Effect of using plastic spacers on toxic fume generation by permitted explosives

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Transaction Paper

Synopsis

Toxic gases, mostly carbon monoxide (CO) and nitrous oxides (NO_x), are invariably generated by commercial explosives under practical conditions of usage because of oxygen unbalance and non-ideal chemical reaction. Permitted explosives are statutorily required to meet the criteria stipulated by regulatory authority for their toxic fume quality for their safe use in underground coal mines.

Solid blasting using P_5 explosives contribute around 60% production from Indian underground coal mines. Low pull and yield per blast in solid blasting has been identified as a reason for low production and productivity of Indian underground coal mines. In an effort to improve performance of solid blasting, it was envisaged to apply air decking between suitable P_5 explosives using high density polyethylene (HDPE) spacers under a Ministry of Coal, Government of India funded project. A non-deflagrating slurry explosive composition having high air gap sensitivity was specially developed for this purpose, so that air decked cartridges get detonated sympathetically with single priming. However, statutory authority in India apprehended that the use of oxygen negative HDPE spacers can influence the generation of toxic gases. The effect of using HDPE spacers on the generation of toxic gases was studied under simulated laboratory conditions with newly developed as well as with three commercial P_5 explosives. The results of studies presented in this paper revealed that the level of carbon monoxide increases linearly and there is no significant effect on the level of oxides of nitrogen due to the use of HDPE spacers with selected explosives. Studies also revealed that this newly developed slurry explosive can be used for air decking up to 15 cm using HDPE spacers of weight not more than 21 g without exceeding the permissible limits for toxic gases.

Introduction

An oxygen balanced explosive is expected to generate carbon dioxide, nitrogen, water vapour, oxides of metals, etc. under ideal detonation conditions. If the amount of oxygen bound in the explosive is insufficient, i.e. the explosive is oxygen negative, the complete combustion of carbon atoms to carbon dioxide may not be possible and as a result carbon monoxide may be formed. On the other hand, if the composition is oxygen positive, then nitrogen atoms may get oxidized to form oxides of nitrogen[1]. The percentage of different chemical compounds in commercial explosives is generally selected in such a way to make it nearly oxygen balanced in order to reduce to the minimum the amount of the toxic gases[1] and also to increase to the maximum the amount of the energy released. Commercial explosives produce toxic gases in measurable quantities because of oxygen unbalance and non-ideal detonation conditions prevailing under their practical condition of usage[2]. Major toxic components of the post detonation gases produced by the commercial explosives are carbon monoxide (CO) and oxides of nitrogen (NO_x)[1,3–5]. Toxic gases generated by explosives meant for use in underground mines may get accumulated in a physiologically harmful concentration in a confined space of underground mines and thus may cause safety problems to the mine personnel[6]. There have been instances of fatal and serious accidents due to blasting fumes in underground mines of coal and non-coal sectors[7–8]. As per Indian Coal Mines Regulation, persons engaged in underground mining activities are not allowed to enter the blasted zone until the elapse of a specified time span when the CO and NO_x levels come down below 50 ppm and 5 ppm respectively. Therefore, as per statutory requirements stipulated by the Directorate General of Mines Safety (DGMS), Mines Regulatory Authority in India, any explosive meant for use in underground coal mines are required to be classified under P_1, P_3 or P_5 permitted groups in India and should not generate more than either 40 litres of CO or 20 litres of NO_x or 50 litres of CO + NO_x per kg of explosives in the standard laboratory condition at standard temperature and pressure[9].

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 SA ISSN 0038–223X/3.00 + 0.00. Paper received Feb. 2007; revised paper received Aug. 2008.

