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National Mining University



**PARAMETERS OF EXPLOSION-PROOF FACILITIES TO AVOID
AIR-BLAST IN THE CONTEXT OF UNDERGROUND ORE MINING**

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The monograph concerns problems of explosion-proof facilities parameters substantiation to avoid air-blast while underground ore mining with the help of drill-and-fire systems. Strength and deformation features of bulkhead protective element have been tested; dependence of its carrying ability on perforation degree and structural component strength features has been determined. Results of theoretical, laboratory, and field research make it possible to substantiate parameters of air-proof bulkhead and develop recommendations concerning its application under specific mining and geological conditions. The monograph is for students, engineers, experts of higher educational institutions, research institutions, and design offices of ore mining branch.

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INTRODUCTION

In ore mining the use of heading-and-stall methods, blasting operations are those basic production processes effecting other application areas. Large-range blasting operations which cause the formation of the air blast are mainly performed. Spreading along mine workings at the great distance they destruct constructions, communications and equipment, and deform support. It causes economic damage to the mining enterprise and leads to the downtime of the mining industry.

In the process of ore mining “Zaporozhye Iron-Ore Industrial Complex” CJSC faces the problem of the negative effect of the air blast on the stowing bulkheads. Their damage results in the penetration of the stowing material into the workings of the mining horizons. It leads to emergency situations at the plant. Moreover, economic loss is about UAH 30-80 thousand a year.

Mining enterprises apply various constructions of the explosion-proof bulkheads to protect underground structures, communications and equipment against air blast. Concrete, wood, metal, anchors, wire rope cables, conveyer belts are used for the purpose. As a rule, these bulkheads are of single use. They are of great weight and structural bulkiness. Thus, it is a problem to deliver them and assemble. Usually, bulkhead parameters are insufficiently substantiated. That leads to the emergency situations (ventilation deterioration, difficulties with staff and equipment delivery etc.).

Methods of bulkhead calculation to prevent air-blast are sophisticated not involving diversity of various designs. Behaviour of air-blast as well as its interaction with different equipment and communications is not adequately investigated. During two last decades, sources practically ignored the problems.

Thus, development of reusable air-blast bulkheads having flexible characteristic, high carrying abilities, small weight and erection quickness is an important problem which solution will help to improve reliability of industrial processes while ore mining by heading-and-stall methods, and decrease labour intensity as for assembling/disassembling explosion-proof bulkheads.

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CHAPTER 1. STATE-OF ART, OBJECTIVE AND TASKS OF THE RESEARCH

1.1. Features of Blasting Operations while Ore Mining

Air-blast is one negative outcomes of blasting operations while ore mining by heading-and-stall methods. The latter are widely used in our country [7, 12, and 13]. Thus, in Krivoi Rog iron-ore field their share is almost 70 %; in the context of “ZIOIC” CJSC it is 100%.

A stope is prepared as follows (Fig.1.1). Stone heads 1 are driven in a footwall and a sidewall of deposit. Then drilling orts 2 are passed; from both sides of the deposit technologic holes 3 and drain holes 4 connect them and working 5 for vibratory feeders. After that sectional blasting forms slot 6.

Ore braking is performed by the ring holes drilled from drilling orts. Chamber is completely drilled before stoping starts. Stopping operations within the chamber carried out with the help of mass explosions [10, 34, and 45].

Underground mass explosions are those required more time for ventilation and work continuation either in a mine or at the territory of a certain area than it is stipulated by routine [10].

As a rule, ore ventilation after mass explosions is about 10-15 hours [43].

Mass explosions are performed according to the standard blasting procedure. It includes technical calculation of mass explosion, its order characteristic of mineable block (panel), parameters of deep holes or chamber charges, estimated indicators of explosion (estimated specific consumption of explosives as well as total quantity of explosives per explosion, amount of blasted rock mass and yield of ore per a meter of a hole etc.) estimation of blasting lone, ventilation; safety measures [35].

Engineering design consists of the following: background (type of explosive, its quantity; charging technique and charge design; the number of holes and charging chambers); blasting parameter table involving actual length of holes and their diameters as well as lengths of their chargeable part; diagrams of actual location of holes (charging chambers) with updated geological and surveying data; plan of explosive network including detonating cord run, location of primers, intervals of delays and blast firing sequence; ventilation scheme involving directions of fresh air and return ventilation air.

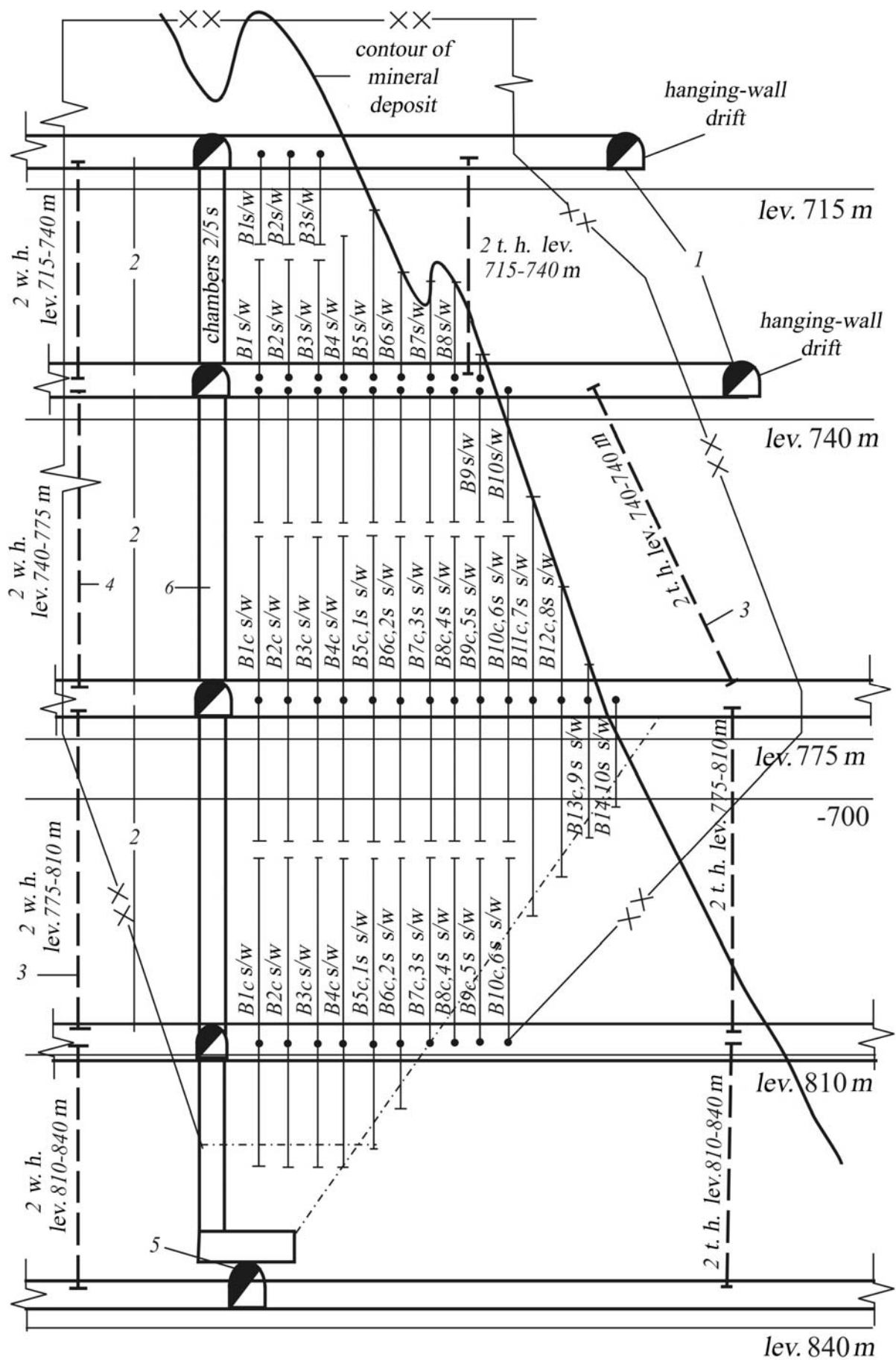


Fig. 1.1. Vertical section of 2/5 chamber in "Ekspluatatsionnaia" mine ("ZIOIC" CJSC)

According to [23-25, 35] instructions, together with mentioned parameters, it is required to identify dangerous areas in terms of air-blast effect; the zones are identified according to “Interim instructions concerning determination of dangerous area boundaries while preparing mass underground explosions” [15]. The boundaries should be determined for a period of charging; introduction of primers into charged holes; and tying in the blast according to nomogram. The task is rather labour-intensive for engineers and technicians due to the great number of both diverging mine workings and serious mass of blasted explosives; it often results in 10-15% of errors in estimations.

Mass explosion in “Ekspluatatsionnaia” mine (“ZIOIC” CJSC) to cut excess of a chamber, amount of explosives is about 14000 kg; if breaking and undermining it is 15000-38000 kg.

As a rule, blasting is simultaneously performed in four or six chambers.

Today “ZIOIC” CJSC applies imported pneumatic equipment to reduce negative effect of air-blast. Before mass explosion the equipment is transported to underground garage where effect of air-blast is excluded [73].

Stowing operations are affected by air-blast in the process of ore mining by heading-and-stall methods. To isolate operating space of mine workings from stowing mixture entry, stowing bulkheads are applied; as a rule, they are made of wood. Almost sixteen stowing bulkheads are installed per one worked-out chamber [27, 63, and 69].

Fig. 1.2 demonstrates standard design of stowing bulkhead. It is installed in orfts when a chamber is being prepared to be filled with consolidating stowing.

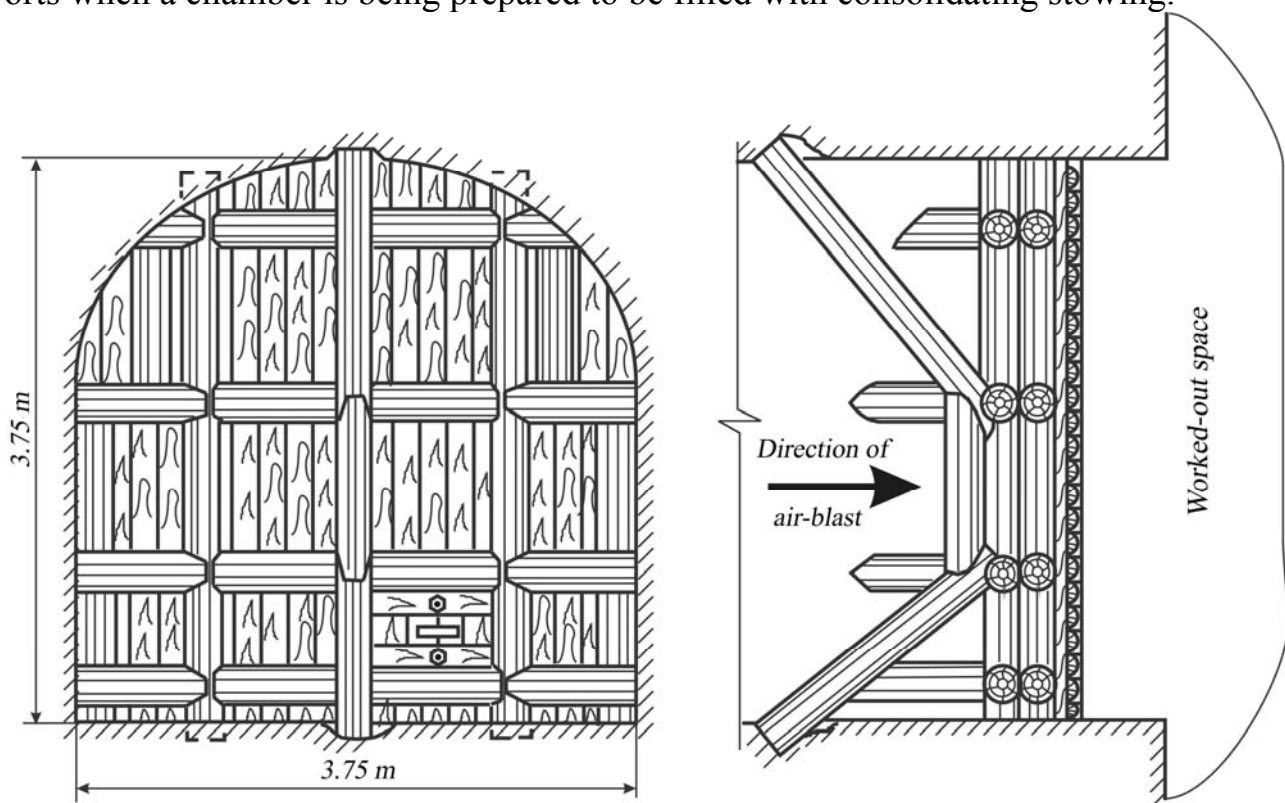


Fig. 1.2. Wooden stowing bulkhead

As Fig. 1.2 explains stowing bulkhead has not any support from worked-out space. Rather often blasting process results in the fact when air-blast reaches mine workings where stowing bulkheads are installed. Even if pressure at the front of air-blast is 0.01 MPa then 1000 kg effort acts on a square meter of a bulkhead damaging it.

On the average, cost of one stowing bulkhead is UAH 2500; its erection takes sixteen shifts.

Explosion-proof bulkheads are applied to protect stowing bulkheads against air-blast. Belt bulkheads and flexible slot bulkheads are widely used. However, their design defects prevent them from meeting modern mining demands in full. As nomograph is used for calculated values of air-blast parameters they can differ from actual ones. As a result explosion-proof bulkheads will not provide required coefficient of air-blast prevention. That involves damage of stowing bulkhead or other protected object factoring into economic loss of the enterprise.

A number of research organizations and higher mining educational institutions (Scientific and Research Ore Mining Institute of State Higher Educational Institution “Kryvyi Rig National University”, Kryvyi Rig National University, N.S.Poliakov Institute of Rock Mechanics of NAS of Ukraine, National Mining University and others) were engaged in the problem of ore mining by means of drilling and blasting connected with the use of explosives and negative effect of air-blast. G.A Voroteliak, I.I. Glas, A.A. Gurin, Y.B. Zeldovich, Y.P. Kaplenko, O.V. Kolokolov, A.S. Kompaniets, A.M. Kuzmenko, V.P. Kurinnoi, V.D. Petrenko, V.S. Rakhutin, M.A. Sadovskii, L.N. Shirin and other scientists considered the problem [18, 19, 49, and 70]. They developed a theory for air-blast parameter calculation in the process of moving within mine workings. Values of destructive effect of the air-blast parameters on equipment, communications, and structures are identified. A number of papers [20, 32, 33, 58, and 70] concern a design of explosion-proof bulkheads, their supporting capabilities, and efficiency of air-blast preventing.

Note, that technological parameters of blasting which effect on air-blast formation and transmission are underresearched. During last two decades the problem did not experience indepth review; moreover, sources had very few publications concerning research of air-blast and protective structures.

Available calculation procedure for air-blast parameters and safe distance for staff and equipment turns out to be rather complicated making difficulties for its implementation.

Current computer technology makes it possible to simplify such a calculation procedure by means of specific software developing. That helps calculate air-blast parameters and plan measures to deal with them.

Developed light and sound materials make it possible to manufacture innovative explosion-proof bulkhead which can be transported to place of installation with little effort.

Set forth information confirms applicability of the problems which solution is unavoidable to improve reliability and safety of underground ore mining using heading-and-stall methods.

1.2. Analysis of Methods and Means for Air-Blast

Methods to Attenuate Air-Blast

To protect underground structures, communications and equipment against air-blast action following methods of its are applied: increase in blasting efficiency; contra-charge blasting; and air-blast using explosion-proof bulkheads.

Such factors as rational location of hole pattern, delay-action blasting, use of stemming, inverse initiation and repetitive initiation of blast-hole charges etc. favour increase in blasting efficiency [18, 19, 70].

It is possible to reduce air-blast intensity at the moment of its formation by means of opposite location of two or more charges, or their distribution over caving area. In the first instance such a location results in air-blast interaction and mutual; in the latter case it decreases energy concentration in one place [45]. However mentioned technique is not widely used.

A method of air-blast by means of barricading it with bulkheads made of various materials (e.g. concrete, rock, water, metal etc.) is the most popular [18, 20]. In their properties explosion-proof bulkheads can be either permanent or temporary ones. They are divided into the three groups: solid, holed, and breaking-down. Solid bulkheads covers section of mine working in full; holed covers it partially. Under the effect of air-blast, breaking-down bulkheads experience crushing and displacing attenuating air-blast energy. As a rule, solid bulkheads prevent air-blast in full; as for holed bulkheads and breaking-down ones, their effect is partial [19].

Solid explosion-proof bulkheads are located where air-blast is expectable. They are constructed in explosive storages; within areas of burning and explosion gases emission being used to localize worked-out chambers. Solid explosion-proof bulkheads should have high protective performance negating any possibility of staff and equipment damaging in mine workings [19].

Temporary explosion-proof bulkheads are very popular in the context of ore mining by heading-and-stall methods. Their aim is to protect underground equipment and structures against air-blast effect.

Temporary Explosion-Proof Bulkheads

Wave-breakers are a row of supports staggered along the length of a mine working. To be more stable they are placed into hitches on the part of air-blast movement. Length of wave-cutters is 10 to 30 m. As a rule, wave-breakers are used to protect mine workings of haulage level. Modest resistance and heavy timber consumption are disadvantages limiting their application. It is reasonable to apply them for air-blast when pressure at the front is not more than 150 kPa. At large pressure supports crash being spread with air-blast. Having great motional energy, blasted-out support may cause destruction of a mine working comparable with air-blast action. The disadvantage involves the fact that each bulkhead made of timber props and joists and planks is of slight strength [18].

Buffer bulkheads (Fig. 1.3, a, and b) are made of round timber with 180 – 250 mm diameter. Length of a bulkhead is not more than 3 m. For its hardening

components of a bulkhead are strapped against each other loosening along a mine working section. Stability of buffer bulkhead is slight; at the front of air-blast it withstands only 200 kPa pressure.

Owing to simple design and short erection period, buffer bulkheads are rather popular for weak air-blast prevention. Heavy timber consumption and slight strength keep them from air-blast prevention in the neighbourhood of explosion zone.

Chump bulkheads are made of round timber with 100-300 mm diameter and of 1.5-3 m length (Fig. 1.3, b). For hardening chumps are strapped against each other in their butts. It is the most reasonable to arrange chump bulkheads in turns to base faces of bulkheads on a side.

Such a technique hardens bulkheads. At the front of air-blast, chump bulkheads withstand up to 200 kPa pressure being intended for air-blast weakening far from explosion zone [70].

Rope bulkheads are made of steel ropes. To erect them holes with 0.6-1 m depth are made along the perimeter of a mine working; hooks are fastened by cotters. A rope in the form of wire netting is pulled on the hooks. Wire rope clips fix crossing points of ropes. Due to considerable perforation rope bulkhead prevents air-blast poorly. However, it properly catches rock pieces following air-blast.

It is possible to weaken air-blast drastically if sandbag bulkhead is housed between two rope bulkheads. Such bulkheads are sandbags (bags of culm), bases or quarry rock. Such a system consisting of two types of bulkhead is rather flexible; at the front of air-blast it withstands up to 1200 kPa pressure.

Labour intensity, cost of materials, as well as disassembling complexity after explosion is the major disadvantage of hybrid bulkheads. Their application is reasonable to protect difficult-to-disassemble before explosion equipment [19].

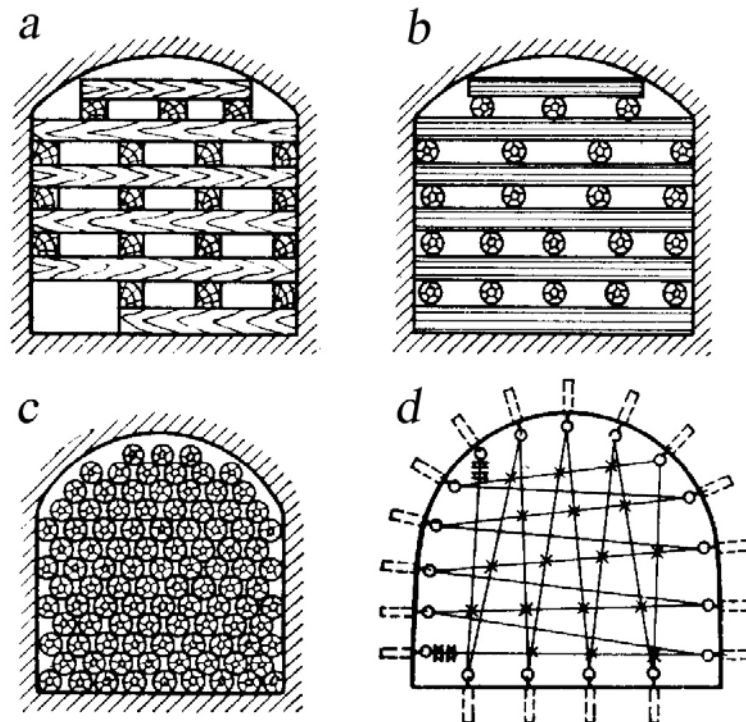


Fig. 1.3. Bulkheads: a. Buffer bulkhead made of pales with access; b. Buffer bulkhead made of round timber; c. Chump bulkhead; d. Rope bulkhead.

Movable (flexible) bulkheads consist of plates of conveyor belt (Fig. 1.4). They are applied to weaken air-blast when outsize pieces crush. Simultaneously they are used to control amount of air. When such a bulkhead is erected, 800-1000 m “window” is left in its central part; the “window” is covered with two pieces of conveyor belt. Air-blast weakening with the help of such a bulkhead is a result of energy consumption to overcome resistance, friction between the bulkhead components as well as for its partial reflection.

Movable bulkheads carry multiply effect of air-blast properly; it is not difficult to mount them; they are rather chip [19].

Flexible slotted bulkheads (Fig. 1.5 a) are temporary structures to prevent air-blast; minimum labour costs have an optimum effect. They are better connected with sides to compare with other designs of bulkheads.

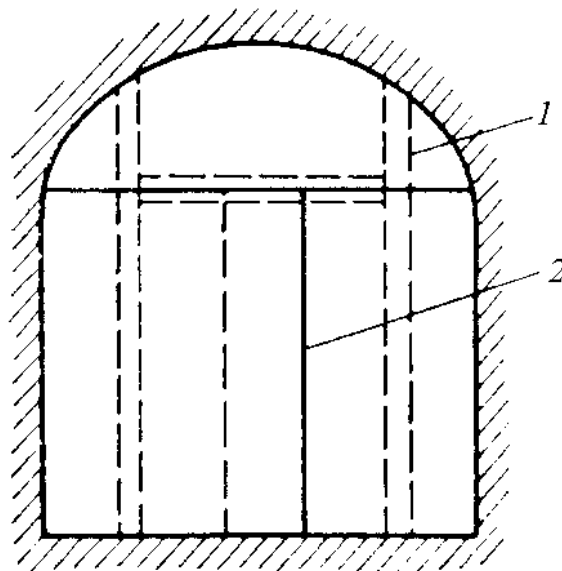


Fig. 1.4. Movable conveyor-belt bulkhead: 1. Props; 2. Door.

Flexible slotted bulkhead consists of a row of props with 20-30 cm diameter; they are bound together with ropes fixed to cleat wedges. In turn, wedges are fixed in holes drilled in sides. Flexible couplings provide minor bulkhead component stresses. Loose props are in a section of a mine working with required slot size between them.

It is possible to increase load-carrying ability of slotted bulkhead by means of stripes of used conveyor belt reinforced with ropes (Fig. 1.5 b). In this situation, timber props are applied to fix belt stripes [19, 70].

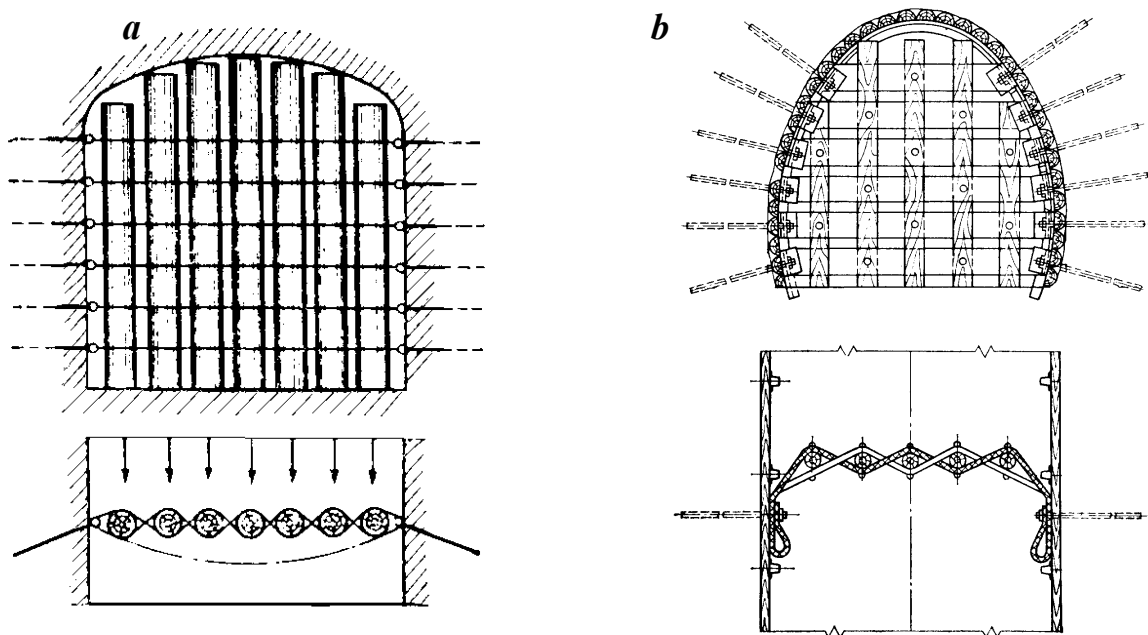


Fig. 1.5. Bulkheads: a. Flexible slotted bulkhead; b. Flexible slotted bulkhead made of conveyor belt.

Analysis of Patents and Inventions

1990-2005 patent search found out eight patents and inventions. Their majority was issued by Committee of the Russian Federation for Patents and Trademarks.

Certificate of autorship No. 1723338 [1]. FACILITY TO PREVENT AIR-BLAST IN A MINE WORKING involves vertical bulkhead with guides elevating to horizontal plane fixed with plated bolts in a roof of a mine working and in its floor. Sloping bulkhead with holes, which axes are perpendicular to the sloping bulkhead, is mounted at prescribed distance from the bulkhead.

Certificate of autorship No. 1726756 [2]. FACILITY TO COVER A MINE WORKING involves arch with opening; in its upper part sealing material is fixed on horizontal axis of rotation. Holding device fastened to a roof is provided to maintain it in upper inoperative position.

In inoperative position sealing material is held with fixing device in uppermost position. When air-blast moves within a mine working, it effects on sealing material. In this situation, turn of sealing material within horizontal axis is possible up to blow on a boundary member. After the blow, sealing material goes below during a turn about horizontal axis; as balances moves pitch-free it becomes vertical. As air-blast consumes certain part of energy to turn sealing material, its intensity takes down.

Certificate of autorship No. 1737132 [3]. FACILITY TO PREVENT AIR-BLAST IN UNDERGROUND WORKING involves flexible components fixed to walling ends connected against each other with the help of joint. Flexible components are mounted between wallings. To prevent separation of wallings from vertical props in the context of reflected air-blast the wallings have retainers. Under the effect of air-blast flexible components sag overcoming forces of elastic deformation of a component located between wallings. As joint is available then experiencing stress they displace along a mine working axis; their contact with vertical props results in

the fact that motion process varies angle between wallings and space between flexible components is formed. When flexible component terminates effect of air-blast flexible components are unset.

