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Calculation of Electromagnetic Radiation Criterion for Rockburst Hazard Forecast in Coal Mines

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Abstract — Intensive micro-fracturing of rock close to mining operations accompanies an increase in the likelihood of rockbursting. This fracturing causes an increase of the electromagnetic radiation (EMR) level by up two orders of magnitude, depending on the mining environment. Several examples of this enhanced EMR are presented in this paper. We first treat the EMR theoretical criterion of rockburst hazard in coal mines and compare it with the empirical criterion of EMR activity that was revealed on the basis of more than 400 different hazardous and non-hazardous situations in underground coal mines. Only the following parameters are needed to estimate the EMR criterion of rockburst hazard: limiting value of gum volume, mine working width, coal seam thickness, and coal elastic properties.

Key words: Rockburst, electromagnetic radiation, fracture, coal mines.

1. Introduction

The phenomenon of rockbursting has long been known in mining. The rockburst hazard increases if the load on a given part of a coal seam exceeds some critical level, while the distance to the stress maximum in the zone of influence of a mine working is lower than the critical value (Petukhov and Lin'kov, 1983). The rockburst hazard is usually determined by some standard geomechanical method, for example, gum volume measurement, measurement of hole diameter or number of disks that are created due to core fracturing as a result of drilling in a highly stressed zone, etc. (Petukhov, 1972). The method of gum volume measurement is generally used in coal mines of the former USSR.

All of these methods are very time-consuming and sometimes dangerous because drilling is required. For these reasons, rockburst hazard forecasting at a mine

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working face must be made short-term and safe. Geophysical methods can help to reduce the risks (FALLON *et al.*, 1997).

As noted by LOCKNER (1993, 1996), there is a strong parallel between the well-known Gutenberg-Richter relation for seismic events (from macro (earthquake) to micro (rock burst)) and power-law frequency – magnitude relationship for acoustic emission (AE) events. This analogy suggests that micro shocks (high frequency and small magnitude) are precursors of macro failure (large magnitude and small frequency) and is the theoretical basis for rockburst forecasting by the AE method (KUKSENKO *et al.*, 1982; MANSUROV, 1994). The EMR frequency range is close enough to the AE band. Therefore, both types of emissions are associated with rock fracture (YAMADA *et al.*, 1989; O'KEEFE and THIEL, 1995; RABINOVITCH *et al.*, 1995). Hence, it would be correct to assume that electromagnetic radiation (EMR) could be useful for rockburst hazard forecasting along with AE. Moreover, being non-contact, the EMR method has advantages over AE. For example, when a rapid and comprehensive prognosis of a short-term mine working region (for example, in a drift face) is needed, the roughness of the mine walls becomes a marked problem for the AE method for rapid data acquisition due to inferior contact between the AE transducer and the mine wall.

Numerous investigations have examined different aspects of the EMR (CRESS *et al.*, 1987; FUJINAWA *et al.*, 1992; NITSAN, 1977; OGAWA *et al.*, 1985; WARWICK *et al.*, 1982; YAMADA *et al.*, 1989; YOSHINO *et al.*, 1993). The EMR amplitude is a function of the crack area (RABINOVITCH *et al.*, 1998, 1999). Moreover, an increase of elasticity, strength, and loading rate enhances the EMR amplitude (GOL'D *et al.*, 1975; NITSAN, 1977; KHATIASHVILI, 1984; FRID *et al.*, 1999).

Since the eighties, the interest in EMR has increased in connection with the problem of rockburst forecasting. KHATIASHVILLI *et al.* (1984) carried out an investigation of EMR in the Tkibulli deep shaft (Georgia) prior to an earthquake of 5.4 magnitude. The registration point (at the shaft position) was located 250 km from the earthquake epicenter. Prior to the earthquake itself, an increase of intensity of the lower part of the spectrum (1–100 kHz) and a corresponding decrease of intensity of higher frequencies (100–1000 kHz) were observed. An increase of the number and the sizes of cracks during the earthquake approach could, perhaps, explain this phenomenon. NESBITT and AUSTIN (1988) registered EMR in a gold mine (2.5 km depth). An EMR signal (1.2 mA/m amplitude) was generated seconds prior to the micro-seismic event (magnitude of −0.4). Registration of EMR activity in Ural bauxite mines showed (SCITOVICH and LAZAREVICH, 1985) that its values sharply increased with rockburst hazard increase. Analogous works in Noril'sk polymetal deposit (Krasnoyarsk region) revealed an increase of EMR amplitude (up to 150–200 mV/m) and activity in the rockburst hazardous zones (RED'KIN *et al.*, 1985). MARKOV and IPATOV (1986) investigated EMR activity changes in an apatite underground mine (Khibin deposit, Kola peninsula) and ascertained that EMR amplitude in rockburst hazardous zones was in the range of 8–25 mV/m and EMR activity here was significantly higher than the regular noise level.