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The bord and pillar method using conventional drilling and blasting techniques for breaking coal contributes 95% of the total production from Indian underground coal mines. Solid blasting is the most commonly used method of blasting for formation of dip/rise or level galleries in the bord and pillar method, which contributes around 60% of total production from Indian underground coal mines. Approved type of permitted P_5 explosives meeting the statutory requirements as per Indian Standard IS 6609 (Part II/ Sec 2)[10] only can be used in solid blasting in Indian underground coal mines. A charge limit of 1 000 g in degree-I mines and 565 g in degree-II and III gassy mines for P_5 explosives have been stipulated by the DGMS. Because of low strength of P_5 explosives, by its design to meet the statutory requirements, and the limitation on its maximum charge weight per hole, an average pull of 0.9–1.1 m and yield of 10–16 tonnes per blast are generally achieved in solid blasting under different Indian geo-mining conditions with gallery dimensions of 3.5–4.5 m width and 2.0–3.0 m height. Performance of solid blasting has never been considered satisfactory for optimum utlization of man and machine at the face. Even recent semi-mechanization of many Indian underground coal mines using side discharge loaders (SDL) and load haul dumpers (LHD) for loading operations could not yield the desired improvement in productivity due to poor utilization of these machines because of availability of less coal at the face after each blast. Therefore, it was imperative to increase the pull and yield of solid blasting in order to improve production and productivity of Indian underground coal mines.

Considering the success of the air decking of explosives in improving blast performance in opencast mining and tunnelling, it was thought to deck suitable P_5 explosive cartridges for improving pull and yield per blast in solid blasting in underground coal mines. However, during air decking in opencast or tunnelling separate initiation for each deck or a device useful for transmission of detonation from one deck to the other (e.g. detonating cord) are used, which are not approved for use in solid blasting in underground coal mines. Spacers made of high density polyethylene (HDPE), which have already been in use in ringhole blasting in the blasting gallery method in Indian coal mines for the last two decades,[11,12] were considered for decking the explosive cartridges. Figure 1 shows the photograph and schematic diagram of HDPE spacers with 10 cm effective spacing length. Each spacer has an arrangement for coupling explosive cartridges at both ends. The internal diameter at the coupling ends is 32 mm, i.e. equal to the diameter of commercial Indian permitted explosives. The diameter of the middle portion of the spacer is around 25 mm. The length of the middle portion of the spacer, is the effective spacing length of the spacer which is 10 cm for the spacer shown in Figure 1.

Figure 2 shows an arrangement of explosive cartridges and spacers for proposed air decking of P_5 explosives in solid blasting. It envisages the use of single priming of initial cartridge and detonation of other cartridges sympathetically due to the inherent air gap sensitivity of the explosive. There is no use of multiple initiations or detonating fuse for transmission of the detonation from primer to other cartridges as they were considered unsafe for use in underground coal mines.

