrochemically at different temperatures (○) for the chromium electrode*

As it is shown in Figure 4, the overall corrosion rate j_{tot} at all temperatures that are used in this experiment are higher than the electrochemical corrosion rates $j_{cor,el}$. This is the result of chemical dissolution of chromium, which takes place directly by reaction of water molecules and atoms of chromium from the electrode surface and not dependent on potentials. Differences between the total chromium dissolution rate determined analytically $j_{tot,anal}$ and electrochemical dissolution rate $j_{cor,el}$ vs. the reciprocal temperature is plotted on the inset in Figure 4. The apparent activation energy was determined from the slope of this linear dependence and it is 62 kJ mol^{-1}. The high value of activation energy indicate that the influence of temperature on reaction of chemical dissolution is large and that contribution of chemical corrosion to the overall corrosion rate is higher at the elevated than the lower temperatures. This should be kept in mind if using data for corrosion rate, obtained at room temperature, for predicting the corrosion behaviour at elevated temperatures. The similar differences in terms of temperature influence likely existing in case of corrosion of other metals that corrode electrochemically and chemically (i.e., Fe, Ni, Mn and other metals).

After immersion into testing solution, the chromium electrode is in a passive state with the characteristic corrosion potential $E_{cor,1}$. During the cathodic polarization at -0.900 V, for several tens of seconds, the passive films are dissolved, whereby the electrodes activated and the corrosion potential $E_{cor,2}$ is then formed.

The chatodic curves recorded on passive chromium in form of the Tafel dia grams for different temperatures are presented in Figure 5. It can be noted that cathodic Tafel slope is approximately -0.060 V dec^{-1} and that the current density increases with temperature. The inset in Figure 5 shows the Arrhenius dependence, obtained at -0.520 V. The apparent activation energy was determined, that is 29 kJ mol^{-1}. Slightly lower value of activation energy is than obtained in the process of hydrogen evaluation on the activated chromium surface (35 kJ mol^{-1}).

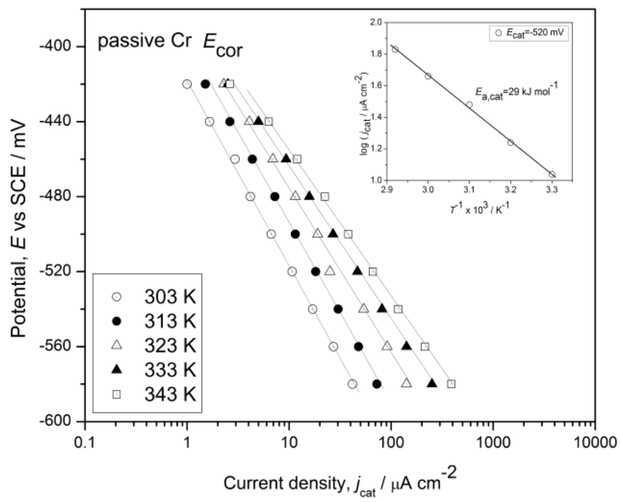

Figure 5 *The chatodic Tafel plots for passivated chromium electrode at different temperature*

Accordingly, the corrosion of active metallic chromium in an aqueous solution of sulphuric acid pH 1 consists of two simultaneous processes corrosion, the electrochemical corrosion and chemical dissolution. With increase of temperate, significantly increases the anodic dissolution, chemical dissolution, and cathodic hydrogen evolution on the bare chromium surface, as well as on the surface coated with chromium oxide in 0.1 M Na_2SO_4 + H_2SO_4 solution, pH 1.

Reaction of the hydrogen evolution, anodic dissolution and chemical dissolution on the activated chromium surface in sulp-huric acid solution, pH 1 in temperature range of 293 to 353 K followed the Arrhe-nius dependence with an apparent activation energy of 35 kJ mol^{-1}.58 kJ mol^{-1} and 62 kJ mol^{-1}, respectively. The apparent activation energy of the hydrogen evolution reaction on chromium oxide covered surface has value of 29 kJ mol^{-1}.

CONCLUSION

Corrosion of the active metallic chromium in aqueous sulphuric acid pH 1 simultaneously flowed by electrochemical and chemical mechanism. The rate of che-mical corrosion is obtained as difference of the total and electrochemical corrosion rate.

Reaction of the hydrogen evolution, anodic dissolution and chemical dissolution of Cr from chromium-activated surface in sulphuric acid solution, pH 1 at temperature from 291 to 353 K followed the Arrhenius law from the apparent activation energy of 35 kJ mol^{-1}, 58 kJ mol^{-1} and 62 kJ mol^{-1}, respectively. A high activation energy of chemical dissolution of chromium, at ele vated temperatures causes to significantly higher chemical corrosion, compared to electrochemical corrosion. The apparent activation energy of hydrogen evolution on the chromium-covered oxide layer has a value of 29 kJ mol^{-1}.

As the result of simultaneous occurrence of reaction of hydrogen evolution on the oxide-covered chromium surface and reaction of anodic dissolution of chromium through the passive film, the stable corrosion potential $E_{cor.1}$ was formed. The other corrosion potential was formed as the results of cathodic hydrogen evolution and anodic dissolution on the bare chromium surfaces, when the chromium surface is depasivated (by cathodic activation, or mechanical action, etc.). In this case, the stable corrosion potential $E_{cor.2}$ establishes.

REFERENCES

[1] Wilde B. E., Hodge F. G., The Cathodic Discharge of Hydrogen on Active and Passive Chromium Surfaces in Dilute Sulphuric Acid Solutions, Electrochim. Acta 14 (7) (1969) pp. 619-627;

[2] Kolotyrkin Ya. M., Florianovich G. M., Anomalnoe rastvorenie metallov. Eksperimentalnie fakti i ih teoreticheskoe tolkovanie, Zashch. Metal. 20 (1) (1984) pp. 14-24;

[3] Dražić D. M., Popić J. P., Anomalous Dissolution of Metals and Chemical Corrosion (Review), J. Serb. Chem. Soc. 70 (3) (2005) pp. 489-513;

[4] Dražić D. M., Popić J. P., Dissolution of Chromium in Sulfuric Acid, J. Serb. Chem. Soc. 67 (11) (2002) pp. 777-783;

[5] Popić J. P., Dražić D. M., Electrochemistry of Active Chromium. Part III. Effect of Temperature, J. Serb. Chem. Soc. 68 (11) (2003) pp. 871-883;

[6] Dražić D. M., Popić J. P., Electrochemistry of Active Chromium: Part 1—Anomalous Corrosion and Products of Chromium Dissolution in Deaerated Sulfuric Acid, Corrosion 60 (3) (2004) pp. 297-304.

[7] Popić J. P., Dražić D. M., Electrochemistry of Active Chromium: Part II. Three Hydrogen Evolution Reactions on Chromium in Sulfuric Acid, Electrochim. Acta 49 (27) (2004) pp. 4877-4891;

[8] Dražić D. M., Popić J. P., Jegdić B., Vasiljević-Radović D., Electrochemistry of Active Chromium. Part IV. Dissolution of Chromium in Deaerated Sulfuric Acid, J. Serb. Chem. Soc. 69 (12) (2004) pp. 1099-1110;

[9] Sukhotin A. M., Khoreva N. K., Passivnost khroma. Osobenosti katodnogo aktivirovaniya khroma, Electrokhimiya 18 (1) (1982) pp. 132-134;

[10] Jegdić B., Dražić D. M., Popić J. P., Structural Effects of Metallic Chromium on its Electrochemical Behavior, J. Serb. Chem. Soc. 72 (6) (2007) pp. 563-578;

[11] Jegdić B., Dražić D. M., Popić J. P., Influence of Chloride Ions on the Open Circuit Potentials of Chromium in Deaerated Sulfuric Acid Solutions, J. Serb. Chem. Soc. 71 (11) (2006) pp. 1187-1194;

[12] Jegdić B., Dražić D. M., Popić J. P., Open Circuit Potentials of Metallic Chromium And Austenitic 304 Stainless Steel in Aqueous Sulphuric Acid Solution and the Influence of Chloride Ions on them, Corr. Sci. 50 (2008) pp. 1235-1244.

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Bore Jegdić, Maja Stevanović, Aleksandar Jegdić**

HEMIJSKO I ELEKTROHEMIJSKO RASTVARANJE HROMA NA SOBNOJ I NA POVIŠENIM TEMPERATURAMA**

Izvod

Ispitivan je uticaj temperature na elektrohemijsko i hemijsko rastvaranje hroma u kiselim rastvorima sulfata. Reakcije izdvajanja vodonika, anodnog rastvaranja i hemijskog rastvaranja hroma sa aktivirane površine hroma u rastvoru sumporne kiseline pH 1 slede Arenijusovu zavisnost sa prividnom energijom aktivacije 35 kJ mol^{-1}, 58 kJ mol^{-1} i 62 kJ mol^{-1}, respektivno. Velika energija aktivacije hemijskog rastvaranja hroma dovodi na povišenim temperaturama do znatno izraženije hemijske korozije u odnosu na elektrohemijsku koroziju.

Ključne reči: *hemijska korozija hroma, elektrohemijsko rastvaranje, prividna energija aktivacije*

UVOD

Paralelno sa elektrohemijskim rastvaranjem hroma odvija i njegovo hemijsko rastvaranje, koje ne zavisi od potencijala i koje je u nekim uslovima dominantan proces rastvaranja, naročito na povišenim temperaturama [1-9]. Hemijsko rastvaranje hroma je uzrok pojavi izdvajanja vodonika, koje ne podleže zakonitostima elektrohemijske kinetike.

U ovom radu vršeno je određivanje energije aktivacije procesa hemijskog rastvaranja hroma, elektrohemijskog rastvaranja hroma, katodnog izdvajanja vodonika i temperaturne zavisnosti brzine elektrohemijske korozije. Takođe, određena je teksture hroma primenom OIM metode (orientation imaging microscopy). Određivanje koncentracije hroma u rastvoru je vršeno primenom atomske apsorpcione spektroskopije (AAS). Vršeno je snimanje anodnih i katodnih polarizacionih krivih i određivanje brzine elektrohemijske korozije primenom različitih elektrohemijskih metoda.

EKSPERIMENTALNI DEO

Pre ispitivanja, površina uzoraka hroma je mehanički polirana stupnjevito brusnim papirom do finoće 1000. Rastvor za ispitivanje je bio 0,1 M Na_2SO_4 + H_2SO_4, pH 1, koji je deaerisan provođenjem prečišćenog azota. Za izvođenje elektrohemijskih ispitivanja korišćena je trodelna staklena elektrohemijska ćelija sa vodenim plaštom za termostatiranje, sa Pt pomoćnom elektrodom i zasićenom kalomelovom elektrodom (ZKE) kao referentnom elektrodom.

Pre merenja, elektroda hroma je aktivirana katodnom polarizcijom na –0,900 V tokom 120 s radi uklanjanja površinskog oksida, koji se na hromu uvek spontano stvara u dodiru sa vazduhom. Elektro-

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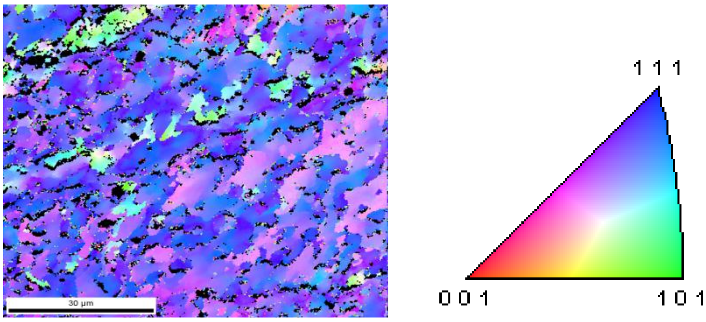
hemijska merenja su izvedena primenom potenciostata-galvanostata PAR 273.

REZULTATI I DISKUSIJA

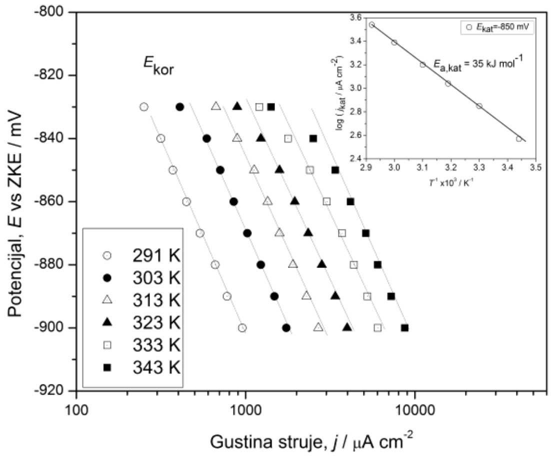
Na slici 1 je prikazana inverzna polarna slika uzorka hroma dobijena OIM metodom. Plavom bojom je označena orijentacija zrna (111) i vidi se da veliki broj zrna na površini elektrode ima upravo tu orijentaciju. Takođe određena je veličina kristalnih zrna, koja su bila malih dimenzija sa velikim stepenom razorijentisanosti. Zapravo, to su zasebna zrna sa sopstvenom orijentacijom.



Sl. 1. *Inverzna polarna slika, tekstura (111) elektrode hroma dobijena OIM metodom. Orijentaciona veličina zrna se može proceniti na osnovu razmere date na slici*

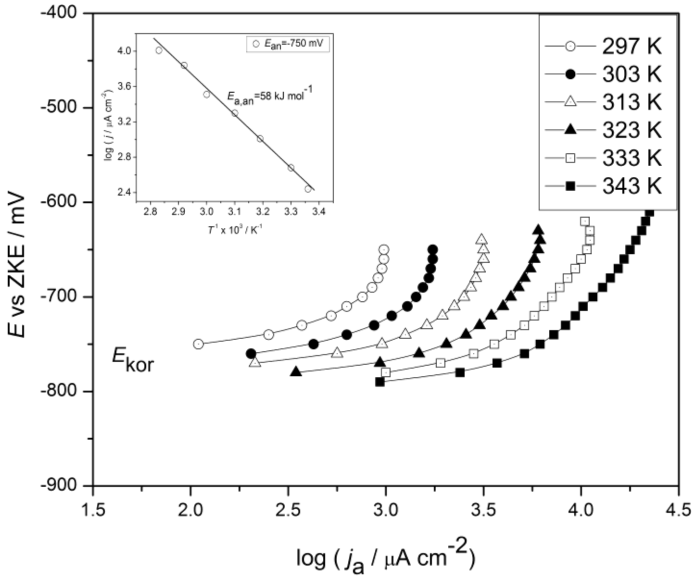
Ispitivan je uticaj temperature na hemijsko i elektrohemijsko rastvaranje elektrode Cr u temperaturnom intervalu od 291 do 353 K u vodenom rastvoru sumporne kiseline, pH 1.

Katodne polarizacione krive snimljene na različitim temperaturama iz oblasti od 291 do 343 K u sumpornoj kiselini pH 1 su prikazane na slici 2. Sa slike se vidi da se sa povećanjem temperature povećava brzina izdvajanja vodonika, pri čemu je varijacija Tafelovih nagiba sa temperaturom bila u teoretski očekivanim okvirima. Isečak na slici 2 prikazuje zavisnost logaritma gustine struje kao funkcije recipročne temperature, za određivanje prividne energije aktivacije, za reakciju izdvajanja vodonika na -0,860 V. Prividna energija aktivacije za reakciju katodnog izdvajanja vodonika je 35 kJ mol^{-1}.



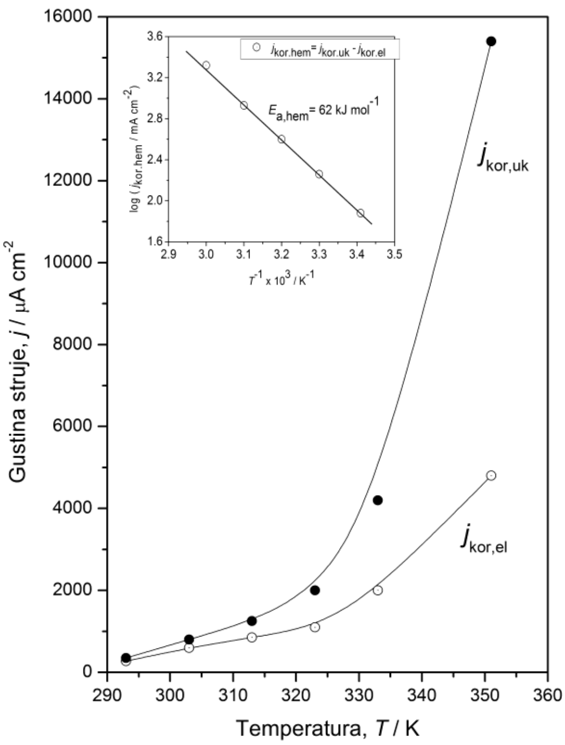
Sl. 2. *Katodne polarizacione krive za elektrodu hroma u vodenom rastvoru 0,1 M Na_2SO_4 + H_2SO_4, pH 1 na različitim temperaturama*

Na slici 3 su prikazane krive anodne polarizacije hroma u rastvoru natrijum-sulfata i sumporne kiseline pH 1 snimljene na različitim temperaturama. Oblik polarizacionih krivih je sličan izuzev što su krive na većim temperaturama pomerene prema većim gustinama struje, kao što se moglo i očekivati. Arenijusova zavisnost za -0,750 V prikazana na isečku na slici 3 daje prividnu energiju aktivacije za reakciju aktivnog anodnog rastvaranja od $E_{a,an}$ = 58 kJ mol^{-1}. To ukazuje da anodna reakcija više zavisi od temperature nego katodna reakcija, što takođe objašnjava promenu korozionog potencijala sa temperaturom u smeru negativnijih potencijala.



Sl. 3. *Anodne polarizacione krive za elektrodu hroma u rastvoru sumporne kiseline pH 1 na različitim temperaturama*

Gustina struje elektrohemijske korozije $j_{kor,el}$ je određivana ekstrapolacijom Tafelovih nagiba na korozioni potencijal i Stern-Gerievom metodom linearne polarizacije, dok je ukupna brzina rastvaranja određivana analizom rastvora primenom atomske apsorpcione spektrofotometrije $j_{uk,an}$, i prikazane su na slici 4. Sa slike 4 se može videti da je ukupna brzina rastvaranja, odnosno ekvivalentna gustina struje za sve temperature veća nego gustina struje elektrohemijskog rastvaranja tj. elektrohemijske korozije. To pokazuje da postoji pored elektrohemijskog značajno hemijsko rastvaranje hroma na svim temperaturama. Ta razlika se povećava sa povećanjem temperature kao što se može videti sa slike 4. Na 353 K ukupna brzina rastvaranja je približno četiri puta veća nego elektrohemijska brzina korozije. U isto vreme to znači da je brzina hemijskog rastvaranja na toj temperaturi približno tri puta veća nego brzina elektrohemijskog rastvaranja.

