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Operation complexity as one of the injury factors of coal miners

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Abstract

Purpose is to identify regularities of miners' injuries in the process of manufacturing operations based upon assessment of labour conditions in terms of energy intensity of a body.

Methods. Analysis of the basic manufacturing operations, monitoring of a working process and functional conditions of bodies of miners, involving methods of mathematical statistics, determined the probability of injury of miners according to the value of their energy losses.

Findings. It has been proved that to avoid potentially hazardous situation it is required to take into consideration energy cost of the performed operations which should correspond to psychophysical potential of miners. Conditional boundary of difficult continuous restless activities has been identified. It is 290 W being the upper boundary of energy losses. If the difficulty index is more than 290 W then the probability of injury of miners is 74%. If the index is 290 up to 464 W then the probability is 60%.

Originality. A relationship between injury level of miners and difficulty of the performed operations has been identified; the relationship is assessed with the help of energy losses by their bodies. Methods to analyze accidents in terms of their situational patterns have been proposed. The methods rely upon a workplace analysis as well as activities before an adverse event and labour conditions in terms of energy losses by victims.

Practical implications. Methods to identify difficulty of labour of miners and duration of compensatory breaks during work performance have been developed. The methods may be quite useful while investigating accidents, assessing labour conditions of miners, and technical documenting. Moreover, they are necessary for the development of measures making labour of miners safe.

Keywords: *hazardous factors, labour conditions, injury ,energy losses, body, difficulty of operations*

1. Introduction

Mining remains the most hazardous world industry. The fact is supported by numerous studies on labour safety during underground mining [1]-[4]. Recently, industrial accident rates have decreased considerably owing to the progress in coal extraction methods and development as well as improvement of measures protecting labour of miners. Nevertheless, despite the abovementioned, the number of injures in the process of underground mining, inclusive of those with fatal consequences, is several times higher as compared to other industries [1].

The majority of the injuries depend upon complex mining and geological conditions of coal seam extraction; a gap between biomechanical and psychophysical capabilities of miners, and pace of equipment operation; inadequate behaviour of staff; and serious engineering mistakes. 80-95% of such accidences results from a human factor [5]-[7]. Usually, the reasons are as follows: violation of rules; erroneous and forced actions by performers or their inactivities. The steps take place while planning and designing. They create objective conditions for incorrect measures in the process of work organization and management as well as in the process of manufacturing activities. Safe operation results from labour conditions. The conditions are characterized by such factors of production environment and labour process as the work difficulty, ambient dust, illumination, noise, vibration, and microclimate. The factors may be both hazardous and dangerous for health and life of miners. Sometimes, they lead to careless and unsafe functioning practices; violations in operation sequences; mistakes by miners etc. Such actions result in accidents. In the majority of the situations, blame is delegated either fully or partially to a victim irrespective of labour conditions and circumstances of the accidents. In this context, the fact of creation of safe working environment is ignored.

At their workplaces, miners cannot evaluate adequately the environment due to intensive psychophysical stress when they work under the conditions of numerous hazards. Mining operations are influenced by ambient dust, vibration, high temperature, barometric pressure, noise, poor illumination, high air speeds, and moisture.

The work of miners is characterized as moderately debilitating and difficult activity with elements of hard physical labour. It is followed by nervous and emotional tension. Moreover, it needs the heightened attention, hearing, vision, and mobility due to the restricted workspace and inconven-

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ient working postures. Under the conditions, miners make mistakes, loose the opportunity to assess situation at their workplaces, and violate production safety rules.

In addition to other unfavourable circumstances, individual noise influence factors into the increase number of overall morbidity and occupational morbidity as well as decrease in labour productivity of miners. 70 up to 90 dB noise intensification in the workplace involve 20% increase in physical and neuro-psych efforts [8]. Noise detracts miners from useful information, warning signals, and alarms. The abovementioned may give rise to emergency and injury.

Vibration is among one of the main factors influencing labour conditions of miners. The matter is that vibrations of machines and their parts often result in malfunctions and hence, sources of injury of miners.

Dusty environment prevents from receiving warning signals and alarms; thus, miners cannot evaluate adequately situations in their workplace.