This very limited overview demonstrates that the EMR is a multi-scale phenomenon that is currently investigated in laboratories and *in situ* (before earthquake and rockburst). However, all EMR mine investigations have usually been empirical, and the degree of their theoretical generalization is not enough to be useful for rockburst forecasting. This paper first considers a development of the theoretical EMR criterion for rockburst forecasting.

2. Comparison of EMR and Gum Methods

The promotion of a new method for rockburst forecasting is a very responsible undertaking. Hence, the new method must be comprehensively compared with the method which is currently being used. In this section of the paper we consider the methodological foundation of the gum method that has been used for rockburst forecasting before discussing EMR and the EMR methodology. Finally, several examples of EMR and gum investigations are presented.

2.1. Methodology of Gum Measurement

Drilling of a highly stressed coal seam leads to an intensive fracturing process in the zone, influenced by the drill hole. The volume of this highly cracked zone depends on the hole diameter, the drilling rate and, especially, the stress level. Hence, if the first two parameters remain invariant for a given coal seam, the stress value in the coal seam (Fig. 1) is responsible for the volume of drilled coal rubble that is recovered from the hole (i.e., from the highly stressed zone drilled by the hole). If the drilling is dry, the drilled coal rubble is called "gum."

The non-dimensional diameter, β, of the highly stressed zone (ratio of the non-elastic deformation zone, diameter D, to the hole diameter $d = 0.043$ m, Fig. 2) can be calculated from the following formula (PETUKHOV, 1972):

$$\beta = -0.5 + \sqrt{0.25 + \left(\frac{3\frac{M_0+M_s}{M_0} n_r - n_r - 2}{n_r - 1}\right)} \ , \tag{1}$$

where n_r is the coefficient of coal loosening on borehole wall that is generally equal to 1.3–1.4, M_0 is the gum volume of a borehole ($M_0 = \pi d^2/4\Lambda$, Λ is the borehole length), and M_s is the gum volume induced by drilling in a stressed zone) (PETUKHOV *et al.*, 1976).

The vertical stress in the coal seam can be determined as follows (PETUKHOV *et al.*, 1976)

$$\sigma_{k\gamma H} = k_*(1 + 2\ln\beta) \ , \tag{2}$$

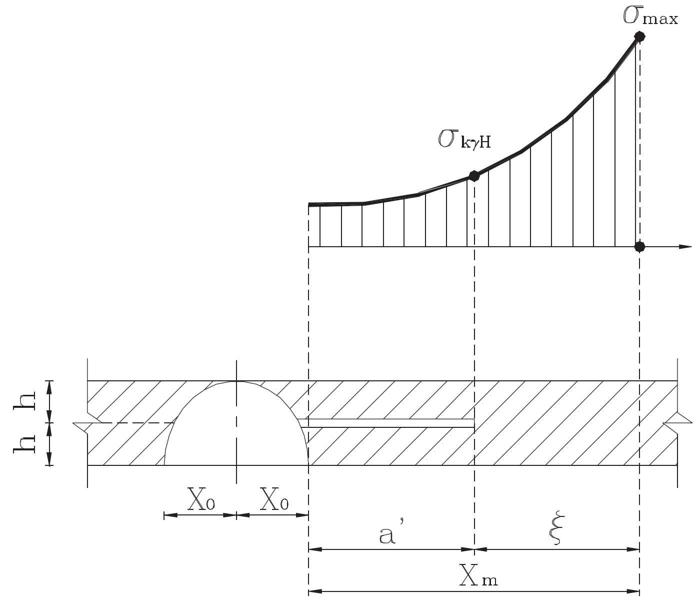

Figure 1
The vertical stress distribution in the zone of influence of the mine working (all parameters are discussed in the text).