Certificate of autorship No. 1765461 [4]. FACILITY TO PREVENT AIR-BLAST consists of buffering components (used automobile tires connected and fastened to vertical props placed in fore-and-aft plane of a mine working).

Certificate of autorship No. 1788290 [5]. FACILITY TO PREVENT AIR-BLAST consists of a bulkhead mounted in a mine working from the blast effect, and a bulkhead mounted on the other side of the mine working. Each bulkhead has vertical props; elastic screen made of conveyor belts is clamped between them. A bulkhead mounted in a mine working from the blast effect is equipped with rock anchor fasteners. Another bulkhead is equipped with fasteners to be connected with ropes, cushioning members, and guides. Cushioning members are grappled within sides. Facing air-blast, bulkhead one is distorted towards bulkhead two. Blocks-ropes system starts shifting; according to guides, bulkhead two starts shifting to bulkhead one producing countercurrent flow to air-blast. Availability of screen two having possibility to shift towards air-blast, provides countercurrent flow as well as increase in a bulkhead reflectivity to improve its efficiency.

Certificate of autorship No. 1802157 [6]. FACILITY TO PREVENT AIR-BLAST IN MINE WORKINGS. Downholes with given diameter and depth are bored in that mine working where blasting is performed. If it is required the downholes are hydrolyzed and overwatered up to collar. Blast charges with primers are placed within the downholes ends. Element-holed hollow columns are located above collars of overwatered holes. Area of blasting line with blast charges is connected to general blasting circuit of technologic charges. Blast charges of water kick are alternatively initiated according to a mode corresponding to delay intervals between technologic charges blasting. High-pressure water currents from column openings are directed towards air-blast front providing massive water curtain within formation plane.

Patent No. 2004824 [51]. TECHNIQUE TO PREVENT AIR-BLAST WHILE BLASTING IN MINE WORKINGS. Separated area of a mine working is cooled down using either cryogen evaporation or cooled air current from vortex tube; then it is filled out with snow obtained in the process of dispersed water cooling. Hard-material plates are placed in snow mass. The plates improve efficiency of loose-material bulkheads.

Patent No. 2027018 [50]. TECHNIQUE TO PREVENT AIR-BLAST provides a device consisting of ropes overhung to a roof of mine working. When air-blast acts on the device, its prevention is a result of interaction with ropes.

Patent No. 2165025 [53]. EXPLOSION-PROTECTIVE BULKHEAD is a device consisting of four groups of stripes placed towards air-blast with undulating gradient of the stripes slope of plane to a mine working fore-and-aft axis varying as follows: 0° , 45° , 150° and 180° . First rows of stripes which planes are parallel to a mine working fore-and-aft axis divide air-blast front into flows; stripes of succeeding rows direct flows of weakened air-blast into slots between planes of inclined stripes reversing flow directions in each row. Even on a slant elongated stripes of the last

row will overlap the basic part of a mine working crosscut area being in a process of preventing air-blast against line hole explosions.

Analysis of patents and inventions show that proposed means of air-blast prevention are massive and have rather complicated design. As a result, procedure of their erection is labour-intensive. Stated help conclude that it is required to develop simpler bulkhead substantiating its parameters.

Efficiency of Air-Blast Weakening with the Help of Bulkheads

Table 1.1 demonstrates characteristics of explosion-proof bulkheads as well as their coefficients of air-blast weakening for various types [19].

Table 1.1

Coefficients of air-blast weakening for bulkheads of various types

Type of bulkhead	Reduced mass of a bulkhead, kg/m ²	Failure pressure, kPa	Coefficient of pressure release	Application area
Buffer	528	100-200	3	Protection of separate objects remotod from explosion area in mine workings requiring ventilation
Chump	790	100-150	1.72	
Flexible slotted	150-200	400-700	2-6*	It is mounted at the distance of no less than 20 m from explosion area in mine workings requiring ventilation in the process of repeated action of air-blast
Flexible slotted made of conveyor belt	100-200	600-900	2-6*	
Wave-breakers	150-200	100-300	1.3 – 2.5	They are designed to prevent air-blast when pressure at the front is not more than 300 kPa in mine workings requiring ventilation

Despite considerable perforation (almost 1/3) buffer bulkhead performs three-fold air-blast weakening. That can be explained by a double row of perforated walls. Breakage of air-blast falling front, compression of air flow following by its expansion, and spherical wave formation occur in the process of the first slots passing.

To compare with buffer bulkheads, chump ones perform weaker pressure at the front of air-blast as single compression and expansion of air flow takes place. Due to slight efficiency, chump bulkheads are not popular.

* Coefficient of air-blast weakening depends of dimensions of a bulkhead and perforation value.

Conveyor-belt movable bulkheads perform good withstanding to repeated action of air-blast, 2-2.5 times weakening at the wave front being recommended for air-blast prevention within haulage levels. Similar conditions are also applicable for mechanically sprayed water weakening air-blast and controlling dust and gas [19].

The analysis shows that slotted bulkheads and conveyor-belt bulkheads are the most popular as they have high prevention coefficient and considerable bearing capacity.

However, those bulkheads are of great material intensity reaching 200 kg/m^2 , and their structural components (3 m timber and conveyor belt) cause difficulties with their delivery. Also it is important to note high labour intensity of available bulkheads assembling/dismantling, and lack of road for staff and equipment.

It is possible to state that basically flexible slotted bulkheads are serviceable. If the bugs are eliminated they can be usefully applied at modern mining enterprises. Light and durable materials are available today. Their application will make it possible to lighten explosion-proof bulkheads and refine their design. Hence, their transportation lightens, and assembling/dismantling is simplified. That is why the work concerns substantiation of parameters and structural components of explosion-proof bulkhead involving up-to-date requirements of mining practice and new structural materials.

1.3. Air-Blast Parameters Determination while Moving within Mine Workings

Power characteristics of air-blast originating in the context of mass explosion in mine workings and effecting on structural components of explosion-proof bulkhead are important to determine its rational parameters.

Air-blast is compression area with jump-in pressure, density, and temperature. It extends over undisturbed air at the supersonic velocity [18, 19, and 70].

Fig. 1.6 explains pressure of air-blast time changes [19]. Its front is forehand. Front of air-blast has increased pressure ΔP , density ρ , temperature T_ϕ ; its supersonic velocity is D_v . Area of compressed air follows the front of air-blast. Within the zone pressure drops down to atmospheric one transforming into depressurization wave. Within compression zone, air velocity depends on pressure: the higher is pressure, the faster wave moves; that is the front of a wave having maximum pressure has maximum velocity as well. On the line of compression zone and decompression one where air pressure is equal to atmospheric ones, gas velocity is zero.

Within depressurization wave where gas pressure, density, and temperature are lower than within undisturbed atmosphere, air flows to a centre of explosion. Moreover, air velocity also depends on difference in atmospheric pressure and pressure within depressurization wave. That results in elongation of compression and depressurization waves depending upon travel.

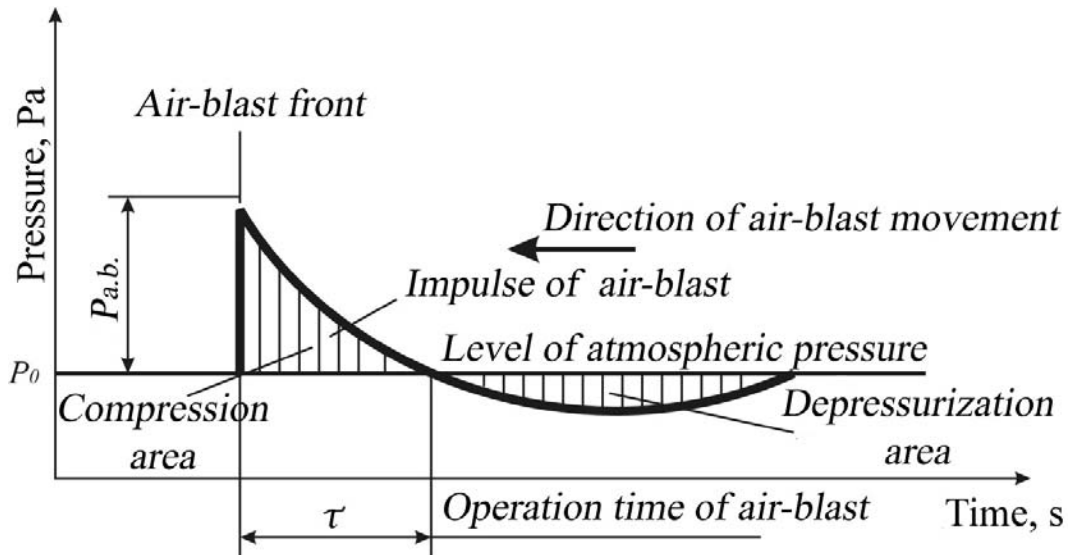


Fig. 1.6. Changes in pressure behind air-blast front

Operation time of excessive pressure zone τ is called operation time of air-blast.

Theory of air-blast [10, 30, and 68] gives a number of ratios between various characteristics at its front. Among them are: dependence of pressure on air-blast velocity; dependence of temperature on pressure; and air-blast dependence of pressure and density.

Air-blast front velocity is determined as follows:

$$D_y = \sqrt{\Delta P \left(\frac{1}{\rho_a} - \frac{1}{\rho} \right)}, \text{ m/s} \quad (1.1)$$

where ΔP is excessive pressure within air-blast front, Pa;

ρ_a is density of undisturbed (at atmospheric pressure) air, kg/m^3 ;

ρ is air density within air-blast front, kg/m^3 .

Energy dissipation in air and air friction on a mine working surface are basic reasons for air-blast in underground workings and channels. Semiempirical dependence explaining a process of pressure within the front of flat air-blast (kPa) is a result of numerous research, and use of dimension and similarity theory [19]:

$$\Delta P = \left(3270 \frac{qn}{RS} + 780 \sqrt{\frac{qn}{RS}} \right) e^{-\frac{\beta R}{d}}, \text{ kPa} \quad (1.2)$$

where q is mass of synchronously blasting explosives, kg;

R is travel by air-blast, m;

β is coefficient involving loss of air-blast energy due to friction on a channel surface (friction coefficient);

d is reduced diameter of a mine working, m;

$$d = 1,12\sqrt{S} \quad , \text{ m};$$

S is total cross-section of mine workings adjoining explosive charge, m^2 ;

n is a coefficient of explosive energy flow to air-blast, unit fractions.

Cofactor one of formula (1.2) determines loss of wave energy to heating and involving air masses increased depending upon distance. Cofactor two involves air-blast energy loss in the process of its dissipation over sides.

Value of friction coefficient is nonconstant depending on air-blast intensity. The higher is pressure at the air-blast front, the higher friction coefficient is. If pressure at the wave front is less than 150 kPa it experiences slight variations. Its increase depending upon air-blast intensity increase can be explained by improved conditions of heat exchange between wave and environment in terms of significant temperature difference.

Presence of moisture and dust in air also effects friction coefficient value. Moreover, the higher is contamination heat and its content in air, the more intensive air-blast is. Friction coefficients are listed in [19].

When borehole charges of explosives are blasted, certain volume of gas stays in broken rock; rest gas is released into mine workings forming air-blast. A problem of determining explosive energy share to form air-blast is complicated as blasting gases can not leave a hole in full. Due to high pressure in charge space, certain part of gas extends over natural cracks of rock mass; rest of gas stays in broken medium not-participating in air-blast formation. In this context, coefficient n is introduced into the formula; the coefficient involves explosive energy flow to air-blast. Coefficients of energy flow to air-blast are also listed in [19].

Formula (1.2) is true for explosives which specific blast energy is 4200J/kg (ammonite No. 6ЖБ). If certain explosives have specific blast energy then mass of charge should be multiplied by a ratio of applied explosives specific blast energy to specific energy of ammonite No. 6ЖБ (Q_{ex}/Q_{am}).

Impulse of air-blast excessive pressure is time effect of excessive pressure per unit of contact area, or the product of air mass moving in wave per velocity [19, 21].

$$I = \int_0^{\tau} \Delta P(\tau) d\tau = \Delta P_{cp} \tau, \text{ Pa}\cdot\text{s} \quad (1.3)$$

$$I = 2500 \frac{qn}{RS} e^{-\frac{\beta R}{2d}}, \text{ Pa}\cdot\text{s} \quad (1.4)$$

As in the case with pressure determining at the front of air-blast, if various types of explosives are applied, mass of charge (1.4) should be multiplied by a ratio of applied explosives specific energy to specific energy of trotyl.

Moving along a mine working, air-blast involves ever-increasing air masses. That very time cross-section area of a mine working experience minor changes, and wave velocity drops depending upon increasing distance to explosion area. That results in fast increase of air-blast increase operation time in mine working to compare with unbounded medium.

Operation time of air-blast positive phase in a mine working is determined as follows:

$$\tau = 0,92 \frac{R}{c_0} \sqrt[6]{\frac{qn}{RS}}, \text{ s} \quad (1.5)$$

where c_0 is sound velocity in undisturbed air.

Air operation time can be measured as a ratio of distance from explosion area to sound velocity in undisturbed air.

Air-Blast in the Process of Short-Delay Blasting

Usually, short-delay blasting of borehole charges and blasthole charges are applied for rock failure. The process plays important part to improve blasting efficiency. Often dispersed firing with up to several seconds delay intervals is used to weaken air-blast.

Several air-blasts following each other are formed in the process of short-delay blasting. The number of waves is adequate to the number of explosions. Intensity of each wave depends on mass and energy of gases. Moving along mine workings, waves interact. As a rule, their interaction nature is determined by air-blast parameters and delay intervals [19, 70].

Impulse of a sum wave is equal to a sum of interacted waves impulses. Pressure increase at the air-blast front resulting from far arbitrary profiled waves meeting also corresponds to the ratio. In the context of numerous overtaking waves, sequencing consideration of wave couple has similar effect:

$$\Sigma I = I_1 + I_2 + \dots + I_n, \text{ Pa}\cdot\text{s} \quad (1.6)$$

$$\Sigma \Delta P = \Delta P_1 \sqrt{\frac{\Sigma I}{I_1}}, \text{ kPa} \quad (1.7)$$

After waves have merged, air-blast effects are enlarged:

$$\Sigma \tau = \frac{\Sigma \Delta P \tau_1}{\Delta P_1}, \text{ s} \quad (1.8)$$

Impulse and Pressure at the Front of Air-Blast in the Context of Passing Turns and Connections of Mine Workings

Following inclined mine workings are the most popular in mines: turns, partings, intersections etc. Air-blast weakens passing through the types of local resistance. Attenuation degree depends on resistance type and on air-blast intensity.

Coefficients of pressure and air-blast impulse in terms of passing turns and intersections in mine workings are listed in [19].

Characterization of Air-Blast Using Nomograph

Pressure and impulse of air-blast can be determined using nomograph (Fig. 1.7) simplifying mathematical calculations according to formulae (1.2) and (1.4) [17].

Pressure and impulse are determined as follows. First dimensionless coefficients K and i are calculated. They are auxiliary values for graphical analysis:

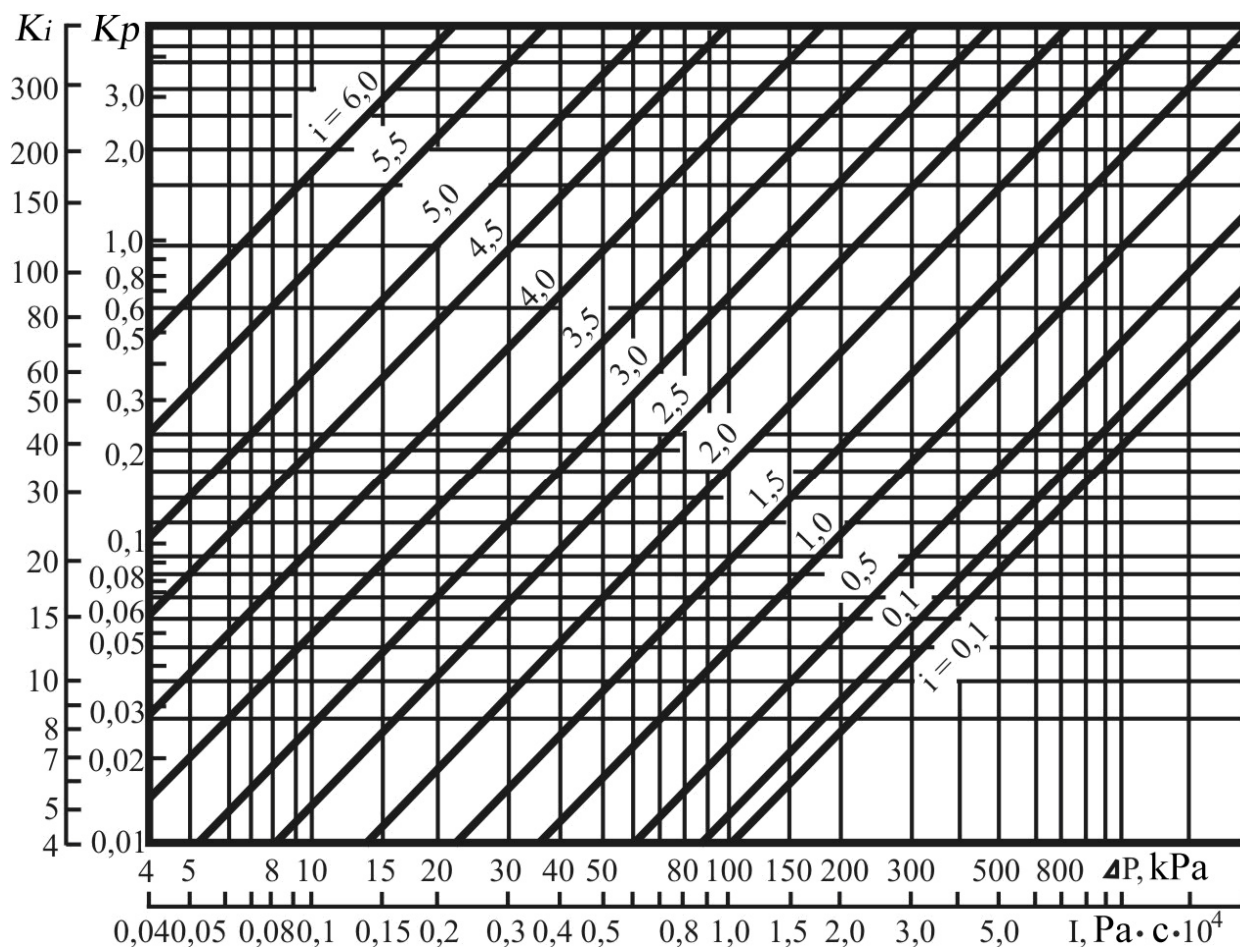


Fig. 1.7. Monogram to determine pressure at the front of air-blast (kPa) and excessive pressure impulse

for pressure at the front of air-blast: $K_p = \frac{qn}{RS}$; $i_p = \frac{\beta R}{d}$;

for air-blast impulse: $K_i = \frac{qn}{S}$; $i_i = \frac{\beta R}{2d}$.

Then K_p ordinates and K_i , ordinates are used for contouring until they intersect inclined lines being adequate to i_p and i_i coefficients. Projections of crosspoints with absciss make target values of pressure at the front of wave as well as excessive pressure impulse. If air-blast faces local resistance then obtained pressure should be divided by a product of attenuation coefficients corresponding to local resistance.

The theory to calculate air-blast parameters was verified in a production environment in the context of grammonite 79/21 open charge blasting in Frunze mine (Krivoi Rog coal field). Explosive charges were placed in a blind drift and a cross drift. SD and MID-2 devices were applied to measure air-blast parameters. Deviation difference in values of singular experiments and averaged ones was not more than 18% [19]. It concerns each series of experiments.

Calculation procedure for air-blast parameters was also controlled in terms of pressure charges, blast-hole charges, borehole charges, and chamber ones. Findings show that deviation of rated values from measured ones is not more than 25 % [19].

Consideration of calculation procedure for air-blast parameters explains that the theory is rather detailed making it possible to determine parameters according to known one. The theory is based upon laboratory measurements and production measurements of air-blast. However, it is rather difficult to apply the theory for heading-and-stall methods due to numerous calculations.

Enterprises use nomogram to determine air-blast parameters [15]. However, it can not involve a delay-blast mode when air-blasts run into one another due to following blast series which increase their intensity. That results in poor calculation accuracy and under-substantiated methods of air-blast controlling; that may imply various damages followed by expenses connected with repair and renewal operations.

1.4. Measuring Equipment to Analyze and Improve Air-Blasts

Various facilities have been applied to determine and analyze actual parameters of air-blast as well as to confirm reliability of theoretical evaluation [18, 19, 58, and 70].

All available devices can be divided into the two groups: electrical devices and mechanical ones; as for their purpose, they are pressure sensors, impulse meters, and velocity sensors.

High frequency of natural oscillations (inertialessness) and great mechanical reliability are the key demands placed on sensors and devices to measure wave pressure [19].

Piezo-electric, condenser-type, inductive, and mechanical sensors and devices are applied to measure air-blast pressure in the form of time function [30].

Piezo-electric sensors. The majority of researches applied piezo-electric sensors for air-blast pressure measuring. The sensors are among electric pressure sensors. They can support momentary load, are very robust characterizing by quick response. Sensed information is recorded by electron oscillographs. The sensors are good to be applied in laboratories. However they are not reliable underground where relative humidity reaches 100%. In terms of single blast, mine is de-energized and staff leaves it. That involves further complication of electronics use underground [70].

Mechanical devices of SD type are more comfortable to record air-blast pressure underground (Fig. 1.8). They are rather light (up to 3 kg), have independent energizing and can measure pressure at the front of air-blast within 10-600 kPa. Aneroid chamber is operating device of the instrument. Natural oscillations of recording unit help controlling air-blast which action time is more than 50 ms; that is they are appropriate underground where action time of a wave usually overtops given value [19].

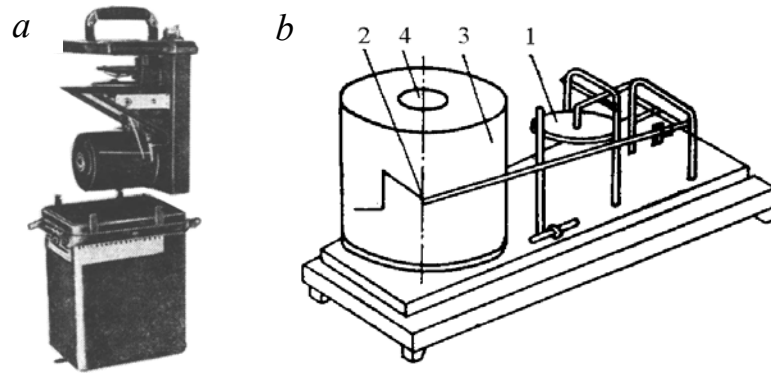


Fig. 1.8. SD device:

a. Overall view; b. Structural scheme;

*1. Aneroid chamber; 2. Wing; 3. Progressive and rotational roller;
4. Electric motor.*

However, the devices are difficult-to-make requiring calibration in laboratory and production environment.

Mechanical pressure indicator MID-2. Mechanical pressure indicator MID-2 (membraneous pressure gauges) (Fig. 1.9) are applied for mass and rapid evaluation of air-blast intensity using a principle of rigidly fixed membrane deflection.

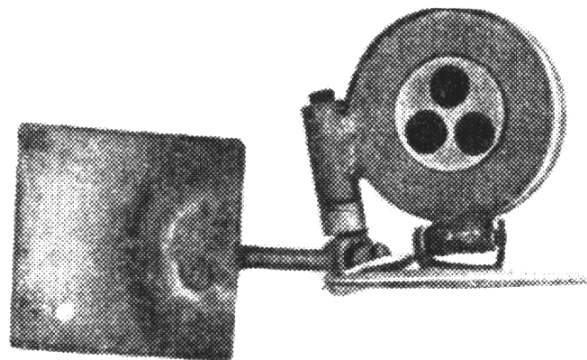


Fig. 1.9. Mechanical indicator (sensor) of pressure.

T.M. Salamakhin used theory and practice to determine difference between excessive pressure (kPa) and membrane deflection [10, 45].

Owing to simple design and compactability, membrane pressure gauges are comfortable for mass pressure measurements at the front of air-blast in mines in the process of single blast with considerable synchronous consumption of explosives. However, obtainment of air-blast pressure parameters while the sensor applying amounts to complicated mathematical calculations. Moreover, such sensors are not meant for air-blast parameters measuring in terms of short-delay blasting.

Besides specific pressure sensors based upon a principle of membrane pressure gauges were designed and manufactured to measure excessive pressure in laboratory and production environment. Their difference is that membranes made of ten

materials were applied for pressure measurements [58]. The sensor is metal cylinder consisting of five sections where external diameter is 38 mm, internal diameter is 24 mm, and length is 250 m. Sections have boxes for different-material membranes meant for certain excessive pressure. Fibre and carton are applied as sealers. Fig. 1.10 demonstrates overall view of the sensor. Previously sensors were calibrated with the help of air-booster compressor KD-250, in a metal pipe, and in production environment in terms of single blast.

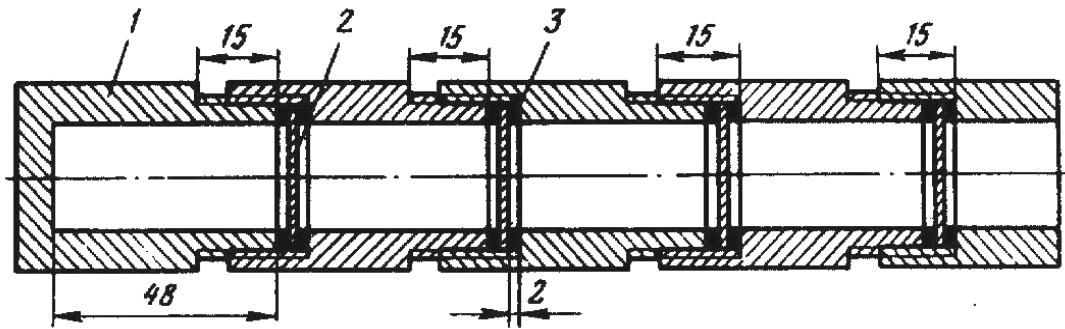


Fig. 1.10. Scheme of pressure gauge:
1. Body; 2. Membrane; 3. Sealer.

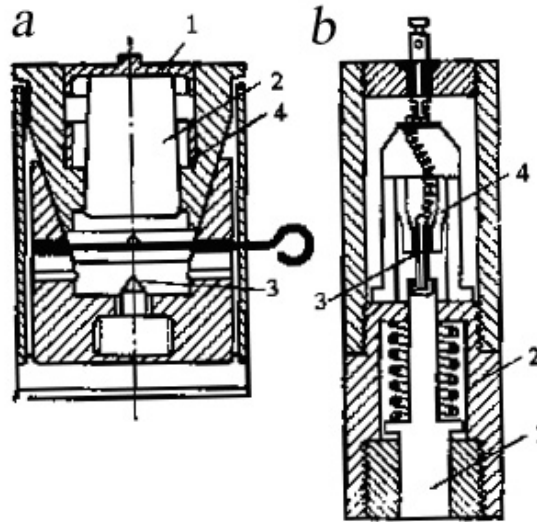
Booster compressor calibrates pressure sensors in such a way to make increase in excessive pressure rather steplike than permanent; that gives possibility to calibrate sensors in close to explosion environment.

Simple design and low price as well as mass use potential are among advantages of the devices. Obtained data re-estimation complexity, fitting of membranes as well as their single use are among disadvantages.