Illumination also influences heavily labour safety. In mine workings, staff operates in poor light conditions. It is difficult for a miner to evaluate situation at own workplace while using mobile rechargeable lamps.

Temperature and air humidity affect significantly human capacity for work. Low temperature-high humidity combination has a tangible cooling effect on miners. Body resistance drops if physical fatigue takes place. Excessive temperature and mine air humidity result in lost productivity. Hence, miners must either simplify or accelerate manufacturing operations which give rise to inevitable mistakes.

It is also important to take into consideration psychophysical conditions of labour of miners. Difficulty is the key index of their operations since miners perform hard work. Physical labour is characterized by the intensive muscle strength and the increased load on the musculoskeletal system and functional systems of the body. Physical heaviness is determined by work strength and value of a static effort involving load weight; travel distance; working postures; nature of working movements; and tension degree of physiological functions. The following can be considered as the key indices of labour difficulty: energy losses of the body, load weight, the number of stereotypic working movements, static load etc. [9].

Several studies determined energy value of certain operations [10]-[13]. Their findings helped identify energy values of the operations [10], [11]; in addition, certain regularities of energy loss impact on miners were defined [12]. Difficulty of operations has been specified to improve working schedules, identify rest periods for miners as well as biomechanical load on the body [13]. Energy losses of the miner's body, fatigue, and potential to be injured depend upon energy consumption of operations. Fatigue favours accidents and injuries. It is subject to working hours; labour conditions; and physical efforts [14].

To resist injury of miners, energy potential of the body should correspond to their psychophysiological load. Studies, concerning interaction between injury level and energy losses by the injured are important. Determination of labour condition influence on the labour safety of miners will help develop technological and organizational measures decreasing injuries in the workplace. The measures are necessary for longwalls characterized by the highest level of manual work, high number of miners, and the peak concentration of harmful and dangerous production factors.

Mostly, research of industrial accidents at mining enterprises focuses on the processing of annual statistical data [15]-[18] and injury evaluating during the basic production operations [19]-[22]. At the same time, it is required to analyze accidents at the level of the certain manufacturing procedures. Studies concerning impact of difficulty of the operations on the injury level of miners are of particular interest. The studies will help develop specific measures to improve safety, and decrease injury within mining sites.

Consequently, the research objective is to identify injury regularities of miners during operation under hazardous labour conditions in terms of energy losses of their bodies. The achievement of the objective is to:

– analyze labour conditions of miners as for the difficulty of their activities;

– evaluate operations, prioring injury of miners, according to energy losses;

– identify impact degree of difficulty of the work on the injury level.

2. Methods

To identify accident level of miners during their performance of certain operations, it is quite expedient to analyze reports on employee injury as well as result of accident investigations. The documents are titled differently in countries: "Work Injury Accident Report", "Accident/Incident Report", "Employee's Report of Injury Form", "Incident Investigation Report", "Act on the Work-Related Accidents" etc. The reports inform on the victims; date, time, and location of the accident; names and positions of the involved miners and authorities; description of events which resulted in the injury; and their conditions and circumstances.

In this context, workplace graphics should also be used; results of chronological observations; time standards for operations; and information by witnesses and injured. Analysis of mining schedules as well as work organization schedules may help identify regularities of injuries of miners.

To determine human work capacity and its correspondence to psychophysical capabilities of labour conditions, it is proposed to define energy losses of a miner's organism. Following known approaches may be helpful: doubly labeled water (DLW); direct calorimetry; indirect calorimetry; accelerometry, heart rate monitor (*HR*), pedometry, and self-report methods [23], [24]. A method determining energy losses depending upon a heart rate is the most popular one to measure physical activity [23].

Physiological and ergonometric characteristics have helped determine dependence of energy losses of a miner's body N_i upon heart rate *HR* being [24]:

$$N_i = 10.4\left(HR - 71.6\right), \text{ W.} \tag{1}$$

Based upon the data on energy losses resulting from certain operations as well as their duration, it is expedient to identify intensity of energy losses by a body, and evaluate labour difficulty of miners [25]. The total work (E_T, J) during operation or their combination within some production cycle during t period is determined using the expression:

$$E_T = \sum_{i=1}^{n}\left(N_i t_i\right), \tag{2}$$

where:

t_i – duration of i^{th} operation, minutes;

N_i – the weighted average of energy losses by i^{th} operation (W+).