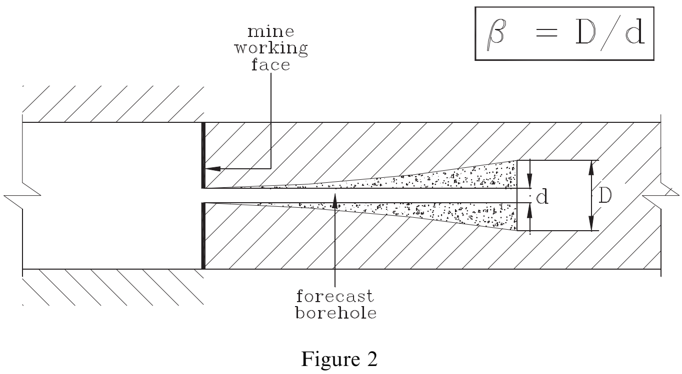

Figure 2
The zone of non-elastic deformation excited by drilling in the high stressed zone (b is the non-dimensioned diameter of this zone: the ratio of the non-elastic deformation zone diameter D to the hole diameter $d = 0.043$ m).

where k_* is the coal shear strength. Forecast boreholes are usually drilled in intervals (the length of each interval is 1 m). Hence, if we determine the gum volume for each meter of the hole, we can predict the vertical stress distribution in the coal seam near the mine working face.

After the drilling of each interval, the gum volume is measured and if it exceeds a definite limiting value (experience at the mining works in North Kuzbass shows that the limiting values are 5 to 8 liters per meter at the fourth and the seventh drilling meter from the drift face, respectively (Table 1)), drilling is stopped, and that part of the mine working, is considered rockburst hazardous.

2.2. *EMR Methodology for Mine Measurement*

Figure 3 explains the EMR activity definition. The EMR activity is defined by the number of intersections of the EMR voltage signal (per unit time) with a given voltage level (of a special counter). The EMR activity was measured by a resonance 100 ± 1 kHz antenna. Our preliminary mine estimation of electromagnetic compatibility conditions showed that the given resonance frequency would allow us to

Table 1

Calculation of rockburst hazardous zone parameters

a', m	Gum volume, l/m	*b*	$\sigma_{k\gamma H}$, MPa	X_m, *m*	ξ, *m*
4.00	5.00	5.03	54.98	6.35	2.35
5.00	6.00	5.71	58.28	6.98	1.98
6.00	6.50	6.02	59.67	7.43	1.43
7.00	7.50	6.60	62.08	7.96	0.96

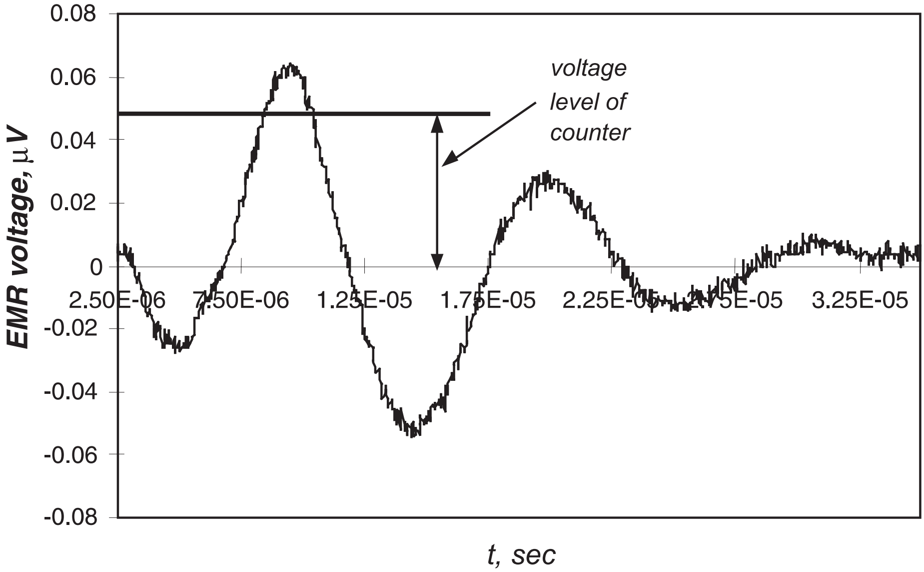

Figure 3
The EMR signal that intersects counter voltage level.