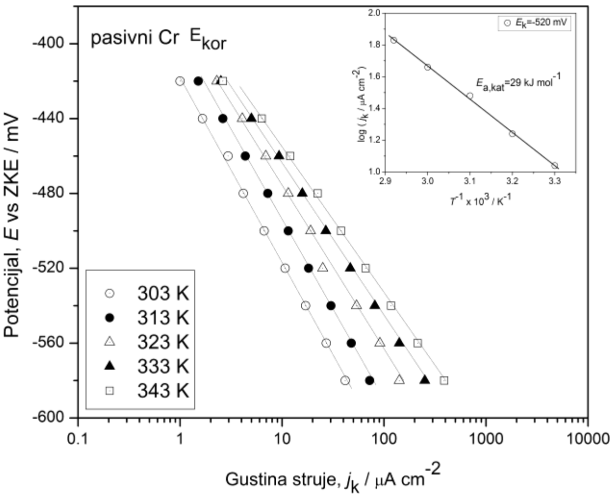


Sl. 4. *Ukupna gustina struje dobijena analitički (●) i gustina korozione struje dobijena elektrohemijski na različitim temperaturama (○) za elektrodu hroma*

Kao što je prikazano na slici 4, ukupne brzine korozije j_{uk} na svim temperaturama koje su korišćene pri ovim eksperimentima su veće nego elektrohemijske brzine korozije $j_{kor,el}$. Ta razlika je posledica hemijskog rastvaranja hroma, koji se odvija direktnom rekcijom molekula vode i atoma hroma sa površine elektrode i koji ne zavisi od potencijala. Razlike između ukupne brzine rastvaranja određene analitički $j_{uk,anal}$ i elektrohemijskih brzina korozije $j_{kor,el}$ su nacrtane u zavisnosti od recipročne vrednosti temperature na isečku na slici 4. Iz nagiba te pravolinijske zavisnosti se može odrediti prividna energija aktivacije i ona iznosi 62 kJ mol^{-1}. Visoka vrednost energije aktivacije ukazuje da je uticaj temperature na reakciju hemijskog rastvaranja prilično velik i da je doprinos ukupnoj brzini korozije veći u oblasti povišenih nego nižih temperatura. To treba imati u vidu kada se koriste podaci o brzini korozije dobijeni na sobnoj temperaturi za predviđanje korozionog ponašanja na povišenim temperaturama. Vrlo je moguće da slične razlike u pogledu uticaja temperature postoje u slučaju korozije ostalih metala koji korodiraju i elektrohemijski i hemijski (tj. Fe, Ni, Mn i drugi).

Hrom se nalazi u pasivnom stanju posle uranjanja u rastvor za ispitivanje, sa karakterističnim korozionim potencijalom $E_{kor,1}$ koji odgovara pasivnom stanju hroma. Tek katodnom polarizacijom na -0,900 V u toku nekoliko desetina sekundi, pasivni films se rastvara, pri čemu se elektroda aktivira. Tada se formira korozioni potencijal $E_{kor,2}$ koji odgovara aktivnom hromu.

Katodne krive snimljene na pasiviranom hromu, prikazane u obliku Tafelovog dijagrama za različite temperature predstavljene su na slici 5. Uočava se da je katodni Tafelov nagib približno jednak -0,060 V dek^{-1} i da se gustina struje povećava sa temperaturom. Isečak na slici 5 predstavlja Arenijusov dijagram dobijen na -0,520 V sa koga se može odrediti prividna energija aktivacije koja iznosi 29 kJ mol^{-1}. To je nešto manja vrednost nego energija aktivacije za izdvajanje vodonika na aktiviranoj površini hroma (35 kJ mol^{-1})



Sl. 5. *Katodne Tafelove zavisnosti za pasiviranu elektrodu B sa slike 4.29. na različitim temperaturama*

Prema tome korozija aktivnog metalnog hroma u vodenom rastvoru sumporne kiseline pH 1 se sastoji od dva simultana koroziona procesa, elektrohemijske korozije i hemijskog rastvaranja. Pokazano je da se na Cr elektrodi u rastvoru 0,1 M Na_2SO_4 + H_2SO_4, pH 1 sa povišenjem temperature značajno ubrzavaju reakcije anodnog rastvaranja hroma, hemijskog rastvaranja hroma, katodnog izdvajanja vodonika na čistoj metalnoj površini, kao i na površini hroma prevučenoj oksidom.

Reakcija izdvajanja vodonika, reakcija anodnog rastvaranja i reakcija hemijskog rastvaranja hroma sa aktivirane površine u rastvoru sumporne kiseline pH 1 u temperaturskom intervalu od 293 do 353 K slede Arenijusovu zavisnost sa prividnom energijom aktivacije 35 kJ mol^{-1}, 58 kJ mol^{-1} i 62 kJ mol^{-1}, respektivno. Prividna energija akti-vacije reakcije izdvajanja vodonika na hromu prekrivenom oksidom ima vrednost 29 kJ mol^{-1}.

ZAKLJUČAK

Korozija aktivnog metalnog hroma u vodenom rastvoru sumporne kiseline pH 1 se odvija paralelno elektrohemijskim i hemijskim mehanizmom. Brzina hemijske korozije se dobija iz razlika ukupne i elektrohemijske brzine korozije.

Reakcija izdvajanja vodonika, reakcija anodnog rastvaranja i reakcija hemijskog rastvaranja Cr sa aktivirane površine u rastvoru sumporne kiseline pH 1 u temperaturnom intervalu od 291 do 353 K slede Arenijusovu zavisnost sa prividnom energijom aktivacije 35 kJ mol^{-1}, 58 kJ mol^{-1} i 62 kJ mol^{-1}, respektivno. Velika energija aktivacije hemijskog rastvaranja hroma dovodi na povišenim temperaturama do znatno izraženije hemijske korozije u odnosu na elektrohemijsku koroziju. Prividna energija aktivacije reakcije izdvajanja vodonika na hromu prekrivenom oksidnim filmom ima vrednost 29 kJ mol^{-1}.

Korozioni potencijal je posledica simultanog odvijanja reakcije izdvajanja vodonika bilo na oksidom prekrivenoj površini hroma sa reakcijom anodnog rastvaranja hroma kroz pasivni film obrazujući stabilni potencijal $E_{kor.1}$ ili katodnim izdvajanjem vodonika i anodnim rastvaranjem ogoljene površine kada se površina hroma depasivira na neki način (katodnom aktivacijom, mehaničkim delovanjem itd.). U tom slučaju uspostavlja se stabilni korozioni potencijal $E_{kor.2}$.

LITERATURA

[1] Wilde B. E., Hodge F. G., The cathodic discharge of hydrogen on active and passive chromium surfaces in dilute sulphuric acid solutions, Electrochim. Acta 14 (7) (1969) pp. 619-627.

[2] Kolotyrkin Ya. M., Florianovich G. M., Anomalnoe rastvorenie metallov. Eksperimentalnie fakti i ih teoreticheskoe tolkovanie, Zashch. Metal. 20 (1) (1984) pp. 14-24.

[3] Dražić D. M., Popić J. P., Anomalous dissolution of metals and chemical corrosion (Review), J. Serb. Chem. Soc. 70 (3) (2005) pp. 489-513.

[4] Dražić D. M., Popić J. P., Dissolution of chromium in sulfuric acid, J. Serb. Chem. Soc. 67 (11) (2002) pp. 777-783.

[5] Popić J. P., Dražić D. M., Electrochemistry of active chromium. Part III. Effect of temperature, J. Serb. Chem. Soc. 68 (11) (2003) pp. 871-883.

[6] Dražić D. M., Popić J. P., Electrochemistry of Active Chromium: Part 1-Anomalous Corrosion and Products of Chromium Dissolution in Deaerated Sulfuric Acid, Corrosion 60 (3) (2004) pp. 297-304.

[7] Popić J. P., Dražić D. M., Electrochemistry of active chromium: Part II. Three hydrogen evolution reactions on chromium in sulfuric acid, Electrochim. Acta 49 (27) (2004) pp. 4877-4891.

[8] Dražić D. M., Popić J. P., Jegdić B., Vasiljević-Radović D., Electrochemistry of active chromium. Part IV. Dissolution of chromium in deaerated sulfuric acid, J. Serb. Chem. Soc. 69 (12) (2004) pp. 1099-1110.

[9] Sukhotin A. M., Khoreva N. K., Passivnost khroma. Osobenosti katodnogo aktivirovaniya khroma, Electrokhimiya 18 (1) (1982) pp. 132-134.

[10] Jegdić B., Dražić D. M., Popić J. P., Structural effects of metallic chromium on its electrochemical behavior, J. Serb. Chem. Soc. 72 (6) (2007) pp. 563-578.

[11] Jegdić B., Dražić D. M., Popić J. P., Influence of chloride ions on the open circuit potentials of chromium in deaerated sulfuric acid solutions, J. Serb. Chem. Soc. 71 (11) (2006) pp. 1187-1194.

[12] Jegdić B., Dražić D.M., Popić J. P., Open circuit potentials of metallic chromium and austenitic 304 stainless steel in aqueous sulphuric acid solution and the influence of chloride ions on them, Corr. Sci. 50 (2008) pp. 1235-1244.

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BUSINESS SUCCESS MANAGEMENT

Abstract

This paper first discusses the essence and purpose of measuring the business success as well as the theoretical-methodological problems in defining model for measuring the overall business success. By expression and measurement of business success the efficiency and effectiveness the functioning of entire system of the company are quantitatively formalized and defined. Modern environment characterized by complexity, uncertainty, frequent and significant changes and the existence of strong competition requires companies to constantly improve the measurement systems for business success. In this paper, disputing the significance of financial performance measures for control and measurement of business success, the necessity to establish a new approach is highlighted where the financial indicators are combined with a large number of non-financial indicators. Experience in practical use of different models is a valuable knowledge showing managers in which direction to go in order to have more effective support in the management process.

Bearing this in mind, the mining companies should improve systems for control and measurement of business success, drawing on the experience of complex business practices or confirmation of all those measures which have acquired the attributes of an effective instrument of management.

***Keywords**: effectiveness, efficiency, measurement of business success, business success model, financial indicators, Prism performance.*

INTRODUCTION

Expressing and measuring of business success is an integral element of the control system, of which adequacy, the effectiveness of the management process directly depends on.

The problem of measuring the overall business success is viewed in terms of purpose, essence and theoretical-methodological problems in defining the model for measuring the overall business success. This issue gains importance in contemporary environments which are characterized by complexity and uncertainty, and where the strong requirements are manifested for meeting the interests of different stakeholders. It is necessary that the mining enterprises take into account the interests of stakeholders in making profit, paying the debts, reliable supply to consumers, adequate remuneration and care about the community.

In order to get knowledge on how to increase the effectiveness of the model for measuring business success, as a prerequisite for efficient management, the existing models are analyzed as a valuable contribution to economic theory and practice. This knowledge is useful for managers of mining companies.

EFFECTIVENESS, EFFICIENCY AND BUSINESS SUCCESS

As concepts that contain and link company objectives, resources and trans

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formation processes that form the basis for realization the objectives, efficiency and effectiveness are essential for every company. Recognizing many similar but different concepts for defining these essential and at the same time the key economic phenomena, it can be assumed that [1]:

- Effectiveness is the request to firstly make the selection of right goals and then, using available resources, to achieve the maximum realization of the selected goals.
- Efficiency is a requirement that the realization of a certain degree of selected targets is achieved with the least use of available resources, i.e. with the greatest rationality of their use.

Effectiveness is therefore focused on the choice of needs that will be met by the company, i.e. the selection of objectives and activities and efficiency is focused on the productive capacity and rational use of resources that a company has.

A similar interpretation is represented in the national literature by D. Grozdanović [2]. A differentiated concept of effectiveness and efficiency is based on the attempt of success differentiation in the work in relation to the market environment and in relation to the internal conditions in production. In doing so, however, the question of measuring or criteria is raised for design such determined success in the work. Effects in the domain of effectiveness depend on the effects in the area of production efficiency. And vice versa, the effects in the field of efficiency are dependent on effects on the basis of effectiveness.

Theoretical and methodological distinction between effectiveness and efficiency is not easy especially when it comes to their measurement. The product is the result of choice but also the result of more efficient or less efficient real production.

The effectiveness of the results is a measure of output tasks or achieving the goal. In the production organizational units that means to achieve planned production tasks qualitatively and quantitatively. Tasks can be achieved, but with the loss of sources used in the transformation process. Therefore both processes must be regarded. The efficiency of the results measure the costs of the sources used for the goal realization, that is the outputs in relation to inputs used [3].

Starting from the essence of economic efficiency and its apparent manifestations of the economy in general the effectiveness and efficiency as economic phenomena at the level of enterprise economy can be defined [1].

- *Economic efficiency* is essentially a manufacturing efficiency, i.e. the ability of efficient organization of the transformation of inputs into outputs of enterprises.
- *Economic efficiency* is an expression of the efficiency of the exchange because the selection of targets that meet societal needs and resources that define the production potential of the company ultimately comes down to the sale and purchase of inputs and outputs, i.e. the overall marketing activities.
- *Allocative efficiency*, term for efficiency in organization of production and exchange, is an expression of the overall efficiency of the company, which includes the effects of the efficiency and effects of effectiveness.

Integration of the efficiency and effectiveness in the unique expression of the overall economic efficiency is a function of measuring the performance of the overall company effects. Through understanding the overall effect, it is possible to manage effectively the economy of enterprises.

The quality of enterprise economy can be accessed through consideration the relationship between a uniquely understood product as the result of production and uniquely conceived social work introduced in reproduction in order to achieve that result.

Quantitative expression the quality of the economy is expressed by business success ***Pu***, which is contained in the relations between the results of reproduction (output) and investments (inputs) to reproduction.

$$P_u = R(O_u)/U(I_n)$$

The quality of enterprise economy as the expression of economic success in achieving objectives degree at the same time is the expression of effectiveness and efficiency of enterprise and business development. In accordance with the statement that the economic significance of efficiency and effectiveness, i.e. only economic efficiency, is just in the teconomy quality and it follows that business success is a quantitative expression of efficiency and effectiveness [2].

MEASUREMENT OF BUSINESS SUCCESS

The problem of measuring the total business success can be seen in terms of purpose, essence and theoretical methodological problems of defining the model for measuring business success.

The purpose of measuring the total business success of the company is clear information on the actual economic efficiency of enterprises, as well as on real economic effects of the new investments in the particular company of interest to the business owners. Continual measurement of business success is a realistic assumption for effective economic management of the company.

In the joint-stock companies, in which the ownership is separated from management, the measurement of business performance allows the owners to control managers who are engaged to manage the company.

The measurement of business success provides, in addition to the management efficiency, more realistic distribution of profits in the so-called financial groups of companies, more realistic view of actual effects of external growth.

The measurement of business success encourages the functioning of stock market, because potential investors (shareholders) have relevant information about their investments.

Expression of business success is a legal requirement without which the company cannot exist. The reported results serve as a basis for calculation and payment of dividends to the shareholders.

The owners, managers and state are interested in measuring the business success. Measuring the business success at the end of business period or continuously if required, is a necessary condition of efficient management and adequate satisfaction of stakeholders' interest.[1]

Substantial interpretation suggests that the overall success of business of concrete enterprise is the expression of the overall economic efficiency. This means that it expresses its overall allocative ability as the ability for selection and procurement of inputs; efficient organization of production as a transformation process and selection and implementation of products and services as the output of enterprises. All economic effects that are manifested in the inputs and outputs to a specific company express the overall economic efficiency [1].

Business success becomes quantitatively determined when measured and estimated by corresponding economic methods formulated in certain indicators or models. The main economic criteria of efficiency are important starting point for expression, monitoring, controlling and directing the relationship between the results and investments. Production volume, total revenue, income and profit are measured on side of the results and workforce, total costs and capital employed on the side of investment.

$$P_u = R(Q;C;D;D_b)/U(L;T;S)$$

If within the enterprise primary goal, the sub goals are viewed such as the production, accumulative and reproductive ability, the mentioned measures on the side of results and investments are formed in the tradition-

[1] *Strategic constituents in the company are its stockholders or owners, customers, creditors, suppliers and other groups without whose cooperation enterprise cannot survive*

nally complex known indicators of productivity ($P=Q/L$), economy ($E=C/T$) and profitability of $R= D(Db)/S$. These partial indicators are determined by the elements of results and investments; they are conditioned by factors forming quality of economy and activities to achieve the efficiency in the use of resources [4].

Expressing the business success by partial indicators as the enterprise economy measures shows the efficiency in functionning the production-financial company's subsystems. This allows the control and guidance the quality of certain subsystems of the economy to a unique integrated goal to achieve the efficiency of the whole company system. However, in expressing and managing the dynamics of business success, divergence and disadvantages of partial indicators as well as the complexity of this issue are manifested. It is caused by different intensity and direction of movement the elements of results and investments under the influence of positive or negative effects within operating activities.

The contemporary theory and practice resolve the expression and measurement problem of business success accepting two attitudes [2]:

- the first is based on the use of a number of individual indicators, where the denominator term is given most often in the form of quantitative evaluation, which is generally not objectified on some basis
- the second is based on an attempt to, along with numerous difficulties and constraints faced by the modern theory and practice, formulate and uses the synthetic term of business success, in the form of more or less integrated, maximum possible objectified model, which, along with mandatory additionnal qualitative indicators, physical expresses the change of overall economic quality.

The scope and content of any set of indicators or integral model of business success, should, on the basis of the basic criteria of economic efficiency, primarily meet the informational, management-control and motivational functions in business [5].

THEORETICAL AND METHODOLOGICAL PROBLEMS OF DEFINING A MODEL FOR MEASURING THE BUSINESS SUCCESS

Moving from a large number of partial indicators on a single indicator of overall efficiency requires solving the problem of reduction to a common denominator for the inputs and outputs of enterprises, as well as developing a complex business and information systems in the company, developed from a concrete model for measuring the business success.

In the constitution of model for expressing the overall business success, a model *Econometer* deserves a special attention as the original creation made by S. Kukoleča [6] which in dynamics record and report all connections and all changes in the shape of results and investments, reduced to a single common measure – working equivalent. The high level of abstraction and perfection in design and development of business success models in general, and specifically to the factors of conditionality, imposed the impression that it is difficult or impossible to achieve its implementation. This is especially true for a period of sixties when there were no support information systems in our companies. Also, that information base, required for measurements according to this model, on a small scale is associated with the official accounting and financial system. This represented one of the main obstacles for the use in practice.

Diligent efforts are also done by domestic scholars (D. Grozdanović and N. Malenović) on constituting the model for overall performance measurement of business success which overcomes some limitations of the original model and its subsequent modification (also by the two above mentioned authors), especially regarding the use of financial reporting information as a basis for calculation of certain elements [7].

The existing theoretical and practical instruments for controlling and directing business development and growth of the company do not allow consideration of a realistic picture of actual efficiency of modern enterprises. Many theoretical models derived from different company theories could not be applied to solve the specific problems in practice of companies. Thus, mathematical methods and models have limited utility in the application and were used for solving hypothetical cases rather than specific problems in the economy of companies.

The problem of efficient business of enterprises in management theories is formulated as the problem of determining maximum usefulness of managers, but since managers do not have unlimited discretion and their goals can be achieved with the conditions set by the owners of shareholders, maximizing of the utility function occurs as the result of problem solutions caused by maximization. Except a dichotomy of interests of the owners on one side, and managers, on the other side, does not identify the other important interests. Access to the objectives of the company changed over the time and techniques and methods of achieving the goals improved, but the basic objectives and their economic content were marginalized.

Financial indicators as the basis of traditional systems for measurement and control of business success have a clear control role bounded by certain period. There from derived sets of various indicators, indices and ratio numbers, just show what the result of business in companies is during the past period and it is not expressed through the overall business success, but according to the partial statements of certain conditions and effects.

With the development of theories that deal with the economy of enterprises, the preconditions are created for development of models to measure the business success for such control of company and management of its economy to emphasize the positive and to reduce negative consequences with satis faction of all t essential interests which are manifested in connection with business, growth and development.

FINANCIAL INDICATORS AS THE BASIS OF TRADITIONAL SYSTEMS OF MEASUREMENT AND CONTROL THE BUSINESS SUCCESS

Common to all traditional systems of financial control and measurement the business success is that they are all based on data that can be obtained on the basis of the accounting system. Giving priority to the use of quantitative accounting information is explained by the fact that accounting as a single integrated system for quantitative analysis of the company, characterized by integrity of business and financial activities of the company and the advantage of numerical expressions from which a value objectivism is derived. Also, the advantage of accounting information is manifested in their capacity to turn different conditions, trends and relationships into a universal, generally accepted unique numeric expression.