The N_i losses are defined from the expression:

$$N_i = \frac{k_w \cdot N_T}{t}, \tag{3}$$

where:

k_w – a work intensity coefficient (k_w = 0.65-0.8 for miners).

A normative value of absolute energy losses body is 290 W for men [26]. If the value is exceeded then such labour conditions are considered as hazardous, and the work is considered as difficult [9]. Ratio between the total actual energy losses by a miner and the normative value characterize labour difficulty coefficient (units):

$$k_d = \frac{N_T}{290}, \tag{4}$$

where:

290 – a conditional boundary of restless continuous work for able-bodied men, W.

If $k_d < 1$ then labour conditions are considered as the safe ones. If the index is exceeded then labour conditions are more intensive. In this context, a miner needs compensatory rest. A break for rest t_r depends upon work difficulty. Following formula determines it:

$$t_r = \left(1 - \frac{1}{k_d}\right) \cdot t_p, \tag{5}$$

where:

t_p – a production period, minutes.

If $k_d < 1$ then no break is required.

Difficult and very difficult operations consume more than 290 W. During two hours a miner can operate rather quickly; then the pace slows down, and fatigue is accumulated. Hence, the total period of brakes for miners should be calculated for a period being no longer than two hours. Intervals between the breaks have to be divided equally during working hours to make the operations safer.

Certain operations in coal mines have been monitored to identify the energy losses. The observations lasted for several shifts starting from descending into the mine up to rising to the surface. Random selection was applied for miners engaged in various operations; physiological and ergonometric characteristics of the workers were recorded.

Depending upon the heart rate measurements (with 8% relative error and 0.95 reliability), each operation was considered from the viewpoint of the required determinations; their number turned out to be 643. Use of the measurements as well as Expression 1 has helped identify average energy losses of body of miners (Table 1). Expression 5 has made it possible to define the recommended break share within the total operational period (Table 1). The indices offer the possibility to evaluate labour conditions, and identify the increased risk areas.

Accidents at mining enterprises are of mass nature and of the random one. It helps describe them by means of proper statistical distribution laws. Such an approach will make it possible to identify impact of labour condition indices on the injury level of miners.

To analyze working environment of miners in the context of coal mines, and define interrelation between difficulty of operations and injury level, reports on accidents in nine stopes of Shakhtoupravlinnia Pivdennodonbaske #1; Shakhtoupravlinnia Pokrovske; Kotliarevska mine; and M.S. Surgai mine (Ukraine) have been applied. Analysis of reports on accidents within a western longwall 14 of c_{18} seam of Shakhtoupravlinnia Pivdennodonbaske has helped determined 20 accidents within a mining site (Fig. 1).