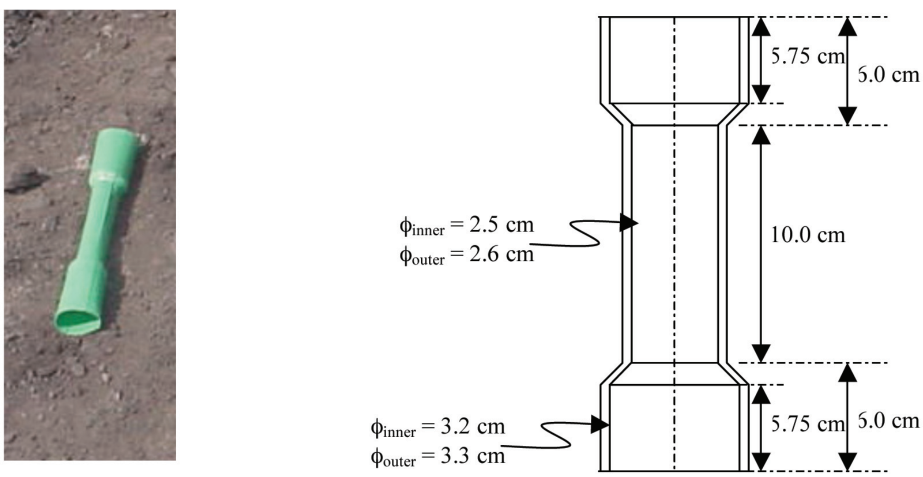

Figure 1—HDPE spacer of 10 cm effective spacing length

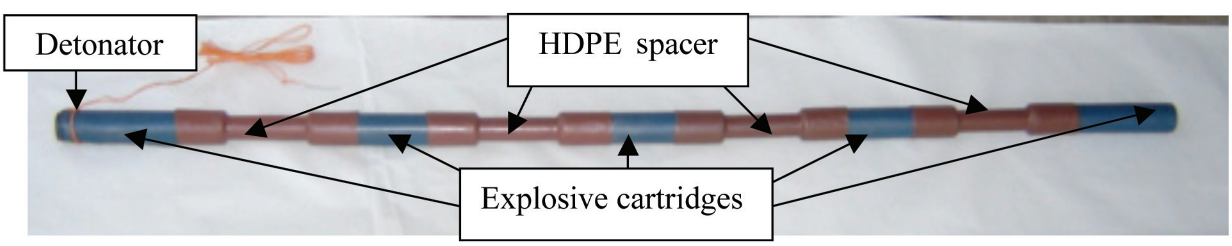

Figure 2—Photograph of five cartridges air decked using four HDPE spacers

Effect of air decking on detonation of receptor cartridges

Chiappetta and Mammele[13] described the air deck between two explosive charges as a form of energy accumulator, which first stores and later releases energy in the form of additional stress waves that produce multiple loadings in the medium. In contrast to the air decked borehole, a solid column explosive generates a large amplitude impulse into the medium that succeeds in creating many micro-fractures, but decays very quickly and the stress field around the charge decays to a quasi-static state. The generation of repeated loading cycles in air decked blasting helps in the growth and branching of micro-fractures leading to improved fragmentation. Researchers have validated this theory by numerical and physical modelling[14,15].

Therefore, air decking of P_5 explosives in solid blasting is expected to increase the pull and yield per blast provided unfailing detonation of receptor cartridges is ensured by suitably selecting the explosive and length of the air decks. But, it was noticed that improper use of air decking with unsuitable explosive may lead to incomplete detonation or misfire of receptor cartridges and deflagration or low order detonation of receptor cartridges. Therefore, the length of the air decks should not exceed the maximum distance over which the detonation wave from a primed cartridge can jump to the receptor cartridge for successful detonation of primed and all receptor cartridges when single priming is used.

Keeping this in view, a special type of slurry explosive was developed by a leading Indian explosive manufacturer which met all the statutory requirements of P_5 explosive and has air an gap sensitivity of 16 cm in open unconfined conditions which is hereafter referred as Sample-A. Figure 3, shows a VOD graph of that explosive when five cartridges with four spacers, as shown in Figure 2 were fired in an open unconfined condition. Figure 3 confirms the detonation of primer and all four receptor cartridges. The slope of the graph represents the VOD of the cartridges. The break in the graph between the VOD graphs of cartridges is due to use of spacers. The consistent slope of primer and all four receptor cartridges confirms a similar VOD of all five cartridges and rules out low order detonation of receptor cartridges. Moreover, additional trials carried out with this and other P_5 type explosives under simulated conditions in an opencast mine revealed that the air gap sensitivity of selected explosives was greater in a coal bed due to higher confinement and Sample-A was able to detonate all receptor cartridges up to an air decking length of 20 cm in all trials.

The use of HDPE spacers for air decking of P_5 permitted explosives in solid blasting can increase the generation of toxic gases in post-detonation fumes due to (i) the oxygen negative quality of the HDPE spacer itself, and (ii) misfire and deflagration of receptor cartridges. However, if the complete sympathetic detonation of receptor cartridges is ensured by the proper selection of explosive and air deck length, the effect of HDPE spacer on post-detonation fume quality due to incomplete detonation or misfire of receptor cartridges and deflagration or low order detonation of receptor cartridges may be neglected. Considering the use of Sample-A explosive having a AGS value of 16 cm in open and 20 cm in a fractured coal bed of an opencast mine with

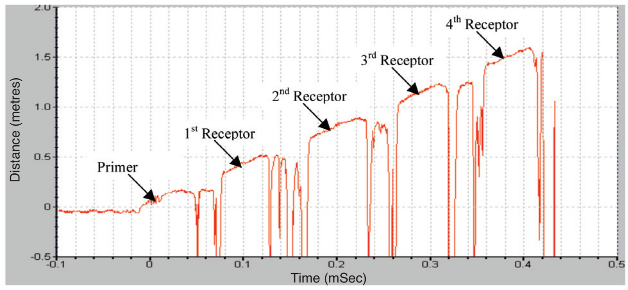

Figure 3—VOD graph of air decked cartridges using HDPE spacers of 16 cm effective spacing length

air decking length not more than 15 cm, the effect of HDPE spacer on post detonation fume quality may be considered to be due to only to the oxygen negative quality of the spacer. This study was aimed at finding out the maximum allowable length and weight of HDPE spacers, which can be used with this explosive without exceeding the permissible limits for toxic gases in post-detonation fumes.