An integrated set of financial statements of most companies in the international practice is consisted of a balance sheet[2] (the statement of financial position), income statement (profit and loss). Although being more and more favored, cash flow statement is not accepted in all countries[3]. Regardless of establishment on the

[2] *One of the key changes in the revised IAS1, published in 2007 refers to the replacement of balance sheet with statement of financial position of the company. As a reason for this terminological changes are functions of this basic financial statement.*

[3] *According to accepted accounting standards, in addition to balance sheet, small businesses companies in our country are obliged to submit income statement and statistical annex to the Business Registers Agency (APR), a medium-sized and large companies are obliged to submit cash flow statement and statement of changes in capital.*

same business and financial transactions and financial universal quantification of these transactions, the financial statements set as an objective chronicler of company gives a variety of information on its activities for a certain period.

Basic information content of the balance sheet date is a book value of the company or the state of assets, liabilities and equity (net asset value) on a particular day.

Income statement is known as a profit and loss account. Basic information content of the income statement is profitability. Balance sheet presents the information on income, expenditure and net profit / loss for the certain period.

All revenues and expenses of a conventionally adopted accounting period, mutual confronted and presented in accordance with the relevant principles and in the appropriate reporting forms, allow determination of the results, profit as positive and loss as negative differences, which at the end of the accounting period are included in the balance sheet as an increase or decrease (the own) capital. This understanding of the income statement indicates the existence of a systematic and organic links between balance sheet and income statement, and this fact indicates that these financial statements in terms of evaluation the efficiency of operations are treated as complementary and interdependent accounting products [8].

Cash-flow statement shows turnover on cash account through cash inflows and outflows as well as free cash flow generated in the period. Cash Flow Statement shows the business, financial and investment inflows and outflows of cash flows of the company during the reporting period. Basic information for control in cash flow statement is liquidity. Also, the cash flow statement carries information about the possibilities of creating value if a discounted free cash flow is implemented.

Certain financial statement items, shown in absolute values, do not give enough information for management. Ratio numbers are obtained by bringing particular positions from balance sheet, income statement and other statements in appropriate relations.

In the control process, the ratio numbers are compared to the past results or the competition results, that is, ratio numbers can be used to monitor the results of the company over time or to monitor the relative position of the company in relation to the competitors. In any case, these relative values provide much richer information than absolute values analyze (financial statement). All ratio numbers can be classified into four major groups: liquidity indicators, turnover (activities) indicators, indicators of solvency (financial structure) and indicators of profitability (profitability) [9].

The aforementioned indicators are actually operational performance measures, namely indicators of the success that measure results of operational decisions. It is obvious that the effects of operational decisions include effects of strategic and tactical decisions [10].

In addition to the simple ratio numbers there are complex ratio numbers that arise by combining the ratio numbers, following a substantial part business process or specific aspects of the business. DuPont formula leads to a synthetic expression of profitability which allows establishing the change as well as causes of changes in profitability, because the overall profitability, that is, the return on total assets is seen as a result of interactions, or interactions of partial indicators of profitability [11].

For the purposes of managers as the internal users of financial and accounting reports in the company, the additional reports on operations can be made which should contribute to making the rational management decisions and taking appropriate actions.

The importance of the financial statements, which reflect the financial business activities of the company as a whole, is reflected in the fact that the analytical interpretation of data contained therein enables identification and monitoring the key financial performance measures of enterprise efficiency. In addition to the traditional criteria of MIA, indicators are used lately that have their stronghold in the concept of value-based management. One of the most important is the economic value added (EVA). The following indicators are lately often used by economic analysts: Earning Before Interest (EBIT) and Earning Before Interest, Taxes, Depreciation and Amortization (EBITDA)

RESULTS OF ECONOMIC THEORY AND PRACTICE IN DEFINING THE MODEL FOR MEASURING THE OVERALL BUSINESS SUCCESS

Despite irreplaceable role of the financial criteria, it is necessary to emphasize its imperfections and incompleteness for the purposes of valid analysis and evaluation of effectiveness. The use of traditional financial measures has certain drawbacks and limitations that are primarily related to: presentation of events that occurred in the previous period, unreliability of comparison base for a longer period, not giving enough importance to the business environment by ignoring the perspective of consumers and competitors. A problem of traditional measures, based on financial indicators, is that they do not take into account the intangible value contained in the knowledge that can greatly increase market value of the company.

Changes in the environment, globalization of the world economy, strong competition and development of information technology leads to the changes in the traditional control apparatus. Industrial economy characterized by physically tangible assets is replaced by a new economy where the most valuable resource becomes intangible assets that include relationships with consumers, employee skills and their knowledge, information and organizationnal culture favorable for innovation, problem solving and general improvement of organization [12].

In terms of developed market, the only sustainable way to create value for business owners at the same time is value creation for their stakeholders. Stakeholders therefore have legitimate interests in the company performance, as well as the specific requirements and needs that arise from the relationship in carrying out certain activities. In addition, the primary (active) stakeholders have a formal, official and contractual relationship with the company, while all the others can be considered as the secondary. Orientation to stakeholders implies that the model of business success include indicators of success in achieving the individual goals of all stakeholders as well as measurements of achieving these goals both expressed by appropriate indicators.

One of the most important roles of management is to find a balance between acceptable financial responsibilities towards the owners and strategic responsibilities to the other stakeholders. The higher the quality of the relationship of companies with stakeholders such as customers, employees, suppliers, communities and others, leads to better financial performance, and ultimately to a higher enterprise value, and shareholding wealth [13].

Model Prism performances – Based on said, and taking into account the causal processes among stakeholders, one of the modern model is formulated, so-called Performance Prism (A. Neely) which is considered to be an integral model because it combines the elements oriented on stakeholders and elements of process oriented models [5]. Prism performance model is shown in Figure 1.

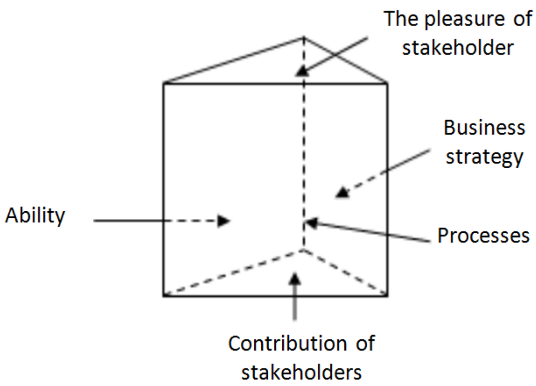

Figure 1 *Prism performance as a model showing business success, according to [14]*

Model Prism performance provides five different but related views, and thus reflects the business success of the company stated by set of indicators differentiated into five key groups, as well as answers to the questions [14]:

- The pleasure of stakeholder (top of the prism) - who are the key stakeholders and what they want or what they need;
- Business strategy (side of the prisms) - which strategy company needs to implement to satisfy the mentioned desires or needs
- Processes (side of the prisms) - what critical processes a company should apply to the set objective, favoring so-called processes that add value to the investment in reproduction
- Ability (side of the prisms) - what ability the key stakeholders should have (employees, customers, community and the owners of capital) in the exercise of applied processes and finally
- Contribution of stakeholders (bottom of the prisms) – what contribution the company can expect from stakeholders if the company's management supports and develops the skills of stakeholders

Management on the basis of these criteria involves defining the target performance measures, comparing achievements with target-setting values, identifying deviations and causes (factors) of deviations, and finally identifying corrective management action. The model is considered valuable because it highlights the dimension of measures ability (resources). The main disadvantage is a big number of criteria that, considering the limited time and ability attention of managers, cannot be used operationally.

Numerous references prove that the application of multidimensional performance measurement system contributes to the effectiveness thereof *(Domanović, 2013,* according to: *Malina, M. A.,& Selto, F. H. 2001; Ittner, C. D and others 2003; Davis, S., & Albright, T. 2004; Crabtree, A. D & De Busk, G.K 2008; Van der Stede, W.A. and others 2006; Tung, A. and others 2011)*. Most of these studies examined the effectiveness of these systems from the perspective of contribution the same financial results [15].

The analyzed models of measurements as well as the other existing models that have proven their applicability in practice are of particular importance to improve the management process. Combining the existing models creates the new ones. The improved measurement systems provide the real preconditions for efficient management, with appropriate support of information systems.

CONCLUSION

In economic theory and business practice in companies, the issues of measuring overall business success is very live and still insufficiently rounded. From the management aspect the design of quality aggregate criteria requires previously solving extremely complex problem of reducing to a common denominator of different criteria for inputs and outputs of enterprises as well as development and use of appropriate information system for monitoring the budget and so the designed aggregate size of business success. Economic theory has offered a solution in the form of the optimal model Econometer. Model of total performance of business success tries to overcome some limitations of the original model and its subsequent modifications, especially regarding the use of financial reporting information as the basis for calculation the certain elements.

The financial measures have an irreplaceable role in the evaluation of enterprise business success; however, it is necessary to point to their imperfection and incompleteness with the need for a valid analysis of business success. In the modern period there is inability of financial indicators to include the intangible resources of the company (intellectual capital) and level of achievement of non-financial company goals (relationship with customers, employees) who are critical for business success in the modern period.

Effective measurement system is one that includes a set of financial and non-financial measures that will enable managers to successfully deal with a large number of business activities and focus on the key factors of business success. Model Prism performance is one such proposal (attempts). But there is no stopping here. In the aim of real overview of the effectiveness and efficiency of the company, looking for solutions providing a new paradigm of enterprise and its appropriate model will continue.

The considered problem in this paper is useful for management of mining companies which will, through greater responsibility to their stakeholders, acquire the attributes of successful enterprise.

REFERENCES

[1] M. Nikolić, N. Malenović, D. Pokrajčić, B. Paunović, Enterprise Economics, Faculty of Economics, Kragujevac, 2003, pp. 122,136,475;

[2] D. Grozdanović, Fundamentals of Enterprise Economics, Faculty of Economics, Kragujevac, 2003, pp. 23, 25,456:

[3] M. Milisavljević, Contemporary Strategic Management, Megatrend University of Applied Sciences, Belgrade, 2005, p. 5;

[4] Lj. Savić, The Tole of Management in Improving the Effectiveness and Efficiency of the Company, Doctoral Dissertation at Megatrend University, Faculty of Business Studies, Belgrade, 2010, p.100;

[5] M. Ratković Abramović, Management of Dynamics of Business Success, the Copyright Issue, ŽELNID - Belgrade, 2005, pp. 67,79;

[6] S. Kukoleča, Ekonometar, Consulting Center, Belgrade, 1994;

[7] B. Krstić, Model of Measurement the Performance of the Overall Business Success of the Company, Faculty of Economics, Niš, 2007;

[8] V. Domanović, J. Bogićević, The Possibilities of the Balanced Scorecard Concept Implementation in Serbia, NDE, Palić, 2011;

[9] B.Pešalj, Company Performance Measurement, Faculty of Economics, Belgrade, 2006, p.63;

[10] D. Djuričin, S. Janošević, Dj. Kaličanin, Management and Strategy, Faculty of Economics, Belgrade, 2013, p. 161;

[11] D. Pokrajčić, Enterprise Economics, Copyright Issue, Čigoja štampa, Belgrade, 2002, p.356;

[12] R. Kaplan and D. Norton, Having Trouble With Your Strategy? Then Mapit!, Harvard Business Review, September-October, 2000, p. 4;

[13] Dj. Kaličanin, The Formulation and Implementation of Strategies of Value Creation, Doctoral Dissertation, Faculty of Economics, Belgrade, 2005, p.15;

[14] A. Neely, Business Performance Measurement, Cambridge University Press, 2003, p. 153;

[15] V. Domanović, The Effectiveness of the Performance Measurement in Terms of Contemporary Business Environment, Ekonomski horizonti, Faculty of Economics, Kragujevac, April 2013.

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UPRAVLJANJE POSLOVNIM USPEHOM

Izvod

U ovom radu se prvo ukazuje na suštinu i svrhu merenja poslovnog uspeha kao i na teorijsko-metodološke probleme u definisanju modela za merenje ukupnog poslovnog uspeha. Izražavanjem i merenjem ukupnog poslovnog uspeha kvantitativno se formalizuje i definiše efikasnost i efektivnost funkcionisanja celokupnog sistema preduzeća. Savremeno okruženje koje odlukuje složenost, neizvesnost, česte i značajne promene i postojanje izražene konkurencije zahteva od preduzeća da stalno unapređuju sisteme merenja poslovnog uspeha. U radu se, ne sporeći značaj finansijskih merila za konntrolu i merenje poslovnog uspeha, ističe neophodnost uspostavljanja novih pristupa gde su finansijski pokazatelji kombinovani sa velikim brojem nefinansijskih pokazatelja. Iskustva u praktičnoj primeni pojedinih modela su vredna saznanja u kom pravcu treba dalje ići da bi menadžeri imali efikasniju podršku u upravljačkom procesu.

Imajući ovo u vidu rudarska preduzeća treba da unapređuju sisteme za kontrolu i merenje poslovnog uspeha, crpeći iskustva iz kompleksne poslovne prakse odnosno utvrđivanju svih onih merila koja su stekla atribute efikasnog upravljačkog instrumenta.

Ključne reči: *efektivnost, efikasnost, merenje poslovnog uspeha, model poslovnog uspeha, finansijski pokazatelji, prizma performansi*

UVOD

Izražavanje i merenje ukupnog poslovnog uspeha sastavni je element upravljačkog sistema, od čije adekvatnosti neposredno zavisi i efikasnost samog upravljačkog procesa.

Problematika merenja ukupnog poslovnog uspeha sagledava se sa aspekta svrhe, suštine i teorijsko-metodoloških problema u definisanju modela za merenje ukupnog poslovnog uspeha. Ova problematika dobija na značaju u uslovima savremenog okruženja koje karakteriše složenost i neizvesnost i gde se ispoljavaju snažni zahtevi za zadovoljavanjem interesa različitih stejkholdera. Rudarska preduzeća takođe moraju uvažavati interese neposrednih stejkholdera u sticanju profita, isplati dugova, pouzdanom snabdevanju kupaca, adekvatnom nagrađivanju, vođenjem računa o doslednosti i dr.

U cilju sticanja saznanja o tome kako povećati efektivnost modela za merenje poslovnog uspeha danas, kao pretpostavke za efikasnije upravljanje analiziraju se postojeći modeli kao vredni doprinosi ekonomske teorije i prakse. Ova su znanja korisna za menadžersku strukturu rudarskih preduzeća.

EFEKTIVNOST, EFIKASNOST I POSLOVNI USPEH

Kao koncepti koji u sebi sadrže i povezuju ciljeve preduzeća, resurse i transfor-

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macione procese koji predstavljaju osnovu za realizaciju ciljeva, efikasnost i efektivnost su od suštinskog značaja za svako preduzeće. Uvažavajući brojne slične, pa i različite koncepte za definisanje ovih suštinskih i istovremeno ključnih ekonomskih fenomena može se poći od toga da [1]:

- *Efektivnost* podrazumeva zahtev da se prvo izvrši izbor pravih ciljeva a potom korišćenjem raspoloživih resursa ostvari maksimalna realizacija izabranih ciljeva.
- *Efikasnost* predstavlja zahtev da se realizacija određenog stepena izabranih ciljeva ostvari uz najmanje korišćenje raspoloživih resursa, odnosno uz najveću racionalnost njihove upotrebe.

Efektivnost je prema tome orijentisana na izbor potreba koje će preduzeće zadovoljavati, odnosno izbor ciljeva i delatnosti kojima če to obezbediti, a efikasnost na proizvodnu sposobnost i racionalnost upotrebe resursa kojima preduzeće raspolaže.

Slično tumačenje zastupa u domaćoj literaturi D. Grozdanović [2]. Diferencirani koncept efektivnosti i efikasnosti bazira na pokušaju diferenciranja uspeha u radu u odnosu na tržišno okruženje i u odnosu na interne uslove u proizvodnji. Pri tome se, međutim, otvara pitanje merenja odnosno kriterijuma za projektovanje tako određene uspešnosti u radu. Efekti u domenu efektivnosti zavise od efekata u domenu proizvodne efikasnosti. Važi i obratno, efekti u domenu efikasnosti su uslovljeni efektima po osnovu efektivnosti.

Teorijsko-metodološko razgraničenje efektivnosti i efikasnosti nije nimalo jednostavno, a pogotovo kada se radi o njihovom merenju. Proizvod je rezultat izbora ali i rezultat efikasnije ili manje efikasne ostvarene proizvodnje.

Efektivnost rezultata je merilo zadataka outputa ili ostvarenja cilja. U proizvodnim organizacionim jedinicama to znači ostvariti planirane proizvodne zadatke kvalitativno i kvantitativno. Zadaci se mogu ostvariti, ali uz gubitak izvora korišćenih u transformacionom procesu. Zbog toga se moraju posmatrati oba procesa. Efikasnost rezultata meri troškove korišćenih izvora za ostvarenje cilja, tj. outputa u odnosu na korišćene inpute [3].

Polazeći od suštine ekonomske efikasnosti i njenih pojavnih manifestacija u ekonomiji uopšte efektivnost i efikasnost kao ekonomski fenomeni na nivou ekonomije preduzeća mogu se definisati [1]:

- *Ekonomska efikasnost* u suštini predstavlja proizvodnu efikasnost odnosno sposobnost efikasnog organizovanja transformacije inputa u outpute preduzeća.
- *Ekonomska efektivnost* predstavlja izraz efikasnosti razmene jer se izbor ciljeva kojima se definišu proizvodni potencijali preduzeća u krajnjoj liniji svodi na prodaju outputa i nabavku inputa, odnosno na sveukupne marketing aktivnosti.
- *Alokativna efikasnost* kao izraz efikasnosti organizovanja proizvodnje i razmene predstvlja izraz ukupne efikasnosti preduzeća koja u sebe uključuje i efekte efikasnosti i efekte efektivnosti.

Integracija efikasnosti i efektivnosti u jedinstveni izraz ukupne ekonomske efikasnosti je u funkciji merenja ukupnih efekata uspešnosti preduzeća. Kroz sagledavanje ukupnog efekta se omogućava efikasnije upravljanje ekonomijom preduzeća. Kvalitet ekonomije preduzeća, može da se oceni kroz sagledavanje odnosa između jedinstveno shvaćenog proizvoda, kao rezultata proizvodnje i jedinstveno shvaćenog društvenog rada unesenog u reprodukciju u cilju ostvarivanja tog rezultata.

Kvantitativni izraz kvaliteta ekonomije izražen je poslovnim uspehom $\boldsymbol{P_u}$, koji je sadržan u odnosima između rezultata reprodukcije (outputa) i ulaganja (inputa) u reprodukciju

$$P_u = R(O_u) / U(I_n)$$

Kvalitet ekonomije preduzeća, kao izraz stepena ekonomske uspešnosti u ostvarivanju ciljeva, istovremeno je i izraz uspešnosti u efektivnosti i efikasnosti preduzeća u poslovanju i razvoju. Saglasno sa konstatacijom da je ekonomsko značenje efektivnosti i efikasnosti, odnosno samo ekonomske efikasnosti upravo u kvalitetu ekonomije sledi istovremeno zaključak da je i poslovni uspeh kvantitativni izraz efikasnosti i efektivnosti [2].

MERENJE UKUPNOG POSLOVNOG USPEHA

Problematika merenja ukupnog poslovnog uspeha može se sagledati sa aspekta svrhe, suštine i teorijsko-metodoloških problema definisanja modela za merenje poslovnog uspeha.

Svrha merenja ukupnog poslovnog uspeha preduzeća su jasne informacije o stvarnoj ekonomskoj efikasnosti preduzeća kao i o realnim ekonomskim efektima novih investicija u konkretno preduzeće za koje su zainteresovani vlasnici preduzeća. Kontinuelno merenje poslovnog uspeha je realna pretpostavka za efikasnije upravljanje ekonomijom preduzeća.