Mathematically, impulse meter is such a case when quasi-elastic effort $\Delta P(t)$ effects on mass; moreover, its action time can be considered sufficiently small to compare with natural oscillation period of a system ($T_0 \geq \tau$). Otherwise a device will only measure indefinite share of impulse. In practical terms it is quite enough to determine initial velocity imposed on a system or determine maximum deviation. In the context of a mine, there can be either piston impulse meters (Fig. 1.11, a) or electromagnetic ones (Fig. 1.11, b). Piston of impulse meter consists of two contact not-connected masses. Mass m_1 perceives wave pressure, transmits it to mass m_2 bulkhead some distance from reference position. Then mass m_2 moves independently. Value of the impulse is determined by measuring piston energy on pressure gauge crimping [18, 19].

Electromagnetic impulse meter (Fig. 1.11, b) is a piston 1 mounted in slider bearings of body 2. Winding 3 going into a gap between two magnets 4 is fixed at the end of the piston opposite to that perceiving air-blast effect. In term of such motion, winding is in the area of uniform magnetic field. It results in electromotive force is induced. The force is proportional to a velocity of relative movement of a winding and magnet as well as impulse to a piston [18].

Structural complexity and labour-intensity of obtained data recalculation are its disadvantages.



*Fig. 1.11. Impulse meter:
a. Piston impulse meter; b. Electromagnetic impulse meter;
1 and 2. Pistons; 3. Pressure gauge; 4. Stopper ring.*

The majority of considered devices are meant to be applied in a laboratory environment. To measure air-blast parameters underground, SD devices, mechanical pressure sensors and facilities using a principle of pressure gauge systems were applied. All of them are meant for expendable determination of air-blast parameters.

Modern blasting techniques for ore mining apply short-delay blasting and air-blast of series of charges moving along mine workings in sequence. In this context it is required to know ultimate intensity of air-blast resulting in maximum damage. Available devices can not determine it in the context of a mine.

Therefore, it is required to develop measuring means for effective engineering measurement of air-blast.

Taking into account high intensity of air-blast, the measuring means should be rather robust, have secure mounting for a mine working, and be reusable.

1.5. General Research Technique

Operational analysis as for air-blast preventing in the process of heading-and-stall ore mining method, application of blast-proof bulkheads, theory of air-blast and devices to study them illustrate:

1. When chambers are prepared for a single blast, boundaries of dangerous zones are calculated for a period of:

- bore-hole charging;
- bringing primers into charged holes; and
- tying in the blast.

The zones are determined on a nomograph to be rather labour-intensive problem for engineers due to a great number of branching in mine workings and

considerable mass of air-blast to be blasted; it often results in 10-15% of calculation errors.

2. A technique to calculate air-blast parameters is well developed; however, it is intensive complicating their determination in the process of single blasts in the context of heading-and-stall method. That makes it difficult to identify rational parameters of explosion-proof bulkheads as well as their locations.

3. Until recently various devices and facilities have been applied to determine actual parameters of air-blast, their analysis and identification of theoretical evaluation reliability. However, modern sources miss their application techniques as well as information concerning their state certification in “Standardization, Metrology and Certification” research and development centre and production start-up.

4. Stowing bulkheads experience effect of air-blast when blasting is performed under the conditions of heading-and-stall methods. Explosion-proof bulkheads are used to protect stowing bulkheads against air-blast. The former have a number of design defects including high consumption of materials, unavailability of a passage through a mine working, assembling and dismantling expensiveness, and high cost. The explosive-proof bulkheads not always can prevent air-blast in full. That results in failure of stowing bulkheads as well as stowing mixture leakage into mine workings. That involves expenditures connected with repair and renewal operations.

As noted above complex technique is applied to solve problems formulated by introduction.

Scientific and technical sources concerning air-blast propagation theory make it possible to identify basic parameters of air-blast, its behaviour in the process of motion through mine workings as well as rating values.

Analysis of explosion-proof bulkheads helps to define reasonable concepts for analytical and physical simulation.

Analytical simulation defines correction rules of proposed explosion-proof bulkhead loading capacity in terms of various design parameters.

Physical simulation will help to determine reliability of dependences developed as a result of analytical simulation.

Software for theoretical study is developed basing upon calculation procedure for air-blast parameters in the process of their motion through mine workings.

Experimental results in a production environment make it possible to obtain actual data and compare them with theoretical ones. The research enables formulating requirements for structural parts of the bulkhead.

Substantiation of explosion-proof bulkhead parameters makes it possible to improve reliability as well as safety of processes while ore mining.

Fig. 1.12 demonstrates structural and logical diagram of the research.

Research technique for explosion-proof bulkhead involves as follows:

- Characterization of air-blast in the process of motion through mine workings;
- Strength and deformation tests for structural parts of a bulkhead;

Characterization of explosion-proof bulkhead under the effect of air-blast.

Air-blast parameters are determined according to a technique stated in [17, 18, 19, 70]. Its nature is as follows: determination of air-blast parameters in a target point of a mine working; distance between blasting and design point along a path of air-blast motion; a type of resistances (branching, narrowing, and widening in mine workings); support type and section area of a mine working; blasting parameters. Air-blast parameters are calculated for openings and chambers of “ZIOIC” CJSC.

Field observations concerning changes in air-blast parameters in the process of its motion along mine workings were performed in openings of “Prokhodcheskaia” mine and during single blast in “Ekspluatatsionnaia” mine (“ZIOIC” CJSC). Maximum discrepancy between theoretical observations and field ones is 22.86% enabling the data use for further research.

The data are applied to formulate demands for structural parts of a bulkhead; it is designed and possible locations for explosion-proof bulkhead are determined.

New polyester-based composite is applied as suppressant meeting the developed demands. Strength and deformation tests were performed in a laboratory of “Orel” Ltd. according to a procedure from [16]. Stiffness coefficient, ultimate elongation of material, and safety were determined as a part of the study. Coefficients of protective element bearing capability have been obtained while simultaneous use of two and three lines.

A technique mentioned in [19] determines characterization of explosion-proof bulkhead under the effect of air-blast. Its principle is: air-blast parameters depend on charge quantity and distance to explosion-proof bulkhead. Loading diagram for bulkhead components is compiled. A value of dynamic coefficient ($k_d = 1 - 2$) is taken to determine static pressure effecting the bulkhead. Techniques from structural mechanics are applied to determine cross force values arising in structural components of a bulkhead.

Laboratories of Institute of Rock Mechanics tested models of explosion-proof bulkhead. They verify results of theoretical calculations.

A combined program and technique developed by the authors involve analytical and applied research. They make it possible to perform reliable substantiation for parameters of explosion-proof bulkhead as well as its technique to be applied in a production environment.

CHAPTER 2. SUBSTANTIATING PARAMETERS OF MOBILE EXPLOSION-PROOF BULKHEAD

2.1. Design of Explosion-Proof Bulkhead and Requirements for it

Rigidity of explosion-proof bulkhead depends on its geometry, material, design, pressure within air-blast front, and load application period. Stiff continuous bulkheads experience maximum load [17].

Approaching stiff barrier air-blast front which has hypervelocity stops. Kinetic energy of air-blast passes into pressure energy. As a result, pressure on a bulkhead increases sharply. Pressurized stratum of air following a wave front slows too. In this case, a bulkhead experience extra load resulting from velocity pressure effect which depends upon airflow rate and its density [19].

Mobile bulkheads are better in terms of resistance to air-blast effect. Ropes, chains, conveyor belt and other materials are applied in a design of bulkheads. Mobile bulkheads spring under the effect of air-blast. In this context, wave energy experiences extra consumption for a bulkhead displacement and elastic strain overcoming. When air-blast has been reflected, a bulkhead resumes original position.

Taking into account disadvantages of available designs of bulkheads, mining peculiarities, and opinion of specialists engaged in erecting bulkheads in mine workings, authors formulate following requirements for existing explosion-proof bulkhead:

- Possibility to apply it in horizontal workings, vertical workings, and incline workings where ventilation is required [9, 64];
- Service reliability (i.e. it should be of adequate strength having resistance to the effect of air-blast);
- A bulkhead should be mobile, perforated. In addition it should comprise elastic structural components;
- Components of a bulkhead should be of low weight for their comfortable transportation along mine workings;
- Labour intensity of protective bulkhead assembly and disassembly should not be more than three m/hrs;
- Minor components should be uniform and fungible;
- Structurally a bulkhead should have various types of perforation for ventilation;
- A bulkhead should be recoverable.

Inclusive of stated authors developed a bulkhead (Fig. 2.1) consisting of suppressant 1 – diametric stripes and lateral stripes both sides of which are pierced with strong caprone threads 2 to feed synthetic rope through. 3. Sides of ropes connecting stripes have loop on their end. Safety catch 4 is attached to the loop. 4. Anchor 5 which length is 0.5 m has a ring at its end for safety catches.

Proposed design of a bulkhead has several advantages. Among them are: quickness of assembly and disassembly; possibility to make a cross-section of a mine

working during short period of time; possibility to assemble a bulkhead with 0.8 to 0.2 perforation coefficient; and lightness of material to cover a mine working.

Polyester, new artificial material is proposed as suppressant. Its mass is 0.9 kg/m^2 ; it has good elastic characteristics and adequate strength. Such a bulkhead will weight about 2 kg/m^2 to be 50-100 times lighter to compare with available bulkheads which mass is 100 to 200 kg/m^2 .

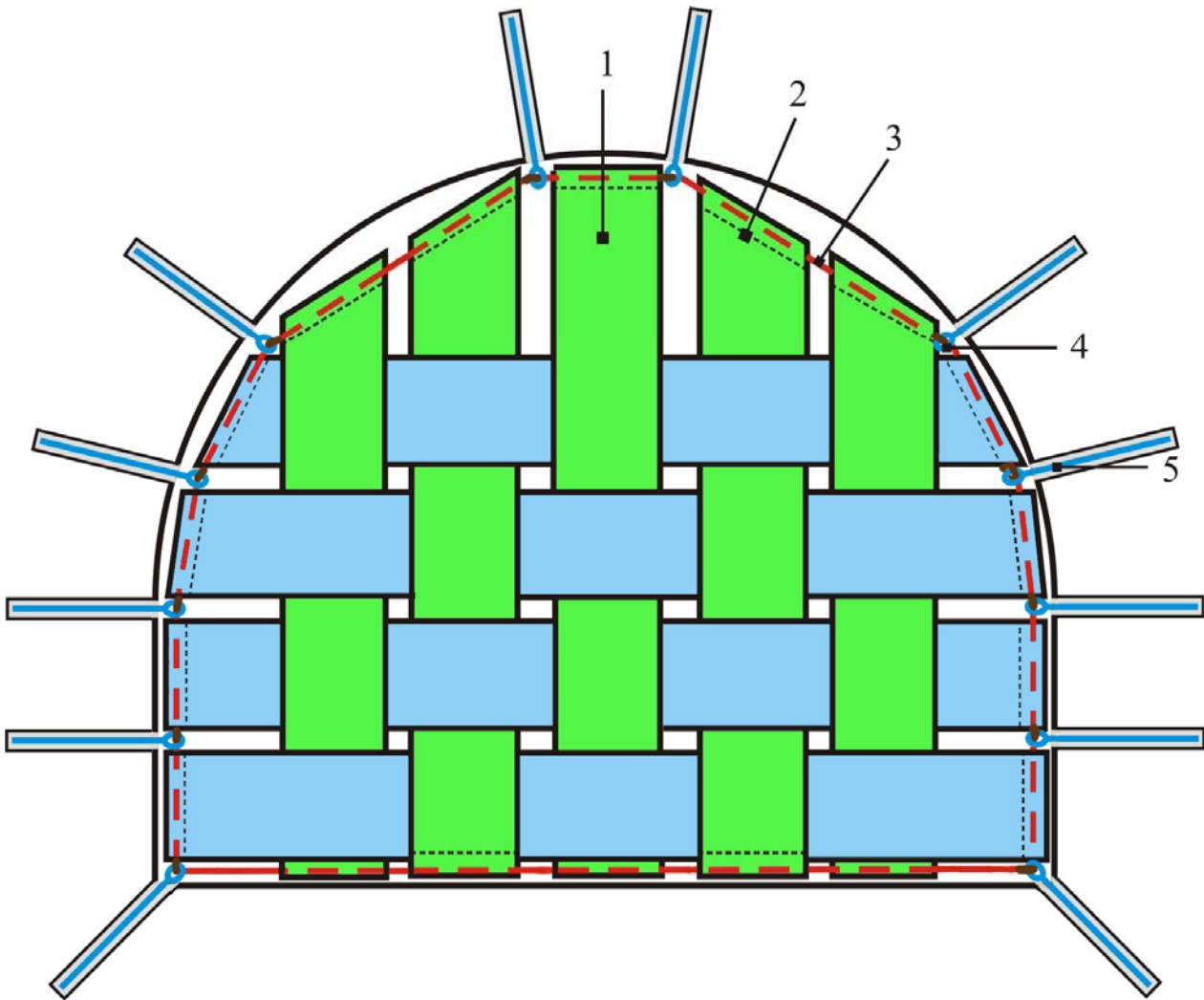


Fig. 2.1. Temporary bulkhead design:

1. Suppressant; 2. Seam; 3. Rope; 4. Safety catch; 5. Anchor.

2.2. Computing Chain for Explosion-Proof Bulkhead Structural Component Strength Characteristics

Fig. 2.2 demonstrates principal analytical model of mobile explosion-proof bulkhead analysis. As it follows from the model, explosion-proof bulkhead is mounted in a mine-working in front of protected object (i.e. stowing bulkhead) in spaced relationship from it.

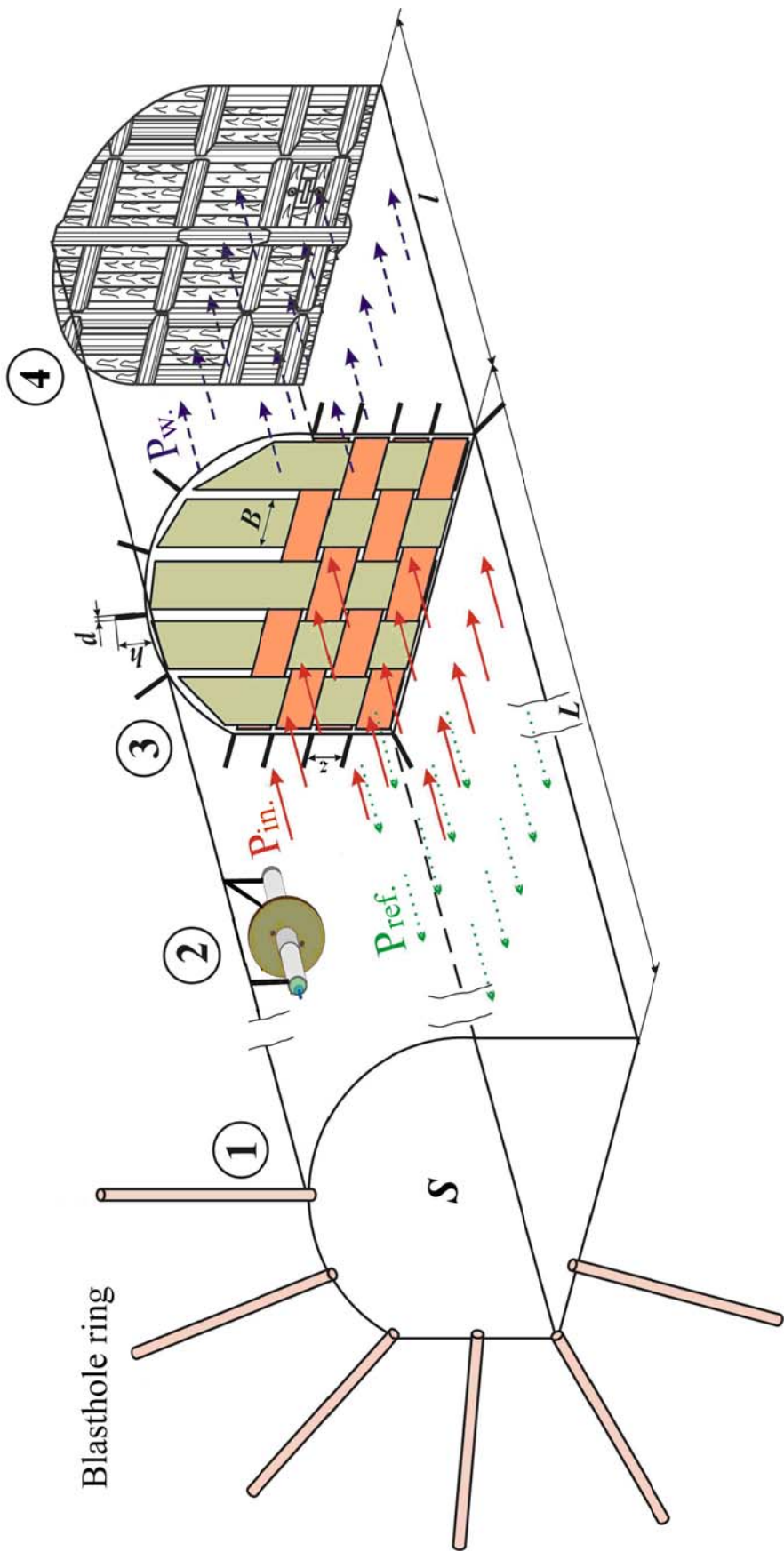


Fig. 2.2. Analytical model to prevent air-blast in underground mine workings:

1. Source of air-blast; 2. Device to measure P_{in} ; 3. Mobile explosion-proof bulkhead; 4. Stowing bulkhead; P_{in} , P_{ref} , and P_w is extra pressure of incident air-blast, reflected air-blast, and weakened air-blast respectively, kPa ; L is distance between explosion point and explosion bulkhead, m ; l is distance between explosion-proof bulkhead and protected object, m ; B is bandwidth of a bulkhead protective element, m ; h is fixing anchor depth, m ; d is fixing anchor diameter, m ; z is distance between anchors, m ; and S is sectional area of a mine working, m^2 .

To determine bearing capacity of bulkhead structural elements it is required to know pressure of air-blast falling down on it. Theoretical determination of air-blast propagation in mine working involves blasting parameters (type of air-blast, its quantity etc.).

Identification of full-range parameters of air-blast requires their instrumental manufacturing measurements. Satisfactory repeatability of theoretical and actual parameters of air-blast will help to make reliable determination of explosion-proof bulkhead parameters as well as its application technique.

B.A. Olisov [19] demonstrates that when actual structure is replaced by equivalent system having single degree of freedom, calculation procedure can be reduced to comparable impulsive force analysis. In this case real load value should be multiplied by dynamic coefficient varying between 1 and 2.

Analysis of explosion-proof bulkhead as for air-blast time-varying effect is as follows [19]:

1. Air-blast parameters are calculated using software on the basis of charge quantity and distance to explosion-proof bulkhead.
2. Analytical model for bulkhead components is diagrammed.
3. A value of dynamic coefficient k_d is taken.
4. As air-blast pressure uniformly distributed along a bulkhead is equivalent to air-blast pressure then static pressure is determined by:

$$\Delta P_s = \Delta P \cdot k_d, \text{ kPa} \quad (2.1)$$

5. Procedures from structural mechanics are applied to determine values cross force arising in structural components of bulkheads.

6. Distance between explosion-proof bulkhead and protected object or another explosion-proof bulkhead is determined by:

$$l = 6,16\sqrt{S}, \text{ m} \quad (2.2)$$

where S is cross-section area of a mine working, m^2 .

7. Degree of air-blast pressure attenuation by means of several explosion-proof bulkheads is determined by:

$$k_w = k_1 \cdot k_2 \cdot \dots \cdot k_i \quad (2.3)$$

where k_i is a coefficient of air-blast pressure attenuation by means of i^{th} bulkhead.

Available explosion-proof bulkheads mentioned in 1.2 were calculated as rigid constructions. Involving the fact that proposed bulkhead will have elastic properties the authors conclude that developing a technique for its parameters determination is required.

Bulkhead stays to be undisturbed if its each component withstands applied load. Therefore first perform strength calculation of one horizontal stripe of a bulkhead.

Fig. 2.3 demonstrates analytical model of explosion-proof bulkhead components.

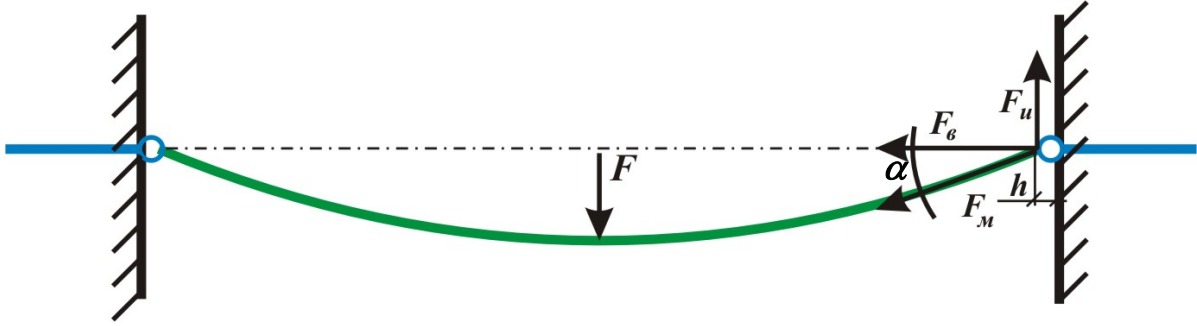


Fig. 2.3. Analytical model of explosion-proof bulkhead:

F is operating force, H; F_u is anchor respond on bending, H; F_e is anchor respond on pulling, H; F_m is respond of bulkhead material, H; α is angle of a bulkhead unbound deflection, degrees.

As the analytical model explains maximum value of applied load F will directly depend on material strength F_m , of a bulkhead unbound deflection α , and strength of anchors.

Maximum possible strength F , which may be applied to a bulkhead stripe, is determined by [56, 77]:

$$F = F_m \sin \alpha = k \cdot \Delta l \cdot \sin \alpha \quad (2.4)$$

where k is stiffness coefficient of material, N/m; and Δl is ultimate elongation of material, m.

Determine anchor respond on bending F_u and angle α . Strength condition of anchor on bending is [56, 77]:

$$\sigma_{\max} \leq [\sigma] \quad (2.5)$$

where σ_{\max} are normal stresses of anchor, Pa; $[\sigma]$ is maximum strength of anchor on bending, Pa.

$$\sigma_{\max} = \frac{M_{\max}}{W}, \text{ Pa} \quad (2.6)$$

where M_{\max} is maximum torque, N·m; W is section modulus, m³.

$$M_{\max} = F_u \cdot h = h \cdot k \cdot \Delta l \cdot \sin \alpha, \text{ N}\cdot\text{m} \quad (2.7)$$

where F_u is response of anchor on bounding, N; h is effective length of anchor:

$$W = \frac{\pi d^3}{32}, \text{ m}^3 \quad (2.8)$$

where d is diameter of anchor, m.

Substituting values M_{\max} and W for (2.6) expression we obtain on rearrangement:

$$\sigma_{\max} = \frac{32h \cdot k \cdot \Delta l \cdot \sin \alpha}{\pi d^3}, \text{ Pa} \quad (2.9)$$

Required quantity of anchors to hold stripes is:

$$n = \frac{\sigma_{\max}}{[\sigma]} = 2 \quad (2.10)$$

Connecting expressions (2.9) and (2.10) we determine angle α :

$$\alpha = \arcsin\left(\frac{2\pi \cdot d^3 \cdot [\sigma]}{32h \cdot k \cdot \Delta l}\right), \text{ degrees.} \quad (2.11)$$

In this context, anchor pulling force is:

$$F_g = F_M \cos \alpha = k \cdot \Delta l \cdot \cos \alpha, \text{ N.} \quad (2.12)$$

Determine static pressure withstood by a stripe of a bulkhead suppressant:

$$P = \frac{F}{S_{\text{no}l}} = \frac{k \cdot \Delta l \cdot \sin \alpha}{S_{\text{no}l}}, \text{ Pa} \quad (2.13)$$

where $S_{\text{no}l}$ is a stripe area, m^2 .

Accepting the fact that pressure will be equally distributed over the whole area of a bulkhead, determine static pressure withstood by the whole bulkhead:

$$F_{\text{bulk.}} = P \cdot S_{\text{bulk.}} = \frac{k \cdot \Delta l \cdot \sin \alpha}{S_{\text{no}l}} S_{\text{bulk.}}, \text{ N} \quad (2.14)$$

where $S_{\text{bulk.}}$ is a bulkhead area, m^2 .

Air-blast pressure withstood by a bulkhead is:

$$\Delta P_{\text{yBB}} = \frac{P}{k_\delta} = \frac{k \cdot \Delta l \cdot \sin \alpha}{k_\delta \cdot S_{\text{no}l.}}, \text{ Pa} \quad (2.15)$$

where k_δ is dynamic factor.

Air-blast energy in the process of its preventing by explosion-proof bulkhead will be consumed with both extension of a suppressant material and friction between its structural components. Therefore, total energy of air-blast prevention by a bulkhead is:

$$W = \left(\frac{k \cdot \Delta l^2}{2} + \Delta P_{VBB} \cdot k_\delta \cdot \mu \cdot S_c^2 \cdot l \right) \cdot N, \text{ J} \quad (2.34)$$

where μ is friction coefficient between structural components of a bulkhead;
 S_c is contact area of structural components, m^2 ;
 l sliding length of structural components, m; and
 N is the number of contacts of structural components, pieces.

In (2.34) formula, component one determines air-blast energy consumption for a bulkhead suppressant extension; component two – for friction between its stripes.

To determine numerical values of bulkhead parameters structural behaviour and deformation properties of protective element are required.

2.3. Software Development to Calculate Parameters of Air-Blast in the Process of Moving along Mine Workings

As it is mentioned, a theory for air-blast parameters calculation is available (front pressure, impulse, front velocity, air velocity behind a front, response time). Taking into account wide variety of mine workings in the process of ore mining with the help of heading-and-stall methods, and their branching variety it is a problem to see about changes in air-blast parameters using available calculation techniques. Hence, the authors conclude that it is required to develop software to calculate air-blast parameters basing upon available calculation technique.

The software should solve a number of problems connected with air-blast propagation within mine workings; theoretical prognosis and analysis of air-blast parameters; use results to select means for struggling against air-blast; and determine safe distances for staff and equipment.

Fig. 2.4 shows the software algorithm.

Control diagram covers following symbols: i is calculation number; q is mass of explosives, kg; b is roughness coefficient of a mine working; n is a factor of explosion energy transfer into air-blast; S is section area of a mine working, m^2 ; R is distance by air-blast from explosion site, m; d is normalized diameter of a mine working, m; k_p is a coefficient of pressure release within air-blast front; k_i is a coefficient of air-blast impulse release; P is pressure within air-blast front, kPa; I is air-blast impulse, Pa·s; t is response time of air-blast, s; P_k is air-blast pressure during first explosion series (in a mode of delay-action blasting), kPa; I_k is air-blast impulse during first explosion series (in a mode of delay-action blasting), Pa·s; t_k is response time of air-blast during first explosion series (in a mode of delay-action blasting), s; y_k is the number of explosion series (in a mode of delay-action blasting); j_k is explosion series number (in a mode of delay-action blasting); q_k is air-blast mass per rate of attenuation (in a mode of delay-action blasting).

Basic set of initial data for the software are following characteristics of mine workings: degree of roughness, length, branching types, cross-section area, normalized diameter, and explosive characteristics: type of explosive, mass of explosive, and ratio of explosion energy transition into air-blast.