Selection of explosives

Although proposed air decking in solid blasting was intended to be done with a specially developed slurry explosive (i.e. Sample-A) packed in blow moulded polyethylene tubes (BMPT) having a 16 cm air gap sensitivity in open unconfined conditions, it was decided to study the effect of using an HDPE spacer on toxic fume generation on other explosives also to corroborate the findings.

There were 14 different commercially available approved types of P_5 explosives manufactured by 11 different manufacturers for use in solid blasting in Indian underground coal mines. The name of the manufacturers, brand name of their P_5 explosives, type of explosives, packing materials and air gap sensitivity values of all Indian P_5 explosives are listed in Table I. As per statutory requirement in India, slurry and emulsion type permitted explosives are required to possess a minimum 2 cm air gap sensitivity value in open unconfined condition. As is evident from Table I, all emulsion and slurry explosives in low density polyethylene (LDPE) packs had an AGS value of 2–3 cm. Slurry explosives with blow BMPT had slightly higher AGS values around 5–9 cm.

One representative sample of slurry explosive in LDPE (Sample-B), slurry explosives in BMPT (Sample-C) and emulsion (Sample-D) each was also selected for studies along with Sample-A. Other details of selected studies as per declaration of manufacturers are given in Table II. Although, it would have been better to quote the energy value and oxygen balance of selected explosives also in Table II, this data was not readily available.

Standard laboratory methodology

Researchers in different countries have studied toxic fume generation by explosives employing various methodologies[4,16–22]. In India too the standard method for assessment of CO and NO_X in the post-detonation fumes of permitted explosives and passing criteria were established after extensive studies under different conditions in the laboratory and under actual

Table I

P_5 explosives of different manufactures

Sl no.	Name of manufacturers	Name of P_5 explosives	Types of explosives	Packing materials	AGS value
1	IBP Co. Ltd.	Indocoal-5	Slurry	LDPE	3 cm
2	Orient Explosives Ltd.	Orecoal–5	Slurry	LDPE	2 cm
3	Maimoon Explosives Ltd.	Meccoal–5	Slurry	BMPT	5 cm
4	Gulf Oil Corporation Ltd.	Pentadyne	Slurry	BMPT	8 cm
5	Tamilnadu Industrial Explosives Ltd.	Telcoal–5	Slurry	LDPE	2 cm
		Powertel–5	Emulsion	LDPE	2 cm
6	Solar Explosives Ltd.	Solarcoal–5	Slurry	BMPT	9 cm
		Solarcoal–5	Slurry	LDPE	3 cm
		Solarcoal–5	Emulsion	LDPE	2 cm
7	Premier Explosives Ltd.	Colex-5	Slurry	LDPE	3 cm
8	Indo Gulf Explosives Ltd.	Detacoal–5	Slurry	LDPE	3 cm
9	Navbharat Fuse Co. Ltd.	Novacoal–5	Slurry	LDPE	2 cm
10	Indian Explosives Ltd.	Powergel P–501	Emulsion	LDPE	2 cm
11	Bharat Explosives Ltd.	Belmx P–501	Emulsion	LDPE	2 cm

Table II

Details of explosive samples selected for studies

Sl no.	Code no. of explosive	Type of explosive	Packing material	Year of commercialization	Density range (g/cc)	Velocity of detonation (m/s)
1	Sample-A	Slurry	BMPT	New	1.05–1.15	3 400–3 800
2	Sample-B	Slurry	LDPE	1985	1.05–1.10	3 000–3 500
3	Sample-C	Slurry	BMPT	1981	1.10–1.20	3 400–3 800
4	Sample-D	Emulsion	LDPE	1999	1.07–1.22	3 500–4 000