U akcionarskim preduzećima u kojima je vlasništvo odvojeno od upravljanja merenje poslovnog uspeha omogućuje vlasnicima kontrolu menadžera koje su angažovali da upravljaju preduzećem.

Merenje ukupnog poslovnog uspeha obezbeđuje pored efikasnosti upravljanja i realniju raspodelu profita tzv. finansijskim grupacijama preduzeća, realnije sagledavanje stvarnih efekata eksternog rasta.

Merenje ukupnog poslovnog uspeha podstiče funkcionisanje berze, jer potencijalni investitori (akcionari) imaju relevantne informacije za svoje investicije.

Izražavanje poslovnog uspeha je i zakonski uslov bez koga preduzeće ne može da postoji. Iskazani rezultati poslužiće kao osnova za obračun i isplatu dividendi akcionarima.

Za merenje poslovnog uspeha, zainteresovani su vlasnici, država i menadžeri. Merenje poslovnog uspeha na kraju poslovnog perioda ili kontinuelno po potrebi je neophodan uslov efikasnijeg menadžmenta, kao i adekvatnije zadovoljavanje interesa različitih stejkholdera.[1]

Suštinsko tumačenje ukazuje na to da je ukupni poslovni uspeh konkretnog preduzeća izraz ukupne ekonomske efikasnosti. To znači da izražava njegovu ukupnu alokativnu sposobnost kako kroz sposobnosti: za izbor i nabavku inputa, efikasno organizovanje proizvodnje kao transformacionog procesa tako i izbor i realizaciju proizvoda i usluga kao outputa preduzeća. Svi ekonomski efekti koji se pojavno manifestuju na inputima i na outputima konkretnog preduzeća izražavaju njegovu ukupnu ekonomsku efikasnost [1].

Poslovni uspeh postaje kvantitativno određen kada je izmeren i ocenjen odgovarajućim ekonomskim metodama uobličenim u određene indikatore ili modele. Osnovni ekonomski kriterijum efikasnosti je značajno polazište izražavanja, praćenja, kontrole i usmeravanja odnosa između pojavnih oblika rezultata i ulaganja. Na strani rezultata mere se: obim proizvodnje, ukupan prihod, dohodak i dobitak, a utrošena radna snaga, ukupni troškovi i angažovani kapital na strani ulaganja.

$$P_u = R(Q; C; D; D_b) / U(L; T; S)$$

Ako se u okviru osnovnog cilja preduzeća posmatraju podciljevi kao: proizvodna, akumulativna i reproduktivna sposobnost navedena merila na strani rezultata i na strani ulaganja uobličavaju se u tradicionalno poznate indikatore kompleksa produktivnosti $(P = Q / L)$, ekonomičnosti $(E = C / T)$ i rentabilnosti $(R = D(D_b) / S)$ [4].

Izražavajući poslovni uspeh parcijalnim indikatorima kao merilima stanja ekonomije preduzeća iskazuje se efikasnost funkcionisanja proizvodno-finansijskog podsistema

[1] *Strategijski konstituenti preduzeća su njegovi stejkholderi, odnosno vlasnici, kupci, kreditori, dobavljači i ostale grupe bez čije saradnje ne može da opstane.*

preduzeća. Na taj način omogućuje se kontrola i usmeravanje kvaliteta pojedinih podsistema ekonomije ka jedinstvenom integralnom cilju ostvarivanja efikasnosti celog sistema preduzeća. Međutim pri iskazivanju i upravljanju dinamikom ukupnog poslovnog uspeha ispoljavaju se divergentnost i nedostaci parcijalnih indikatora i kompleksnost ove problematike. To je uslovljeno različitim intenzitetom i smerom kretanja samih elemanata rezultata i ulaganja pod uticajem pozitivnih ili negativnih dejstava u sklopu poslovnih aktivnosti.

Problem svodnog izražavanja i merenja ukupnog poslovnog uspeha savremena teorija i praksa rešava prihvatanjem dva stava [2]:

- prvi se bazira na korišćenju brojnih pojedinačnih indikatora, pri čemu je svodni izraz dat najčešće u vidu kvalitativne ocene, koja po pravilu nije objektivizirana po nekom osnovu,
- drugi zasnovan na pokušaju da se, uz brojne teškoće i ograničenja na koje nailazi savremena teorija i praksa, formuliše i koristi sintetički izraz poslovnog uspeha, u vidu, manje ili više integralnog, maksimalno moguće objektiviziranog modela koji, uz obavezne dopunske kvalitativne pokazatelje, agregatno iskazuje promenu ukupnog ekonomskog kvaliteta preduzeća.

Obuhvat i sadržaj, bilo seta indikatora, bilo integralnog modela ukupnog poslovnog uspeha, treba da, na osnovu bazičnog kriterijuma ekonomske efikasnosti, prvenstveno zadovolji informacionu, upravljačko-kontrolnu i motivacionu funkciju u poslovanju preduzeća [5].

TEORIJSKO-METODOLOŠKI PROBLEMI DEFINISANJA MODELA ZA MERENJE POSLOVNOG USPEHA

Prelazak sa velikog broja parcijalnih pokazatelja na jedan jedinstven pokazatelj ukupne efikasnosti zahteva rešavanje problema svođenja na zajednički imenitelj za inpute i outpute preduzeća, kao i razvijanje kompleksnog poslovno-informacionog sistema u preduzeću razvijenog iz konkretnog modela za merenje poslovnog uspeha.

U konstituisanju modela za izražavanje ukupnog poslovnog uspeha posebnu pažnju zavređuje model *Ekonometar* kao originalna tvorevina S. Kukoleče [6], kojim se u dinamici evidentiraju i iskazuju sve veze i sve promene oblika rezultata i ulaganja, svedenih na jedinstvenu zajedničku meru – radni ekvivalent. Visok nivo apstrakcije i perfektnosti u koncipiranju i razradi modela poslovnog uspeha u globalu, te posebno prema faktorima uslovljenosti, nametnuli su utisak da je teško ili nemoguće ostvariti njegovu primenu. To važi naročito za peiod šesdesetih godina kada nije postojala podrška informacionih sistema u našim preduzećima. Takođe ta informaciona osnova, potrebna za merenje prema ovom modelu u maloj meri je povezana sa zvaničnim računovodstveno-finansijskim sistemom. Ovo je predstavljalo jednu od bitnih prepreka za značajniju primenu u praksi.

Vredni su napori takođe domaćih teoretičara (D. Grozdanović i N. Malenović) na konstituisanju modela *Merenje ukupne performanse poslovne uspešnosti* kojim se prevazilaze određena ograničenja izvornog modela i njegovih kasnijih modifikacija (takođe od strane pomenutih autora) posebno u pogledu korišćenja sistema finansijskog izveštavanja kao informacione osnove za proračun pojedinih elemenata [7].

Postojeći teorijski i praktični instrumenti kontrole i usmeravanja poslovanja, rasta i razvoja preduzeća ne omogućavaju sagledavanje realne slike stvarne efikasnosti savremenih preduzeća. Mnogi teorijski modeli, proizašli iz različitih teorija preduzeća, nisu mogli biti primenjeni za rešavanje konkretnih problema u praksi preduzeća. Tako su matematički metodi i modeli imali ograničene domete u primeni, služili su za rešavanje hipotetičkih slučajeva, a ne konkretnih problema u ekonomiji preduzeća.

Problem efikasnog poslovanja preduzeća se u menadžerskim teorijama formuliše kao problem određivanja maksimalne korisnosti menadžera, ali s obzirom da menadžeri ne poseduju neograničenu diskreciju i da svoje ciljeve mogu da ostvare uz uslove koje postavljaju vlasnici – akcionari, maksimiziranje funkcije korisnosti se javlja kao rezultat rešenja problema uslovljene maksimizacije. Sem dihotomije interesa vlasnika s jedne i menadžera s druge strane ne identifikuju se drugi značajni interesi. Pristup ciljevima preduzeća se tokom vremena menjao gde su usavršavane tehnike i metode ostvarivanja ciljeva ali su bazični ciljevi i njihova ekonomska sadržina marginalizovani.

Finansijski pokazatelji kao osnova tradicionalnih sistema merenja i kontrole poslovnog uspeha imaju svoje jasne kontrolne uloge omeđene određenim vremenskim periodima. Iz njih izvedeni setovi raznih indikatora, indeksa i racio brojeva, samo pokazuju kakav je rezultat poslovanja preduzeća u proteklom periodu i to ne izraženo kroz ukupan poslovni uspeh već prema parcijalnim iskazima pojedinih stanja i efekata.

Razvojem teorija koje se bave ekonomijom preduzeća stvaraju se pretpostavke za usavršavanje modela za merenje poslovnog uspeha, za takvu kontrolu preduzeća i upravljanje njegovom ekonomijom da se pozitivne konsekvence potenciraju, a negativne smanje na najmanju meru uz zadovoljenje svih bitnih interesa koji se ispoljavaju u vezi sa njegovim poslovanjem, rastom i razvojem.

FINANSIJSKI POKAZATELJI KAO OSNOVA TRADICIONALNIH SISTEMA MERENJA I KONTROLE POSLOVNOG USPEHA

Zajedničko za sve tradicionalne sisteme finansijske kontrole i merenja poslovnog uspeha je da se u celini zasnivaju na podacima koji se mogu dobiti na osnovu računovodstvenog sistema. Davanje prednosti korišćenju kvantitativnih računovodstvenih informacija obrazlaže se činjenicom da računovodstvo kao jedini integralni sistem kvantitavne analize preduzeća karakterišu integralnost obuhvata poslovno-finansijskih aktivnosti preduzeća, prednost numeričkog izraza i iz toga proizilazi vrednosni objektivizam. Takođe, prednost računovodstvenih informacija se manifestuje u njihovom svojstvu da različita stanja, tokove i relacije pretvori u jedan univerzalni, opšte prihvaćeni jedinstveni brojčani izraz.

Inače, integralni set finansijskih izveštaja većine preduzeća u međunarodnoj praksi čine bilans stanja[2] (izveštaj o finansijskom položaju) i bilans uspeha (račun dobitka i gubitka). Mada je vremenom sve više favorizovan, izveštaj o tokovima gotovine nije prihvaćen u svim zemljama.[3] I pored njihove baziranosti na istim poslovno-finansijskim transakcijama i univerzalnog finansijskog kvantifikovanja ovih transakcija, set finansijskih izveštaja kao objektivni hroničar preduzeća emituje različite informacije o njegovim aktivnostima za određeni period.

Osnovni informacioni sadržaj bilansa stanja (engl. Balance sheet) je knjigovodstvena vrednost preduzeća odnosno stanje aktive, obaveza i kapitala (neto vrednost aktive) na određeni dan.

Bilans uspeha (engl. Income statement) je poznat kao račun dobitka i gubitka (engl. P&L – Profit and Loss Account). Osnovni informacioni sadržaj bilansa uspeha je profitabilnost. Bilans uspeha prikazuje

[2] *Jedna od ključnih izmena u revidiranom IAS1, objavljenom 2007. godine, odnosi se na zamenu naziva bilans stanja (Balance sheet) u izveštaj o finansijskom položaju preduzeća (Statement of financial position). Kao razlog ove terminološke promene navodi se isticanje funkcije ovog osnovnog finansijskog izveštaja.*

[3] *Prema prihvaćenim računovodstvenim standardima mala preduzeća u našoj zemlji su u obavezi da dostavljaju Agenciji za privredne registre (APR) osim bilansa stanja i bilansa uspeha i statistički aneks, a srednja i velika preduzeća izveštaj o tokovima gotovine i izveštaj o promenama na kapitalu.*

informacije o prihodima, rashodima i neto dobitku/gubitku za određeni period. Međusobno konfrontirani svi prihodi i rashodi jednog konvencionalno usvojenog obračunskog perioda raščlanjeni i prikazani u skladu sa odgovarajućim principima i u odgovarajućoj izveštajnoj formi omogućavaju utvrđivanje rezultata dobitka kao pozitivne i gubitka kao negativne razlike, koja se na kraju obračunskog perioda obuhvataju u bilansu stanja kao povećanje i smanjenje (sopstvenog) kapitala. Ovakvo shvatanje bilansa uspeha ukazuje na postojanje sistematske i organske veze između bilansa stanja i bilansa uspeha, a ova činjenica ukazuje na to da se ovi finansijski izveštaji sa aspekta ocene efikasnosti poslovanja tretiraju kao komplementarni i međuzavisni proizvodi računovodstva [8].

Izveštaj o tokovima gotovina (engl. Statement of Cash Flows) pokazuje promet na računu gotovine preko priliva i odliva gotovine kao i generisan slobodan gotovinski tok u periodu. Izveštaj o tokovima gotovine pokazuje poslovne, finansijske i investicione prilive i odlive novčanih tokova preduzeća u toku izveštajnog perioda. Osnovna informacija za kontrolu koju izveštaj o tokovima gotovine nosi je likvidnost. Takođe, izveštaj o tokovima gotovine nosi informacije o mogućnostima stvaranja vrednosti ukoliko se izvrši diskontovanje slobodnog novčanog toka.

Pojedine pozicije finansijskih izveštaja, prikazane u apsolutnim vrednostima ne daju dovoljno informacija za upravljanje. Dovođenjem pojedinih pozicija bilansa stanja i bilansa uspeha i drugih izveštaja u odgovarajuće odnose dobijaju se racio brojevi. U procesu kontrole racio brojevi se porede sa prošlim rezultatima ili rezultatima konkurencije. Dakle, racio brojevi se mogu koristiti za praćenje rezultata preduzeća tokom vremena ili za praćenje relativne pozicije preduzeća u odnosu na konkurente. U svakom slučaju ove relativne vrednosti pružaju mnogo bogatije informacije u odnosu na analizu apsolutnih veličina (pozicije finansijskih izveštaja). Sve racio brojeve možemo klasifikovati u četiri velike grupe: pokazatelje likvidnosti, pokazatelje obrta (aktivnosti), pokazatelje solventnosti (finansijske strukture) i pokazatelje rentabiliteta (profitabilnosti) [9].

Pomenuti pokazatelji predstavljaju, zapravo, operativna merila performansi, tj. pokazatelje uspeha koji mere rezultate operativnih odluka. Očigledno je da su u efektima operativnih odluka sadržani i efekti strategijskih i taktičkih odluka [10].

Pored jednostavnih racio brojeva postoje i složeni racio brojevi koji nastaju kombinovanjem osnovnih racio brojeva, praćenjem bitnog dela poslovnog procesa ili specifičnih aspekata poslovanja. Po osnovu *DuPont* formule dolazi se do sintetičkog izraza rentabilnosti koji omogućava da se ustanovi promena kao i uzroci promene rentabilnosti, jer se ukupna rentabilnost, tj. prinos na ukupna sredstva posmatra kao rezultat uzajamnog delovanja, ili interakcije parcijalnih pokazatelja rentabilnosti [11].

Značaj finansijskih izveštaja, koji odražavaju poslovno-finansijske aktivnosti preduzeća kao celine, ogleda se u tome što analitička interpretacija podataka sadržanih u njima omogućava identifikovanje i praćenje ključnih finansijskih merila efikasnosti preduzeća. Pored ovih tradicionalnih merila u poslednje vreme se koriste i pokazatelji koji imaju svoje uporište u konceptu upravljanja zasnovanog na vrednosti. Jedan od najznačajnijih je dodata ekonomska vrednost (Economic Value Added – EVA). Danas se često koriste od strane ekonomskih analitičara i pokazatelji profit pre kamate i poreza (Earning Before Interest and Taxes – EBIT) i profit pre kamate, poreza, amortizacije i otpisa (Earning Before Interest, Taxes, Depreciation and Amortization – EBITDA).

REZULTATI SAVREMENE EKONOMSKE TEORIJE I PRAKSE U DEFINISANJU MODELA ZA MERENJE UKUPNOG POSLOVNOG USPEHA

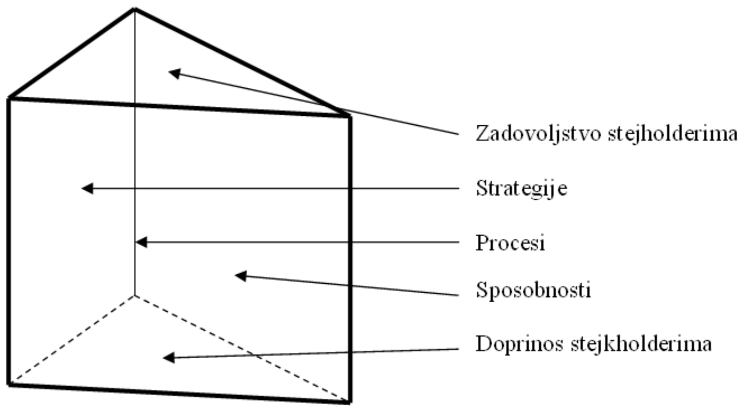
I pored nezamenljive uloge finansijskih merila potrebno je ukazati na njihovu nesavršenost i nepotpunost za potrebe validne analize i ocene efikasnosti. Primena tradicionalnih finansijskih merila pokazuje izvesne nedostatke i ograničenja koja se pre svega odnose na: prikazivanje događaja koji su se desili u prethodnom periodu, nepouzdanost baze poređenja za duži vremenski period, ne pridaju dovoljno važnosti poslovnom okruženju zanemarujući perspektivu potrošača i konkurenata. Problem tradicionalnih merila koja se baziraju na finansijskim indikatorima je da ona ne uzimaju u obzir neopipljivu vrednost sadržanu u znanju koja u velikoj meri može da uveća tržišnu vrednost preduzeća.

Promene u okruženju, globalizacija svetske privrede, izražena konkurencija, razvoj informacione tehnologije dovodi do promena u tradicionalnoj upravljačkoj aparaturi. Industrijsku ekonomiju koju karakteriše fizički opipljiva aktiva zamenjuje nova ekonomija u kojoj najvredniji resurs postaje neopipljiva aktiva koja obuhvata odnose sa potrošačima, veštine zaposlenih i njihovo znanje, informacionu tehnologiju i organizacionu kulturu plodnu za inovacije, rešavanje problema i opšte unapređenje organizacije [12].

U uslovima razvijenog tržišta jedini održivi način za stvaranje vrednosti za vlasnike preduzeća je istovremeno ostvarivanje vrednosti i za njegove stejkholdere. Stejkholderi, dakle, imaju legitimne interese u obavljanju aktivnosti preduzeća, kao i određene zahteve i potrebe koje proizilaze iz povezanosti u obavljanju određene aktivnosti. Pri tome, primarni (aktivni) stejkholderi imaju formalne, zvanične i ugovorne odnose sa preduzećem, dok se svi ostali mogu tretirati sekundarnim (pasivnim). Orijentacija na stejkholdere podrazumeva da se u model poslovnog uspeha uključuju i pokazatelji uspešnosti u ostvarivanju pojedinačnih ciljeva svih stejkholdera kao i merenja ostvarivanja tih ciljeva, i jedno i drugo se izražavaju odgovarajućim indikatorima.

Jedna od najvažnijih uloga menadžmenta je da pronađe prihvatljiv balans između finansijske odgovornosti prema vlasnicima i strategijske odgovornosti prema ostalim stejkholderima. Menadžeri moraju poći od činjenice da je finansijska odgovornost preduslov za kasnije ispunjenje strategijske odgovornosti. Međutim, ovaj odnos nije jednosmeran. Viši kvalitet odnosa preduzeća sa stejkholderima kao što su potrošači, zaposleni, dobavljači, zajednica i dr. vodi boljim finansijskim performansama, a na kraju većoj vrednosti preduzeća i akcionarskog bogatstva [13].