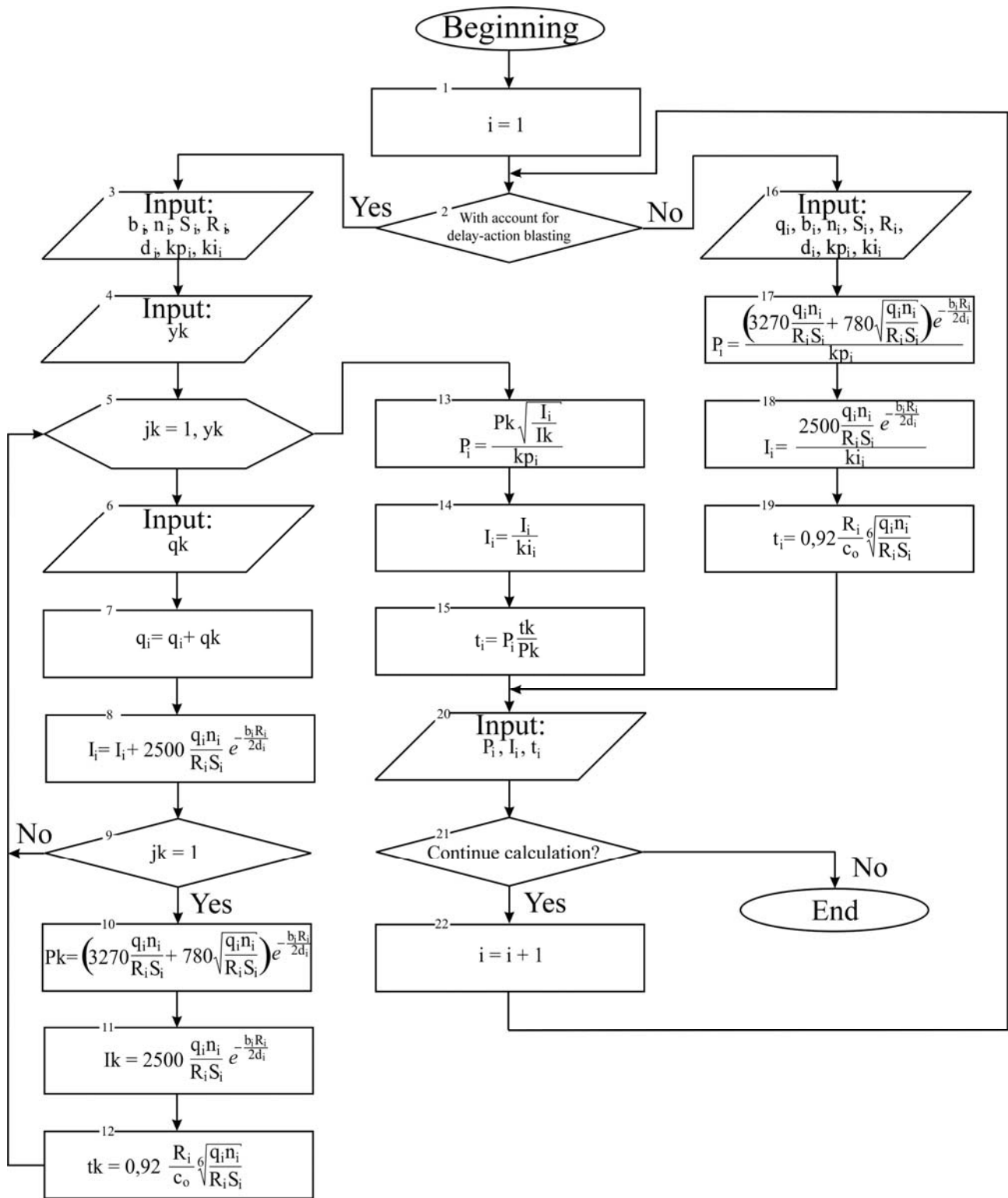


Fig. 2.4. Software algorithm to calculate air-blast parameters

In the process of blasting within target point of a mine working such air-blast parameters as pressure, impulse, and response time are calculated as follows [19]:

- Distance between air-blast charge and design point along motion path of air-blast is calculated. If parallel mine workings are available, then either shorter path is accepted or air-blast parameters are calculated for both directions;

- Pressure within front, specific impulse, and air-blast response time are calculated involving local resistances. If surface roughness factor of mine workings and normalized diameter have running values then they are determined by [17, 19]:

$$\beta_c = \frac{\beta_1 R_1 + \beta_2 R_2 + \dots + \beta_n R_n}{\sum R}$$

$$d = \frac{d_1 R_1 + d_2 R_2 + \dots + d_n R_n}{\sum R}, \text{ m}$$

where $\beta_1, \beta_2, \dots, \beta_n$ are roughness factors of air-blast specific space intervals; d_1, d_2, \dots, d_n are normalized diameters within air-blast specific space intervals, m; and

R_1, R_2, \dots, R_n is length of sites of mine workings where β and d values are constant.

Types of local resistances as well as their number are determined in plans and mining sections; numerical values of coefficients are given in software.

To compare values of air-blast parameters obtained with the help of available nomograph and software, construct comparative graph. To do that, accept initial data:

Explosion of fan of holes takes two series. Mass of explosives in series one is 2540 kg; mass of explosives in series two is 1472 kg; grammonite 79/21 is applied as explosive; roughness factor of mine workings is 0.04; coefficient of explosion energy transition to air-blast is 0.1; normalized diameter of a mine working is 3.94 m; and total area of section adjoining charge is 24.8 m². Air-blast runs within straight mine working.

Table 2.1 demonstrates results of air-blast parameter calculations using nomogram and software.

As nomogram prevents from calculating air-blast parameters in a mode of delay-action blasting air-blast parameters for variation one will be calculated for total mass of explosives.

Table 2.1.

Comparative Calculation of Air-Blast Parameters

Distance, m	50	60	70	80	90	100	110	120	130	140	150
Air-blast pressure, kPa (N)	800	700	500	400	290	250	220	170	160	150	130
Air-blast pressure, kPa (SW)	789	614	489	397	326	271	227	192	163	139	119
Divergence, %	1.38	12.29	2.20	0.75	12.40	8.40	3.18	12.94	1.88	7.33	8.46

Represent the data graphically.

As Table 2.1 explains divergence of air-blast parameter calculations using nomogram (N) from software (SW) is within 0.75-12.40%. That depends on the fact that software provides more accurate calculation of air-blast parameters involving such factors as explosive type and a mode of delay-action blasting.

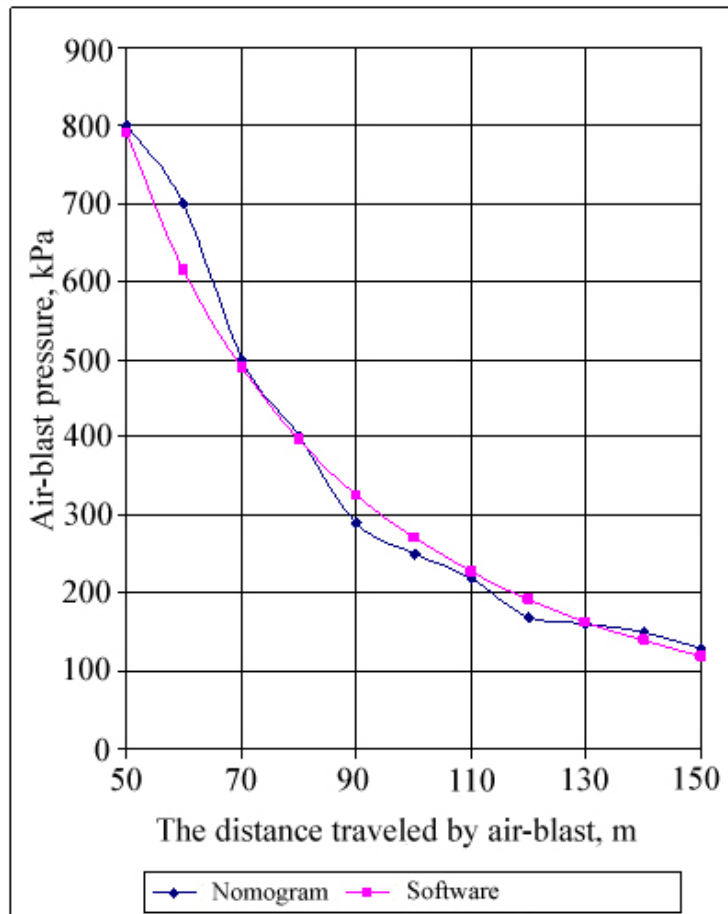


Fig. 2.5 Graphic comparison of air-blast calculated parameters

Fig 2.5 explains that air-blast pressure calculated using nomogram has steplike variations to compare with smooth results obtained with software.

It means that the software can compute air-blast parameters rapidly and more accurately making it possible to solve problems connected with air-blast propagations within mine workings.

2.4. Substantiating Strength Properties of a Bulkhead

To substantiate strength properties of mobile explosion-proof bulkhead as well as its location one should know changes in numerical values of air-blast parameters in the context of its propagation within mine workings.

Theoretical research concerning changes in air-blast parameters is based upon 2/5s chamber of “Ekspluatatsionnaia” mine (“ZIOIC” CJSC).

As it is mentioned single blast is performed in accordance with standard plan of explosion conducting. Table 2.2 explains technical data of single blast. Fig. 2.6 demonstrates location of wells in a chamber.

Well charge (depending upon well bottom) consists of a column of bulk explosive (grammonite 79/21) and trinitrotoluene block T-400g with detonating cord. Initially closing plug is placed, then primer (ammonite No.6ЖБ) with two electric detonators (prime and backup), and closing plug.

Considering the fact that explosion will be simultaneously performed within each drilling level, it is required to make individual calculation of changes in air-blast parameters.

Calculate air-blast parameters for 740 m level. Data of single blast engineering design (Table 2.2, Fig. 2.7) and a plan of 740 m level are involved.

Series one includes 7 to 12 wells (roofs and floors); series two – 13 to 16 wells. Tables 2.3 and 2.4 explain characteristics of wells, angle of wells, total length, explosive type, and charge length in a well.

Table 2.2

Technical data of chamber 2/5s single blast

Factors	Units	Total	Level 715	Level 740	Level 775	Level 810
Volume of broken rock mass	Thousand tons	6.2				
Diameter of a well	mm	130	130	130	130	130
The number of wells	pieces	70	10	20	20	20
Total length of wells	m	1076	108	306	340	322
To be charged	m	883	35	266	300	282
Mass of bulk explosives per square meter	kg	14.6	14.6	14.6	14.6	14.6
Mass of explosives per square meter of a well (primer./ explosive cartridge)	kg	6.0/0.4	6.0/0.4	6.0/0.4	6.0/0.4	6.0/0.4
Quantity of explosives: a) Total	kg	13448.3	682.6	4012.5	4508.0	4245.2
Granulated (grammonite 79/21)	kg	13038.7	657.0	3884.5	4380.0	4117.2
Packaged (ammonite No.6ЖБ)	kg	384	24	120	120	120
Trinitrotoluene blocks T-400g	kg	25.6	1.6	8	8	8
b) detonating cord	m	1267	59	386	420	402
c) electronic detonators	pieces	128	8	40	40	40
Including those on delay:						
Delay series ЭД-3Д	$T_{\text{delay, S}}$					
7	0.5	72	-	24	24	24
8	0.75	56	8	16	16	16
Length of electroexplosive cord	m	1000				
Rated specific consumption of explosives	kg/t	2.161				
Extraction per a meter of a well	t	5.90				

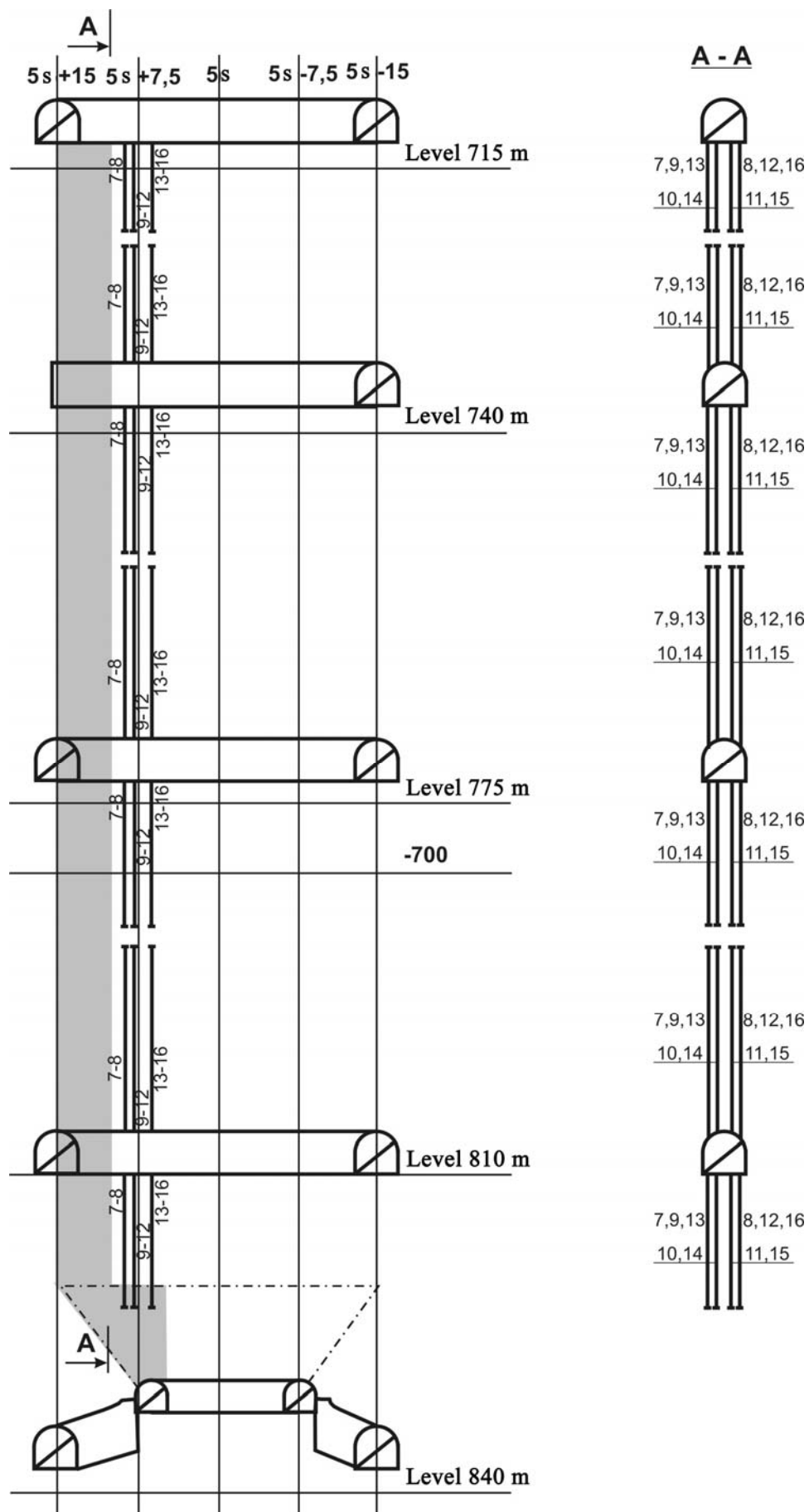


Fig. 2.6. Location of wells while shaping slot in 2/5s chamber of “Ekspluatatsionnaia” mine (“ZIOIC” CJSC).

Table 2.3

Characteristic of wells of 2/5s chamber roof of 740 m level

No.	Inclination angle, degrees	Length, m				Explosives, kg	
		Total	On bulk explosive			bulk	stick/ block
			Out of charge		charged		
			stope	mouth			
7	90	13	-	2	11	160.6	6.0/0.4
8	90	12	-	2	10	146.6	6.0/0.4
9	90	22	-	2	20	292.0	6.0/0.4
10	90	19	-	2	17	248.2	6.0/0.4
11	90	19	-	2	17	248.2	6.0/0.4
12	90	19	-	2	17	248.2	6.0/0.4
13	90	11	-	2	9	131.4	6.0/0.4
14	90	14	-	2	12	175.2	6.0/0.4
15	90	14	-	2	12	175.2	6.0/0.4
16	90	14	-	2	12	175.5	6.0/0.4
Sum:		157	-	20	137	2001.1	60/4

Table 2.4

Characteristic of wells of 2/5s chamber foot of 740 m level

No.	Inclination angle, degrees	Length, m				Explosives, kg	
		Total	On bulk explosive			Bulk	stick/ block
			Out of charge		charged		
			stope	mouth			
7	-90	15	-	2	13	189.8	6.0/0.4
8	-90	15	-	2	13	189.8	6.0/0.4
9	-90	15	-	2	13	189.8	6.0/0.4
10	-90	15	-	2	13	189.8	6.0/0.4
11	-90	14	-	2	12	175.2	6.0/0.4
12	-90	15	-	2	13	189.8	6.0/0.4
13	-90	15	-	2	13	189.8	6.0/0.4
14	-90	15	-	2	13	189.8	6.0/0.4
15	-90	15	-	2	13	189.8	6.0/0.4
16	-90	15	-	2	13	189.8	6.0/0.4
Sum:		149	-	20	129	1883.4	60/4

The calculations concern each possible direction (rout) of air-blast motion.

Initial data for calculations are as follows: mass of blasting series one is 2540 kg; mass of blasting series two is 1472 kg; coefficient of mine working roughness is 0.04; coefficient of explosive energy transition into air-blast is 0.1; normalized diameter of mine working 3.94 m; and total area of mine workings adjoining charge is 24.8 m².

Point 2.3 explains calculation technique for air-blast parameters.

Fig. 2.7 represents obtained data graphically to analyze performed calculations.

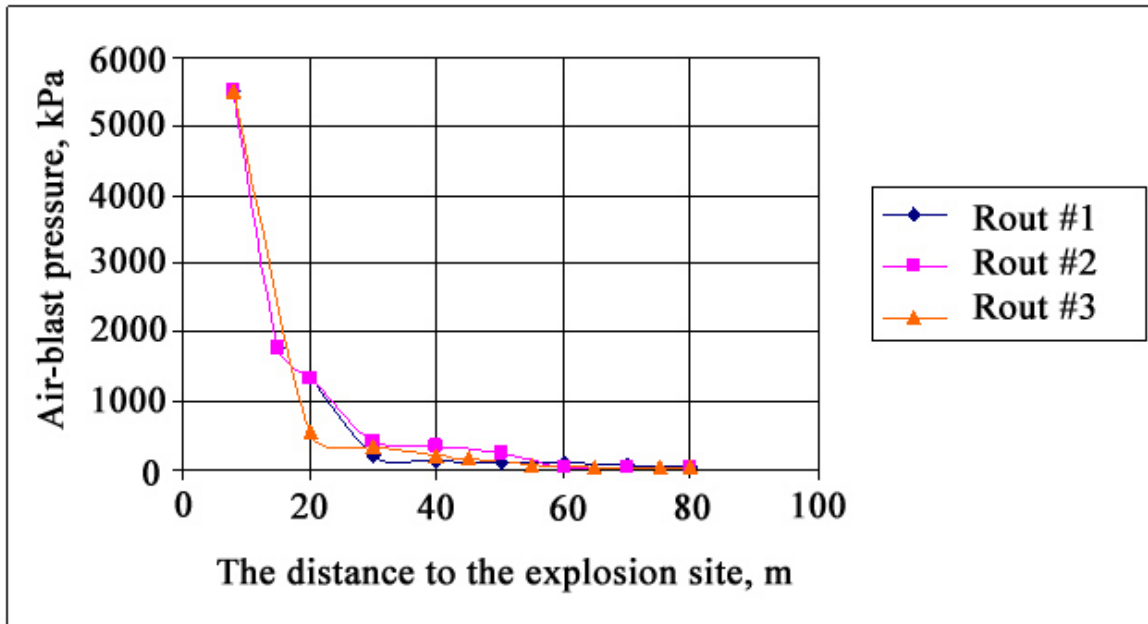


Fig. 2.7. Changes in air-blast pressure in the process of its motion within mine workings

The graph demonstrates changes in air-blast pressure according to all three routs.

As the graphs demonstrate air-blast pressure experiences sharp 27.5 times decrease (from 5.5 MPa to 0.2 MPa) within the first thirty meters. That depends on both natural attenuation and air-blast passing through branching in mine workings. In the following air-blast intensity experiences slow decrease becoming about 10kPa at the distance of more than 80 m.

The graph shows jump-in air-blast pressure depending upon motion of air-blast within branching of mine workings.

For descriptive reasons, the results are shown within a level plan (Fig. 2.8).

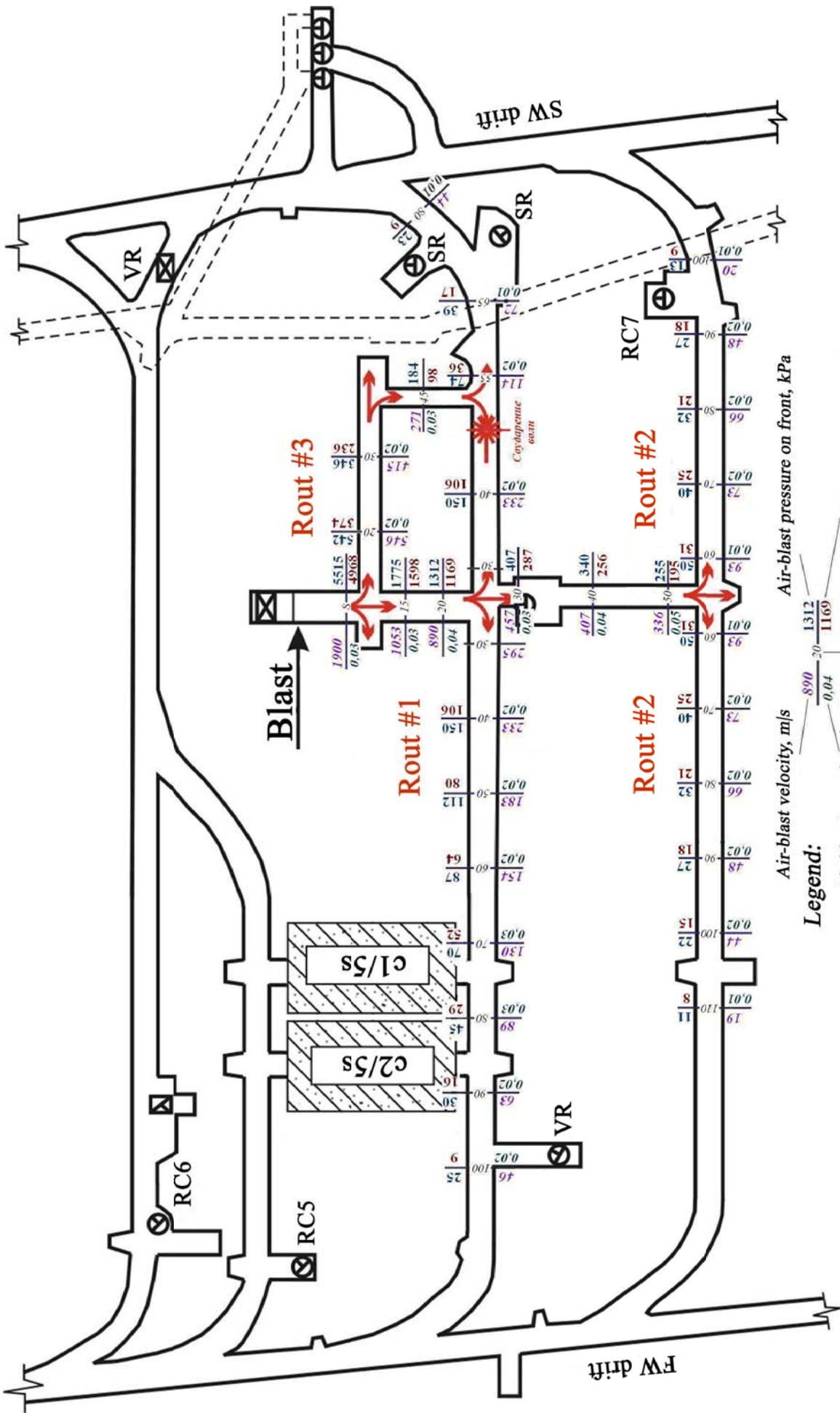


Fig. 2.8. A plan of 740 m level in "Ekspluatatsionnaia" mine ("ZIOIC" CJSC) with air-blast parameter values.

It follows from Fig. 2.8 that today it is impossible to localize air-blast in the near explosion zone at the distance of 15 to 20 m from it taking into account great pressure within a front of air-blast (1-6 MPa). However, when air-blast passes turns and junctions of mine workings, air-blast experience sharp attenuation (down to 400-550 MPa); that gives possibility to localize it within adjoining mine workings using explosion-proof bulkheads.

Thus, authors substantiate a design of mobile elastic bulkhead which should withstand extra pressure of attenuating air-blast (about 600 kPa). Its difference from available bulkheads is in lightness of structural components. That allows human handling within mine workings as well as assembling and dismantling simplification.

Conclusions

1. Both design of explosion-proof bulkhead and demands for it have been developed using analysis of available designs of explosion-proof bulkheads, structural and technological troubleshooting with account of mining practice requirements.

2. To determine strength characteristics of a bulkhead structural components computing chain has been developed using available techniques and features of proposed design with account of elastic properties of a bulkhead protective component.

3. Dependences are described to determine maximum load on a bulkhead involving strength and deformation properties of structural components. Besides air-blast pressure value it can withstand is also determined.

4. To analyze a character of air-blast propagation within branched system of mine workings based upon available air-blast theory, software has been developed to solve a number of problems connected with air-blast propagation within mine workings; to carry out theoretical prognosis and analysis of air-blast parameters; to select means of preventing air-blast according to the calculation results determining safe distance for staff and equipment.

5. The software is applied to calculate various alternatives of blast loading which results are used to substantiate strength characteristics of explosion-proof bulkhead structural components.

CHAPTER 3. LABORATORY RESEARCH OF MOBILE EXPLOSION-PROOF BULKHEAD

3.1. Research of Strength Characteristics and Deformation Properties of a Bulkhead Suppressant

As point 2.2 notes strength characteristics and deformation properties of a bulkhead suppressant are required to determine parameter values of explosion-proof bulkhead.

According to standards by the authors structural components of explosion-proof bulkhead should meet following demands: low weight, high strength, and elasticity. Polyester-based materials are those most closely meeting the demands placing to safety components of a bulkhead. Their mass is 650 to 1200 g/m²; they are rather strong and elastic

To identify parameters of specific explosion-proof bulkhead, polyester having 900g/m² density is selected. Its strength characteristics and deformation properties have been analyzed.

Laboratory of “Orel” Ltd. Company performed the research using tensile machine PT-250-M2 (Fig. 3.1) in accordance with 17316 – 71 GOST (Estimation method for breaking force and tensile elongation) [7].

According to GOST requirements polyester is used for samples which dimensions are 10×100, 15×100, and 20×100 mm.

The samples are cut longitudinally and transversally; in this context samples should not follow each other.

One end of a sample under test is fixed with top terminal of tensile machine. Another end is put into lower terminal giving its preliminary load using specific device for pretension; then lower terminal is fixed tightly.

A process of a sample tensioning involves writing down the readings of loading range and elongation up to complete sample break.

The research determines following dependences:

1. Dependence of a sample elongation on load applied.
2. Dependence of a sample elongation and breaking force on a quantity of simultaneously braking stripes.

Average of parallel tests for longitudinal direction and transverse direction is considered as a result of the research [31].