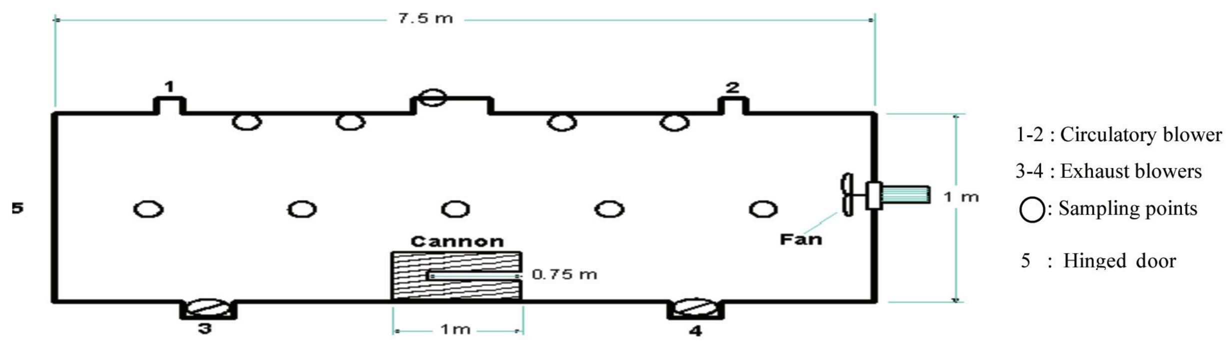

Figure 4—Experimental arrangements in laboratory fume chamber

blasting conditions in underground coal mines[23].

The laboratory set-up for determination of toxic gases in post-detonation fumes of permitted explosives in India consists of a 7.5 m long cylindrical steel fume chamber of 6 m^3 volume having a circular hinged door at one end and closed at the other end to contain the post-detonation products. There is provision for closed circuit circulatory forcing and exhaust blowers to mix the post-detonation products uniformly. There are ten surface holes on the fume chamber for drawing samples for analysis of toxic components in the post-detonation products of the explosives. A steel cannon, 1 m long with 38 mm diameter and 75 cm long axial bore, is placed on the floor of the fume chamber for firing the explosive. A schematic diagram of the experimental arrangements is shown in Figure 4.

As per the official testing procedure adopted in India, 50 g of the explosive are inversely initiated inside the bore of the cannon placed on the floor of the cylindrical steel fume chamber without any stemming. Post-detonation gaseous products generated by explosives were contained inside the closed fume chamber. After 10 minutes of closed circuit circulation for homogeneous mixing, at least four samples of post-detonation fumes were drawn from the sampling points made on the surface of the fume chamber[24]. These samples were analysed by Graham Lawrence apparatus for CO and by spectrophotometer for NO_x values. To eliminate the effect of ambient temperature and pressure on the volume of the samples taken, a correction factor was multiplied to get the volume (V_{STP}) at standard temperature and pressure, i.e. 25°C and 760 mm of mercury[25].

Table III

Weights of spacers of two different effective spacing lengths

Sl no.	Effective spacing length of spacer	Total length of spacer	Number of spacers weighed	Weight (g)			
				Min	Max	Average	Standard deviation
1	10 cm	22 cm	100	12.35	18.76	14.69	1.44
2	47 cm	59 cm	100	27.49	39.04	32.04	3.21

Table IV

Weights of different lengths of spacers

Sl no.	Effective spacing length of spacer	Total length of spacer	Weight (g)		
			Min	Max	Average
1	12 cm	24 cm	13.17	19.85	15.62
2	15 cm	27 cm	14.39	21.50	16.10
3	20 cm	32 cm	16.44	24.24	18.45