Na prethodno navedenoj osnovi, a uvažavajući uzročno-posledične procese između samih stejkholdera formuliše se jedan od savremenih modela, tzv. **Model Prizma performansi (A. Neely)**, koji se smatra integralnim modelom, zato što objedinjuje elemente modela orijentisanih na stejkholdere i elemente procesno orijentisanih modela [5]. Model prizma performansi je prikazan na *slici 1.*



Sl. 1. *Prizma performansi kao model iskazivanja poslovnog uspeha (prema [14])*

Model Prizma performansi pruža pet različitih, ali povezanih pogleda, a time i izraza poslovnog uspeha preduzeća iskaznog setom indikatora diferenciranih u pet ključnih grupa kao odgovora na pitanja [14]:

- zadovoljstvo stejkholderima (vrh prizme) – ko su ključni stejkholderi i šta oni žele, ili šta im treba;
- strategije poslovanja (strana prizme) – koju strategiju preduzeće treba da primeni da bi zadovoljilo navedene želje ili potrebe;
- procesi (strana prizme) – koje kritične procese preduzeće treba da primeni ka zadatom cilju, favorizujući tzv. procese koji dodaju vrednost na ulaganja i reprodukciju;
- sposobnost (strana prizme) – koje sposobnosti treba da imaju ključni stejkholderi (zaposleni, kupci, društvena zajednica i vlasnici kapitala) u ostvarivanju primenjenih procesa, i konačno
- doprinos stejkholdera (dno prizme) – koje doprinose preduzeće može očekivati od stejkholdera, ako menadžment preduzeća podržava i razvija sposobnosti stejkholdera.

Upravljanje na bazi ovih merila podrazumeva definisanje ciljnih merila performansi, upoređivanje ostvarenja sa ciljnim vrednostima, identifikovanje odstupanja i uzroka (faktora) odstupanja, i na kraju identifikovanje korektivnih upravljačkih akcija. Model se smatra vrednim zato što ističe i dimenziju merila sposobnosti (resursa). Glavni nedostatak je preveliki broj merila, koja se s obzirom na ograničeno vreme i mogućnosti pažnje menadžera ne mogu operativno koristiti.

Brojna literatura dokazuje da primena višedimenzionalnih sistema merenja performansi doprinosi efektivnosti istih (Domanović, 2013. prema: Malina, M. A. & Selto, F. H. 2001; Ittner, C.D. i dr. 2003; Davis, S. & Albright, T. 2004; Crabtree, A. D. & De Busk, G. K 2008; Van der Stede, W. A. i dr. 2006; Tung, A. i dr. 2011). Većina ovih studija ispitivala je efektivnost ovih sistema iz perspektiva doprinosa istih finansijskim rezultatima [15].

Analizirani modeli merenja poslovnog uspeha i drugi postojeći modeli koji su dakazali svoju primenljivost u praksi, od posebne su važnosti za unapređenje upravljačkog procesa. Kombinovanjem postojećih modela stvaraju se novi. Unapređeni sistemi merenja pružaju realne pretpostavke za efikasnije upravljanje uz odgovarajuću podršku informacionih sistema.

ZAKLJUČAK

U ekonomskoj teoriji i poslovnoj praksi preduzeća vrlo je aktuelna i još uvek nedovoljno zaokružena problematika merenja ukupnog poslovnog uspeha. Sa upravljačkog aspekta dizajniranje kvalitetnog agregatnog merila zahteva prethodno rešavanje izuzetno kompleksnog problema svođenja na zajednički imenitelj različitih merila za inpute i outpute preduzeća kao i razvijanje i korišćenje odgovarjućeg informacionog sistema za proračun i praćenje tako projektovane agregatne veličine poslovnog uspeha. Ekonomska teorija u domaćoj literaturi je ponudila rešenje u vidu originalnog modela *Ekonometar*. Modelom *Ukupne performanse* poslovne uspešnosti nastoje se prevazići određena ograničenja izvornog modela i njegovih kasnijih modifikacija posebno u pogledu korišćenja sistema finansijskog izveštavanja kao informacione osnove za proračun pojedinih elemenata.

Finansijska merila imaju nezamenljivu ulogu u oceni poslovnog uspeha preduzeća, međutim, neophodno je ukazati na njihovu nesavršenost i nepotpunost za potrebe validne analize poslovnog uspeha. U savremenom periodu dolazi do izražaja nemogućnost finansijskih pokazatelja da obuhvate nematerijalne resurse preduzeća (intelektualni kapital) i stepen ostvarenja nefinansijskih ciljeva preduzeća (odnos sa kupcima, zaposlenima) koji su u savremenom periodu kritični za poslovni uspeh preduzeća.

Efektivan sistem merenja je onaj koji uključuje set finasijskih i nefinasijskih merila koja će omogućiti menadžerima da se uspešno suoče sa velikim brojem poslovnih aktivnosti i fokusiraju na ključne faktore poslovnog uspeha. Model *Prizma performansi* je jedan od takvih predloga.

U cilju realnog sagledavanja efektivnosti i efikasnosti preduzeća i dalje će se tragati za rešenjima na koja će odgovor moći da pruži nova paradigma preduzeća i njoj primereni modeli.

Razmatrana problematika u radu je korisna za upravljanje rudarskim preduzećima koja će putem veće odgovornosti i prema svojim stejkholderima steći atribute uspešnog preduzeća.

LITERATURA

[1] M. Nikolić, N. Malenović, D. Pokrajčić, B. Paunović, Ekonomika preduzeća, Ekonomski fakultet, Beograd, 2005, str. 122, 136, 475.

[2] D. Grozdanović, Osnovi ekonomike preduzeća, Ekonomski fakultet, Kragujevac, 2003, str. 23, 25, 456.

[3] M. Milisavljević, Savremeni strategijski menadžment, Megatrend Univerzitet primenjenih nauka, Beograd, 2005, str. 5.

[4] Lj. Savić, Uloga menadžmenta u unapređenju efektivnosti i efikasnosti preduzeća, Doktorska disertacija, Megatrend univerzitet, Fakultet za poslovne studije, Beograd, 2010, str. 100.

[5] M. Ratković Abramović, Upravljanje dinamikom poslovnog uspeha, Autorsko izdanje, Beograd, 2005, str. 67,79.

[6] S. Kukoleča, Ekonometar, Konsalting centar, 1994, Beograd.

[7] B. Krstić, Model merenja performansi ukupne poslovne uspešnosti preduzeća, Ekonomski fakultet, Niš, 2007.

[8] V. Domanović, J. Bogićević, Mogućnosti primene Balanced Scorecard koncepta u Srbiji, Naučno društvo ekonomista Srbije, Naučni skup Novi metodi menadžmenta i marketinga u podizanju konkurentnosti srpske privrede, Palić, 2011.

[9] B. Pešalj, Merenje performansi preduzeća, Ekonomski fakultet, Beograd, 2006, str. 63.

[10] D. Đuričin, S. Janošević, Đ. Kaličanin, Menadžment i strategija, Ekonomski fakultet, Beograd, 2013, str. 161.
[11] D. Pokrajčić, Ekonomika preduzeća, Autorsko izdanje-Čigoja štampa, Beograd, 2002, str. 356.
[12] R. Kaplan and D. Norton, Having Trouble With Your Strategy? Then Mapit!, Harvard Business Review, September-October, 2000, p. 4.
[13] Đ. Kaličanin, Formulisanje i primena strategija stvaranja vrednosti, Doktorska disertacija, Ekonomski fakultet, Beograd, 2005, str. 15.
[14] A. Neely, Business Performance Measurement, Cambridge University Press, 2003, p. 153.
[15] V. Domanović, Efektivnost sistema merenja performansi u uslovima savremenog okruženja, Ekonomski horizonti, Ekonomski fakultet, Kragujevac, 2013.

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SELECTION OF THE OPTIMAL MODEL OF INTEGRATED SUSTAINABLE MANAGEMENT SYSTEM IN THE MINING COMPANIES****

Abstract

The multi-criteria analysis for the selection of the optimal model of integrated management system was conducted in this paper in order to improve the performance of mining companies. Integrated management system is the process of integrating of different management systems in a contemporary business as a requirement for each company in order to survive in the market. Modern companies that have implemented integrated management system work better, have arranged processes, improve its structure and culture for the management practice, and have continual improvements of all processes.

Mining companies are in a very difficult position in Serbia. Their business is specific because it is characterized by a high complexity, obsolete and complex organizational structure, inadequate management practices, everyday functioning and many other problems. In that context, authors are proposing four models of integrated management systems that could be applicable in mining companies in order to improve their performance. Also, the appropriate criteria for the selection of the optimal model are defined. AHP method is applied for the selection and ranking of the models of integrated management system. The obtained results give an optimal model of integrated management system that is applicable with the best results in terms of performance improvement and sustainability of mining companies in Serbia.

Keywords: *Integrated system management, Mining, AHP method*

1 INTRODUCTION

Implementation of the integrated management system (IMS), composed of different management systems, has received a lot of attention in recent years. The integrated management system is defined as a comprehensive management tool that links all elements of the business system in a unique and comprehensive system of processes management in the organization, in order to meet the demands of stakeholders [1]. Today, there are more models of implementation of the IMS, and they were created based on the specific requirements of stakeholders and the companies themselves. Companies that have implemented the optimal model of IMS, have significant benefit such as: continuous improvement of processes, obtaining a unique quality of products and services,

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improving the organizational culture, the greater degree of satisfaction of stakeholders and others. The additional value of integrated management systems is that they are in accordance with a concept of sustainable development that institutes a balance between technological development necessary for economic prosperity and survival of the environment and society as a whole [2]. The key issue for the management of the mining companies is to align management system with different standards, and consequently how to make internal alignment of partial management systems in the company. Additionally, it is often difficult to take the advantage of already implemented system, and to choose the optimal model of IMS. Because of its specificity, the mining companies must first identify the requirements of stakeholders and subsequently select an optimal model of implementation of the IMS. Since all elements of standardized management systems are mutually compatible, it enables all partial management systems to form a single integrated management system (IMS) in which there are strong interconnections between the individual elements of the system [3]. Accordingly, the integrated management system is established through the commitment of the organization's management to implement the requirements of standards, raising awareness about the importance of planning processes and continuous improvement of business processes, thus creating the conditions for success.

The commercial success of mining companies precedes proper selection of the optimal model of IMS that will bring significant improvements in time, such as higher level of satisfaction of all stakeholders from the owner, manager, and to the end user of products and services, i.e. consumer or customer.

2 MODELS OF INTEGRATED MANAGEMENT SYSTEMS

There are a numerous models of IMS that have been successfully applied in commercial companies. Basic models of IMS originally were the quality management system (ISO 9001) and the system of environmental management (ISO 14001), which later became integrated into the system management of health and safety (OHSAS 18001). Further development led to the creation of the new models of IMS that take into account the type of activity of certain companies, as well as all interested parties and stakeholders. The system that in itself integrates the requirements of several standards primarily aims to satisfy the demands of many stakeholders, because it is often the case that different stakeholders require different management systems, i.e. management systems compliant only with certain standards or [4].

This paper explores the practices of sustainable mining companies implementation the optimal model of IMS, analyzed by Analytical Hierarchy Process (AHP method). AHP is one of the multi-criteria decision-making methods for the selection of the best solution among several alternatives [5]. The advantage of this method is that it can simultaneously consider both financial and non-financial factors in the process of selecting the optimal model of IMS [6]. There are four alternatives that are discussed here (four models of IMS) which have been successfully applied in developed countries. These models are based on the fundamental principles and the process approach in the development of the integration process of management.

2.1 Wilkinson – Dale's model (alternative A1)

The integrated systems in Wilkinson – Dale's model consists of: the system of quality management (QMS), the system of environmental management (EMS) and the system of occupational health and safety (OHSAS) [7] – Figure 1. Differentiation and specificity of this model is that it includes an integrated culture and elements of TQM model (Total Quality Management). Wilkinson – Dale's model of integration depends on the requirements and policies of any organization or interested party. Stakeholders may be managers (a successful business), employees themselves (wages, working conditions), suppliers (long term collaboration), customers (quality and price of a product), community (environment), owners (profits) and others.

This model can be implemented by any organization that takes the quality system, environmental protection system and the system of protection of health and safety at work as a priority in their business. Also, this model can be implemented by organizations that are involved in the activities of TQM works of continuous improvement.

Wilkinson and Dale model puts a great importance to sustainability culture in organizations that could lead to the creation of organizational culture which enhances the implementation of the integration system.

It is very important for the mining company that implements the IMS to select a model that takes into consideration a national culture, because it can improve the successful realization of this process. The importance of incorporation of national culture model is explained in a work of Geert Hofstede's [8]. Geert Hofsted is the most cited social science author - 123707 citations in Google Scholar [9]. Authors of this paper have considerable experience in research of organizational and national culture relations in Serbia [10, 11]).

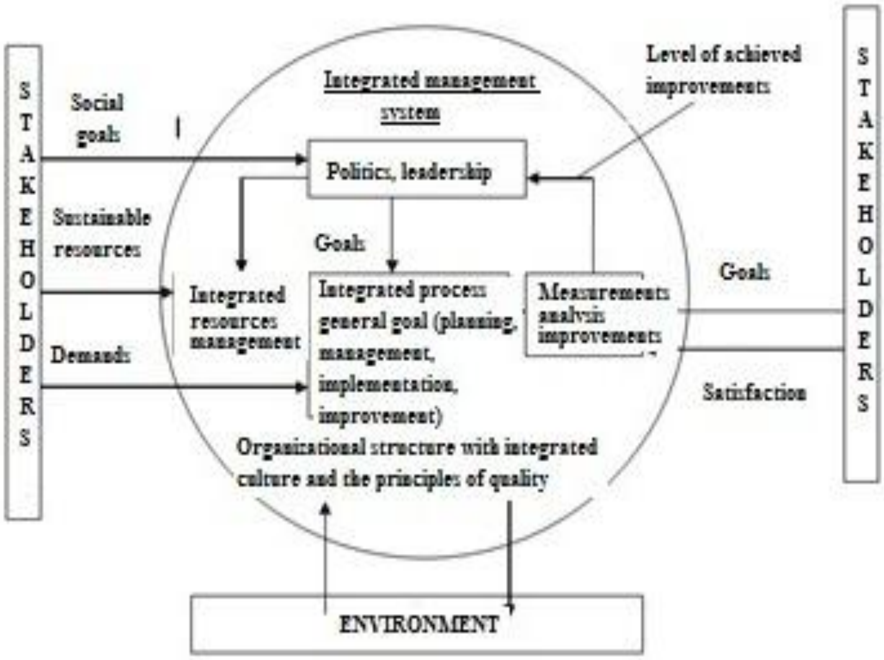

Figure 1 *The extended Wilkinson – Dale's model of IMS [7]*

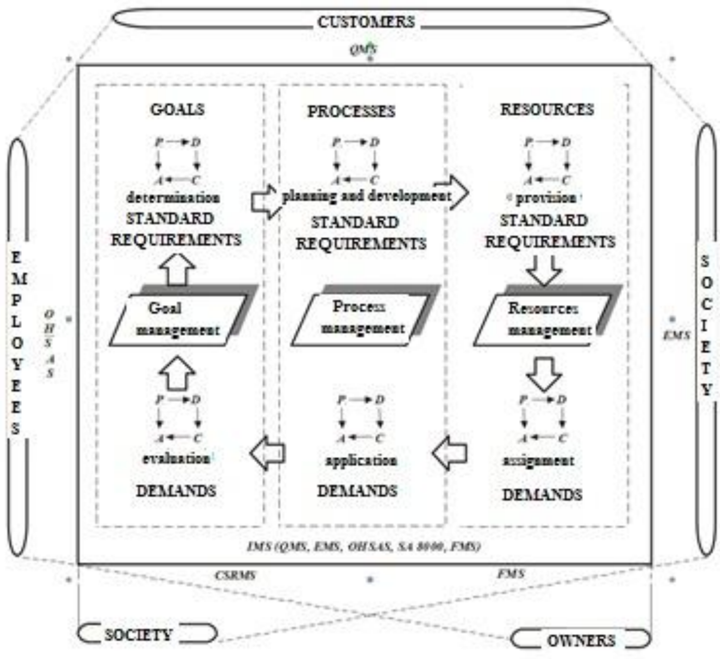

Figure 2 *Karapetrovic's model [13]*

2.2 Karapetrovic's model (alternative A2)

This model includes integration of five systems - QMS, EMS, OHSAS, the corporate social responsibility management system (CSRMS) and the financial management system (FMS). This means that the model includes the requirements of the standards and requirements of stakeholders. The model is based on a systematic approach and the PDCA cycle - plan, do, check and act - improve.

The focus of Karapetrovic's model, except for customers, is directed to the satisfaction of stakeholders of the community (environment), staff reductions (injury), management (reducing business risk), as well as other stakeholders [12, 13]. The implementation of management systems is done through management to objectives, process management and resource management - Figure 2. Karapetrovic's model is compatible with the PDCA management system, because it considers all processes with a goal to their continual improvement and enhancements. These processes are: goals, planning and development processes, resourcing, scheduling, resource management, application in management processes and evaluation of management objectives.

This model is applicable to all industrial companies - manufacturing and service industries.

Characteristics of the company (type of activity, their specifics, size and demands of stakeholders) instigated development of the new standardized management system (MSS - Management Systems Standards) in order to meet their specific requirements and easier implementation of the IMS.

2.3 The process model (alternative A3)

In this model, each process, sub-process and activity has inputs – the demands of stakeholders, and outputs - satisfaction of stakeholders - Figure 3. During production the measurements, analysis and improvements are carried out by management supervision.

The management systems that are based on essentially procedural approach of ISO 9000 can be identified through integration strategy [14].

Specifics of the process model are reflected through the application of process approach, and it integrates the N systems: QMS, EMS, OHSAS and Food Safety Management System (HACCP). These standards have similarities within their structure, so the integration of the standards can be made on the basis of identical and specific requirements that must be resolved in the management process. That is why the process approach represents a new management approach. The essence of the standards for management systems (ISO 9001, ISO 14001, OHSAS 18001 and ISO 22000) is precisely in the processes management.

The process model during its implementation requires knowledge about the organization, the requirements of stakeholders, defining management methodology, determining the necessary resources and the implementation of all procedures with continuous improvement and enhancement. During the implementation of the process model, person in charge, owner or manager of the process is responsible for the documentation, implementation requirements (products or services) and measurement of satisfaction of stakeholders. Also, employees and all participants in the process are responsible for the realization of the implementation of this process.

This model is highly represented in Serbia (in approximately 96 % of all companies).

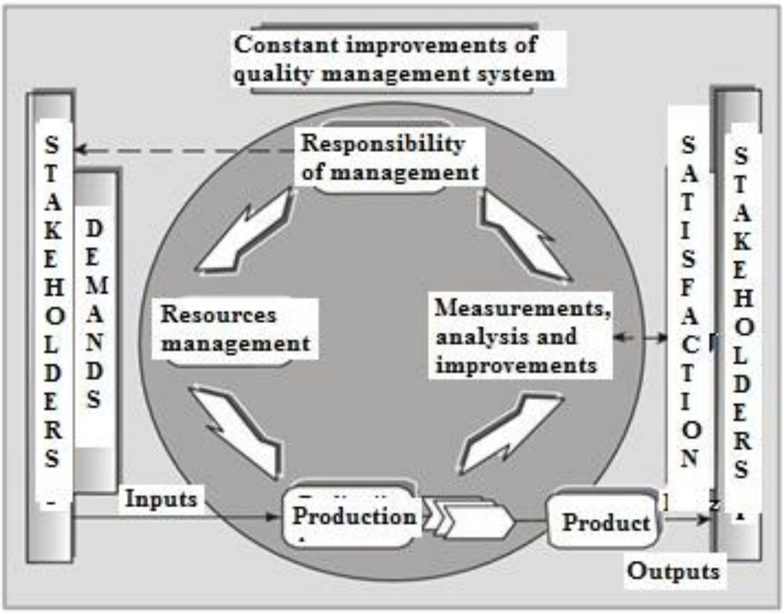

Figure 3 *Model of quality management system based on processes [14]*

2.4 EFQM excellence model (alternative A4)

EFQM excellence model was created by the European Foundation for Quality Management in 1992 and promoted in 1999. The model is the basis for the European Quality Award for the following:

- large companies and
- small and medium companies

Unlike the others, this model is based on philosophy of Total Quality Management (TQM) and on two systems-integration (interoperability), such as quality management system and environmental management system (EFQM, 1998, EFQM, 2002) – Figure 4.