accurately extract the useful signal from the industrial background noise. As is known, the shortest wavelength band of measuring system is quite necessary to increase system sensitivity. The *Q* factor, in our case, is 50, that results in a system sensitivity not lower than 0.1 mV/m. The EMR amplitude near the mine face ranges between 5–50 mV/m (the antenna was normally located 1 m from the mine working face), which is at least one order of magnitude larger than the amplitude of the industrial noise level (FRID, 1990, 1997a).

At all studied points 30 electromagnetic radiation activity readings were taken with a duration of 10 sec each. Thus one cycle of EMR measurement at one point was of 5 min's duration. This method allowed us to determine a stable mean that characterized EMR activity at a given point.

After registration of EMR activity, the degree of the rockburst hazard at a given point of the mine working was measured by the gum volume method, which involved drilling.

2.3. An Example of EMR Measurements in Coal Mines

The first example of EMR registration at a zone of pillar influence is shown in Figure 4. The EMR sequential measurements (profiling with 3 m profiling spacing) were carried out in an extraction gallery that partly drifted into the zone of pillar influence. Duration of the EMR measurement was 5 min (see Section 2.2) at each profiling point (110 min for all profiles). As can be seen, EMR activity is anomalous

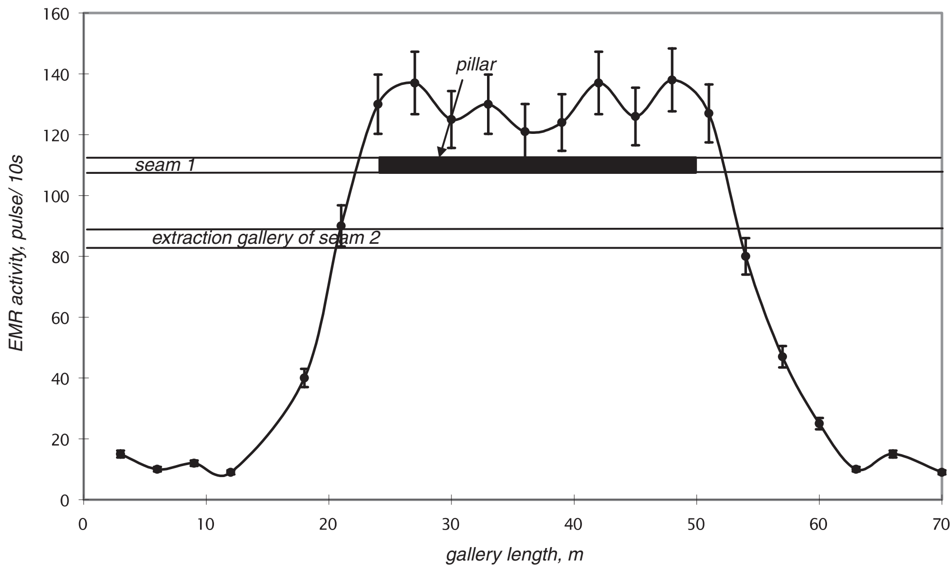

Figure 4
EMR profiling at the zone of pillar influence. The error in EMR activity is of the order of ±7.5%, while in gum value is of the order of ±0.5 l/m.

under the pillar (120–140 pulse/10 s). Gum value measurements revealed the existence of a rockburst hazard in this region (gum value was about 7–12 l/m).

Figure 5 shows the second example of an EMR registration during pillar unloading. The average level of EMR activity during the period of 21 October to 16 November was 130–150 pulse/10 s. Measurement of the gum volume showed that this pillar was rockburst hazardous (gum volume was 8–10 l/m). Unloading was performed by the drilling of 100 mm diameter holes. The holes enabled us to decrease the pillar brittle response. Drilling began on 17 November. This led to pillar unloading and both gum volume and EMR activity gradually decreased (Fig. 5).