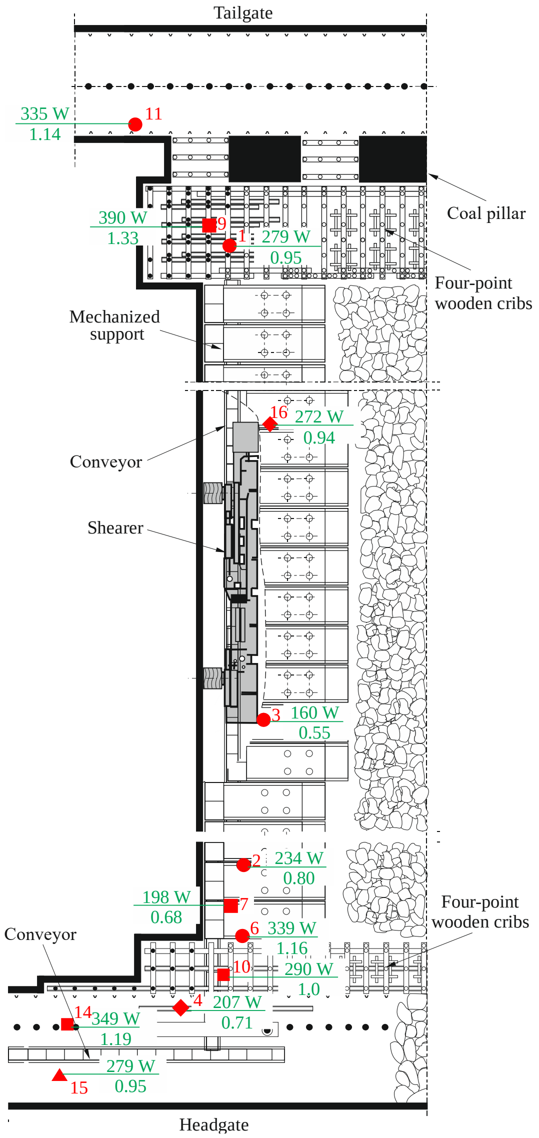


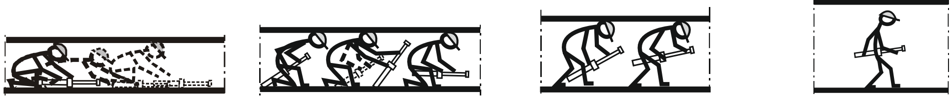
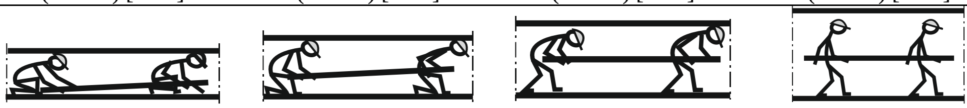
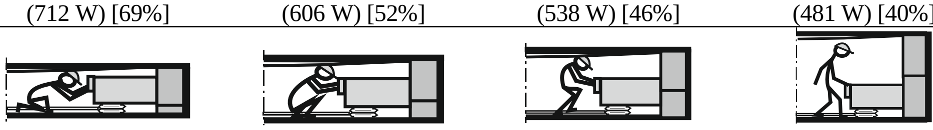
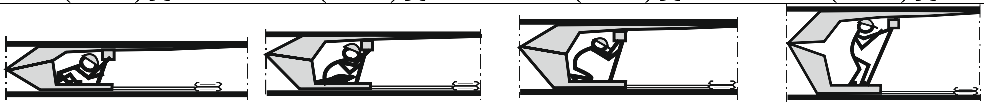
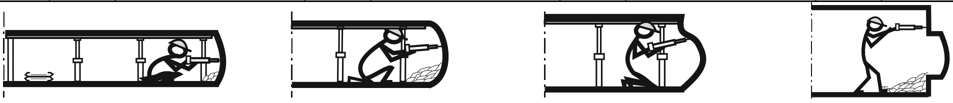
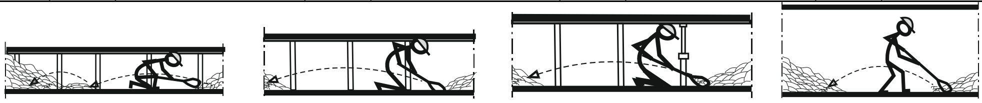
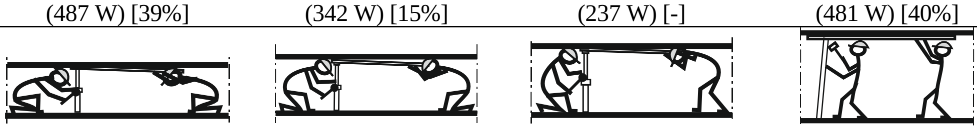
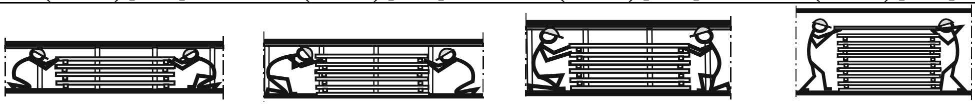
Figure 1. Mining schedule of a western longwall 14 of c_{18} seam; accident areas are specified (■ – injuries by machines and mechanisms; ● – injuries resulting from the dropped objects and materials; ▲ – injuries resulting from people fall; ♦ – injuries resulting from rock fall)

Situational analysis of the events, resulting in accidents, has been made in terms of operational schedule (Fig. 1) and in terms of a timetable of the work organization. For each case, chronology of basic activities of the production process up to the adverse moment origination has been developed.