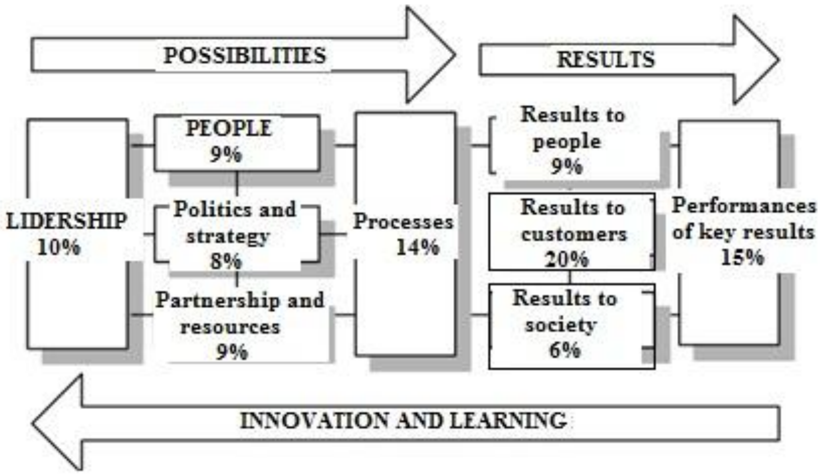

Figure 4 *EFQM excellence model [15]*

This model has nine criteria where five are related to opportunities that show what the company does, while others refer to results. The results show the extent to which the organization uses opportunities.

The EFQM excellence model is applicable in companies whose requirements are such that they can develop their own approaches to achieving excellence. Within this model, there are a few basic concepts that are required for its implementation, namely:

- orientation to results, where results show excellence that are satisfaction of stakeholders;
- focus on customers, where the excellence is creating a stable customer;
- leadership and consistency determination, where is the excellence in leadership with a persistent feature;
- process and facts management, where is the excellence management company on the basis of processes and facts;
- inclusion of employees and their development, where is the excellence in employees motivation to increase contributions;
- improvement, innovation and continuous education, where the excellence is in innovation to create the

possibility for more sophisticated operations;

- development of partnership, where excellence is manifested through the development and maintenance of partnerships with the increasing value;
- social responsibility, where excellence is reflected in overcoming some minimum obligations in the company and where the company aims to more responsible understanding of the demands of society.

The criteria for achieving the business excellence are: leadership, people, policy and strategy, partnership and resources, processes, results to customers and society, and finally results that make the satisfaction of all stakeholders.

Common features of the EFQM model, the process model, Karapetrovic's model and Wilkinson - Dale's model are: systemic approach, continuous improvement, satisfying demands of all stakeholders, reducing the extensive documentation and that they are applicable in the all types of organizations including mining companies.

3 DEFINING THE CRITERIA FOR SELECTION OF THE OPTIMAL MODEL OF IMS

The criteria include the most important characteristics for the selection of the optimal model of implementation of the IMS in mining companies, namely:

The cost of implementation of the IMS (criterion C1) is a very important factor for the choice of an optimal model of IMS. The cost of implementation is determined for each proposed model of IMS in mining companies and influence is proportional to the obtained results.

The expected effects of the IMS (criterion C2) is a very important factor that has a major influence in selecting process of the optimal model of implementation of IMS. By implementation of optimal model of IMS, mining companies should make significant improvements, such as building a model of organizational culture aligned with national culture, better implementation of its policies and strategies, greater employee satisfaction, injuries reduction at work, constant improvement of resources (material, financial and human), continuous improvement of business processes, improvements of corporate governance, satisfied external and internal customers, a better relationship to society, improving environmental protection, operations according to all the rules and regulations, the ability of business to the global market, the advantage in participating in the tender, cost reduction, etc.

The time required for implementation of the IMS (criterion C3) is also a very important factor that significantly influences the choice of optimal method of IMS. For example, if the implementation takes longer period than expected, some of the interested party will not met the requirements, which implies that their dissatisfaction reflects on the others, so that all can led to bad reputation of mining company within the community. Some of these models of IMS demand a shorter implementation period which can be very important for mining companies.

The applicability of the model (criterion C4) is a criterion that indicates the degree of implementation possibilities of a particular model of IMS in mining companies. Some models are easier to implement and others more difficult. The aim is that mining companies choose the model that is not difficult to implement and that it will bring many long-term benefits to them. In addition, mining companies must take into account many factors, such as their own specificities, equipment condition, the structure of labor, management of the companies and others.

4 AHP METHOD

AHP is a quantitative technique that allows the structuring of complex decision problems with multiple criteria and provides an objective methodology for a wide range of decisions.

AHP is based on decomposition the complex decision problems in multi-dimensional hierarchical structure of objectives, criteria and alternatives. After that, impact assessment of criteria is done. Then comparison of the alternatives in relation to each criterion is made, and final ranking of alternatives is obtained.

Assessment of the relative impact of each criterion and comparison of alternatives in relation to the criteria is performed by matrix of comparison. These include: the formation of matrix of comparisons at each level of the hierarchy, starting from the second level down; calculation of weight coefficients for each element of the hierarchy and the assessment of the degree of consistency in order to check the consistency of the entire process.

According to that, a set of alternatives {A1, A2, ..., An} is defined, as well as a set of criteria weight coefficients {w1, w2, ..., wn}.

Comparison of criteria and alternatives is made on the basis of the scale with scores from 1 to 9 – Table 1.

Table 1 *Scale of comparison of decision elements*

Dominance description	Value
Equal	1
Weak dominance	3
Strong dominance	5
Very strong dominance	7
Absolutely dominance	9
2, 4, 6, 8 are intermediate values	

The result of the comparison of criteria is the matrix that has the following form:

$$W = \left[w_i / w_j \right] = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix}$$

After that, the comparison of pairs of alternative is performed in respect to each criterion, to give the matrix A in which a comparison element a_{ij} represents the ratio of the weight of the coefficient A_i alternative compared to the alternative of A_j.

$$A = \left[a_{ij} \right] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

The elements A_{ij} represent the relationship between the weight coefficients w_i / w_j where w is the weight vector of each alternative.

The matrix has a reciprocal properties, in which the $a_{ji}=1/a_{ij}$.

After the comparison, weight coefficients are calculated and vector of coefficients is obtained $w = [w_1,w_2, . . . ,w_n]$ which is calculated on the basis of Saati procedure in two steps.

First, the matrix of pairs comparison $A = [a_{ij}]_{nxn}$ is normalized, then weights are calculated.

The normalization is performed by the following equation:

$$a_{ij}^* = a_{ij} \Big/ \sum_1^n a_{ij} \qquad (1)$$

for all $j = 1,2,..., n$.

Weight coefficients are calculated by the following equation:

$$w_i = \sum_1^n a_{ij}^* \Big/ n \qquad (2)$$

for all $j = 1,2,..., n$.

After the comparison, the Consistency Ratio is checked. Consistency Ratio should have a value lower than 0.1. Otherwise, they must reconsider the values that are entered into a matrix of comparison.

Consistency Ratio is calculated as follows:

$$CI = (\lambda_{\max} - n)/(n-1) \qquad (3)$$

where λ_{max} is an important parameter of the AHP method and it is used as a reference index for displaying information when calculating the Consistency Ratio (CR). CR is calculated as follows:

$$CR = CI/RI \quad (4)$$

where *RI* represents the random consistency index obtained randomly from comparison matrices.

The final ranking of alternatives is made by synthesis of results from all levels.

5 RESULTS OF THE SELECTION OF THE OPTIMAL MODEL OF IMS

After defining the criteria and models of IMS (alternatives) it is performed their evaluation and ranking by AHP method. Criterium DecisionPlus software was used for calculation.

The first step is defining the multi-dimensional hierarchical structure of objectives, criteria and alternatives - Figure 5.

Thereafter, the weight coefficient of criteria is calculated according to the scale of comparison given in Table 1. The comparison results are shown in Table 2 and Table 3.

Table 2 *Definition of weight coefficient of criteria*

Criteria	C1	C2	C3	C4
C1	1	1/5	5	2
C2		1	8	5
C3			1	1/5
C4				1

Table 3 *Results of weight coefficients criteria*

Criteria	C1	C2	C3	C4
Weight coefficients	0.193	0.624	0.045	0.138
Consistency Ratio	0.084<0.1			

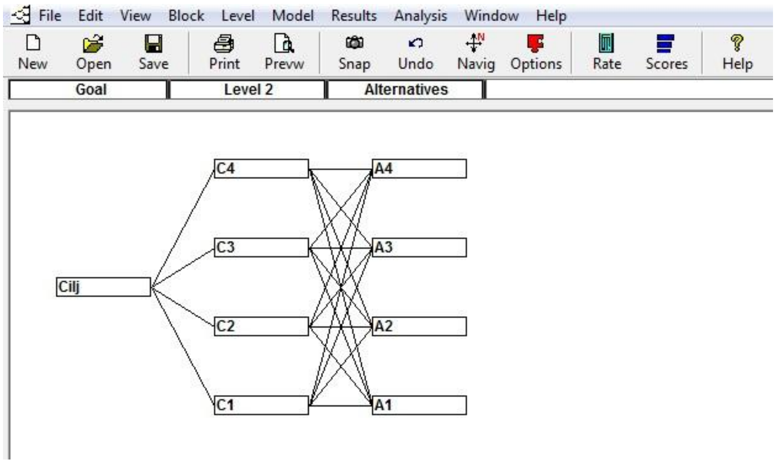

Figure 5 *Decision-making hierarchy (Criterium DecisionPlus software)*

In the next step, a comparison of models of IMS (alternatives) is done with regard to all four criteria defined - Table 4-7.

Table 4 *Comparison of alternatives with regard to a criterion C1*

Alternatives	A1	A2	A3	A4
A1	1	2	1	1
A2		1	2	1/2
A3			1	1/3
A4				1
Consistency Ratio	0.077<0.1			

Table 5 *Comparison of alternatives with regard to a criterion C2*

Alternatives	A1	A2	A3	A4
A1	1	1/3	1/5	1
A2		1	1/3	3
A3			1	7
A4				1
Consistency Ratio	0.012<0.1			

Table 6 *Comparison of alternatives with regard to a criterion C3*

Alternatives	A1	A2	A3	A4
A1	1	3	5	1
A2		1	3	1/3
A3			1	1/5
A4				1
Consistency Ratio	0.016<0.1			

Table 7 *Comparison of alternatives with regard to a criterion C4*

Alternatives	A1	A2	A3	A4
A1	1	1/3	1/3	1
A2		1	1	3
A3			1	3
A4				1
Consistency Ratio	0.00<0.1			

Finally, after the all calculations, the results of ranking are obtained - Table 8. The best solution is alternative A3 (The process model of IMS). In the second place is an alternative A2 (Karapetrovic's model), in the third place is an alternative A4 (EFQM excellence model) and on the last place is an alternative A1 (Wilkinson-Dale's model).

Table 8 *The final rank of models of IMS*

No.	Model of IMS	Result
1.	A3 (The process model of IMS)	0.449
2.	A2 (Karapetrovic's model)	0.246
3.	A4 (EFQM excellence model)	0.157
4.	A1 (Wilkinson-Dale's model)	0.148

6 THE ANALYSIS OF RESULTS

Analysis includes criteria and their impact on the ranking of the models of IMS, as well as the models of IMS itself.

When analyzing the criteria, the most important are their weights, because that is their measure of influence on the result of ranking of alternatives or models of IMS. Table 3. shows that the criterion C2 (the expected effects of the IMS) has the greatest impact on the result of the ranking because its weight coefficient is 0.624. This means that it affects with 62.4% for a decision with regard to other criteria. Also, this shows that in the selection of the optimal model of IMS, the most important is what will the mining companies get after its implementation, i.e. which the positive effects companies will achieve.

In the second place is the criterion C1 (the cost of implementation of the IMS), which affects 19.3% on the result of ranking. This shows that the costs of implementation of the optimal model of IMS is very important for mining companies, considering that they are in a difficult financial situation.

In the third place is criterion C4 (the applicability of the model), which affects with 13.8% on the process. This shows that it is very important to the mining companies the suitable level of a particular model of IMS for use in conditions in which they operate. Implementation of the IMS requires forming a team for implementation, the acquisition of new knowledge, application of new methods, management and procedures, overcoming resistance, implementation and control of the obtained results.

Finally, the least influential is the criterion C3 (the time required for implementation of the IMS) with weight ratio of 0.045. This shows that the time required for the implementation of IMS, although important, are in the background compared to other effects that are expected from this system.

The analysis of the final ranking of alternatives (model IMS) starts from the optimal (best) alternative. It is the alternative A3 (the process model of IMS) which has the highest value of the results of 0.449. The reason is that this model focuses precisely on that what is the strongest feature of mining companies – the existence and continuous performing of very complex and many processes during the work. Processes are the place where most can be done, which is the goal of this model. On the other hand, this model of IMS integrates various systems such as QMS, EMS, OHSAS, and all employees of the companies. All this enables significantly improvements of performances of mining companies in most or all areas of their functioning.

The second highest ranking of alternative is A2 (Karapetrovic's model). It discusses the integration of five systems - QMS, EMS, OHSAS, corporate social responsibility management system (CSRMS) and financial management system (FMS) and it is turned towards the continuous improvement process. Unlike the previous model, it is more complex, more demanding and less suitable for mining companies in our country.

In third place is the alternative A4 (EFQM excellence model), while in the last place is alternative A1 (Wilkinson –Dale's model). The difference in the results between these models is small. Their disadvantage compared to the previous two models of IM is that they to a lesser extent consider the processes, then they are less adapted to mining companies and therefore, they can provide the lower results. The good side of these models is that they integrate into their structures the environmental management system, which is very important for mining companies.

CONCLUSION

Authors have conducted the multiple criteria decision-making method in order to select the optimal model of Integrated Management System (IMS) in mining companies in Serbia. Selection of the optimal model of IMS is one of the most important strategic decisions of mining companies. Four models of IMS are analyzed: Wilkinson Dale's model (alternative A1), Karapetrovic's model (alternative A2), the process model (alternative A3) and the EFQM excellence model (alternative A4). Four criteria for the ranking are also considered : the cost of implementation of the IMS (criterion C1), the expected effects of the IMS (criterion C2), the time required for implementation of the IMS (criterion C3) and the applicability of the model (criterion 4).

Ranking of models of IMS was performed by the AHP method for multiple criteria decision making. In this method, weight coefficient of criteria for ranking is calculated first, then the proposed models of IMS are assessed and their full ranking is done.

The applied method for multiple criteria analysis –AHP, can be of great help to decision-makers because it allows easy and high quality analysis of influential factors and parameters. The best model of IMS for mining companies in Serbia chosen based on the results of AHP method was the process model (alternative A3). The most influential criteria for a complete ranking of alternatives (IMS models) are the expected effects of the IMS (criterion C2) and the cost of implementation of the IMS (criterion C1).

REFERENCES

[1] Djekic, V. et al., Importance of Interoperability Information and Information Systems in the Implementation of the Model IMS. International Scientific Conference Managament, Mladenovac, Serbia (2012) 171-175;

[2] Heleta M., Quality Management, Singidunum University, Belgrade, Serbia (2008) 5;

[3] Brzakovic M., Interoperability and Information Security in Organizations of Strategic Importance in Emergency Situations-Doctoral Dissertation, Faculty of Security, Belgrade, Serbia (2009);

[4] Volanovic S., The Development of a General Model for the Implementation of the Integrated Management System Based on Risk Assessment Processes in Organizations, Doctoral Dissertation, Faculty of Technical Sciences, Novi Sad, Serbia (2014);

[5] Saaty T.L., The Analytical Hierarchy Process, New York: McGraw-Hill (1980);

[6] Bogdanovic D. et al., Selection the Optimum Method of Rehabilitation the Degraded Ore as around the Bor River Downstream from the Flotation Tailing Dump Bor. Journal of Mining and Metallurgy Engineering Bor, 4 (2014) 137-146;

[7] Wilkinson G., Dale B., Integrated Management Systems: a Model Based on Total Quality Approach, Managing Service Quality, 11(5) (2001) 318-330;

[8] Hofstede G. H., Culture's Consequences: Comparing Values, Behaviors, Institutions and Organizations Across nations. Ed. Geert Hofstede. Sage (2001);

[9] https://scholar.google.com/citations?user=Q2V0P6oAAAAJ&hl=en&oi=ao (accessed 13.05.2015)

[10] Paunkovic J., Educational Programs for Sustainable Societies Using Cross-Cultural Management Method, Global Sustainable Communities Handbook: Green Design Technologies and Economics (2014): 387- Butterworth Heinemann imprint of Elsevier, Elsevier Copyright © 2014;

[11] Paunkovic J., Zikic S., Cvetkovic A., Sustainable Utilization of Health Care Technologies is Influenced by Organizational and Cultural Factors – A Case Study. Advances in Biomedicine and Health Science, (2013) 57;

[12] Karapetrovic S., Measuring of Integrated Management Systems, Measuring Business Excellence, 7(1) (2003) 4-13;

[13] Karapetrovic S., Jonker J., Integration of Standardized Management Systems: Searching for a Recipe and Ingredients, Total Quality Management, 14(04) (2003) 451-459;

[14] Petrovic M., The Process Approach to Integrated Management, 33. National Conference on Quality: Quality Festival, AQS and Quality Centre, Kragujevac, Serbia (2008);

[15] European Foundation for Quality Management (EFQM), EFQM Model for Business.

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IZBOR OPTIMALNOG MODELA INTEGRISANOG ODRŽIVOG SISTEMA MENADŽMENTA U RUDARSKIM KOMPANIJAMA****

Izvod

U radu je primenjena multikriterijumska analiza za izbor optimalnog modela integrisanog sistema menadžmenta u cilju poboljšanja performansi rudarskih kompanija. Integrisani sistem menadžmenta koji predstavlja proces integracije različitih sistema menadžmenta u savremanom poslovanju su postala obaveza svake kompanije radi opstanka na tržištu. Savremene kompanije koje su implementirale integrisani sistem menadžmenta bolje funkcionišu, imaju uređene procese, poboljšavaju svoju strukturu i kulturu radi izvršenja aktivnosti upravljanja i stalnog unapređenjasvih procesa.

Rudarske kompanije u našoj zemlji se nalaze u vrlo teškoj situaciji. Njihovo poslovanje je vrlo specifično, jer se one karakterišu velikom složenošću, zastarelim i kompleksnim organizacionim strukturama, neodgovarajućim načinom upravljanja, rada, funkcionisanja i dr. Polazeći od toga, u ovom radu su predložena četiri modela integrisanog sistema menadžmenta koji su primenljivi u rudarskim kompanijama, a u cilju poboljšanja njihovih performansi. Takođe, definisani su odgovarajući kriterijumi za izbor optimalnog modela. Za izbor i rangiranje modela integrisanog sistema menadžmenta je primenjena AHP metoda. Dobijeni rezultat daje optimalni model integrisanog sistema menadžmenta koji je primenljiv i koji može da ostvari najbolje rezultate u cilju poboljšanja performansi rudarskih kompanija u našoj zemlji.