Figure 6 shows an example of EMR monitoring during drift excavation in an intensively changeable thickness of coal seam. The regular thickness of the coal stratum was 1.5–1.7 m. A sharp decrease of the thickness of coal stratum was associated with a rockburst hazard increase (a decrease of coal stratum thickness induces a stress maximum nearer the drift face and hence a rockburst hazard increase). For example, on 7 and 26 January and on 4 March the coal stratum thickness decreased to 0.5–0.7 m, with a corresponding gum volume and EMR activity increase up to 7–10 l/m and 150–400 pulse/10 s, respectively.

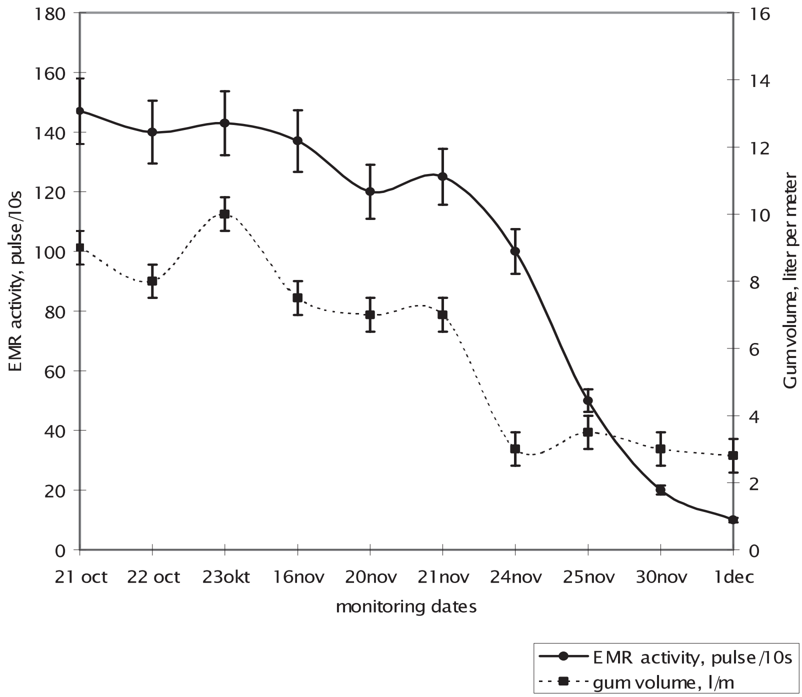

Figure 5

EMR monitoring during pillar unloading. The error in EMR activity is of the order of ±7.5%, while in gum value is of the order of ±0.5 l/m.

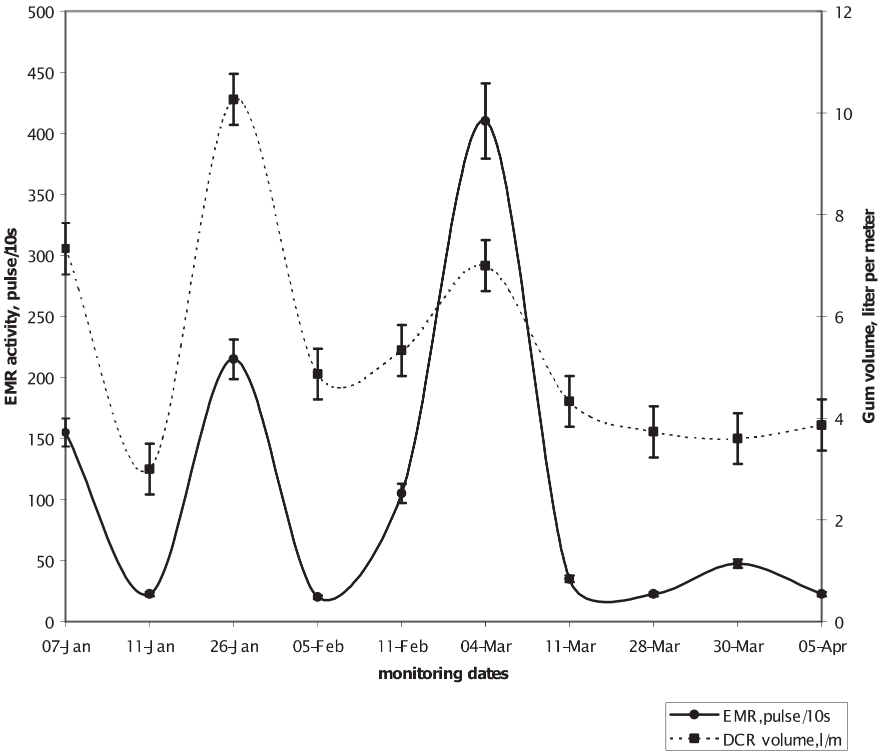

Figure 6
EMR monitoring during drift excavating in an intensively changeable thickness of coal seam. The error in EMR activity is of the order of ±7.5%, while in gum value is of the order of ±0.5 l/m.