3. Results and discussion

Based upon the information on the operation duration and energy loss, depending upon the activity type, the total energy consumption by a miner has been calculated as well as difficulty coefficient (Table 1). It has been identified that in the majority of cases miners operated without any excess of the allowed energy (290 W). Four cases demonstrated exceedence by 1.14-1.33 times.

Table 1. The results of determination of average energy losses by miners for the certain working postures while performing the basic operations

Operation	Working postures of miners (average energy losses, W) depending upon an actual operation as well as working space height *h* (the recommended break share for a shift, %)			
	h = 0.65-0.89 m	*h* = 0.90-1.05 m	*h* = 1.06-1.70 m	*h* > 1.70 m
Load-free movement 	(558 W) [48%]	(475 W) [39%]	(422 W) [31%]	(377 W) [23%]
Load movement by one person 	(935 W) [69%]	(796 W) [64%]	(707 W) [59%]	(628 W) [54%]
Load movement by several people 	(712 W) [69%]	(606 W) [52%]	(538 W) [46%]	(481 W) [40%]
Coal shearer operation 	(277 W) [-]	(218 W) [-]	(174 W) [-]	(156 W) [-]
Mechanized support operation 	(513 W) [43%]	(452 W) [36%]	(425 W) [32%]	(408 W) [29%]
Coal breaking by means of a pickhammer 	(418 W) [31%]	(418 W) [31%]	(454 W) [36%]	(427 W) [32%]
Use of a shovel to throw: – rock; – coal 	(768 W) [62%] (452 W) [36%]	(716 W) [59%] (411 W) [29%]	(704 W) [59%] (411 W) [29%]	(746 W) [61%] (439 W) [34%]
Foot cleaning 	(487 W) [39%]	(342 W) [15%]	(237 W) [-]	(481 W) [40%]
Installation of hydraulic supports 	(362 W) [20%]	(349 W) [17%]	(349 W) [17%]	(338 W) [14%]
Installation of timber supports 	(614 W) [53%]	(593 W) [51%]	(593 W) [51%]	(565 W) [49%]
Chock construction using tie bars 	(396 W) [27%]	(337 W) [14%]	(299 W) [3%]	(267 W) [-]

99 cases of accidence with miners have been analyzed for eight stopes. The following can be considered as the key injury sources: individual carelessness and ignoring of official duties. The cases prevail in 94.5%.

Relying upon the values of energy losses by miners, preceding accidents, sample for statistical analysis has been formed. For 99 units of the sample, indices of statistical distribution function $F^*(x)$ have been calculated (Table 2); and its graph has been plotted (Fig. 2). Previously, the sample consistency with normal distribution has been examined [27].

Since the observations are numerous, Sturges rule has been applied to the extended intervals [28]:

$$k = 1 + 3.322 \log n. \quad (6)$$

According to calculations, k = 7.6; hence, there are eight intervals. Their dimension is:

$$h = \frac{x_{\max} - x_{\min}}{k} = \frac{699 - 160}{8} = 67.375 .$$

Table 3 demonstrates frequency and values of the statistical distribution function.

Table 2. Calculation results for the values of statistical distribution function to develop grouped statistical series

Random value interval, W	Value of the random X value within corresponding interval, W	n_i frequency, units	Value of the statistical distribution function $F^*(x)$, units
$x \leq 148$	–	0	0
$148 < x \leq 172$	160, 169, 169	3	0.030
$172 < x \leq 196$	179	1	0.040
$196 < x \leq 220$	198, 203, 207, 216, 216, 219	6	0.101
$220 < x \leq 244$	223, 224	2	0.121
$244 < x \leq 268$	–	0	0.121
$268 < x \leq 292$	268, 272, 272, 273, 273, 279, 286, 286, 287, 287, 290, 290, 292	13	0.253
$292 < x \leq 316$	301, 302, 303, 311, 311, 314, 315, 315, 316	9	0.343
$316 < x \leq 340$	318, 320, 323, 326, 329, 329, 333, 333, 335, 339	10	0.444
$340 < x \leq 364$	341, 343, 344, 344, 345, 346, 348, 349, 357, 358, 358, 362	12	0.566
$364 < x \leq 388$	366, 368, 369, 372, 374, 376, 377, 377, 384, 386, 387, 388	12	0.687
$388 < x \leq 412$	393, 397, 397, 397, 398, 401, 402, 404, 412	9	0.778
$412 < x \leq 436$	417, 424, 425, 427, 431	5	0.828
$436 < x \leq 460$	438, 442, 448, 449, 449, 459	6	0.889
$460 < x \leq 484$	463, 479	2	0.909
$484 < x \leq 508$	–	0	0.909
$508 < x \leq 532$	509, 529	2	0.929
$532 < x \leq 556$	548, 551	2	0.949
$556 < x \leq 580$	560, 563	2	0.970
$580 < x \leq 604$	–	0	0.970
$604 < x \leq 628$	614, 621	2	0.990
$628 < x \leq 652$	–	0	0.990
$652 < x \leq 676$	–	0	0.990
$676 < x \leq 700$	699	1	1.000