Ključne reči: *integrisani sistem menadžmenta, rudarstvo, AHP metoda*

1. UVOD

U zadnje vreme se velika pažnja poklanja implementiranju Integrisanog sistema menadžmenta (ISM) koji je sastavljen od različitih sistema menadžmenta. Integrisani sistem menadžmenta se definiše kao sveobuhvatni alat menadžmenta koji povezuje sve elemente poslovnog sistema u jedinstven i celovit sistem upravljanja procesima u organizaciji a radi zadovoljavanja zahteva zainteresovanih strana [1]. Danas postoji više modela imlementacije ISM-a koji su nastali na osnovu specifičnih zahteva stejkholdera i samih kompanija. Kompanije koje su implementirale za njih optimalni model ISM-a imaju značajne koristi od toga, kao što su: stalno poboljšanje procesa, dobijanje jedinstvenog kvaliteta proizvoda i usluga, poboljšanje organizacione kulture,

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**** *Ovaj rad je proistekao kao rezultat projekta TR34023 "Razvoj tehnoloških procesa prerade nestandardnih koncentrata bakra u cilju optimizacije emisije zagađujućih materija" finansiranog od strane Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije*

veći stepen zadovoljstva zainteresovanih strana i dr. Kvaliet predstavlja koncept za održivi razvoj koji uspostavlja bilans između tehnološkog razvoja neophodnog za ekonomski prospertitet i opstanka životne sredine i društva u celini [2]. Ključna pitanja za menadžment rudarskih kompanijasu kako uskladiti sistem menadžmenta sa različitim standardima, zatim kako izvršiti međusobno interno usklađivanje parcijalnih sistema menadžmenta kompanije, kako iskoristiti već implementirani sistem i nakraju, kako izabrati optimalni model ISM-a. Rudarske kompanije zbog svoje specifičnosti moraju prvo da identifikuju zahteve zainteresovanih strana, a onda, na osnovu toga da dođu do optimalnog modela implementacije ISM-a. Pošto su svi elementi standardizovanih sistema menadžmenta međusobno kompatabilni, to omogućuje da svi parcijalni sistemi menadžmenta čine jedinstveni integrisani menadžment sistem (ISM) u kom postoje jake međusobne veze između pojedinih elemenata sistema [3]. Shodno tome, sistem integrisanog menadžmenta se uspostavlja kroz opredeljenost menadžmenta organizacije za implementaciju zahteva standarda, širenje svesti o značaju uređenja procesa i stalnog poboljšanja poslovnih procesa čime se stvaraju uslovi za uspeh.

Poslovnom uspehu rudarskih kompanija prethodi pravilan izbor optimalnog modela ISM-a koji će tokom vremena doneti značajna poboljšanja kao što su veći stepen zadovoljstva svih zainteresovanih strana od vlasnika, menadžera, pa do krajnjeg korisnika proizvoda i usluga, odnosno potrošača ili kupca.

2. MODELI INTEGRISANOG SISTEMA MENADŽMENTA

Danas postoji veliki broj modela ISM-a koji su uspešno primenjeni u poslovnim kompanijama. Osnovni modeli ISM-a su prvobitno bili sistem menadžmenta kvaliteta (standard ISO 9001) i sistem upravljanja zaštitom životne sredine (standard ISO 14001), da bi kasnije došlo do integracije i sistema upravljanja zdravljem i bezbednošću na radu (standard OHSAS 18001). Daljim razvojem se došlo do stvaranja novih modela ISM-a koji uzimaju u obzir vrstu delatnosti određene kompanije, kao i sve zainteresovane strane ili stejkholdere. Sistem koji u sebe integriše zahteve više standarda prvenstveno obezbeđuje zadovoljenje zahteva više zainteresovanih strana zato što je čest slučaj da različite zainteresovane strane zahtevaju različite sisteme upravljanja, tj. sisteme upravljanja usaglašene samo sa određenim standardom ili standardima [4].

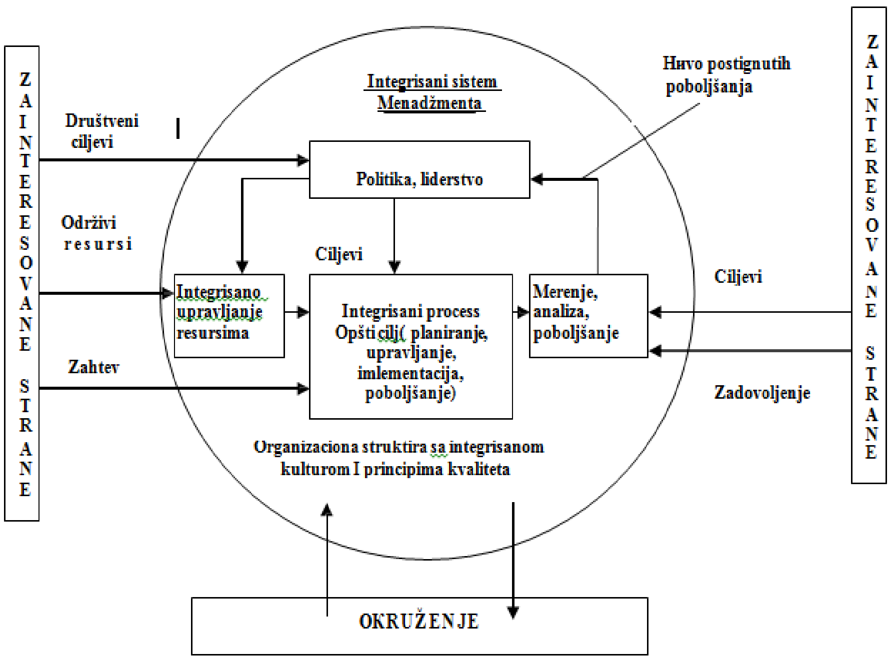
U ovom radu se direktno obrađuje održive rudarske kompanije sa aspekta implementacije optimalnog modela ISM-a pomoću Analitičko Hijerarhijskog Procesa (AHP metoda). AHP je jedna od metoda višekriterijskog odlučivanja za donošenje odluka pri izboru najpovoljnijeg rešenja između više alternative [5]. Prednost ove metode je u tome što ona može istovremeno da razmatra i finansijske i nefinansijske faktore pri postupku izbora optimalnog modela ISM-a [6]. Kao alternative su ovde razmatrana četiri modela IMS-a koji su uspešno primenjeni u razvijenim zemljama. Ovi modeli su zasnovani na osnovnim postavkama i procesnom pristupu tako da se iz toga razvija proces integracije menadžmenta.

2.1. Wilkinson-Dale-ov model (Alternativa A1)

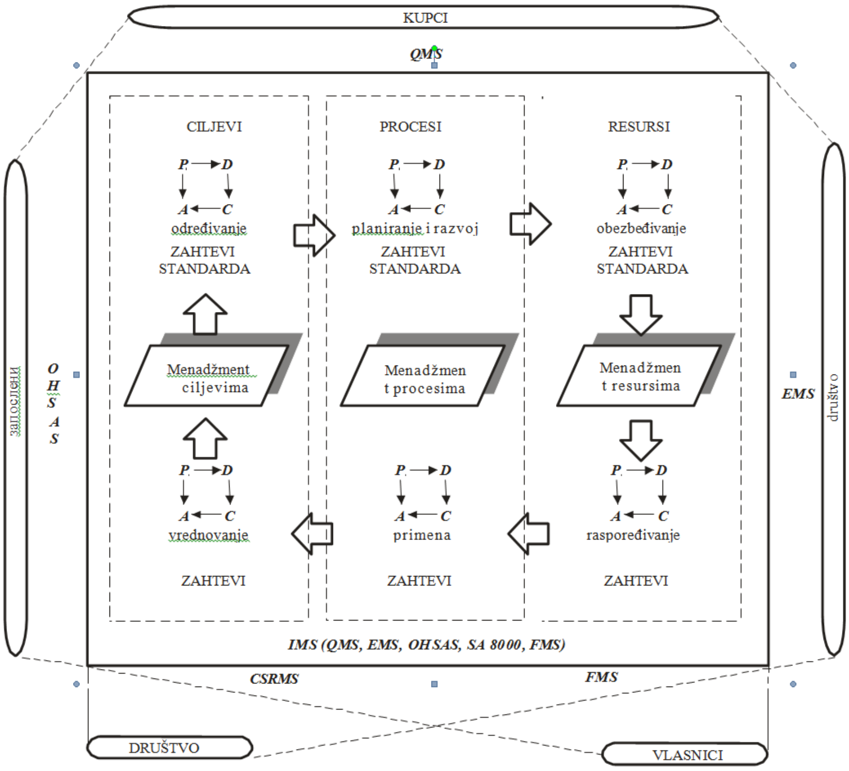
Sistemi integracija kod Wilkinson – Dale-ovog modela su: sistem menadžmenta za kvalitet (QMS), sistem menadžmenta zaštite životne sredine (EMS) i sistem menadžmenta zaštitom zdravlja i bezbednosti na radu (OHSAS) [7] - slika 1. Diferencijacija i specifičnost ovog modela je u tome što on uključuje integrisanu kulturu i elemente modela TQM-a (Total Quality Managament). Wilkinson – Dale-ov model integracije zavisi od zahteva i politike svake organizacije, odnosno od zainteresovanih strana. Zainteresovane strane mogu biti menadžeri (uspešno poslovanje), sami zaposleni (zarade, uslovi rada), dobavljači (dugoročna saradnja), kupci (kvalitet i cena proizvoda), društvena zajednica (životna sredina), vlasnici (profit) i dr. Ovaj model može da implementira svaka organizacija koja uzima sistem kvaliteta, sistem zaštite životne sredine i sistem zaštite zdravlja i bezbednost na radu kao prioritet u svom poslovanju. Takođe, ovaj model može da implementiraju i organizacije koje su uključene u aktivnosti TQM-a radi kontinualnih poboljšavanja.

Wilkinson i Dale u ovom modelu daju veliki značaj održivoj kulturi za integraciju kako bi moglo doći do stvaranja kulturnih organizacija što pomaže brzom implementtiranju samog sistema integracije.

Za rudarsku kompaniju koja implementira ISM je jako bitno da ima ugrađen model "nacionalne kulture", jer to može dovesti do uspešne realizacijeovog procesa. Koliko je značajan i relevantan odnos organizacione i nacionalne kulture govori podatak o citiranosti Hofstedovih radova [8]. On je najcitiraniji autor iz oblasti društvenih nauka (123707 citata - Google Scholar [9]). Autori ovog rada su objavili rezultate svojih istraživanja o povezanosti organizacione i nacionalne kulture u Srbiji u više oblasti [10, 11].



Sl. 1. *Prošireni Wilkinson – Dale model ISM –a [13]*



Sl. 2. *Model IMS – a Karapetrovića*

2.2. Model Karapetrovića (Alternativa A2)

Kod ovog modela su uključena pet sistema integracije – QMS, EMS, OHSAS, korporacijski menadžment sistem socijalne odgovornosti (CSRMS) i finasijski sistem menadžmenta (FMS). To znači da su uključeni zahtevi standarda i zahtevi zainteresovanih strana. Model se zasniva na sistematskom pristupu i ciklusu PDCA – planiraj, uradi, proveri i deluj – unapredi.

Kod modela Karapetrovića, osim kupaca, fokus je usmeren i na zadovoljenje interesne grupe društvene zajednice (zaštita životne sredine), zaposlenih (smanjenja povreda na radu), menadžmenta (smanjenje rizika poslovanja), kao i drugih zainteresovanih strana [9, 10]. Realizacija menadžment sistema se vrši kroz upravljanje prema ciljevima, upravljanje procesima i upravljanje resursima – slika 2. Model Karapetrovića je kompatabilan sa PDCA pristupom sistema menadžmenta, jer on razmatra sve procese sa ciljem njihovog stalnog unapređenja i poboljšanja. Ti procesi su: određivanje ciljeva, planiranje i razvoj procesa, obezbeđivanje resursa, raspoređivanje menadžment resursa, primena u menadžment procesima i vrednovanje menadžment ciljeva.

Ovaj model je primenljiv za sve industrijske kompanije – proizvodne i uslužne delatnosti.

Karakteristike kompanija (vrste delatnosti kompanija, njihove specifičnosti, veličine i zahteva interesnih grupa) su uslovile razvoj novih standardizovanih menadžment sistema (MSS – Managament Systems Standards) za zadovoljenje njihovih specifičnih zahteva i lakšeg implementiranja ISM-a.

2.3. Procesni model (Alternativa A3)

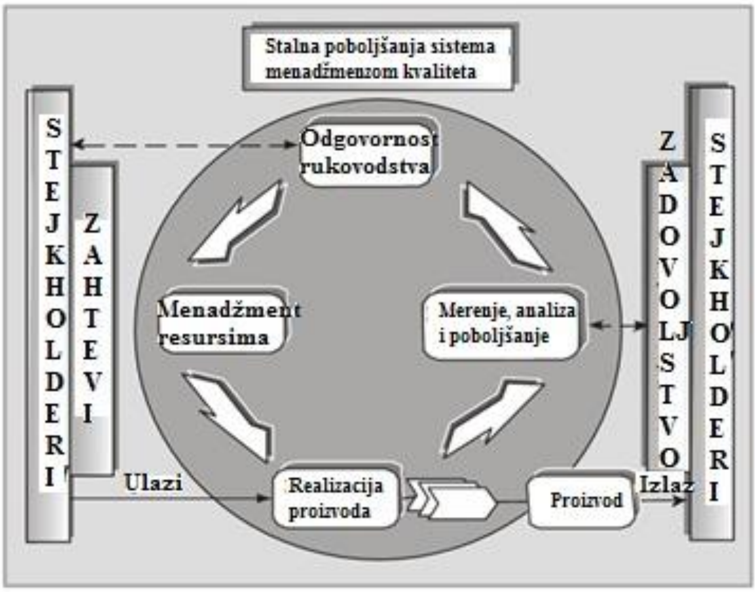
Kod procesnog modela svaki od procesa, podprocesa i aktivnosti imaju ulaze, a to su zahtevi stejkholdera i izlaze – zadovoljstvo stejkholdera –slika 3. U toku realizazacije proizvoda vrše se merenja, analize i poboljšanja uz odgovornost rukovodstva sa odgovarajućim resursima, stalnim poboljšanjem sistema menadžmenta i dr.

Prema [11] sisteme menadžmenta koji se baziraju na suštini procesnog pristupa iz ISO 9000 je moguće indetifikovati kroz strategiju integracije.

Specifičnosti kod procesnog modela se ogledaju kroz primenu procesnog pristupa, a integriše se N sistema i to: QMS, EMS, OHSAS i sistem menadžmenta bezbednosti hrane (HACCP). Ovi standardi imaju sličnosti u okviru njihove strukture tako da je integraciju standarda moguće izvesti na osnovu identičnih i specifičnih zahteva na koje se mora odgovoriti pri upravljanju procesa. To je razlog što procesni pristup predstavlja novi pristup menadžmenta. Suština standarda za sisteme menadžmenta (ISO 9001, ISO 14001, OHSAS 18001 i ISO 22000) upravo je u upravljanju procesima.

Procesni model prilikom implementiranja zahteva poznavanje procesa organizacije, zahteve interesne grupe, definisanje metodologije upravljanja, određivanje neophodnih resursa i sprovođenje svih procedura uz stalno unapređivanje i poboljšanje. Pri implementiranju procesnog modela ISM-a za dokumentaciju, realizaciju zahteva (proizvoda ili usluga) i merenja zadovoljstva stejkholdera odgovorni su osoba koja je zadužena, vlasnik procesa ili menadžer, a za realizaciju zaposleni i svi učesnici procesa.

U našoj zemlji je najviše zastupljen ovaj model ISM-a i to u 96,23% preduzeća.



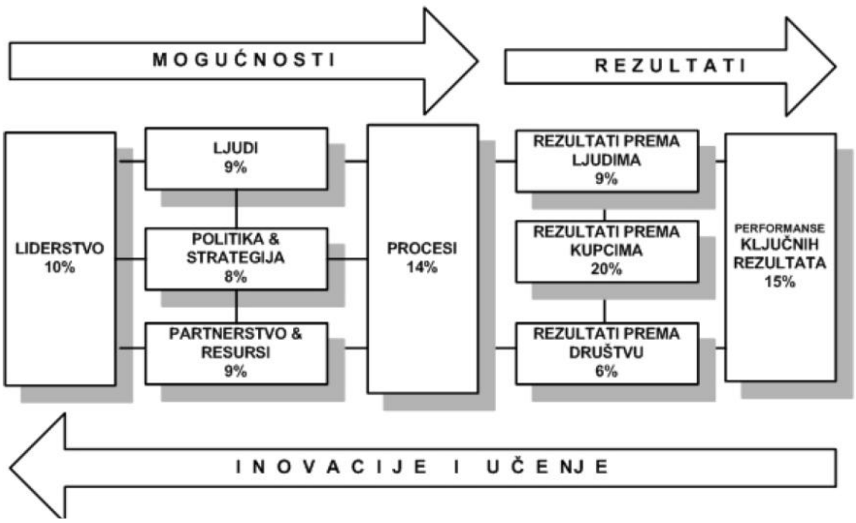
Sl. 3. *Model sistema menadžmenta kvalitetom zasnovan na procesima [14]*

2.4. EFQM model izvrsnosti (Alternativa A4)

EFQM model izvrsnosti je izgradila Evropska fondacija za mendžment kvaliteta 1992. godine i unapređen je 1999. godine. Model služi kao osnova za dodelu evropske nagrade za kvalitet i to za:

- velike kompanije i
- mala i srednja preduzeća.

Za razliku od drugih, ovaj model ima za bazu filozofiju menadžmenta totalnim kvalitetom (TQM) i zasniva se na integraciji dva sistema (interoperabilnost) i to sistema menadžmenta kvalitetom i sistema menadžmenta životnom sredinom (EFQM, 1998., EFQM, 2002.) – slika 4.



Sl. 4. *EFQM model izvrsnosti [15]*

Ovaj model ima devet kriterijuma pri čemu se pet odnose na mogućnosti koji pokazuju šta kompanija radi, dok se ostali odnose na rezultate. Rezultati pokazuju u kojoj meri organizacija koristi mogućnost.

Model EFQM je primenljiv kod onih kompanija čiji su zahtevi takvi da mogu da izgrade sopstvene pristupe u postizanju izvrsnosti. Unutar ovog modela ima nekoliko baznih koncepta koji su obavezni za njegovu primenu, a to su:

- orijentisanost na rezultate, gde rezultati pokazuju izvrsnost koji su zadovoljstvo stejkohldera;
- fokusiranost na kupce, gde je izvrsnost kreiranje postojanog kupca;
- liderstvo i postojanost odlučnosti, gde je izvrsnost u liderstvu sa postojanim odlikama;
- menadžment procesima i činjenicama, gde je izvrsnost upravljanje kompanijom na osnovu procesa i činjenica;
- uključivanje zaposlenih i njihov razvoj, gde je izrsnost u motivisanju zaposlenih radi povećanja doprinosa;
- poboljšanje, inovacije i stalno edukacija, gde do izvrsnosti dovodi kreiranje

inovacija i mogućnost za savremenije poslovanje;

- razvoj partnerstva, gde se izvrsnost manifestuje kroz razvoj i održavanje partnerstva uz povećavanje vrednosti;
- društvena odgovornost, gde se izvrsnost ogleda u prevazilaženju nekih minimalnih obaveza u društvu i gde kompanija teži odgovornijem razumevanju zahteva društva.

Kriterijumi za ostvarenje poslovne izvrsnosti su: liderstvo, ljudi, politika i strategija, partnerstvo i resursi, procesi, rezultati prema kupcima i društvu i na kraju rezultati koji su zadovoljstvo svih zainteresovanih strana.