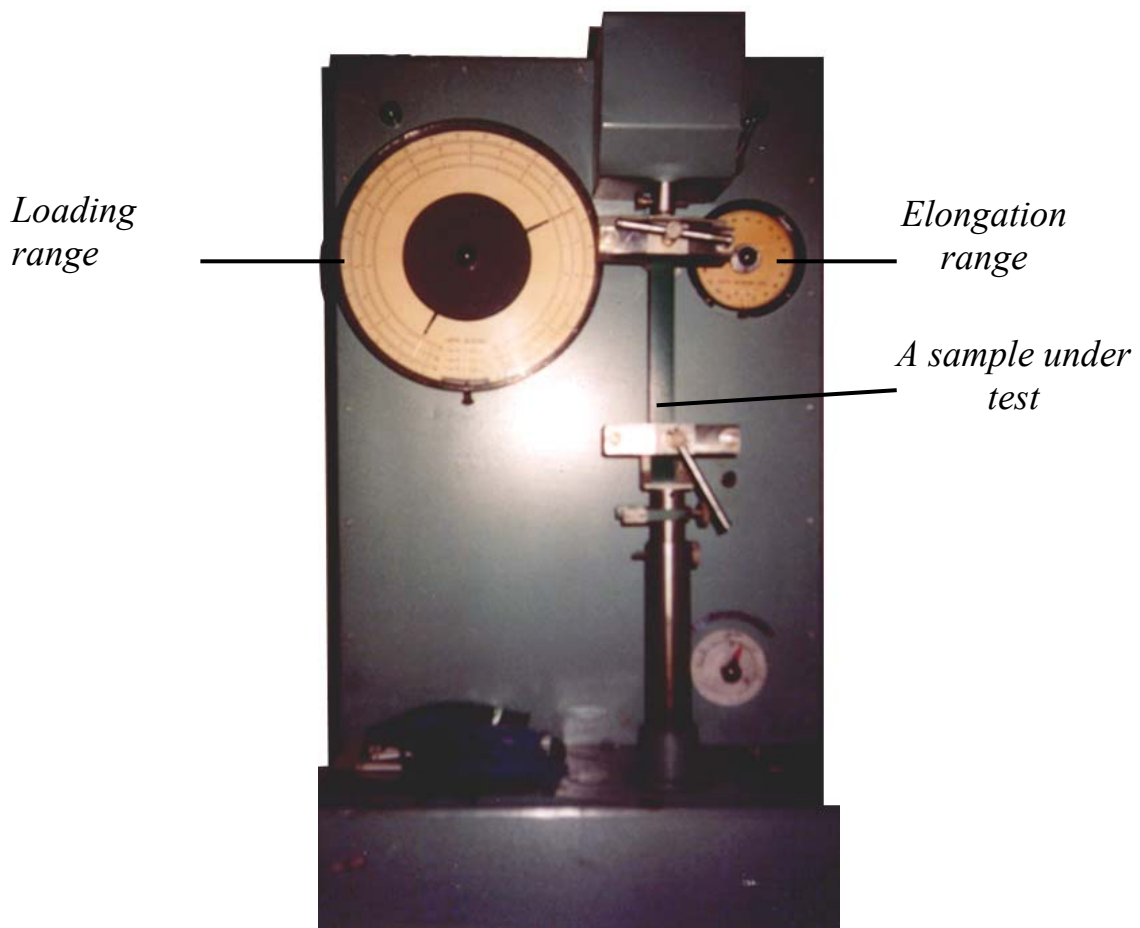


Fig. 3.1. Material test using tensile machine PT-250-M2
 Table 3.1 and Fig. 3.2 explain results of the tests part one.

Table 3.1

Test results for 900 g/m² polyester

Material dimensions, mm					
10×100		15×100		20×100	
Load, N	Elongation, m	Load, N	Elongation, m	Load, N	Elongation, m
0	0	0	0	0	0
100	0.0037	100	0.0027	100	0.0020
200	0.0107	200	0.0065	200	0.0042
300	0.0157	300	0.0115	300	0.0072
400	0.0192	400	0.0150	400	0.0110
500	0.0215	500	0.0177	500	0.0137
600	0.0245	600	0.0200	600	0.0157
630	0,0260	700	0.0220	700	0.0177
Material break		800	0.0240	800	0.0195
		900	0.0265	900	0.0207
		Material break		1000	0.0225
				1100	0.0240
				1200	0.0250
1220	0.0260				

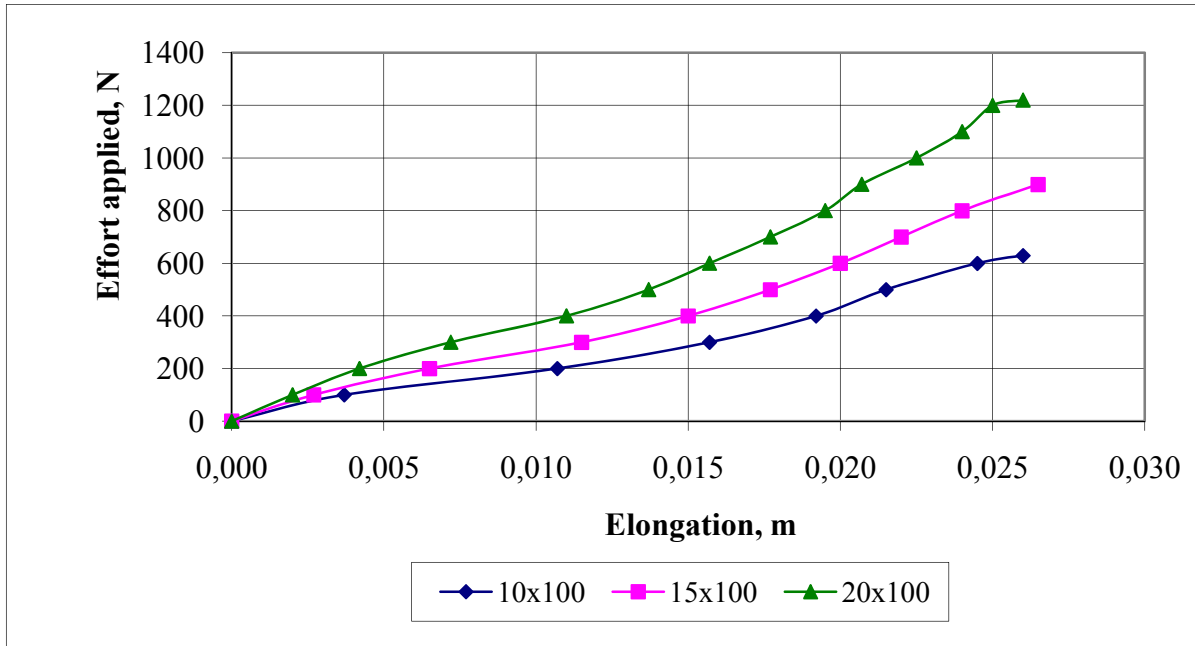


Fig. 3.2. Dependence of material break of effort applied

Fig. 3.2 explains that maximum material elongation under which Hooke's law operates is about 10% of breaking strain.

In this context determine dependence material elongation on effort applied. To this effect samples were tested within their elastic characteristics. Table 3.2 and Fig. 33 demonstrate the results.

Table 3.2

Characteristics of material within Hooke's law application

Material dimensions					
10x100		15x100		20x100	
Elongation, m	Elastic force, N	Elongation, m	Elastic force, N	Elongation, m	Elastic force, N
0	0	0	0	0	0
0.0005	14.0	0.0005	18.5	0.0005	24.0
0.0010	27.0	0.0010	37.0	0.0010	51.0
0.0015	40.0	0.0015	56.0	0.0015	75.0
0.0020	54.0	0.0020	74.0	0.0020	102.0
0.0025	68.0	0.0025	93.0	0.0025	126.0

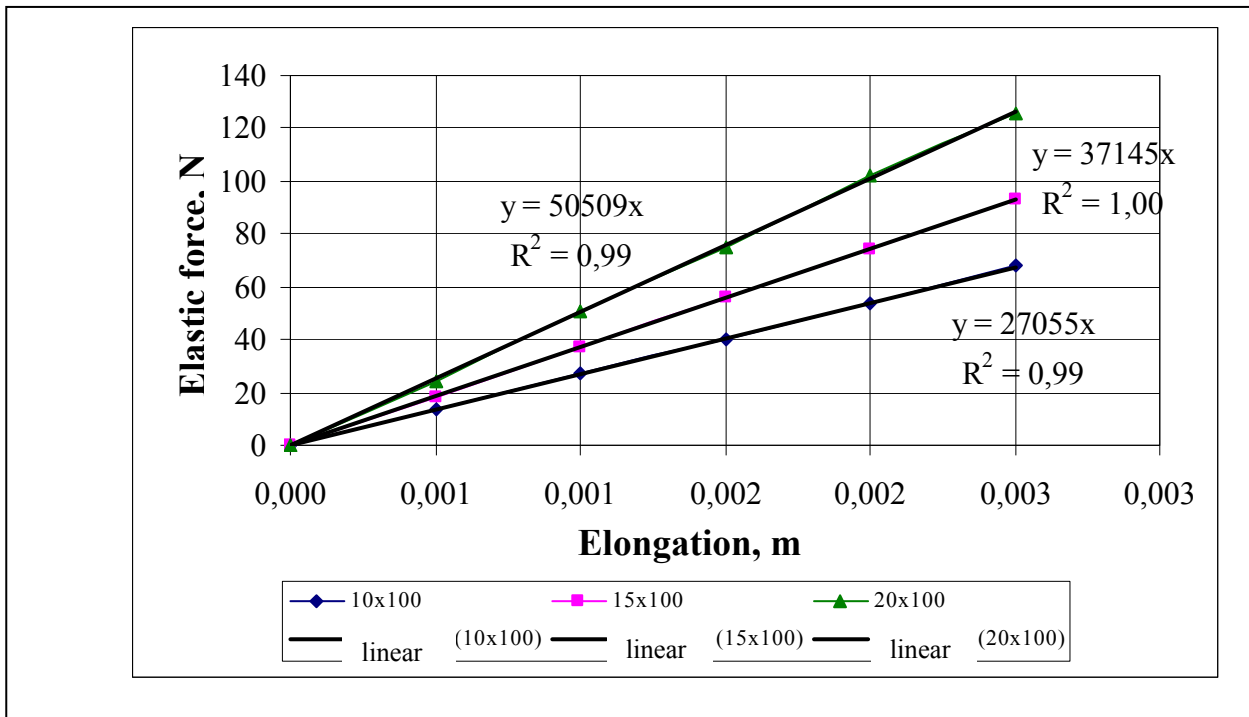


Fig. 3.3 Characteristics of material

Such characteristics of material as rigidity and maximum elongation can be determined after material has been tested in a line zone. Coefficients of sample rigidity are a result of Table 3.2. data interpolating. Fig. 3.3 and Table 3.3 explain results of interpolation.

Table 3.3

Material characteristics

Dimensions of a stripe, mm	Maximum elongation, m	Material rigidity, N/m	Coefficient of determination
10x100	0.0025	27055	0.99
15x100	0.0025	37145	1.00
20x100	0.0025	50509	0.99

Bulkhead material should function within a zone of Hooke's law operation. Whereas maximum effort of material break is much greater than within a zone of elastic deformations. Hence dividing break effort of material by effort arising within Hooke's law results in strength factor of material.

Table 3.4 demonstrates calculations of strength factor.

Table 3.4

Calculations of strength factor

Dimensions of a stripe, mm	Break load, N	Working load, N	Strength factor
10x100	630	67.64	9.3
15x100	900	92.86	9.6
20x100	1220	126.27	9.7

Some cases require significant increase in supporting power of explosion-proof bulkhead which involves overlapping stripes. Strength properties and deformation properties of two and three bunched stripes of material were tested. Table 3.5 and Fig. 3.4 demonstrate results.

Table 3.5.

Test results concerning dependence of a stripe braking force on the quantity of stripes being simultaneously broken

Dimensions, mm	The number of stripes, pieces	Breaking force, N	Elongation, m
10x100	1	690	0.0260
10x100	2	1143	0.0258
10x100	3	1388	0.0253

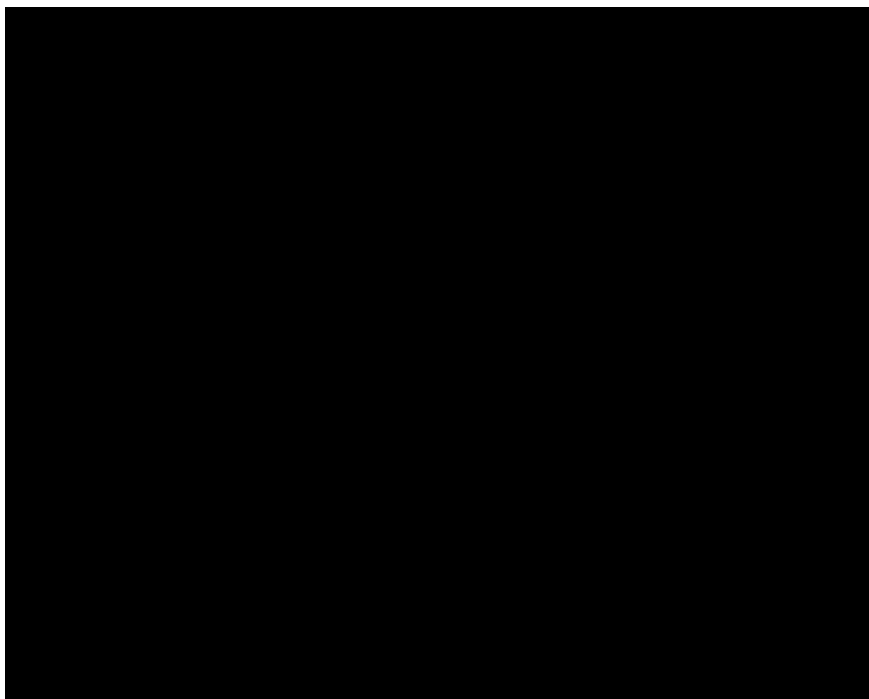


Fig. 3.4. A graph of a stripe braking force depending upon the number of stripes

Test data reduction makes it possible to obtain coefficients of supporting power increase if:

- Two stripes 1.66
- Three stripes 2.01

The chapter involves tests of a bulkhead suppressant strength properties and deformation properties. Working characteristics and safety factor have been determined.

Actual parameters of an explosion bulkhead protective element make it possible to calculate its parameters.

Working model of a bulkhead has been manufactured and laboratory tested to determine reliability of estimates of bearing capability of a bulkhead structural components calculated according to a technique described in point 3.4.

3.2. Similarity criteria

To manufacture a bulkhead model one should first identify similarity criteria which will make it possible to determine actual parameters of a bulkhead.

Determination of similarity criteria involves specification of basic parameters identifying a process of a bulkhead deformation. The parameters are as follows: S is sectional area of a mine working, m^2 ; l is length of a bulkhead stripe, m ; h is width of a bulkhead stripe, m ; Δl is absolute elongation of a bulkhead material, m ; k is material rigidity, N/m ; and F is force acting on a bulkhead, N [66].

Let's denote geometrical parameters $l, h, \Delta l$ as L .

Compile following table to determine similarity criteria:

P_i		$[M]$	$[L]$	$[T]$
P_1	L	$\mu_1 = 0$	$\lambda_1 = 1$	$\tau_1 = 0$
P_2	S	$\mu_2 = 0$	$\lambda_2 = 1$	$\tau_2 = -2$
P_3	k	$\mu_3 = 1$	$\lambda_3 = 0$	$\tau_3 = -2$
P_4	F	$\mu_4 = 1$	$\lambda_4 = 1$	$\tau_4 = -2$

where $[M]$, $[L]$, and $[T]$ are respectively dimensions of mass, length, and time in SI system;

P_i are basic values characterizing a process of a bulkhead deformation; and μ_i, λ_i, τ_i are dimension degrees for each basic value P_i .

Quantity of independent similarity criteria is equal to $s - r = 4 - 3 = 1$ where s is quantity of key parameters (basic values); and r is matrix rank.

Assume similarity criterion [66]:

$$\Pi_1 = \frac{k \cdot l}{F} \quad (3.1)$$

According to similarity theory not only constant parameters can be taken as causal variables; however, it is required for values of model and nature to be constant.

Taking into account the fact that time factor stays to be constant assume time scale equal to 1:

$$T_c = \frac{T_m}{T_n} = 1 \quad (3.2)$$

Determine length scale:

$$L_c = \frac{L_h}{L_m} \quad (3.3)$$

Determine mass scale. As one and same material with 900g/m² density is applied we obtain:

$$M_c = \frac{M_h}{M_m} = \frac{\rho \cdot S_h}{\rho \cdot S_m} = \frac{L_h^2}{L_m^2} = L_c^2 \quad (3.4)$$

Result ratios to determine parameters of nature:

$$\begin{aligned} S_h &= S_m \cdot L_c^2 & L_h &= L_c \cdot L_m & \Delta L_m &= L_c \cdot \Delta L_h & h_h &= L_c \cdot h_m \\ k_h &= k_m \cdot M_c & F_h &= F_m \cdot L_c \cdot M_c \end{aligned}$$

Check the ratios choice:

$$\frac{k_h \cdot l_h}{F_h} = \frac{k_m M_c \cdot l_m L_c}{F_m M_c L_c} = \frac{k_m \cdot l_m}{F_m}$$

Thus, to calculate parameters of a bulkhead model and compare them with laboratory results similarity criteria are identified. They help to determine strength properties and deformation properties of suppressant both for model and real conditions using research results from point 3.1.

3.3. Analysis of explosion-proof bulkhead model

Design of mine working model and fixing anchors are of following dimensions:

Width of a mine working	0.247 m;
Height of a mine working	0.209 m;
Cross-section of a mine working	0.05 m ² ;
Length of anchor free nose	0.007 m;
Diameter of anchor	0.003 m.

Determine optimum bending of a bulkhead material using (2.11). For the purpose identify initial dimensions of a stripe receiving width of a mine working model as its length:

$$L_c = 2.47$$

Length of a stripe is $l = 0.247$ m;

Width of a stripe is $h = 0.0247$ m;

Maximum elongation of material is $\Delta l = 0.006175$ m;

Coefficient of material rigidity is $k = 165060$ N/m;

Angle of protective element of a bulkhead camber is $\alpha = 25^\circ$.

Taking into account camber angle of a bulkhead and a mine working width, a stripe length is $l = 0.272$ m.

Similar specifying of a stripe length will help to calculate its characteristics.

Length of a stripe is $l = 0.272$ m;

Width of a stripe is $h = 0.0272$ m;

Area of a stripe is $S = 0.0074$ m²;

Maximum elongation of material is $\Delta l = 0.0068$ m;

Coefficient of material rigidity is $k = 200164$ N/m.

After geometry of stripes had been determined the authors designed a model of explosion-proof bulkhead shown in Fig. 3.5.



Fig. 3.5. Model of explosion-proof bulkhead

Wood has been used for a mine working model; screws with ring-type clinches have been used as anchors. Caprone thread has been applied as a rope. Tails of a bulkhead stripes have been pierced using “polyester-10”.

Area of a bulkhead is 0.037m²; in such a case perforation coefficient is $0.037/0.05 = 0.74$.

Using (2.13) determine static pressure which a bulkhead model should withstand:

$$P = 78 \text{ kPa.}$$

In this context, effort to a bulkhead is:

$$F = 2886 \text{ N}$$

The effort means that when applying to explosion-proof bulkhead it should not experience any structural damage. Control was performed in a laboratory environment. The model was tested in a laboratory of Institute of Rock Mechanics using hydraulic press 3иМ П-50 GOST 8908-75 (Fig. 3.6).

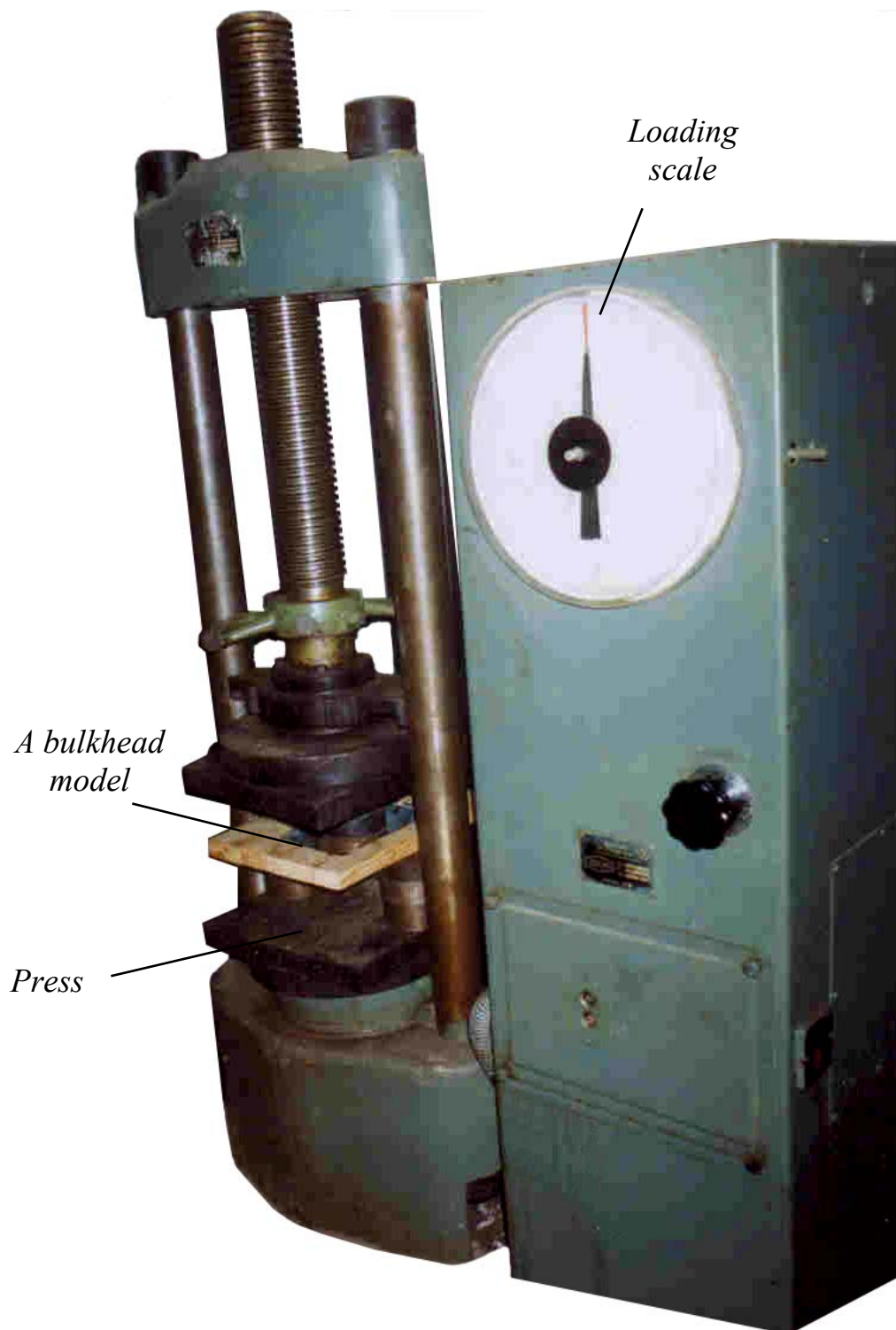


Fig. 3.6. Explosion-proof bulkhead model test

Before tests started, supports for a bulkhead model were mounted on a press. One more support was mounted at the top right on bulkhead. Then press was energized and 2800 N effort was fed (Fig. 3.7).

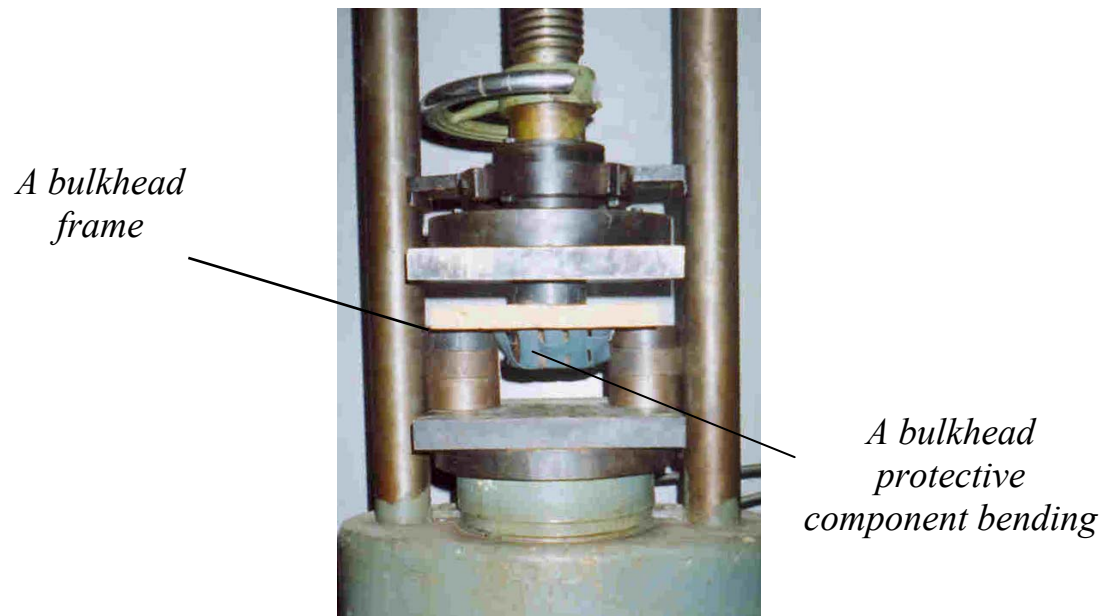
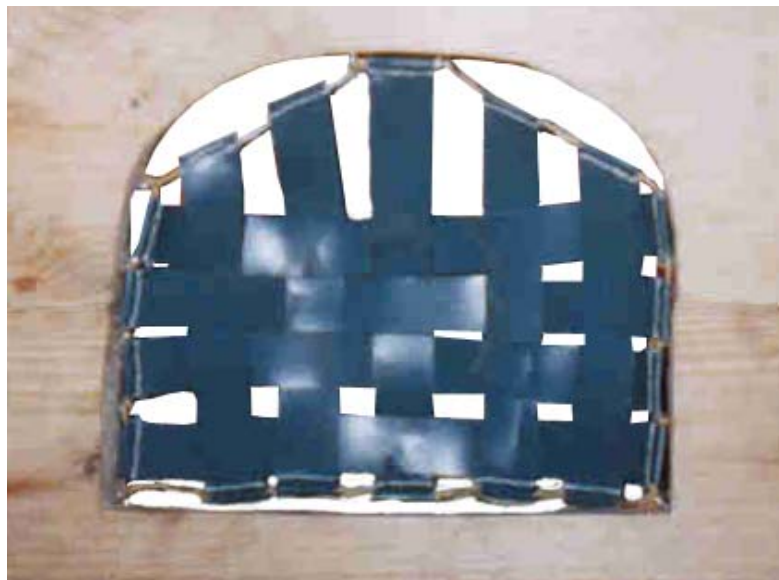


Fig. 3.7. A bulkhead model under pressure.

To control possibility of multiply use, rated force was applied five times. Fig. 3.8 demonstrates a bulkhead model after tests.



Puc. 3.8. An explosion-proof bulkhead model after tests.

After tests length of longitudinal stripe was 0.274 m, and its elongation was 2 mm. It means that after rated load was applied to a bulkhead protective component became yielding a little. Such a property is quite acceptable to the samples. However,

structural components of a bulkhead are not destroyed which confirms reliability of its load bearing ability estimates; besides it helps to identify real parameters of explosion-proof bulkhead according to developed technique.

3.4. Characterization of a bulkhead

Mine workings of “Zaporozhskii Zhelezorudnyi Kombinat” CJSC in which explosion-proof bulkhead will be installed are of following geometry: width of a mine working is 3.65 m; height of a mine working is 3.65 m; sectional area is 12.4 m².

Using similarity criteria determine length scale for the mine working:

Effective length of a bulkhead stripe is 4.027 m.

Production time of a bulkhead may involve a problem of changes in its perforation to ventilate mine workings. In this context it is required to calculate bulkhead parameters for different perforation degree.

To increase or decrease bulkhead perforation one should either increase or decrease width of a protective component stripe width. Moreover length of the stripe should stay constant not to vary optimum bending angle of a bulkhead.