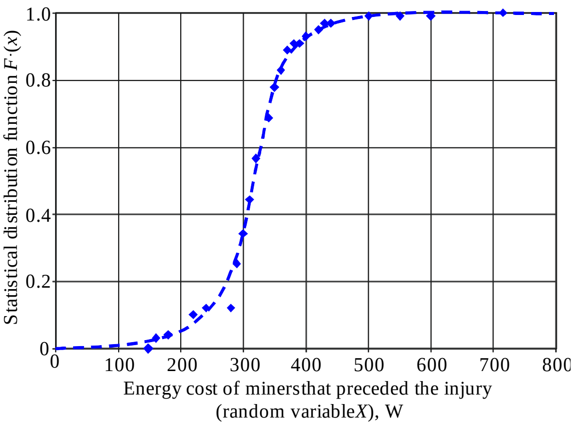


Figure 2. Graph of statistical distribution function of a random energy loss value

Figure 3 shows a distribution histogram of the total number of the injured miners.

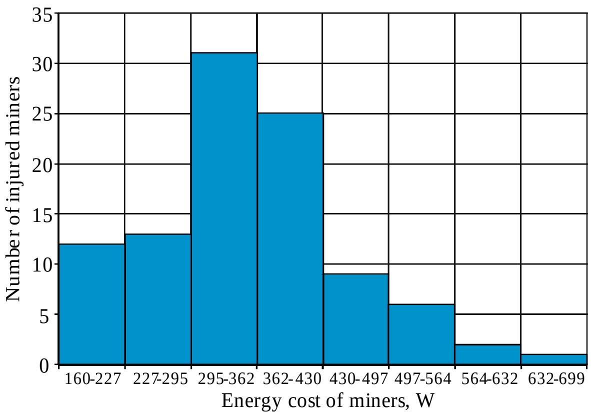


Figure 3. Frequency histogram of distribution of the total number of the injured miners in terms of the extended intervals

Table 3. Calculation results of the values of statistical distribution function in terms of the extended intervals

Random value intervals, W	n_i frequency, units	Value of the statistical distribution function $F^*(x)$, units
$160 < x \leq 227.375$	12	0.121
$227.375 < x \leq 294.75$	13	0.253
$294.75 < x \leq 362.125$	31	0.566
$362.125 < x \leq 429.5$	25	0.818
$429.5 < x \leq 496.875$	9	0.909
$496.875 < x \leq 564.25$	6	0.970
$564.25 < x \leq 631.625$	2	0.990
$631.625 < x \leq 699.00$	1	1.000

25% of the accidents happen if energy losses are up to 295 W; 56% take place if energy losses are 295 up to 430 W; and 18% occur if energy losses exceed 430 W.

To analyze empiric function, following statistical indices of sampling frame have been calculated: median, mode, asymmetry, and excess. Median value turned out to be 348 W. Hence, asymmetric distribution is of a moderate nature. Average random value being 353.6 is about 345.3 mode, and 348.0 median which supports normal distribution of the sampling frame. The distribution is conical with right-side asymmetry. Such a variation coefficient as 28.35% < 30% indicates uniformity of the frame as well as its poor variation.

Pearson's chi-squared test has been applied to verify the hypotheses on the normal distribution of the sampling frame. Insignificant discrepancy has been identified between empiric and theoretical frequencies (Fig. 4) matching the hypothesis on the normal distribution of the sampling frame coincidence of empirical and analytical data is 97.4%.