Figure 7 shows an example of an anomalous EMR activity and gum value in a mine excavation that was opened at a distance of 8 m from uplift with a 2 m amplitude. The EMR and the gum monitoring as the excavation moved away from the uplift show a gradual decrease.

Altogether, we have carried out EMR investigations in more than 400 different rock-gas outburst conditions in underground coal mines (North Kuzbass deposit) (FRID, 1990, 1997a,b; FRID *et al.*, 1992). Our investigations indicate that an increase of rockburst hazard, accompanied by an increase of EMR activity, occurs when pillars are found above mine working, where geological faults exist in the area, and/or where seam thickness sharply diminishes (FRID, 1997b). These investigations also showed that the highly stressed zone near mine workings is the source of the EMR (FRID, 1990, 1999). Analysis of all data enabled us to determine the following empirical criterion of EMR activity:

$$N > N_{\mathrm{emp}} \ , \tag{3}$$

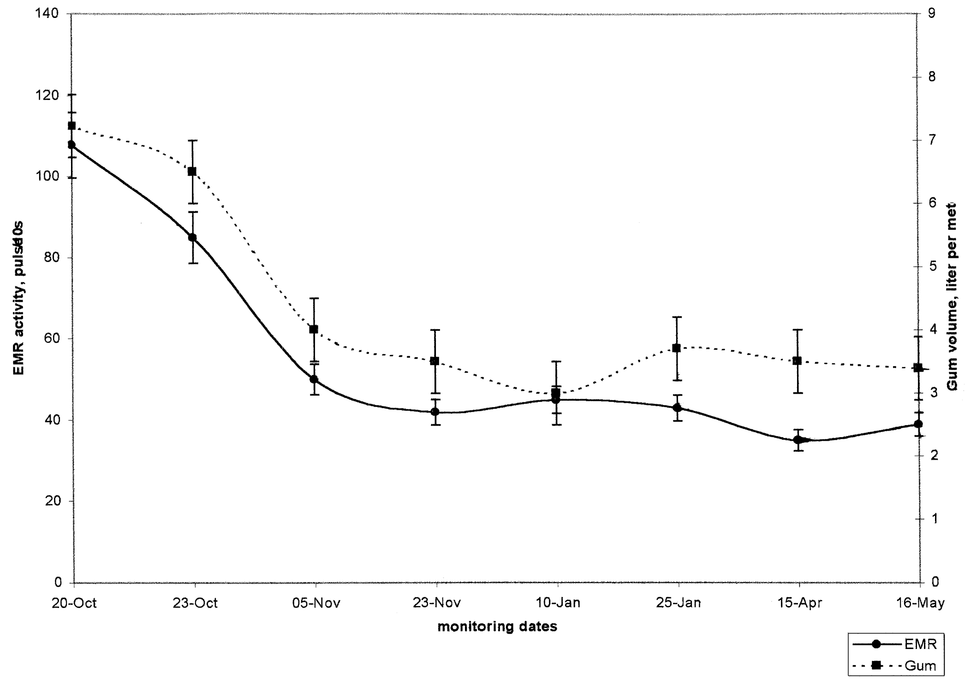

Figure 7
Anomalous EMR activity and gum value in the mine excavation near the uplift. The error in EMR activity is of the order of $\pm 7.5\%$, while in gum value is of the order of ± 0.5 l/m.

where N is the value of EMR activity registered in a mine working, and N_{emp} is the limiting value of EMR activity (115–120 pulse per 10 sec, FRID, 1997b). If the value of the EMR activity, N, exceeds N_{emp}, a rockburst hazard exists.