Increase/decrease of a bulkhead protective component stripe width results in its changes in terms of strength properties and deformation ones. Thus, it is required to obtain dependence of material rigidity coefficient on a bulkhead protective component stripe width. To do that, use the results of material strength tests (Table 3.2) as well as similarity criteria obtained. Following dependence is an effect of interpolation results (Fig. 3.9).

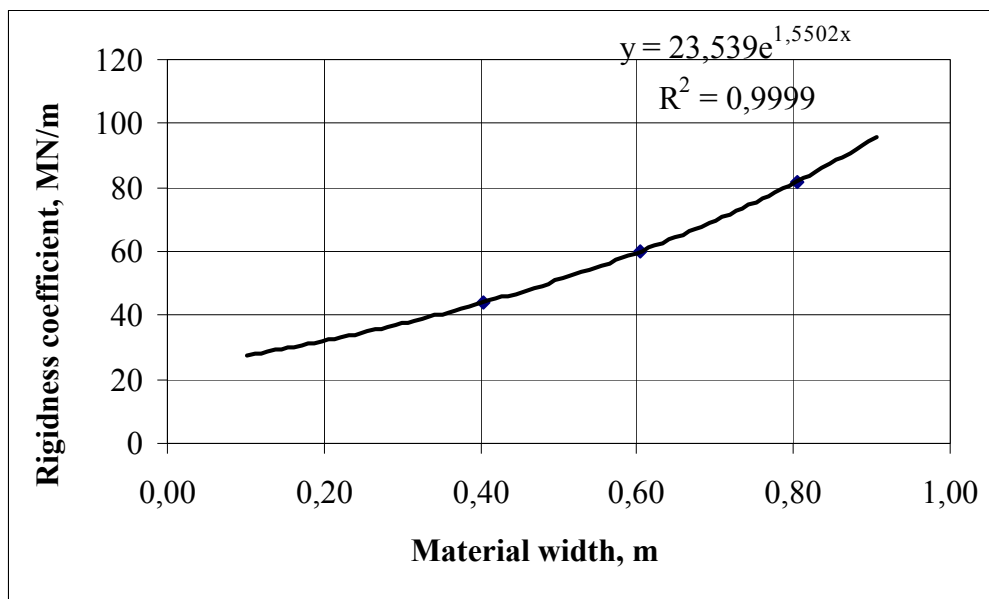


Fig. 3.9. A graph of rigidity coefficient dependence on material width

$$y = 23,5e^{1,55x}, \text{ MN/m} \quad (3.1)$$

where y is material rigidity coefficient, MN/m;
 x is material width, m.

Dependence obtained (3.1) allows calculating protective component strength properties and deformation ones for different perforation of protective component.

As experiments demonstrate (p. 3.1.) maximum elongation of material slightly depends on a stripe width. Therefore, it is 0.1 m for relevant environment.

Armature with 20 mm diameter and 0.5 m length is proposed to be applied as anchors (material is GOST 380 – 71 St. 5 carbon steel which strength is 620 MPa [56]).

Technique presented in points 2.1. and 2.2. was applied to calculate explosion-proof parameters. Table 3.6 explains them.

Source [19] involves perforated bulkhead air-blast attenuation coefficient.

Table 3.6.

Characteristics of explosion-proof bulkhead in terms of different perforation degree

Bulkhead deformation degree	0.8	0.6	0.4	0.2
Air-blast attenuation coefficient	1.086	1.265	1.670	2.860
Length of a bulkhead stripe, m	4.03	4.03	4.03	4.03
Width of a bulkhead stripe, m	0.11	0.21	0.32	0.42
Area of a stripe, m ²	0.43	0.86	1.28	1.71
Maximum elongation of material, m	0.1	0.1	0.1	0.1
Material rigidity coefficient, MN/m ²	27.75	32.71	38.56	45.45
Air-blast pressure, kPa	1372	809	635	562
Energy consumed to expand bulkhead stripes, MJ	2.77	3.27	3.86	4.54
Energy consumed for friction between structural components of a bulkhead, MJ	0.01	0.01	0.02	0.08
Total energy to prevent air-blast with the help of a bulkhead, MJ	2.78	3.28	3.88	4.62
Air-blast pressure involving frictional energy, kPa	1370	810	640	570
Ultimate anchor bending strength, MPa	374	440	519	612
Effort for anchor pulling, MN	1.26	1.48	1.75	2.06

Results presented in Table 3.6 make it possible to obtain following dependences:

- Dependence of a bulkhead perforation degree on a stripe width (Fig. 3.10);
- Dependence of air-blast attenuation coefficient on a bulkhead perforation degree (Fig. 3.11);
- Dependence of maximum possible air-blast pressure applied to explosion-proof bulkhead on its perforation degree (Fig. 3.12).

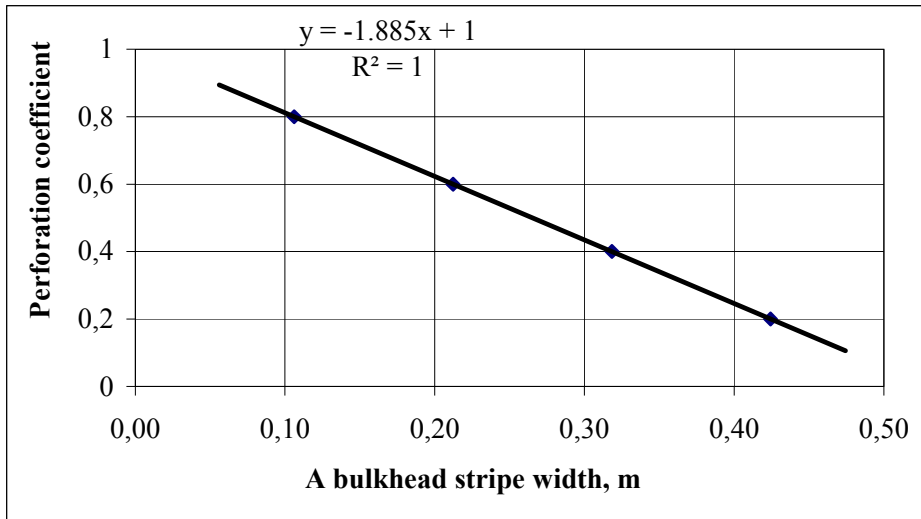


Fig. 3.10. Dependence of a bulkhead perforation degree on a stripe width

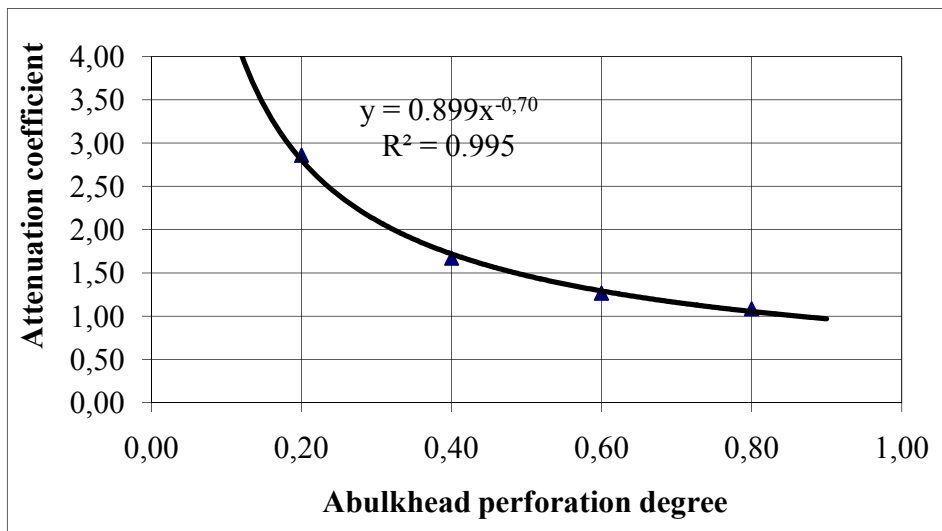


Fig. 3.11. Dependence of air-blast attenuation coefficient on a bulkhead perforation degree

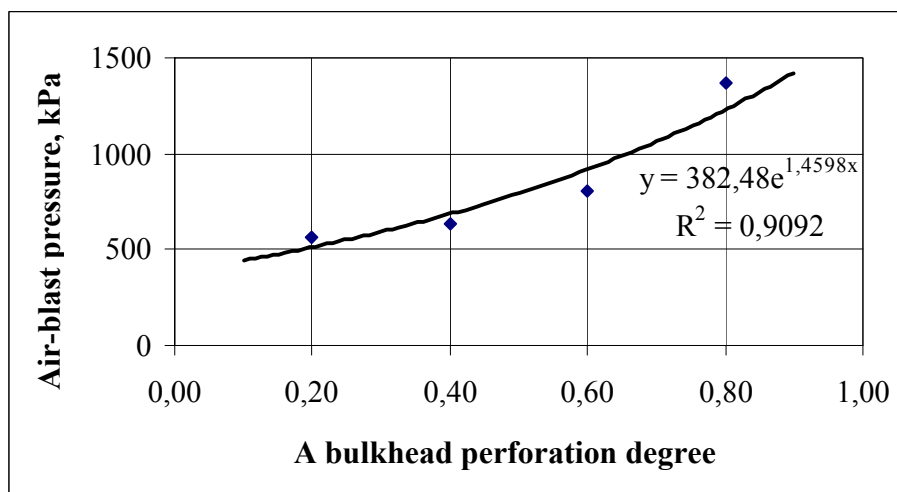


Fig. 3.12. Dependence of air-blast pressure on a bulkhead perforation degree

Conclusions

1. To calculate explosion-proof parameters one should know strength parameters and deformation properties of its protective component; polyester with 900 g/m^2 density is chosen as material. Laboratory of "Orel" Ltd. tested it using PT-250-M2 tensile machine according to GOST 17316-71; its rigidity coefficient and maximum elongation have been obtained.

2. Working model has been manufactured and laboratory tested to verify calculation of explosion-proof structural components bearing capacity. To construct a bulkhead and recalculate the research results for real conditions, similarity criteria have been substantiated.

3. A bulkhead model has been analyzed by a laboratory of Institute of Rock Mechanics of National Academy of Sciences of Ukraine using hydraulic press 3иМ П-50 GOST 8908-75. The research confirms results of theoretical calculation making it possible to substantiate explosion-proof bulkhead parameters.

4. Theoretical research and laboratory research have determined that:

- Bearing capability of explosion-proof bulkhead depends on its free bending angle (optimum angle is 25°) and perforation degree varying on exponential dependence; if increase is 0.2 to 0.8, it experiences 2.4 times increase. That makes it possible to use air-blast pressure estimated value for determination of explosion-proof bulkhead rational perforation, protective component stripe width, and attenuation coefficient;

- Adopted parameters of fixing anchors are adequate for rated values of a bulkhead bearing capacity;

- Bearing capacity of a bulkhead protective material can be increased (1.66 and 2.01 times respectively) if two or three bunched stripes are applied as protective component.

CHAPTER 4. FIELD OBSERVATION OF AIR-BLAST PROPAGATION BEHAVIOUR AND A TECHNIQUE TO APPLY EXPLOSION-PROOF BULKHEAD

Point 2.4. involves theoretical calculation on changes in air-blast parameters in the process of single blast; point 3.4. determines explosion-proof bulkhead parameters basing upon calculation and laboratory research.

To verify theoretical research as well laboratory one, field observation of air-blast propagation behaviour within mine workings in the process of single blast. “Prokhodcheskaia” and “Ekspluatatsionnaia” mines of “ZIOIC” CJSC were involved.

4.1. Development of a device to analyze air-blast parameters

Mathematical model of measuring device

Analysis of facilities to measure air-blast parameters demonstrates that a device used for research in a production environment is unavailable today. Consequently authors conclude that designing of a device to determine air-blast impulse is required. Its idea is as follows: determination of air-blast intensity requires certain area to be effected. So called elastic components (i.e. helical spring) can be applied as a sensing element. They are widely used in devices and automatic devices to perform various functions.

The fact that while working elastic components can develop adequate efforts proportional to deformations regardless of their spatial position is their fundamental property. In a great measure elastic components can change their dimensions and configuration depending upon value of external force or internal pressure within system [8, 76].

Offset value of elastic component is index of air-blast intensity.

Fig. 4.1 demonstrates analytical model of measuring device.

Consider differential equation system with one degree of freedom when disturbing arbitrary force Q acts (the force unalters on periodic law) [28, 40, 38, 76].

Motion equation is

$$mx''+cx'+kx = Q \quad (4.1)$$

where m is mass of the device moving element, kg;

c is viscosity of mechanical friction);

k is rigidity coefficient, N/m.

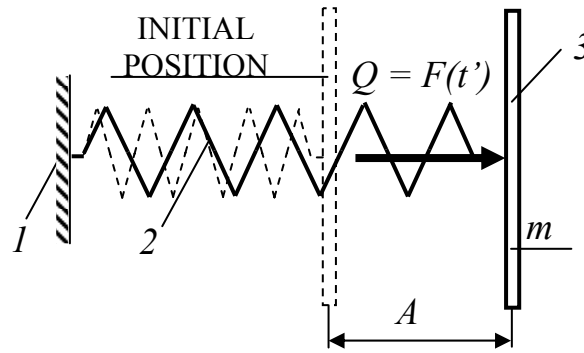


Fig. 4.1. Analytical model of measuring device: 1. Support; 2. Helical tension spring; 3. Flat disk with S , m^2 area and m , kg mass; Q . Disturbing force, N ; A . Amplitude of a spring vibration, m .

Dividing left and right side of equation (4.1) by m we obtain:

$$x'' + \frac{c}{m}x' + \frac{k}{m}x = \frac{Q}{m} \quad (4.2)$$

where $\frac{Q}{m} = \frac{F(t')}{m} = f(t') = q$ is disturbing force referred to mass unit of measuring device moving element.

It is supposed that force q is a function of fictitious time t' as Fig. 4.2 explains. Then increment of impulse qdt' (shaded rectangle in Fig. 4.2) can be calculated at certain time moment t' . The impulse imparts velocity increment to unit mass: $dx' = qdt'$.

Consider the velocity increment as initial velocity at time moment t' .

Introducing following symbols: $2n = \frac{c}{m}$ and $p^2 = \frac{k}{m}$, rewrite (4.2) as:

$$x'' + 2nx' + p^2x = q \quad (4.3)$$

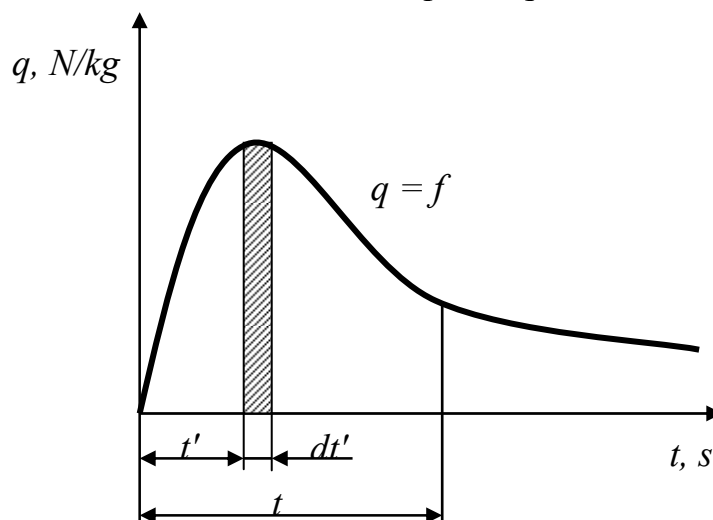


Fig. 4.2. Graph of perturbing force time changes

If in the right side of (4.3) equation $q = 0$ then we obtain equation of natural oscillation with dampening:

$$x'' + 2nx' + p^2x = 0 \quad (4.4)$$

General equation (4.4) is:

$$x = e^{-nt}(C_1 \cos \omega t + C_2 \sin \omega t) \quad (4.5)$$

where C_1 and C_2 are integration constants determined from initial conditions.

Wave circular frequency ω under oscillation dampening is

$$\omega = \sqrt{p^2 - n^2} \quad (4.6)$$

To determine constants C_1 and C_2 being a part of solution (4.5) assume that at $t = 0$ disk is not displaced about initial point; that is $x_0 = 0$ having instantaneous initial velocity \dot{x}_0 . Substituting the values for (4.5) solution and its time derivative, we find:

$$C_1 = 0,$$

$$C_2 = \frac{\dot{x}_0}{\omega}.$$

Substituting determined values C_1 and C_2 for (4.5) we obtain:

$$x = e^{-nt} \frac{\dot{x}_0}{\omega} \sin \omega t \quad (4.7)$$

Substituting increment velocity value $dx' = qdt'$ for (4.7) solution we obtain a displacement increment value at any time moment t :

$$dx = e^{-n(t-t')} \frac{qdt'}{\omega} \sin \omega(t-t') \quad (4.8)$$

As similar effect is a result of each increment of qdt' impulse within $t' = 0$ to $t' = t$, continuous action of perturbing force q factors into following expression for full movement of a disk:

$$x = \frac{e^{-nt}}{\omega} \int_0^t e^{-nt'} q \sin \omega(t-t') dt' \quad (4.9)$$

Mathematics calls similar representations Duhamel integral [50].

Expression (4.9) is full displacement of a disk under the effect of perturbing force q within 0 to t interval. It covers both steady modes of motion and unsteady

ones making it possible to analyze mechanical system behaviour under oscillations when unspecified perturbing force effects.

If dampening effect is neglected we obtain $n = 0$ and $\omega = p$; as a result, expression (4.9) is:

$$x = \frac{1}{p} \int_0^t q \sin p(t-t') dt' \quad (4.10)$$

Suppose that constant time-independent force Q_1 is unexpectedly applied to a disk with mass m .

Heaviside function [54] explains similar character of dynamic loading. In that event, $q_1 = \frac{Q_1}{m} = \text{const}$. Then expression (4.10) is:

$$x = \frac{q_1}{p} \int_0^t \sin(t-t') dt'$$

The integral is easily calculated giving:

$$x = \frac{q_1}{p^2} (1 - \cos pt) = \frac{Q_1}{k} (1 - \cos pt) \quad (4.11)$$

It follows from (4.11) that under the conditions of sudden constant value application, oscillations with $\frac{Q_1}{k}$ amplitude imposed on static displacement of the same value $\frac{Q_1}{k}$ take place (Fig. 4.3).

Hence, maximum disk move taking place under the conditions of sudden application of force Q_1 is twice more than moves resulting from force Q_1 in terms of its static application.

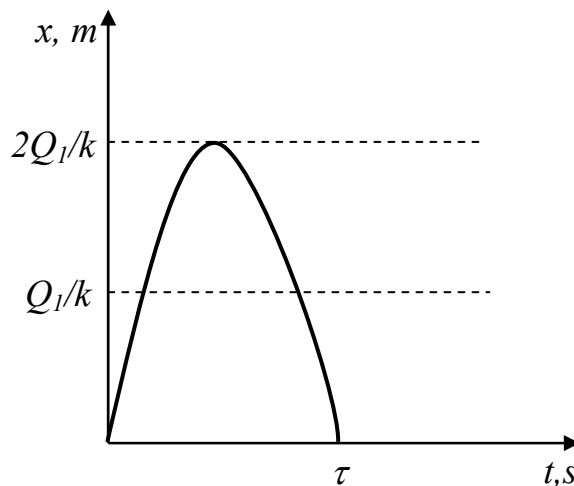


Fig. 4.3. A graph of sensing device time displacement in the context of single power impulse effect

In above case, constant force Q acts during infinitely large period of time. But if it acts only within time interval t_1 then rectangular impulse takes place (Fig. 4.4).

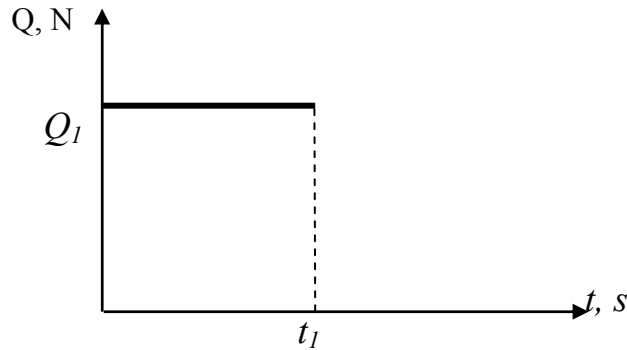


Fig. 4.4. A graph of rectangular impulse

In the course of time when force is not equal to zero, system behaviour coincides with that in expression (4.11). But behaviour during following t_1 period can be determined using Duhamel integral written for every of two time intervals: 0 to t_1 and t_1 to t . Only first time interval integrating gives result differing from zero as within time interval two a function of perturbing force is equal to zero. Summing up above, solution for the case can be represented as:

$$\begin{aligned} \text{if } 0 \leq t \leq t_1 & \quad x = \frac{Q_1}{k}(1 - \cos pt) \\ \text{if } t \geq t_1 & \quad x = \frac{Q_1}{k}[\cos p(t - t_1) - \cos pt] \end{aligned} \quad (4.12)$$

Similar method to obtain the same result as in expression (4.12) is in determining of a system motion and velocity at t_1 moment using expression (4.11)

$$\begin{aligned} x_{t_1} &= \frac{Q_1}{k}(1 - \cos pt_1) \\ \dot{x}_{t_1} &= \frac{Q_1 p}{k} \sin pt_1 \end{aligned} \quad (4.13)$$

Amplitude of measuring device spring natural oscillation arising after effect of rectangular impulse can be determined by:

$$A = \sqrt{x_{t_1}^2 + \left(\frac{\dot{x}_{t_1}}{p}\right)^2} \quad (4.14)$$

Substituting values x_{t_1} and \dot{x}_{t_1} from (4.13) we find after simplification:

$$A = \frac{Q_1}{k} \sqrt{2(1 - \cos pt)} = \frac{2Q}{k} \sin \frac{pt_1}{2} = 2 \frac{Q}{k} \sin\left(\frac{\pi t_1}{\tau}\right) \quad (4.15)$$

where τ is a period of a spring natural oscillations.

$$\tau = \frac{2\pi}{p} = \frac{2\pi}{\sqrt{\frac{k}{m}}}$$

Then expression to calculate oscillation amplitude A is as follows:

$$A = \frac{2Q}{k} \sin \left(\frac{\pi t_1}{\frac{2\pi}{\sqrt{\frac{k}{m}}}} \right) = \frac{2Q}{k} \sin \left(\frac{\sqrt{\frac{k}{m}} t_1}{2} \right) \quad (4.16)$$

Expression (4.15) explains that amplitude of natural oscillation depends on t_1/τ ratio. Taking $t_1 = \frac{\tau}{2}$ as impulse time we obtain value of amplitude A :

$$A = \frac{2Q_1}{k} \quad (4.17)$$

In such a case, force Q is acting in motion direction from 0 to A performing positive sign work. When the force starts acting in the extreme position, then a system lacking amortization to conserve energy. As a result, natural oscillations arise concerning initial motion $2Q/k$ adequate to t_1 moment.

Taking notice of amplitude A and impulse time t_1 one can find force Q which produces effect on a measuring device:

$$Q = \frac{Ak}{2 \sin \left(\frac{\sqrt{\frac{k}{m}} t_1}{2} \right)}, \text{ N} \quad (4.18)$$

Taking notice of force Q and area of sensing device disk determine air-blast pressure producing effect on sensing device disk:

$$P = \frac{Ak}{2S \sin\left(\frac{\sqrt{\frac{k}{m}}t_1}{2}\right)}, \text{ Pa} \quad (4.19)$$

Multiplying the expression on a period of force applied, we obtain air-blast impulse:

$$I = \frac{Ak}{2S \sin\left(\frac{\sqrt{\frac{k}{m}}t_1}{2}\right)} t_1 \quad (4.20)$$

If $t_1 = \frac{\tau}{2}$

$$P = \frac{Ak}{2S} \quad (4.21)$$

where A is maximum of sensing device motion, m;
 k is the system elastic element rigidity; N/m;
 m is motion sensor mass, kg;
 t_1 is impulse time, c;
 S is sensing device disk sectional area, m².

Involving energy dissipation, we obtain computational error. As a rule, energy dissipation determining (consideration of viscous resistance) factors into no more than 10% error for mechanical systems with low frictional losses (devices).

Analysis of measuring device characteristics

Basing upon analytical model of numerical scheme of a device for air-blast impulse determination, authors have designed following structure (Fig. 4.5).

Measuring device consists of body 1 being a pipe which diameter is 34 mm. The pipe has a slot 9. Spring 7 is fixed to a bearing face. On the other side it is attached to measuring disk 4 by means of moving core 8. Movable base 3 attached to measuring disk is to direct the disk movement on the pipe. Rubber gasket 2 joins end face of a movable base.

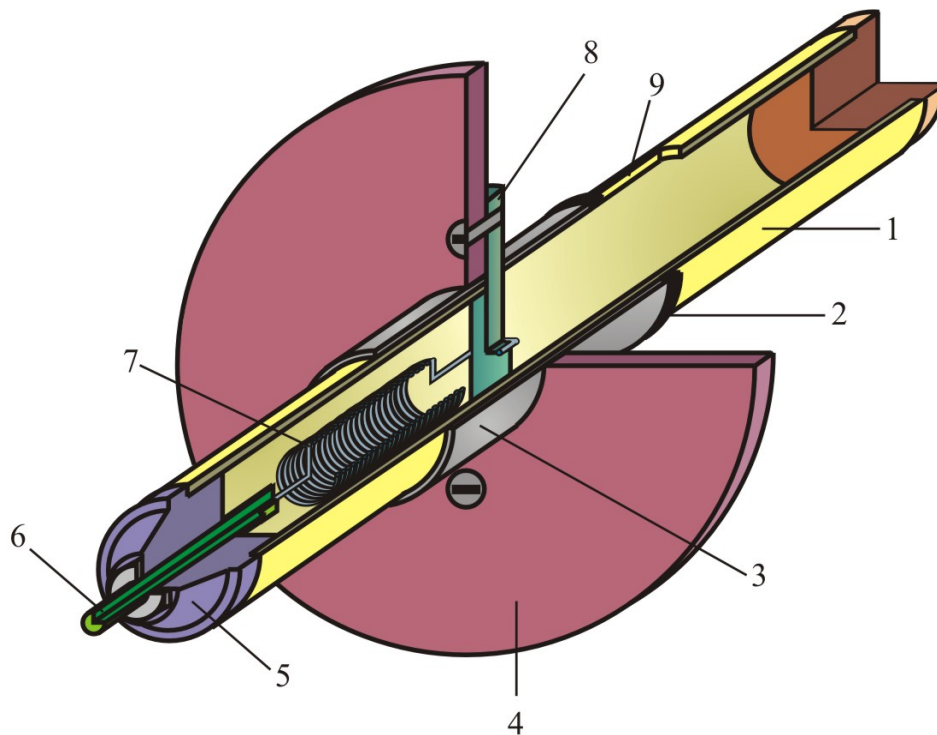


Fig. 4.5. Device to determine air-blast impulse:
 1. Body; 2. Rubber gasket; 3. Movable base;
 4. Measuring disk; 5. Cone; 6. Adjusting core;
 7. Spring; 8. Movable core; 9. Slot.

To impose minimum initial tension on a spring, the device is equipped with adjusting screw 6 which can be displaced using screwed joint along cone 5 whereby depressing a spring or tightening it.

Mechanism of the measuring device is as follows: pressure within air-blast front has an effect on measuring disk 4. Depending on its area, force is created to stretch spring 7. To determine maximum stretch of a spring, the measuring device is equipped with rubber gasket; effected by movable base it shifts with it along the measuring device base. When effect on measuring disk is over, it resets, and rubber gasket shows its run measured with the help of caliper [62].