Analysis of the statistical indices shows that maximum probability of injury of miners is if energy losses are 353.6 W (Fig. 4).

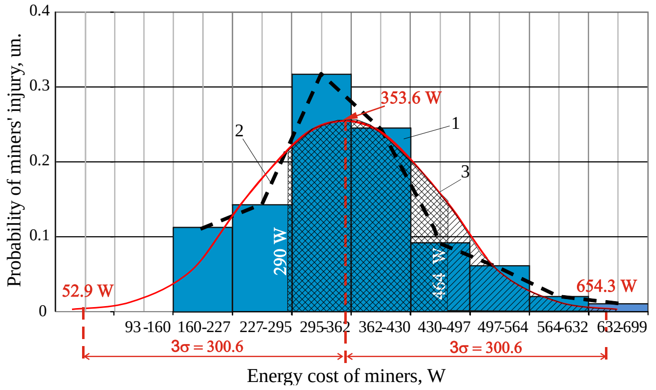


Figure 4. Histogram (1); empirical differential curve (2); theoretical differential curve (3)

The injury probability is 10% less within the sites where energy losses are less than 224 W (for operations with low difficulty) or if the losses are more than 500 W (if very difficult operations are not numerous). Distribution nonuniformity has been studied with the help of the statistical distribution development which involved Pareto chart [29].

To develop Pareto chart, energy losses in terms of intervals were assumed as a random value; and relative frequencies were assumed as a function (Table 4). The random value division into the intervals, Public Health Standards and Rules, concerning different labour conditions, were taken into consideration [9].

Table 4. Injury distribution depending upon the energy losses by miners

Intervals of energy losses, W	The number of accidents (frequency), units	Rate of accidents (relative frequency), %
$116 < x \le 174$	3	3.030
$174 < x \le 232$	8	8.081
$232 < x \le 290$	13	13.131
$290 < x \le 348$	27	27.273
$348 < x \le 406$	25	25.253
$406 < x \le 464$	13	13.131
$464 < x \le 522$	2	2.020
$522 < x \le 580$	5	5.051
$580 < x \le 638$	2	2.020
$638 < x \le 699$	1	1.010
Total	99	100.000

According to the Standards, values of energy losses are classified as follows:

– class 1 (optimal) – up to 174 W;
– class 2 (permissible) – 174-290 W;
– class 3.1 (risky) – 291-348 W;
– class 3.2 (risky) – 349-406 W.

The energy loss intervals have been ordered in terms of the decrease in the number of accidents (Table 5).

Corresponding dependence graph has been plotted based upon the accumulated rate of accidents in terms of energy loss intervals (Fig. 5).

The dependence has helped understand that 68% of accidents fall into 32% of energy loss range. In such a way, 290-464 W range of energy losses by miners is the most injury-causing one. The range corresponds to the risky labour conditions (group A in terms of difficulty). Energy losses, involved in the interval, need attention by the authorities while the working process organizing to offset the risk of injury-causing situations.

Table 5. Accumulated rate of accidents in terms of energy loss intervals

Accumulated proportion of energy loss intervals, %	Intervals of energy losses, W	Rate of accidents, %	Accumulate rate of accidents, %
10.0	$290 < x \le 348$	27.273	27.273
20.0	$348 < x \le 406$	25.253	52.526
30.0	$406 < x \le 464$	13.131	65.657
40.0	$232 < x \le 290$	13.131	78.788
50.0	$174 < x \le 232$	8.081	86.869
60.0	$522 < x \le 580$	5.051	91.920
70.0	$116 < x \le 174$	3.030	94.950
80.0	$464 < x \le 522$	2.020	96.970
90.0	$580 < x \le 638$	2.020	98.990
100.0	$638 < x \le 699$	1.010	100.000