The time needed to determine the degree of rockburst hazard by EMR and gum methods at a given point is about 5 and 30 min, respectively. The reduced time is a significant advantage of EMR forecasting. However, the time required for data collection to establish an empirical EMR criterion at a mine is considerably longer, even extending to some years. The only way to reduce this time is to develop a theoretical model of this criterion. The following section first establishes an EMR theoretical criterion of rockburst hazard in coal mines and compares it with the EMR empirical criterion.

3. *Analysis of EMR Changes due to Coal Seam Stress Increase*

The general aim of this section is to estimate the cracking rate (the number of crack events per unit time) associated with the measured EMR activity. However, to determine this value, we must calculate the volume of the rockburst hazard zone and the size of cracks.

3.1. Calculation of Rockburst Hazard Zone Volume

Drilling for gum volume measurements in the mine is usually conducted up to the depth of increased stress $\sigma_{k\gamma H}$, although the stress maximum is usually not measured due to instrument gripping (as a result of the hole squeezing around the drill rods) in the borehole. However, for the theoretical EMR analysis it is important to know the volume of the highly stressed zone, and hence the distance from the mine working face extending to the stress maximum.

The distance to the stress maximum (Fig. 1) can be calculated as follows (PETUKHOV *et al.*, 1976):

$$X_m = \frac{1.23X_0}{\left(\frac{\sigma_c}{\sigma_{k\gamma H}}\frac{(X_0+a')}{h}\right)^{\frac{2}{3}}} + a' \tag{4}$$

where X_0 is the mine working half width, a' is the distance from the mine working face to a boundary of the zone of increased stress ($\sigma_{k\gamma H}$, Fig. 1), h is the coal stratum half thickness, and σ_c is the coal uniaxial compressive strength (11 MPa (FRID, 1990)). If we assume that the drift width, $2X_0 = 3$ m (typical for vent and tramming drifts in North Kuzbass mines) and the coal stratum thickness is $2h = 2$ m (also a representative value), we can calculate distance reaching the stress maximum from equation (4). Table 1 shows that for all rockburst hazardous conditions (4–7 meters from the mine working face, FRID, 1997b) the stress maximum is about $\xi = 1$ m from the commencement of the stressed zone ($\sigma_{k\gamma H}$ one, Fig. 1).

Let us assume that the rockburst hazard zone before coal drifting has a parallelepiped form with a width equal to the drift width ($2X_0 = 3$ m), a height equal to the coal stratum thickness ($2h = 2$ m), and a length equal to the distance from the origin of the $\sigma_{k\gamma H}$ stress zone to the stress maximum ($\xi = 1$ m). Hence, the volume of the rockburst hazard zone would be 6 m^3.

Formation of the 6 m^3 stressed zone cannot be developed instantly. As noted by KUKSENKO *et al.* (1982, 1987) the time to form a highly stressed zone is associated with its dimension. This relation is valid for laboratory fracture experiments, mine pillar loading, rockbursts and even for earthquakes (KUKSENKO *et al.*, 1985; MANSUROV, 1994) and can be fitted by the following formula

$$T = 10^{3.75}L\ , \tag{5}$$

where T is the time of stressed zone formation (sec), and L is the average dimension of the stressed zone (m).

If the volume of the stressed zone is 6 m^3, its average dimension, L, would be about 2.5 m, and according to formula (5) the time necessary to develop this zone formation will be approximately 4 hours.

3.2. EMR Source Size Estimation

Assuming that the cracking rate, n, is nearly constant during the whole period of highly stressed zone formation, this enables us to calculate, n, as follows

$$n = \frac{N'}{T} \quad , \tag{6}$$

where N' is the number of cracks created in volume V.

The crack length is associated with the time from the EMR pulse origin up to its envelope maximum (RABINOVITCH *et al.*, 1998, 1999). For 100 kHz pulses (FRID, 1997a,b), this time is about $T' = 10$–15 μs (FRID, 1990; RABINOVITCH *et al.*, 1998).