The research task

To interpret readings of the device one should know its numerical parameters (i.e spring force, area of measuring disk, and mass of movable component). Thus, laboratory research should determine coefficient of a spring force, and mass of measuring device movable component in terms of different disk diameters. To apply measuring device in the context of short-delay blasting one should identify reset time of movable component.

Determining mass of movable component and coefficient of measuring device spring force

Mass of measuring device movable component with various disk areas was determined by means of electronic weighing machine PHILIPS HR 2390 which absolute error is 0.02 g. Table 4.1 shows results.

Table 4.1.

Mass of measuring device movable component in terms of various disk areas

Disk area, m ²	Mass of movable component, kg
0.01	0.368
0.07	0.412

To determine value of spring force coefficient, measuring device is placed upright. Sensing device is loaded by weights having certain mass; simultaneously stretch of a spring was measured using caliper.

Coefficient of a spring force is determined by:

$$k = \frac{F_{ynp}}{x}, \text{ N/m} \quad (4.22)$$

where F_{ynp} is a spring force, N;
 x is a spring stretching, m.

To determine a spring force one should have various mass weights.

Successive placing of weights on the sensing device makes it possible to develop a spring elastic force. In this particular case it is:

$$F_{ynp} = mg, \text{ N} \quad (4.23)$$

where m is total weight of load and measuring equipment sensing device, kg;
(mass of the sensing device is 0.368 kg);
 g is gravity, m/c².

Obtained data are tabulated.

Table 4.2.

Data to determine a spring force

No.	Mass acting on a spring m , kg	A spring stretching x , m	Elastic force F , N	Rigidity coefficient k , N/m
1	0.0	0.000	0.0	-
2	0.5	0.007	4.9	700.0
3	1.0	0.011	9.8	890.9
4	1.5	0.017	14.7	864.7
5	2.0	0.021	19.6	933.3
6	2.5	0.029	24.5	844.8
7	3.0	0.031	29.4	948.4
8	3.5	0.038	34.3	902.6
9	4.0	0.043	39.2	911.6
10	4.5	0.051	44.1	864.7

Fig. 4.6 demonstrates graph of a spring force.

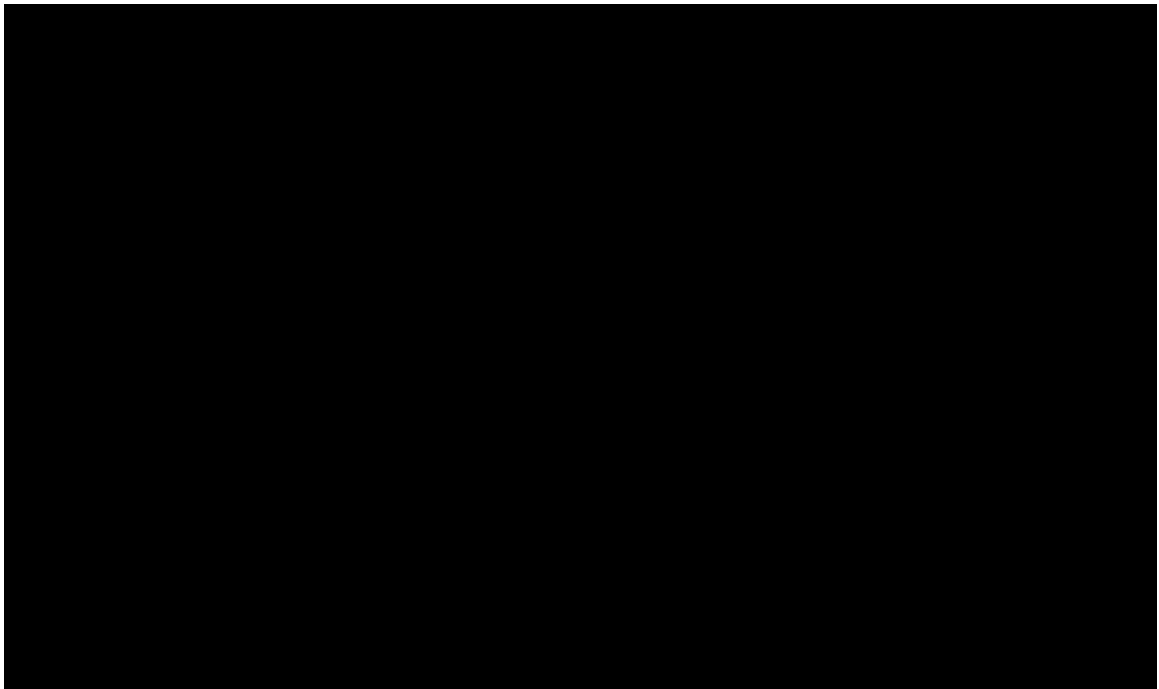


Fig. 4.6. Graph of a spring force

Data interpolation results in equation characterizing a spring elastic force:

$$F_{ynp} = 891,5x, \text{ N} \quad (4.24)$$

where F_{ynp} is elastic force of a spring, N;
 $k = 891.5$ is coefficient of a spring force, N/m;
 x is a spring stretching, m.

Determination of measuring equipment movable component reset time

As short-delay blasting is applied in mines for rock mass breaking, air-blasts follow each other. If distance from explosion site is small it can be supposed that air-blast lateness will be matched by time of blast delay. Accordingly, let's determine reset time of the disk.

$$T = 2\pi\sqrt{\frac{M}{k}}, \text{ s}$$

Substituting numerical values M and k we obtain $t = 0,13$ s.

Reset time of the disk is shorter than minimum delay period (0.15 c); thus, the measuring equipment can be used in terms of short-delay blasting.

Specification of the measuring equipment

Laboratory research allows determining its following characteristics:

Spring force	$k = 891.5 \text{ N/m};$
Minimum disk area	$S_{min} = 0.01 \text{ m}^2;$
Maximum disk area	$S_{max} = 0.07 \text{ m}^2.$

Mass of sensing device in terms of:

- Minimum disk area	$m_{min} = 0.368 \text{ kg};$
- Maximum disk area	$m_{max} = 0.412 \text{ kg}.$

Parameters of measuring component stroke are: 0.00 – 0.13 m.

To simplify interpretation of measuring equipment readings, transform (4.19) and (4.20) formulae substituting values of the device characteristics. The formulae will be as follows:

For measuring device with 0.07 m^2 disk area:

$$P = \frac{6,367 A}{\sin(23,26t)}, \text{ Pa} \quad (4.25)$$

$$I = \frac{6,367 A}{\sin(23,26t)} t, \text{ Pa}\cdot\text{s} \quad (4.26)$$

For measuring device with 0.01 m^2 disk area:

$$P = \frac{44,575 A}{\sin(24,61t)}, \text{ Pa} \quad (4.27)$$

$$I = \frac{44,575 A}{\sin(24,61t)} t, \text{ Pa}\cdot\text{s} \quad (4.28)$$

where A is measuring device readings, mm;
 t is load action period, s.

The device may be applied to measure air-blast pressure within 0 to 500 Pa·s. That allows making measurements both in terms of blasting operations in blind drifts and single blast while ore breaking.

The data supplemented by air-blast charge size and impulse on air-blast theory make it possible to determine measuring disk area as well as optimum location of the equipment in mine workings.

4.2. The Measuring Device Experimental Check in terms of Blasting Operations

Experts from Dnipropetrovsk Regional Research and Development Centre of Standardization, Metrology and Certification have got to know with the measuring device. They distinguish that many devices use a spring as sensing element. Hence, using a spring in considered measuring device is expedient.

At the same time, the authors have been explained that only those devices being in a production chain and widely used should have governmental certification. Since devices to measure air-blast parameters are not available today, the Centre of Standardization, Metrology and Certification has not any equipment to calibrate such equipment.

However, when experts have familiarized themselves with the measuring device analysis they provide the concurrence with the results.

Technical sources [18] mention that evaluation of the device should involve air-blast of given value taking into consideration dynamics of load application. That makes it possible to verify mathematical model of the measuring device as well as determine actual parameters of air-blast during its motion within mine workings.

The measuring device has been tested in blind drifts of “Prokhodcheskaia” mine (“ZIOIC” CJSC).

First location points for measuring devices have been determined. To do that, software calculated air-blast parameters on length of a mine working; then (4.25)-(4.28) formulae determined scheduled reader of the measuring device.

Fig. 4.7 demonstrates installation diagram of the measuring device to perform research in blind drifts.

To install the device within a mine working holes which length was 0.5 m were made in ribs. Split tube (1) and screwed cleat wedge (2) were installed in them (2) (Fig. 4.8). The tube was fixed within the hole. The measuring device (4) was fixed to a frame (3) with the help of screw (5).

Blasting followed the procedure. Distance to a working face, cross section of a mine working, type of explosive, its weight, delay time between explosion series, stemming type, and explosion weight in each blasting series were recorded.

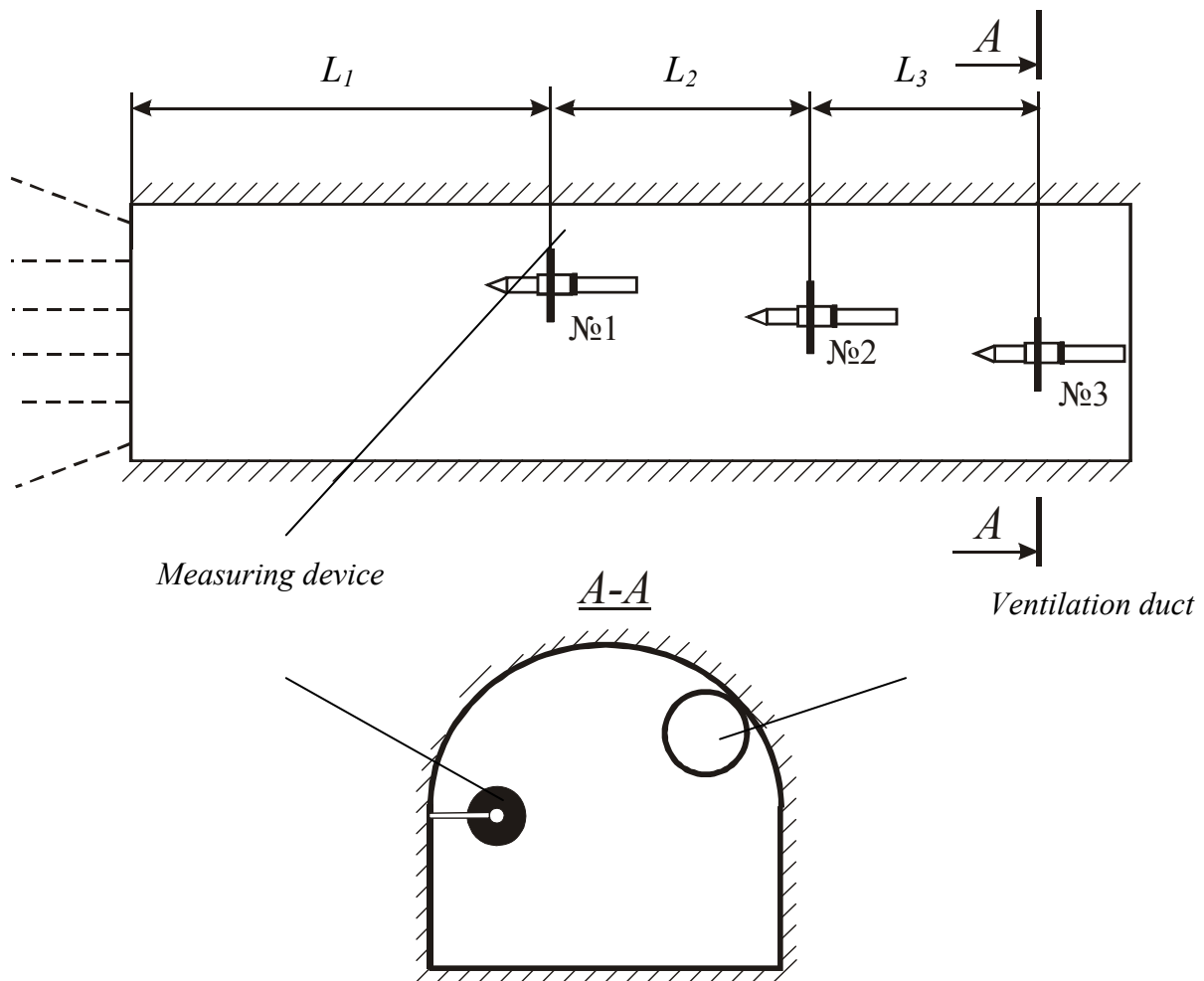


Fig.4.7. installation diagram for measuring device in development working

Measuring results were logged.

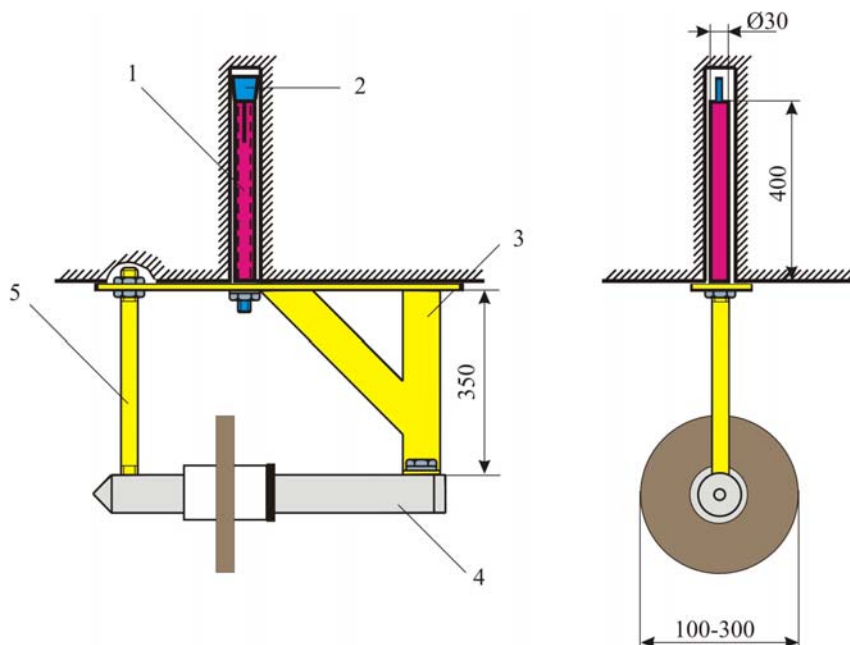


Fig. 4.8 Fixing diagram for measuring device in a mine working.

Functional specifications of workings being driven

Experimental check of the measuring equipment took place in the process of driving of mine workings within various levels of “Prokhodcheskaia” mine (“ZIOIC” CJSC).

Figures 4.9 and 4.10 demonstrate plans of holes and charge design in drifting faces. Table 4.3 shows functional specifications of working faces.

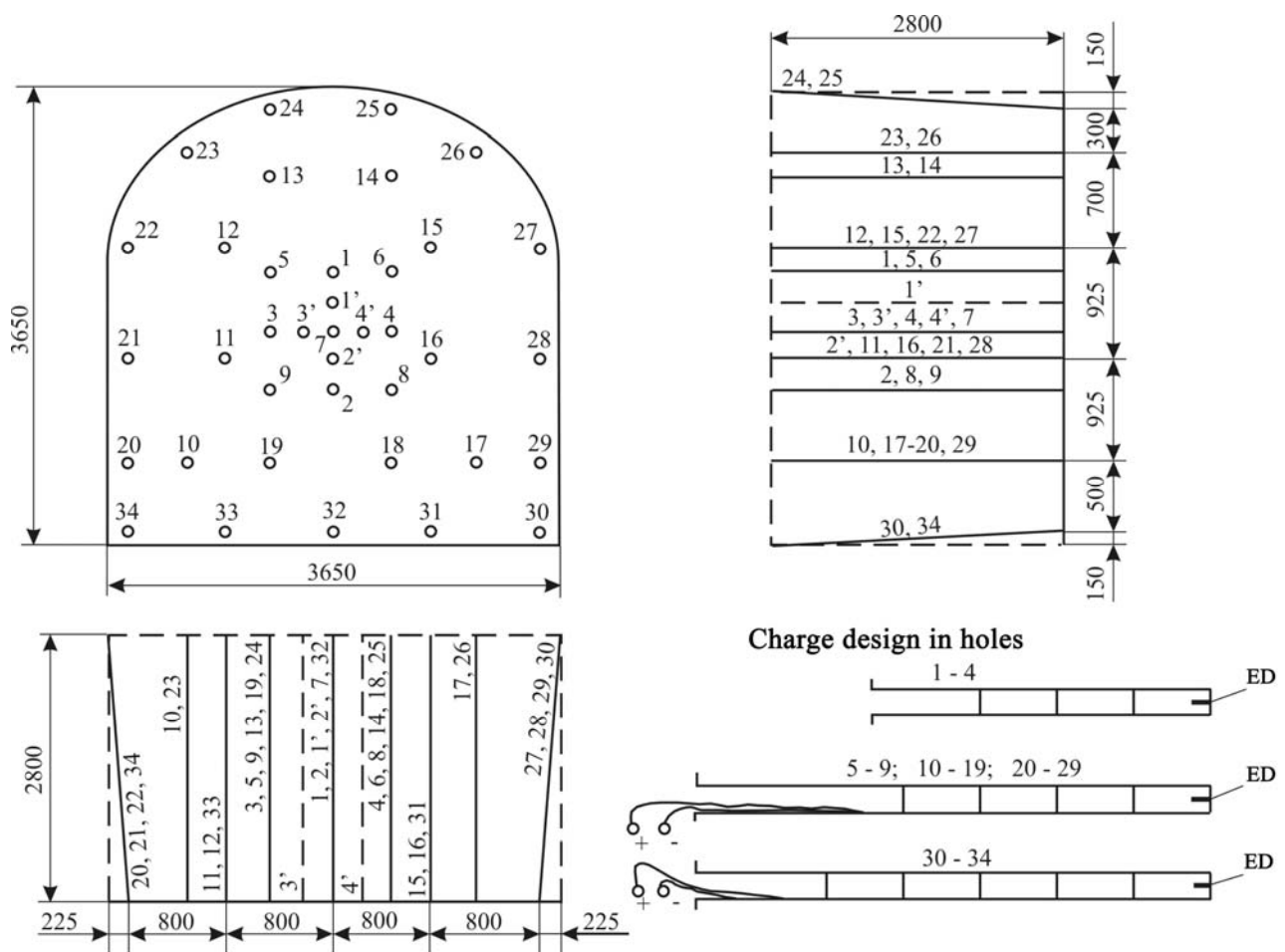


Fig. 4.9. Plan of holes and charge design in faces of 775m level (ort 1s+15) and 810m level (ort 4n+15)

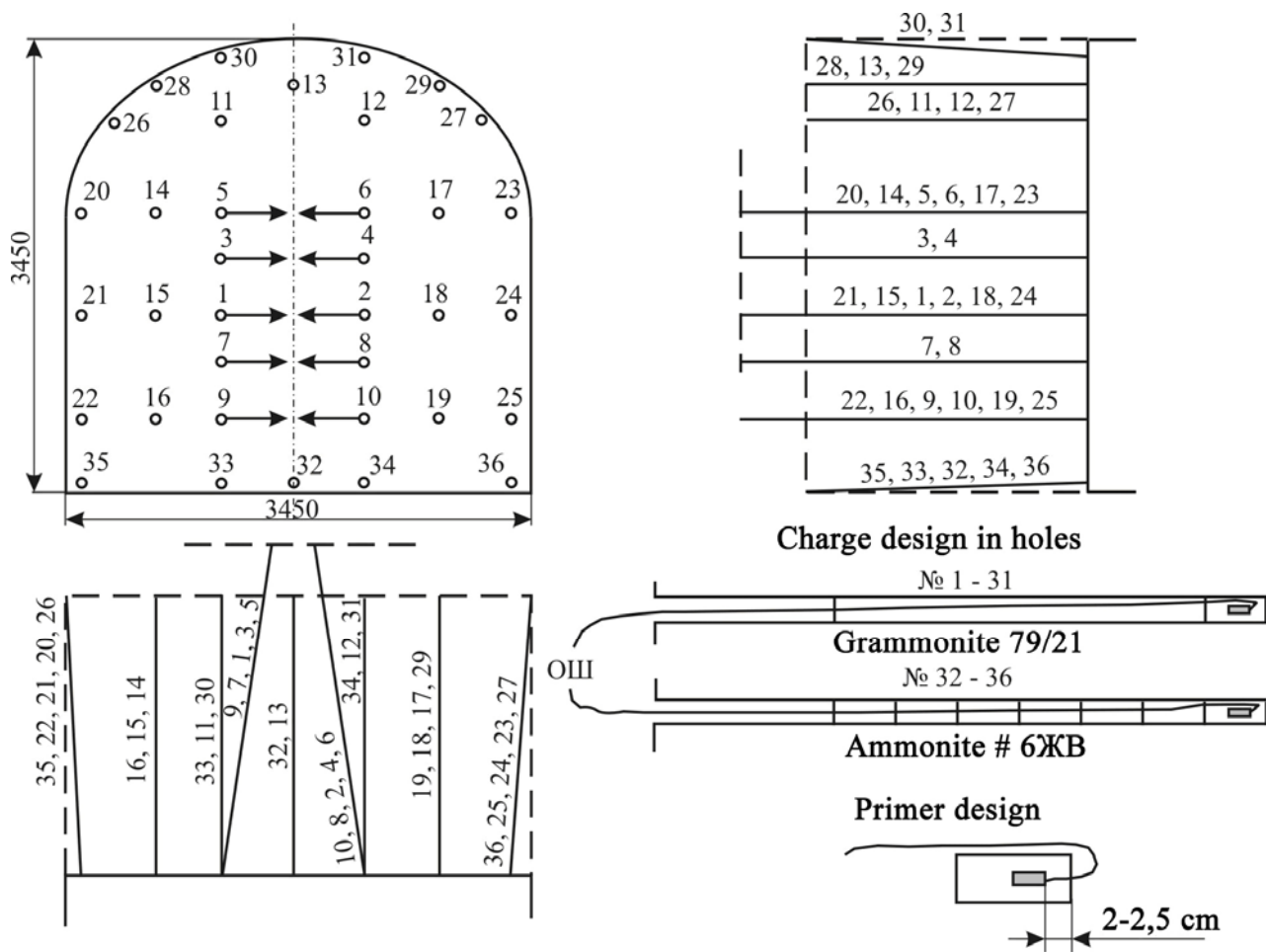


Fig. 4.10. Plan of holes and charge design in face of 740 m collecting ventilation drift (CVD) 17s-20s

Table 4.3.

Functional specifications of workings being driven

Designation	775m level (ort 1s+15)		810m level (ort 4n+15)		740m level (CVD 17s-20s)	
Section of a mine working, m ²	12.4		12.4		11	
Strength category (Protodiakonov classification)	8		10		4	
The number of holes per cycle	38		38		36	
BER (Blasthole efficiency ratio)	0.8		0.9		0.99	
Type of explosive applied	Ammonite # 6ЖБ		Ammonite # 6ЖБ		Grammonite 79/21	
Diameter of holes, mm	64		57		43	
Depth of holes, mm	2800		2800		2400	
Diameter of a chuck, mm	55		48		32	
Types of holes	Hole #	Explosive weight, kg	Hole #	Explosive weight, kg	Hole #	Explosive weight, kg
Key holes	1-4	12	1-4	16	1-10	24.0
	5-9	20	5-9	25		
Outside holes	10-19	40	10-19	50	11-19	21.6
Line holes	20-29	40	20-29	50	20-31	28.8
Foot holes	30-34	25	30-34	30	32-36	7.0
Total:	137 kg		171 kg		81.4 kg	
Stemming type	No stemming					
Blasting method	Electric				Electric and fire	

Localization of Measuring Devices in Mine Workings

To localize measuring devices theoretical values of air-blast parameters in terms of their motion within considered mine workings were calculated.

Taking into account the fact that in mine workings explosive weight is modest (to compare with single blasts) and mine workings are rather short (20 to 60 m) air-blast parameters were calculated on explosion series.

Table 4.4 demonstrates calculation results for a mine working of 810 m level (ort 4n+15).

Since weight of explosion synchronously blasting in outside holes and line holes is equal only series of line holes were calculated.

Table 4.4

Calculation of air-blast parameters of 810 m level working face (ort $4n+15$)

Ordinal number	Initial data						Calculation results		
	q, kg	S, m ²	d, m	R, m	B	n	p, kPa	i, Pa·c	t, c
<u>Key holes</u>									
1	25.00	12.40	3.94	20.00	0.040	0.350	213.81	79.66	0.03
2	25.00	12.40	3.94	30.00	0.040	0.350	144.97	50.48	0.04
3	25.00	12.40	3.94	40.00	0.040	0.350	107.48	35.98	0.06
4	25.00	12.40	3.94	50.00	0.040	0.350	83.57	27.36	0.07
<u>Line holes</u>									
5	50.00	12.40	3.94	20.00	0.040	0.190	226.91	86.49	0.03
6	50.00	12.40	3.94	30.00	0.040	0.190	153.54	54.80	0.04
7	50.00	12.40	3.94	40.00	0.040	0.190	113.67	39.07	0.06
8	50.00	12.40	3.94	50.00	0.040	0.190	88.29	29.71	0.07

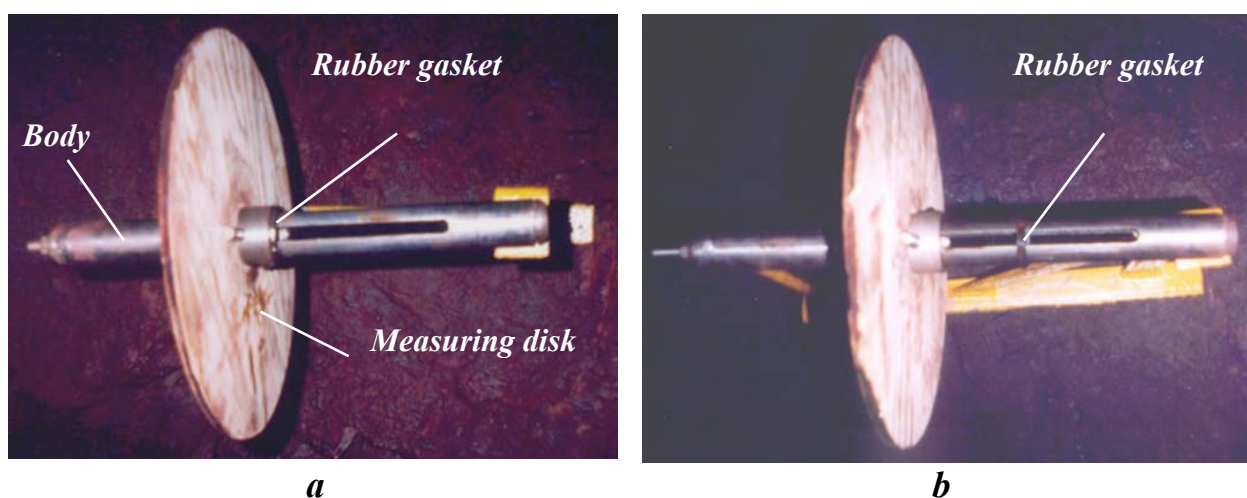
According to calculations (Table. 4.5) maximum intensity of air-blast will take place in terms of line charges blasted after slot has been formed. Hence subsequent calculations were performed for charges blasting for two exposed surfaces.

Range of air-blast impulse meets the requirements of the measuring device with maximum disk area; the device may be installed in a mine working at the distance of 15 to 65 m from a working face.

Results of Calibration. Their Analysis.

In accordance with calculation performed the measuring devices have been installed in mine workings at 14.5 to 62 m distance.

Fig. 4.11 demonstrates installation process of the measuring device in a mine working.



*Fig. 4.11. Measuring device in a mine working:
a. Before explosion; b. After explosion*

Table 4.5 explains measuring results.