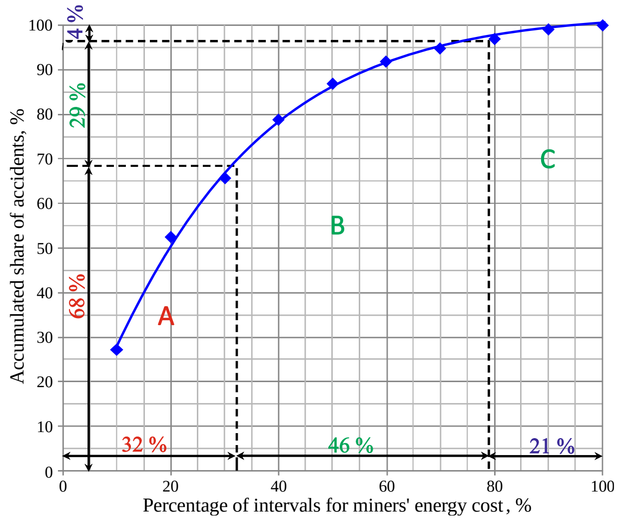


Figure 5. Dependence of the accumulated accident rate upon the proportion of energy loss intervals

B and C groups involve ranges belonging to risky labour conditions. Nevertheless, the conditions are characterized by a small number of accidents since it is impossible to operate with more than 464 W load over a long term.

Analysis of injury within the studied stopes has shown that 75.8% of accidents happen if energy losses by miners are more than 290 W. Taking into consideration the fact that the random value distribution is subject to a normal law, the probability of injury of miners within 291-654.2 W energy loss interval was determined according to 3σ rule and became 73.5%. For 291-464 W interval, considered as the most injury-causing, the probability was 60.2%.

4. Conclusions

A fatigue degree of miners, operating in hazardous environment, has been evaluated in terms of energy losses depending upon heart rate. Based upon the measurements of heart rate of miners in stopes, the average energy losses have been determined. The recommended values of break duration have been calculated to optimize mining schedule. The approach helps achieve decrease in injury rate.

Changes in heart rate of miners have been identified depending upon their activity types. If heart rate increases 76 up to 168 bpm then energy losses by miners vary from 46 up to 1003 W. The majority of operations are performed under risky conditions when energy losses by miners are more than 290 W.

Statistical processing of indices of energy losses by miners has helped define that 68% of accidents fell into 32% of the analyzed energy loss range, i.e. 290 up to 464 W. Injury probability for miners, losing more than 290 W of energy, is 74%; 60% of them are within 290-464 W range.

It has been recommended to develop labour protection measures if operations involve more than 290 W energy losses, i.e. such organization of work where energy losses cannot exceed 290 W or implementation of hourly break for compensational rest of miners. The break should be 15 to 69% of operating time depending upon the work difficulty.

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Важкість виконуваних операцій як один з чинників травмування шахтарів вугільних шахт

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Мета. Метою дослідження є встановлення закономірностей травмування шахтарів при виконанні основних виробничих операцій на основі оцінки умов праці за величиною енерговитрат їх організму.

Методика. На основі аналізу основних виробничих операцій, спостереження за робочим процесом та функціональним станом організму гірників із залученням методів математичної статистики визначалася ймовірність травмування шахтарів за величиною їх енергетичних витрат.

Результати. Доведено, що з метою недопущення виникнення травмонебезпечних ситуацій необхідно враховувати енергетичну вартість виконуваних робіт, яка має відповідати психофізіологічним можливостям шахтарів. Встановлена умовна межа важкості безперервної роботи без відпочинку, яка складає 290 Вт і є верхньою межею енерговитрат. За умов показника важкості вище 290 Вт ймовірність травмування шахтарів складає 74%. У діапазоні показника важкості від 290 до 464 Вт ймовірність травмування шахтарів складає 60%.

Наукова новизна. Встановлено взаємозв'язок між рівнем травматизму шахтарів та важкістю виконуваних робіт, яка оцінюється величиною енерговитрат їх організму. Запропоновано методику аналізу нещасних випадків за їх ситуаційною картиною. В основу методики покладено аналіз робочого місця й операцій до настання несприятливої події, та умов праці за величиною енерговитрат потерпілих.

Практична значимість. Розроблено методику визначення важкості праці гірників і тривалості компенсаційних перерв під час виконання робіт. Вона може бути використана при розслідуваннях нещасних випадків, оцінюванні умов праці гірників та складанні гірничотехнічної документації. Запропонована методика є необхідною під час розробки заходів щодо створення безпечних умов праці гірників.

Ключові слова: *небезпечні фактори, умови праці, травматизм, енергетичні витрати, організм, важкість робіт*