Zajedničke karakteristike modela EFQM, procesnog modela, modela Karapetrovića i modela Wilkinson - Dale su: sistemski pristup, stalna poboljšanja, zadovoljenje zahteva svih zainteresovanih strana, smanjenje obimne dokumentacije i to što oni nemaju ograničenja u pogledu vrste organizacije uključujući i rudarske kompanije.

3. DEFINISANJE KRITERIJUMA ZA IZBOR OPTIMALNOG MODELA ISM-A

Kriterijumi sadrže najvažnije karakteristike za izbor optimalnog modela implementacije ISM-a u rudarskim kompanijama, a to su:

Troškovi uvođenja ISM-a (kriterijum C1) je vrlo važan factor za donošenje odluke pri izboru optimalnog modela ISM-a. Troškovi uvođenja se određuju za svaki predloženi model ISM-a u rudarskim kompanijama i njihov uticaj je srazmeran dobijenim rezultatima.

Očekivani efekti ISM-a (kriterijum C2) je jako bitan faktor koji ima veliki uticaj pri donošenju odluke pri izboru optimalnog modela implementiranja ISM-a. Rudarske kompanije implementacijom optimalnog modela ISM-a treba da ostvare značajna poboljšanja, kao što su: izgradnja modela „nacionalne kulture“, bolja realizacija svoje politike i strategije, veće zadovoljstvo zaposlenih, smanjenje povreda na radu, stalna poboljšanja resursa (materijalnih, finasijskih i ljudskih), kontinualno poboljšanje procesa poslovanja, poboljšanje upravljanja kompanijom, zadovoljniji eksterni i interni kupci, bolji odnos prema društvu, poboljšanje zaštite životne okoline, poslovanje po svim propisima i pravilima, mogućnost poslovanja na globalnom tržištu, prednost prilikom učešća na tenderu, smanjenje troškova i dr.

Vreme implementacije ISM-a (kriterijum C3) je takođe, veoma važan faktor koji značajno utiče na izbor optimalne metode ISM-a. Na primer, ako se izabrani model imlementira duži vremenski period od predviđenog, nekim od zainteresovana strana neće biti ispunjeni zahtevi, što povlači da se njihovo nezadovoljstva odražava na ostale, tako da sve to dovodi do loše reputacije rudarske kompanije u okviru društvene zajednice. Neki od ovih modela ISM-a imaju kraći period implementiranja što može da bude veoma značajno za rudarske kompanije.

Primenljivost modela (kriterijum C4) je kriterijum koji ukazuje na stepen mogućnosti implementacije određenog modela ISM-a u rudarskim kompanijama. Neke modele je lakše implementirati, a druge teže. Cilj je da rudarska kompanija izabere onaj model koji nije težak za implementaciju i koji će joj dugoročno doneti mnogobrojne koristi. Pri tome, rudarska kompanija mora da uzme u obzir mnogobrojne faktore, kao što su određene njene specifičnosti, nivo opremljenosti, struktura radne snage, menadžment kompanije i dr.

4. AHP METOD

AHP je kvantitativna tehnika koja omogućava strukturiranje kompleksnog problema odlučivanja sa više kriterijuma i pruža objektivnu metodologiju koja se primenjuje na širok spektar odluka.

AHP polazi od dekompozicije složenog problema odlučivanja u višedimenzionalnu hijerarhijsku strukturu ciljeva, kriterijuma i alternativa. Nakon toga, vrši se procena uticaja kriterijuma, onda se upoređuju alternative u odnosu na svaki kriterijum i vrši se konačno rangiranje alternativa.

Procena relativnog uticaja svakog kriterijuma i poređenje alternativa u odnosu na kriterijume se vrši preko matrice poređenja. To uključuje: formiranje matrice poređenja na svakom nivou hijerarhije, počev od drugog nivoa nadole; proračun težinskih koeficijenata za svaki element hijerarhije i procena stepena konzistentnosti u cilju provere konzistentnosti celokupnog procesa.

U tom cilju, definiše se skup alternativa $\{A_1, A_2, ..., A_n\}$ i skup težinskih koeficijenata kriterijuma $\{w_1, w_2, ..., w_n\}$.

Upoređenje kriterijuma i alternativa vrši se na bazi skale sa ocenama od 1 do 9 – tabela 1.

Tabela 1. *Skala poređenja elemenata odlučivanja*

Dominantnosti	
Opis	**Ocena**
Jednako	1
Slaba dominacija	3
Jaka dominacija	5
Vrlo jaka dominacija	7
Apsolutna dominacija	9
2, 4, 6, 8 su međuvrednosti	

Rezultat upoređenja kriterijuma predstavlja matrica koja ima sledeći oblik:

$$W = \left[w_i / w_j \right] = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix}$$

Nakon toga, vrši se upoređenje parova alternativa u odnosu na svaki kriterijum, pri čemu se dobija matrica poređenja A u kojoj element a_{ij} predstavlja odnos težinskog koeficijenta alternative A_i u odnosu na alternativu A_j.

$$A = \left[a_{ij} \right] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix}$$

Elementi A_{ij} predstavljaju odnos između težinskih koeficijenata w_i/ w_j gde je w vektor težine svake alternative.

Matrica ima recipročna svojstva, kod koje su $a_{ji}=1/a_{ij}$.

Posle izvršenog upoređenja računaju se težinski koeficijenti i dobija se vektor koeficijenata $w = [w_1, w_2, . . . , w_n]$ koji se računa na bazi Satijeve procedure u dva koraka.

Prvo, matrica upoređenja parova $A = [a_{ij}]_{nxn}$ se normalizuje, a zatim se izračunavaju težine.

Normalizacija se vrši pomoću sledećeg obrasca:

$$a_{ij}^{*} = a_{ij} \Big/ \sum_{1}^{n} a_{ij} \tag{1}$$

za sve $j = 1,2,..., n$.

Za izračunavanje težinskih koeficijenata koristi se sledeći obrazac:

$$w_i = \sum_{1}^{n} a_{ij}^{*} \Big/ n \tag{2}$$

za sve $j = 1,2,..., n$.

Nakon upoređenja, vrši se provera stepena konzistentnosti. Stepen konzistentnosti treba da ima vrednost manju od 0,1. U suprotnom, moraju se ponovo razmatrati vrednosti koje su unete u matricu poređenja.

Stepen konzistentnosti se računa na sledeći način

$$CI = (\lambda_{\max} - n)/(n-1) \tag{3}$$

gde λ_{max} predstavlja značajan parametar kod AHP metode i on se koristi kao referentni indeks za prikazivanje informacija kod proračuna stepena konzistentnosti (*CR*). *CR* se računa na sledeći način:

$$CR = CI / RI \tag{4}$$

gde *RI* predstavlja slučajni indeks konzistentnosti dobijen nasumice iz matrice upoređenja.

Određivanje konačnog ranga alternativa vrši se sintezom rezultata koji su dobijeni na svim nivoima.

5. REZULTATI IZBORA OPTIMALNOG MODELA ISM-A

Nakon definisanja kriterijuma i modela ISM-a (alternativa) vrši se njihova ocena i rangiranje primenom AHP metode. Pri tome, za proračun je korišćen softver Criterium DecisionPlus.

Prvi korak je definisanje višedimenzionalne hijerarhijske strukture ciljeva, kriterijuma i alternativa – slika 5.

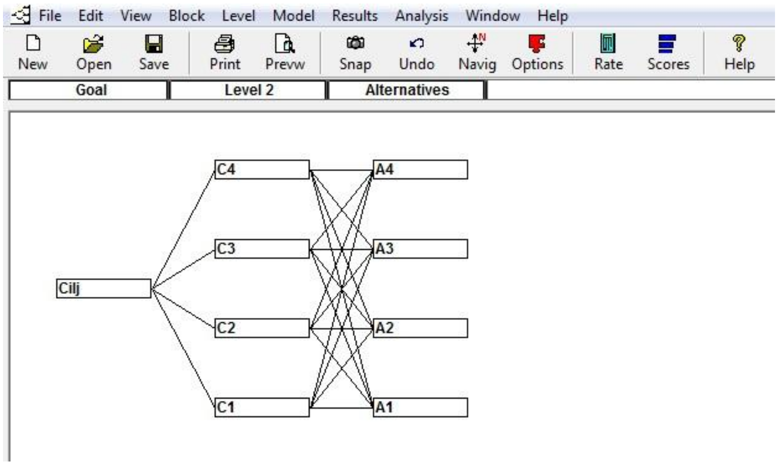
Nakon toga vrši se određivanje težinskih koeficijenata kriterijuma uz pomoć skale poređenja koja je data u tabeli 1. Rezultati poređenja su prikazani u tabelama 2 i 3.

Tabela 2. *Definisanje težinskih koeficijenata kriterijuma*

Kriterijumi	**C1**	**C2**	**C3**	**C4**
C1	1	1/5	5	2
C2		1	8	5
C3			1	1/5
C4				1

Tabela 3. *Rezultati težinskih koeficijenata kriterijuma*

Kriterijumi	**C1**	**C2**	**C3**	**C4**
Težinski koeficijenti	0.193	0.624	0.045	0.138
Stepen konzistentnosti	0.084<0.1			



Sl. 5. *Hijerarhija odlučivanja (Criterium Decision Plus softver))*

U sledećem koraku se vrši upoređivanje modela ISM-a (alternativa) u odnosu na sva četiri definisana kriterijuma – tabele 4 - 7.

Tabela 4. *Upoređenje alterntiva u odnosu na kriterijum C1*

Alternative	A1	A2	A3	A4
A1	1	2	1	1
A2		1	2	1/2
A3			1	1/3
A4				1
Stepen konzist.	0.077<0.1			

Tabela 5. *Upoređenje alterntiva u odnosu na kriterijum C2*

Alternative	A1	A2	A3	A4
A1	1	1/3	1/5	1
A2		1	1/3	3
A3			1	7
A4				1
Stepen konzist.	0.012<0.1			

Tabela 6. *Upoređenje alterntiva u odnosu na kriterijum C3*

Alternative	A1	A2	A3	A4
A1	1	3	5	1
A2		1	3	1/3
A3			1	1/5
A4				1
Stepen konzist.	0.016<0.1			

Tabela 7. *Upoređenje alterntiva u odnosu na kriterijum C4*

Alternative	A1	A2	A3	A4
A1	1	1/3	1/3	1
A2		1	1	3
A3			1	3
A4				1
Stepen konzist.	0.00<0.1			

Na kraju, nakon izvršenih proračuna dobijeni su rezultati rangiranja – tabela 8. Rezultati pokazuju da je najbolje rešenje alternativa A3 (procesni model ISM-a).

Na drugom mestu je alternativa A2 (model Karapetrovića), na trećem mestu je alternativa A4 (EFQM model izvrsnosti) i na poslednjem mestu je alternativa A1 (Wilkinson - Dale-ov model).

Tabela 8. *Konačni rang modela ISM-a*

Red. br.	Model ISM-a	Rezultat
1.	A3 (Procesni model ISM-a)	0.449
2.	A2 (model Karapetrovića)	0.246
3.	A4 (EFQM model izvrsnosti)	0.157
4.	A1 (Wilkinson-Dale-ov model)	0.148

6. ANALIZA DOBIJENIH REZULTATA

Analiza obuhvata kriterijume i njihov uticaj na rangiranje modela ISM-a i same modele ISM-a.

Kada se analiziraju kriterijumi, najvažniji su njihovi težinski koeficijenti, jer je to njihova mera uticaja na rezultat rangiranja alternativa, odnosno modela ISM-a. Iz tabele 3. se vidi da kriterijum C2 (očekivani efekti ISM-a) ima najveći uticaj na rezultat rangiranja jer njegov težinski koeficijent iznosi 0,624. To znači da on utiče sa 62,4% na donošenje odluke u odnosu na ostale kriterijume. To pokazuje da je kod izbora optimalnog modela ISM-a najvažnije šta će rudarske kompanije dobiti nakon njegove implementacije, odnosno koje će sve pozitivne efekte one ostvariti, što je i cilj ovog procesa.

Na drugom mestu po uticaju je kriterijum C1 (troškovi uvođenja ISM-a), koji utiče sa 19,3% na rezultat rangiranja. To pokazuje da su troškovi implementacije optimalnog modela ISM-a vrlo važni za rudarske kompanije, s obzirom da se one nalaze u teškoj finansijskoj situaciji.

Na trećem mestu po značaju se nalazi kriterijum C4 (primenljivost modela), koji utiče sa 13,8% na ovaj proces. To pokazuje da je za rudarske kompanije vrlo važno koliko je određeni model ISM-a pogodan za primenu u uslovima u kojima one funkcionišu. Implementacija ISM-a zahteva formiranje tima za uvođenje, sticanje novih znanja, primena novih metoda rada, upravljanja i procedura, savladavanje otpora, samo uvođenje i kontrolu dobijenih rezultata.

Na kraju, najmanje uticajan kriterijum je C3 (vreme implementacije ISM-a) koji ima težinski koeficijent od 0,045. To pokazuje da je vreme koje je potrebno za uvođenje ISM-a, iako važno, u drugom planu u odnosu na ostale efekte koje se očekuju od ovog sistema.

Kod analize konačnog ranga alternativa (modela ISM-a) polazi se od optimalne (najbolje) alternative. To je alternativa A3 (procesni model ISM-a) koji ima najveći vrednost rezultata od 0,449. Razlog je u tome što se ovaj model fokusira upravo na ono što je najjača karakteristika rudarskih kompanija, a to je postojanje i neprekidno odvijanje vrlo kompleksnih i mnogobrojnih procesa u toku rada. Procesi su mesta gde se najviše može uraditi, što je i cilj ovog modela. Sa druge strane, ovaj model ISM-a integriše razne sisteme kao što su QMS, EMS, OHSAS, ali i sve zaposlene u kompanijama. Sve to omogućava značajno poboljšanje performansi rudarskih kompanija u najvećem broju ili u svim oblastima njihovog funkcionisanja.

Na drugom mestu po rangiranju se nalazi alternativa A2 (model Karapetrovića). On razmatra integraciju pet sistema – QMS, EMS, OHSAS, korporacijski menadžment sistem socijalne odgovornosti (CSRMS) i finasijski sistem menadžmenta (FMS) i okrenut je ka stalnim poboljšanjima procesa. Za razliku od prethodnog modela, on je složeniji, zahtevniji i manje pogodan za rudarske kompanije kod nas.

Na trećem mestu je alternativa A4 (EFQM model izvrsnosti), dok je na poslednjem mestu alternativa A1 (Wilkinson-Dale-ov model). Razlika u rezultatu između ovih modela je mala. Njihov nedostatak u odnosu na prethodna dva modela ISM-a je u tome što se oni u manjoj meri bave procesima, zatim manje su prilagođeni rudarskim kompanijama i time, manji su rezultati koji oni mogu da pruže. Dobra strana ovih modela je u tome što oni integrišu u svoj model sistem menadžmenta životnom sredinom, što je vrlo važno kod rudarskih kompanija.

ZAKLJUČAK

U ovom radu je primenjena višekriterijumska metoda donošenja odluke u cilju izbora optimalnog modela Integrisanog sistema menadžmenta (ISM) u rudarskim kompanijama u našoj zemlji. Izbor optimalnog modelaISM-a je jedna od najznačajnijih strateških odluka rudarskih kompanija. Analizirana su četiri modela ISM-a – Wilkinson-Dale-ov model (alternativa A1), model Karapetrovića (alternativa A2), procesni model (alternativa A3) i EFQM model izvrsnosti (alternativa A4). Takođe, razmatrana su četiri kriterijuma za rangiranje – troškovi uvođenja ISM-a (kriterijum C1), očekivani efekti ISM-a (kriterijum C2), vreme implementacije ISM-a (kriterijum C3) i primenljivost modela ISM-a (kriterijum C4).

Rangiranje modela ISM-a je izvršeno pomoću AHP metode za višekriterijumsko odlučivanje. Kod ove metode, prvo se vrši određivanje težinskih koeficijenata kriterijuma za rangiranje, a onda ocenjivanje predloženih modela ISM-a i njihovo kompletno rangiranje.

Primenjena metoda za višekriterijumsku analizu može biti od velike pomoći donosiocima odluka, jer omogućava laku i kvalitetnu analizu uticajnih faktora i parametara. Na osnovu dobijenih rezultata AHP metodom, izabran je najbolji model ISM-a za rudarske kompanije u našoj zemlji, a to je procesni model (alternativa A3). Najuticajniji kriterijumiza kompletno rangiranje alternativa (modela ISM-a) su očekivani efekti ISM-a (kriterijum C2) i troškovi uvođenja ISM-a (kriterijum C1).

LITERATURA

[1] Đekić, V. et al., Importance of inter operability information and information systems in the implementation of the model IMS. Internacional Scientific Conference Managament, Mladenovac, Serbia (2012) 171-175.

[2] Heleta M., Menadžment kvaliteta, Univerzitet Singidunum, Beograd, Srbija (2008) 5.

[3] Brzaković M., Interoperabilnost i bezbednost informacija u organizacijama od strateškog značaja u vanrednim situacijama – Doktorska disertacija, Fakultet bezbednosti, Beograd, Srbija (2009).

[4] Volanović. S, Razvoj opšteg modela za implementaciju Integrisanog sistema menadžmenta na osnovu procene rizika u procesima organizacija, Doktorska disertacija, Fakultet Tehničkih Nauka, Novi Sad, Srbija (2014).

[5] Saaty T. L., The Analytical Hierarchy Process, New York: McGraw-Hill (1980).

[6] Bogdanović D., Obradović Lj., Miletić S.: Izbor optimalne metode sanacije degradiranih površina oko borske reke nizvodno od flotacijskog jalovišta Bor, Mining and Metallurgy Engineering Bor, 4(2014) 147-156.

[7] Wilkinson G., Dale B., Integrated management systems: a model based on total quality approach, Managing Service Quality, 11(5) (2001) 318-330.

[8] Jenkić R., Kulture i organizacije - Organizacijske kulture Geerta Hofstedea, Zbornik radova Pravnog fakulteta u Splitu, 1 (2011) 103-123.

[9] https://scholar.google.com/citations?user=Q2V0P6oAAAAJ&hl=en&oi=ao (accessed 13.05.2015)

[10] Paunkovic J., Educational Programs for Sustainable Societies Using Cross-Cultural Management Method. Global Sustainable Communities Handbook: Green Design Technologies and Economics (2014): 387- Butterworth Heinemann imprint of Elsevier, Elsevier Copyright © 2014.

[11] Paunkovic J., Zikic S., Cvetkovic A., Sustainable Utilization of Health Care Technologies is Influenced by Organizational and Cultural Factors – A Case Study. Advances in Biomedicine and Health Science, (2013) 57.

[12] Karapetrović S., Measuring of integrated management systems, Measuring Business Excellence, 7(1) (2003) 4-13.

[13] Karapetrovic S., Jonker J., Integration of standardized management systems: searching for a recipe and ingredients, Total Quality Management, 14(04) (2003) 451-459.

[14] Petrović M., Procesni pristup integrisanom menadžmentu, 33. Nacionalna konferencija o kvalitetu: Festival kvaliteta, AQS i Centar za kvalitet, Kragujevac, Srbija (2008).

[15] European Foundation for Quality Management (EFQM), EFQM Model for Business.

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[1] Willis B. A., Mineral Procesing Technology, Oxford, Pergamon Press, 1979, pg. 35. (for the chapter in a book)

[2] Ernst H., Research Policy, 30 (2001) 143–157. (for the article in a journal)

[3] www: http://www.vanguard.edu/psychology/apa.pdf (for web document)

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[2] H. Ernst, *Research Policy*, 30 (2001) 143–157. *(za članak u časopisu)*

[3] www: http://www.vanguard.edu/psychology/apa.pdf *(za web dokument)*

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