Table 4.5

Designation	775m level (ort 1s+15)			810m level (ort 4n+15)			740m level CVD 17s-20s		
	1	2	3	1	2	3	1	2	3
Device number	1	2	3	1	2	3	1	2	3
Distance to a working face, m	37.7	43.2	62.0	18.1	23.7	28.5	14.5	16.9	21.0
Readings, mm	65	54	27	112	109	92	45	40	33
BER	0.80			0.88			0.99		

As Table 4.5 demonstrates a spring stretch varies within 27-112 m depending upon distance between measuring device and working face.

Air-blast pressure is calculated depending upon a spring stretch by (4.25). However the calculation involves operating time of air-blast.

Dependence of air-blast operation time increase on run can be determined with the help of software using functional specifications of a working face (Table 4.3).

Then calculate air-blast pressure according to the measuring device readings to compare them with theoretical calculations. Following step is to determine pressure effected the measuring device. Transforming expression (1.3) we obtain:

$$\Delta P_{cp} = \frac{I}{\tau}, \text{ Pa} \quad (4.29)$$

Table 4.6 demonstrates calculation results.

Table 4.6

Air-blast pressure calculations according to readings of measuring devices

Mine working	Distance to a working face, m	$P_{изм}$, Pa	Air-blast operation time _(theor.) , s	Air-blast mass velocity, m/s	P_{cp} , Pa	ΔP , %
775m level (ort 1s+15)	37.7	451	0.05	190	777	72.35
	43.2	349	0.06	173	550	57.38
	62.0	179	0.08	121	261	45.48
810m level (ort 4n+15)	18.1	1110	0.03	332	2539	128.80
	23.7	865	0.04	268	1414	63.35
	32.3	638	0.05	233	1006	57.69
CVD 17s-20s	14.5	639	0.02	161	1068	67.22
	16.9	568	0.02	139	905	59.32
	21.0	468	0.02	124	712	52.02

Actual data obtained as a result of measurements (Table 4.6, P_{H3M} , Pa) were applied to construct graphs of changes in air-blast pressure within mine working (Fig. 4.12).

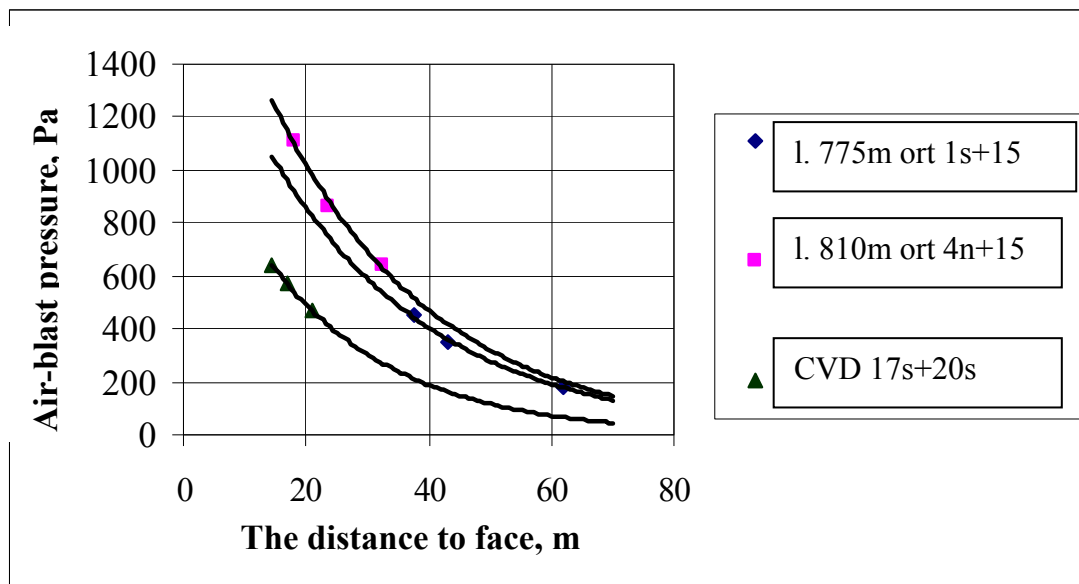


Fig. 4.12. Changes in air-blast pressure within mine workings under consideration

As the graphs explain pressure is changed exponentially. For example, in 775 m level (ort 1s + 15 n) mine working 20m to 40m increase in distance results in sudden pressure drop (from 850 Pa down to 400 Pa); if distance varies from 40 m to 600m then pressure drops from 400 Pa down to 200 Pa. In each mine working, nature of air-blast pressure change is in keeping with air-blast theory.

Comparison of theoretical calculations with readings of measuring devices (Table 4.6) shows that difference in readings decreases if distance by air-blast increases and its velocity decreases. It depends on the fact that in terms of a mine working section air-blast pressure varies in values due to air flow friction on a mine working form depending directly on its velocity. Fig. 4.13 represents changes in air-blast pressure on a mine working form within 775 m level (ort 10+15).

To make objective comparison of the data with theoretical calculations one should apply modifying factor involving air-blast average pressure and pressure in the neighbourhood of a mine working where it is significantly lower.

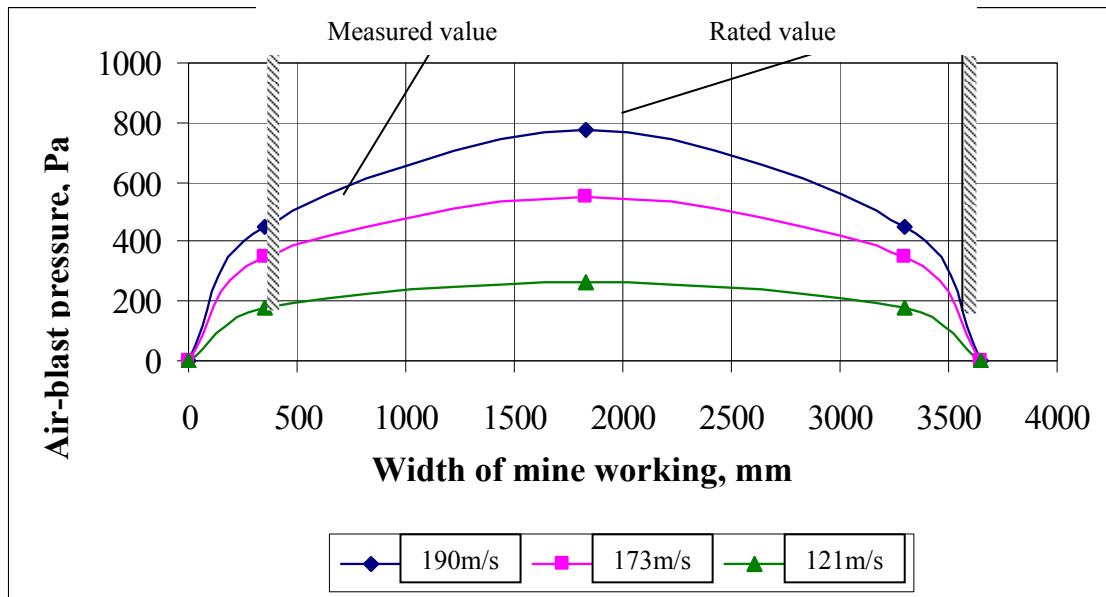


Fig. 4.13. Changes in pressure in terms of horizontal section of a mine working at various air-blast velocities.

Compile Table 4.7 to calculate modifying factor. The Table involves rated air-blast velocity, air-blast pressure, and measured air-blast pressure. Modifying factor is ratio of $P_{cp} / P_{изм}$ division. Correlation analysis has been used to obtain dependence of modifying factor value on air-blast velocity being:

$$k = 1,25e^{0,0015v} \quad (4.30)$$

where v is mass velocity of air flow behind the air-blast front, m/s.

Table 4.7

Calculation of modifying factor for air-blast velocity

Air-blast mass velocity, m/s	P_{cp} , Pa	$P_{изм}$, Pa	Modifying factor
190	777	451	1.72
173	550	349	1.58
121	261	179	1.46
332	2539	1110	2.29
268	1414	865	1.63
233	1006	638	1.58
161	1068	639	1.67
139	905	568	1.59
124	712	468	1.52

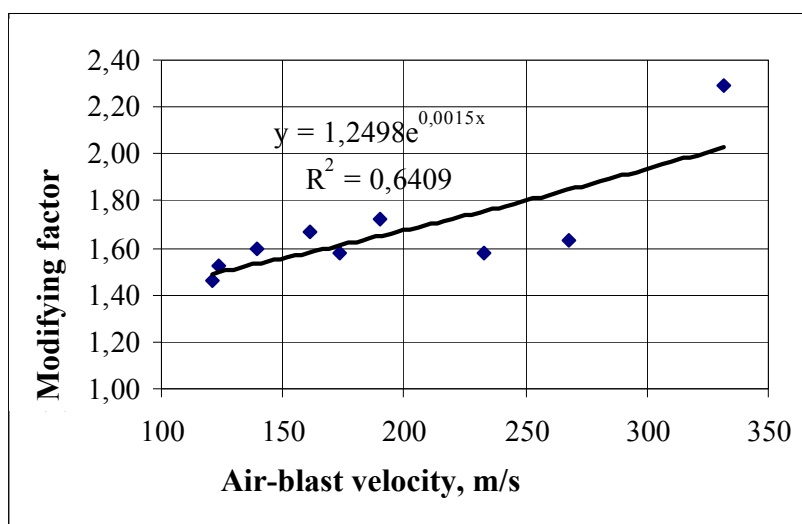


Fig. 4.14 Dependence of modifying factor value on air-blast velocity

Table 4.8 explains calculation of measurement errors.

Table 4.8

Measurement error calculation

Mine working	Distance to working face, m	Air-blast mass velocity, m/sec	$P_{\text{изм}}$, Pa	$P_{\text{теор}}$, Pa	$P_{\text{попр}}$, Pa	P, %
775 m level (ort 1s+15)	37.7	190	451	777	750	3.66
	43.2	173	349	550	565	2.73
	62.0	121	179	261	268	2.70
810 m level (ort 4n+15)	18.1	332	1110	2539	2283	11.23
	23.7	268	865	1414	1616	12.50
	32.3	233	638	1006	1131	11.05
CVD 17s-20s	14.5	161	639	1068	1017	5.04
	16.9	139	568	905	874	3.49
	21.0	124	468	712	704	1.07

The research help formulate the following:

Negative action of explosion can be corrected with the help of design parameters of mobile air-proof bulkhead depending upon a mine working section and pressure within the front of air-blast increasing from a form to central part in the ratio:

$$\frac{P_u}{P_\kappa} = 1,25e^{0,0015v},$$

where P_u and P_κ are air-blast pressure values in the central part of a mine working and in its neighbourhood at the distance of 350 mm; v is air-blast velocity in the central part of a mine working, m/s. That makes it possible to perform efficient control of air-blast within mine workings.

Thus:

- Experimental check of the measuring device under production conditions has demonstrated its efficiency as well as possibility to analyze air-blast parameters in the context of single blasts.

- Air-blast parameters have been measured in the neighbourhood of a mine working form where air-blast numerical parameters are quite smaller to compare with those in its central part owing to air flow friction on a mine working form.

- Modifying factor has been determined to make objective comparison

Correction factor has been determined to make objective comparison of data obtained and theoretical calculations. It allows determining air-blast parameters in the central part of a mine working. Relative error between theoretical calculations measurement results has been identified. Its average is 5.94%. From engineering viewpoint it means that measuring device designed by the authors gives exact readings.

4.3. Field Observation of Air-Blast Parameters in Terms of Single Blast

Field observation of air-blast parameters was carried out in “Ekspluatatsionnaia” mine in 2/5s chamber of 740 m level under the conditions for which theoretical calculations were performed.

Locations for the measuring devices were determined using developed software. Quantity of simultaneously blasted explosives, a mode of short-delayed explosion, and characteristics of explosives and the level mine workings have been involved.

Locations for the measuring devices relied on calculated and plotted air-blast parameters (Fig. 2.8) and characteristics of measuring devices which disk area was 0.01 m².

For example, on route 1 of air-blast movement at the distance of 50 m from explosion site, rated impulse of air-blast was 106 Pa·s, and expected value of the

measuring device mobile component displacement value was about 40 mm. Locations on 2 and 3 routes were determined similarly (Fig 4.15).

Table 4.9 explains the measuring results.

Table 4.9

Measuring results

Device number	#1	#2	#3
Distance to explosion site, m	45	50	48
Readings, mm	31	46	27

Specify air-blast pressure in measuring device locations including correction factor for air-blast velocity; compare the measuring results with theoretical data (Table 4.10).

Table 4.10

Instrumental and theoretical values of air-blast within measurement points

Device number	Air-blast operating time (theor.), S	Air-blast mass velocity, m/s	$P_{изм}, Pa$	$P_{поп}, Pa$	$P_{теор}, Pa$	P, %
1	0.03	260	1325	2445	3004	22.86
2	0.02	130	2547	3868	4575	18.27
3	0.05	336	1655	3424	3900	13.90

As Table 4.11 explains divergence in rated data and experimental values varies within 13.9-22.86%. Such a divergence may be explained by large branching and various characteristics of mine-workings within which air-blast moves.

Moreover the divergences are within tolerable limits; that makes it possible to use actual air-blast parameters to substantiate parameters of explosion-proof bulkhead.

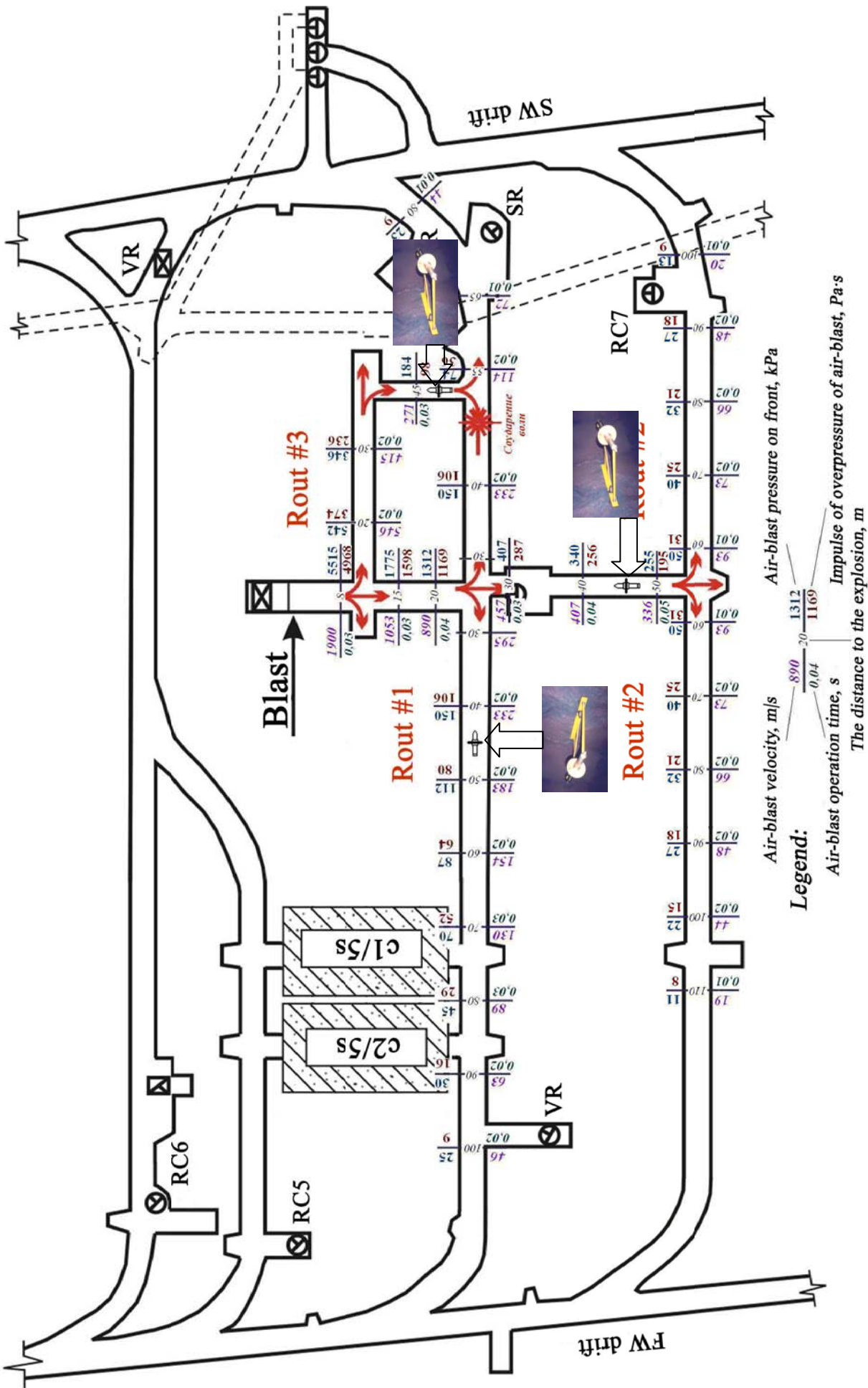


Fig. 4.15. Plan of 740m level with measuring point locations and air-blast parameter values

4.4. Technique to Apply Mobile Explosion-Proof Bulkhead

For heading-and-stall method, explosion-proof bulkheads can be practically erected in all mine workings requiring ventilation. Furthermore one should take into consideration dimensions of a bulkhead suppressant. As the bulkhead components are light-weight (2 kg per 1m²) they are delivered manually to their place of installation; previously pneumatic rigs “Boomer” make holes for fixing anchors and a bulkhead.

Installation places of for explosion-proof bulkheads are determined with the help of mining plans. Expected air-blast pressure is previously calculated on the data of single blast engineering design using technique represented in 2.3. Specifications (Table 4.11) of air-blast pressure rated value help selecting explosion-proof bulkhead perforation involving its attenuation factor to calculate pressure behind the bulkhead. If air-blast rated pressure is not attenuated down to accepted value then following bulkhead is mounted at the distance of five or six equivalent diameters of a mine working from previous bulkhead [19].

Availability of openings in bulkheads maintains possibility to ventilate mine workings both before blasting and after it.

Explosion-proof bulkhead is mounted immediately before blasting starts. A bulkhead assembling is to join ropes' ends 3 locating at the ends of suppressant 1 with previously mounted anchors 5 with the help of safety catches 4 (Fig. 2.1). Thus labour intensity of a bulkhead mounting roughly is 2 m/hrs.

Table 4.11

Specification of elastic explosion-proof bulkhead

Designation	Units of measurement	Factor			
Application area		In horizontal mine workings, incline mine workings, and vertical mine workings to be ventilated			
The number of fixing anchors	pieces	12			
Anchor diameter	mm	20			
Anchor shouldering into a mine working (no more than)	mm	50			
Mass of 1 m ² of a bulkhead	kg	2			
Perforation coefficient		0.8	0.6	0.4	0.2
Dimensions of protective component stripe:					
Length	m	4.03	4.03	4.03	4.03
Width	m	0.11	0.21	0.32	0.42
Bearing capability	kPa	1373	810	640	571
Coefficient of air-blast pressure attenuation		1.086	1.265	1.670	2.860
Assuring factor		9			
Cost of 1 m ² of a bulkhead	UAH	70			

Thus the chapter represents technique to localize air-blast in terms of single blast within a stope.

4.5. Economic Assessment of Explosion-Proof Bulkhead Application

The research makes it possible to substantiate both parameters and application technology of elastic explosion-proof bulkhead. Explosion-proof bulkheads are effective in terms of hard ore underground mining reliability and safety.

To avoid air-blast negative effect, “ZIOIC” CJSC applies explosion-proof bulkheads made of conveyor belts mounted to a roof. Their free ends were placed on a floor alongside of air-blast motion. When air-blast acts on conveyor belt certain share of its energy is consumed by a bulkhead free end displacement; certain share of the energy was reflected. Owing to the fact, air-blast was avoided.

Considerable weight of a belt is the bulkhead disadvantage. Thus, 1 m² of a belt with 0.8m width weighs 20.5 kg. A belt with 5m length and 4 m² area weighs 82 kg.

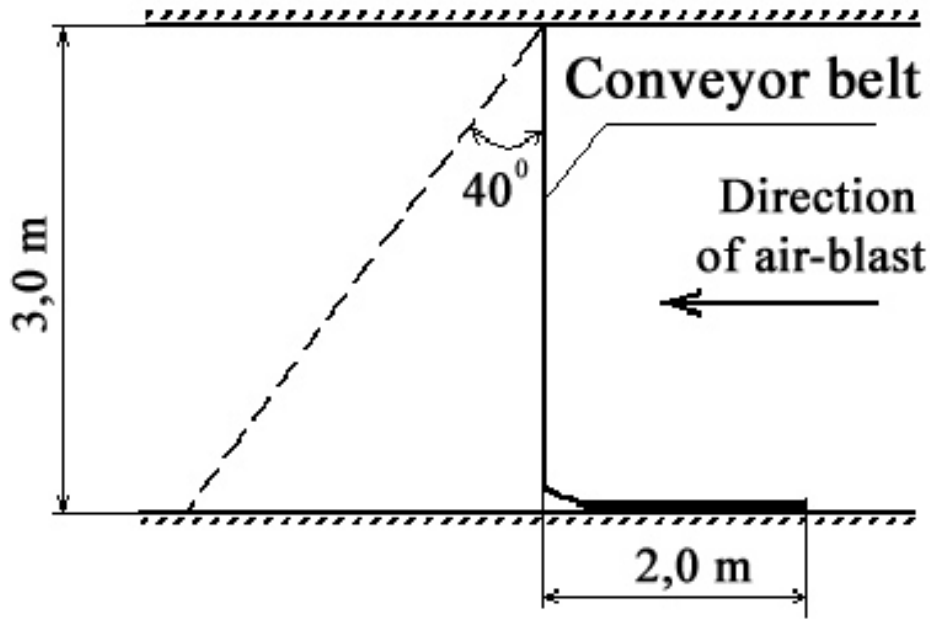


Fig. 4.16 demonstrates analytical model of a bulkhead made of conveyor belt.

Efficiency per 1 m² of mobile elastic explosion-proof bulkhead per one unit is determined as follows [47, 48, 80]:

$$\mathcal{E}_m = \frac{C_\phi}{N_\phi} - \left(\frac{C_m}{N_n} + \mathcal{Z}_{ycm} \right), \text{ UAH},$$

where C_ϕ are actual expenses to erect 1 m² of available bulkheads, UAH/m²;

N_ϕ is the number of available bulkhead mountings;

C_m is material cost for 1 m² of mobile elastic explosion-proof bulkhead, UAH/m²;

N_n is the number of mobile elastic explosion-proof bulkhead mountings;

\mathcal{Z}_{ycm} is cost to mount 1 m² of mobile elastic explosion-proof bulkhead in terms of salary, UAH/m².

Efficiency of one mobile elastic explosion-proof bulkhead during its mechanical life is determined by:

$$\mathcal{E}_{nep} = \mathcal{E}_m \cdot S \cdot N_n, \text{ UAH}$$

where S is a bulkhead area, m².

Table 4.13 explains cost calculation of explosion-proof bulkhead mounting in terms of base version and proposed one.

Efficiency of 1 m² of mobile elastic explosion-proof bulkhead per one mounting is:

$$\mathcal{E}_M = \text{UAH } 735.7.$$

Efficiency of one mobile elastic explosion-proof bulkhead application for a mine working which area is 12.4 m² during its mechanical life (tenfold application) is:

$$\mathcal{E}_{nep} = \text{UAH } 91228.$$

Thus, value of rated efficiency to apply one proposed explosion-proof bulkhead after its tenfold use is almost UAH 90000.

Table 4.13

Cost calculation to mount explosion-proof bulkhead

Cost element	Units of measurements	Cost of a unit, UAH	Quantity	Total cost, UAH	Expenditures connected with 1 m ²
<u>Base variation</u>					
Salary for:				554.03	44.68
- workers				465.62	37.55
- technologists				88.41	7.13
Social insurance payments				207.82	16.76
Materials:				10600.00	854.84
- anchors	pieces	100	4	400.00	32.26
- rubber-fabric transportation belt	mm ²	620	16	9920.00	800.00
- steel rope	M	70	4	280.00	22.58
Depreciation charge				530.00	42.74
Expenditures connected with transportation				318.00	25.65
TOTAL				12209.85	984.67
<u>Proposed variation</u>					
Salary for:				398.78	32.16
- workers				310.37	25.03
- technologists				88.41	7.13
Social insurance payments				149.57	12.06
Materials:				2287.20	184.45
- anchors	pieces	100	12	1200.00	96.77
- polyester 900 g/m ²	m ²	30	19.84	595.20	48.00
- capronic rope	m	40	12.3	492.00	39.68
Depreciation charge				228.72	18.44
Expenditures connected with transportation				22.87	1.84
TOTAL				3087.14	248.96

Conclusions

1. Measuring device has been designed to analyze air-blast nature within mine workings. Its designing involved the development of analytical model and mathematical model which made it possible to produce a device with predetermined parameters.

2. Laboratory research to specify mass of mobile component and the measuring device spring force coefficient. Reset time of the mobile component has been identified as it is required to interpret readings in the context of short-delay blasting.

3. The measuring device has been experimentally checked in terms of blasting in three development workings of “Prokhodcheskaia” mine (“ZIOIC” CJSC).

4. Actual data processing and their comparison with theoretical ones show that average measuring error is 5.9%. The fact means that the measuring device can be used in a wide range of air-blast parameter changes.

5. Air-blast parameters in terms of single blast have been measured. Obtained instrumental values of air-blast movement within complicated network of mine workings have verified theoretical calculations making it possible to develop a technique for explosion-proof bulkhead application.

OVERALL CONCLUSIONS

Using analytical, physical and field research the paper has solved relevant theoretical and practical problem of substantiation of explosion-proof bulkhead parameters to prevent air-blast while underground ore mining with the help of drill-and-fire system. It is based on relations between single blast while ore mining and localization of air-blast with the help of explosion-proof bulkheads.

Basic scientific and practical results are as follows:

1. Design and parameters have been substantiated; measuring device has been designed to analyze air-blast parameters in terms of industrial blasting.

2. Propagation nature of air-blast in terms of construction of development workings and single blast has been determined. The results have been used to obtain numerical values of air-blast pressure required to substantiate parameters of explosion-proof bulkhead and develop its use recommendations.

3. Software was developed to calculate air-blast parameters while propagating within mine workings. It helps improving accuracy while calculating pressure, impulse, and air-blast operating period up to 15% taking into consideration a type of explosion applied and short-delay blasting mode.

4. Dependence has been determined as for air-blast pressure changes on a mine working cross-section ($P_y / P_\kappa = 1.25e^{0.0015v}$). It has also been identified that it is 1.5 to 1.7 times higher in the central part of a mine working to compare with border zone.

5. Calculation technique for mobile explosion-proof bulkhead as well as its design has been developed. The design has elastic characteristic making it possible to lighten explosion-proof bulkhead and increase its bearing capability.

6. It has been determined that bearing capability of mobile explosion-proof bulkhead directly depends on protective component free deflection angle (optimum angle is 25°) and perforation degree varying in accordance with exponential law $y = 382.5e^{1.5x}$; it experiences 2.4 times increment with 0.2 to 0.8 increase.

7. Recommendations have been elaborated as for explosion-proof bulkhead use to determine its parameters with the help of developed software.

8. Recommendations are provided concerning effective blasting and localization of air-blast in terms of "ZIOIC" CJSC. Software has been implemented as for interim operating procedure to determine borders of dangerous zones while preparing underground single blasts.

Technical committee of "ZIOIC" CJSC analyzed the design of elastic explosion-proof bulkhead and its application technique, and accepted it for implementation.

Economic potential of one bulkhead application per its operating life (tenfold application) is UAH 90000.

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