As noted by MARDER (1996), crack velocity does not exceed the Raleigh wave velocity V_R. For our case, V_R is of the order of 1100 m/s (FRID, 1990). Hence the length of the crack, ℓ, that radiates a 100 kHz EMR pulse would be

$$\ell = V_R T' = 1.1\text{–}1.65\,\text{cm} \quad . \tag{7}$$

3.3. Estimation of EMR Activity in a Hazardous Zone

As follows from the kinetic theory of failure (ZURKOV *et al.*, 1969; REGEL *et al.*, 1972; PETROV and GOROBETZ, 1983), the maximum number of cracks of length, ℓ, in a volume, V, is limited by the following relation

$$N' = \frac{V}{(k\ell)^3} \quad , \tag{8}$$

where k is about 3, the concentration factor. N' ranges between 170,000–45,000 and its average value is 107,500. Hence the limiting cracking rate (according to formula (6)) will be $n_{\text{lim}} = 7.7$ events per second. Consequently a rockburst hazard situation is predicted when the cracking rate, n, is larger than its limit value, n_{lim},

$$n > n_{\text{lim}} \quad . \tag{9}$$

The final step is to associate this criterion of cracking rate with a definite parameter of the EMR. There are numerous EMR parameters that could be measured in a mine; for example, EMR activity (as defined in Section 2.2), the number of EMR events (often registered as the number of EMR peaks) per unit time, or the energy of EMR pulses per unit time determined, for instance, by the summation of pulse amplitude squared x pulse duration per unit time, etc. All these parameters characterize only the EMR rate (number of EMR events per unit time). Therefore, comparing some EMR measured parameter, EMR activity in our case, with the cracking rate criterion, can lead to a correlation of the EMR rate with the cracking rate.

As we noted above, the EMR activity is the number of intersections (per unit time) by the EMR signal amplitude with a specific voltage level of the counter. The number of intersections formally depends on the EMR amplitude, i.e., the higher the EMR pulse amplitude, the larger the number of intersections that can cross a defined voltage threshold. However, our experience shows that the EMR amplitude is stable enough (5–50 mV/m) and does not deviate more than one order of magnitude from its average level. This phenomenon may be explained in the following manner: the EMR amplitude is a function of the crack square (crack width x crack length, RABINOVITCH *et al*., 1998, 1999) and this implies that the EMR amplitude is inversely proportional to the frequency (RABINOVITCH *et al*., 1999). Hence, if we select a definite frequency range (i.e., a definite crack width) to measure EMR activity, we discriminate by this way, a range of the EMR amplitude will be registered (the EMR amplitude deviation observed in laboratory conditions by RABINOVITCH *et al*. (1999) is also not more than one order for a given frequency).

The amplitude of EMR pulses quickly decreases after 2–3 periods (Fig. 3, RABINOVITCH *et al*., 1998). To differentiate the EMR data from mine industrial noise we preset the voltage level of our counter to register only a maximal half-wave of the signal (Fig. 3). Thus, the maximal half-wave intersects a set voltage level twice (Fig. 3), and the value of the EMR activity will be twice as high as the cracking rate:

$$N_{th} = 2n_{\lim} = 15.7 \text{ EMR pulse/sec } (157 \text{ EMR pulses}/10\,\text{sec}) \ . \tag{10}$$

Consequently, the theoretical criterion of rockburst hazard is the following: a rockburst hazard condition is predicted if the EMR activity, N, is larger than $N_{th} = 157$ EMR pulses per 10 seconds:

$$N > N_{th} \ . \tag{11}$$

As seen, the calculated $N_{th} = 157$ EMR pulses per 10 sec and the empirical $N_{\text{emp}} = 115$–120 pulses per 10 sec criteria are close enough.

Generalizing formulas (6, 9–11) we can formulate a theoretical EMR criterion via the theoretical value of cracking rate, for a given mine situation

$$N > N_{th} = kn_{\lim} \ , \tag{12}$$

where N is the measured in mine working value of a definite EMR parameter, N_{th} is the theoretical limiting value of this EMR parameter, k is the coefficient that depends on the type of measured EMR parameter (coefficient, k, for our case is equal 2, but if we measure the number of EMR peaks, k will be equal 1), and $n_{\lim}$ is the limiting cracking rate.

Our theoretical approach based on a minor number of parameters (limiting value of gum volume, typical mine working width, coal seam thickness, and coal uniaxial compressive strength) enables us to estimate a value of the EMR criterion that must be verified by mine investigations. Its adoption would significantly reduce the time to develop an EMR criterion and simplify EMR use in coal mines.

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