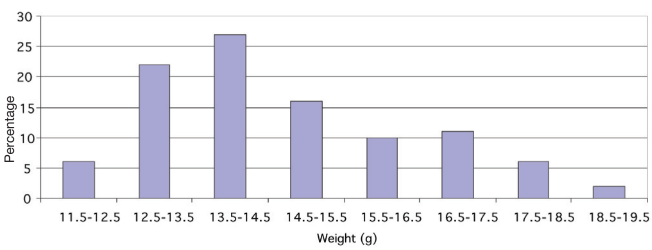

Figure 5(a)—Weights of 10 cm spacers

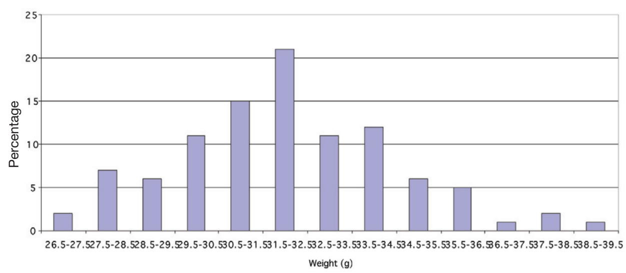

Figure 5(b)—Weights of 47 cm spacers

Determination of weight of spacers for fume studies

Weights of 100 nos. of spacers of two different effective air gap collected from blasting gallery mines in India were measured and are listed in Table III. Figures 5(a) and 5(b) show the bar chart of the weight of 10 cm spacers and 47 cm effective spacing length spacers respectively.

The weight of any length of spacer with coupling length of L_1 and effective spacing length of L_2 can be expressed as follows:

$$W = 2 \times W_1 \times L_1 + W_2 \times L_2 \quad [1]$$

where,

W_1 = weight per unit length of end portion (g/cm)
L_1 = length of end portions (cm)
W_2 = weight per unit length of middle portion (g/cm)
L_2 = length of middle portion, i.e. effective spacing of spacer (cm).

Using the weights of spacers mentioned in Table III and Equation [1], the minimum, average and maximum weights of different lengths of spacers were extrapolated and listed in Table IV. From Equation [1], it is evident that reducing the density of plastic material of spacer and length of the end portion of the spacer without compromising its strength and stiffness may reduce the weight of the spacer per unit weight of explosive for a given effective spacing length.

The weight of each commercial cartridge of P_5 explosives in India is generally 185 g. Therefore, even in Degree I mines not more than five cartridges of P_5 explosives can be used in a hole in solid blasting in Indian underground coal mines. Keeping in mind the proposed use of spacers with explosives in different possible configurations, the weight of spacers per 50 g of explosives are given in Table V.

It can be observed in Table V that the maximum weight of a spacer per 50 g of explosive may vary between 1.01 and 4.56 g under different possible configurations of use of explosive cartridges in the shot holes along with different lengths of spacers up to 15 cm depending on different possible combinations of explosive cartridges and spacers. Five cartridges with four spacer combinations give the highest weight of spacer per unit weight of explosive.

Effect of spacer on toxic fumes

Spacers proposed to be used for air decking were made of high density polyethylene (HDPE). HDPE is long-chain linear polymerization (without branching) of ethylene by a catalytic process and has the chemical formula of $(\text{-}CH_2\text{-}CH_2\text{-})_n$. Thus, HDPE contains mostly carbon and hydrogen atoms in the ratio of 85 g:15 g by weight. One gramme of HDPE requires approximately 3.43 g of oxygen for complete oxidation to carbon dioxide and water. An HDPE spacer, being an oxygen negative substance, can influence the quantity of toxic gases produced by the detonation of explosives under proposed

Table V

Average and maximum weight of spacers per 50 g of explosive under different configurations

Explosive cartridges	Number of spacers	Configuration for proposed use	Weight of spacer per 50 g charge weight (g)					
			10 cm spacer		12 cm spacer		15 cm spacer	
			Avg	Max	Avg	Max	Avg	Max
2	1	1P + S + 1R	1.99	2.54	2.11	2.68	2.18	2.85
3	1	2P + S + 1R*	1.32	1.69	1.41	1.79	1.45	1.90
3	2	1P + S + 1R + S + 1R	2.65	3.38	2.81	3.58	2.90	3.80
4	1	2P + S + 2R	0.99	1.27	1.06	1.34	1.09	1.43
4	2	2P + S + 1R + S + 1R	1.99	2.54	2.11	2.68	2.18	2.85
4	3	1P + S + 1R + S + 1R+ S + 1R	2.98	3.80	3.17	4.02	3.26	4.28
5	1	3P + S + 2R	0.79	1.01	0.84	1.07	0.87	1.14
5	2	2P + S + 2R + S + 1R	1.59	2.03	1.69	2.15	1.74	2.28
5	3	2P + S + 1R + S + 1R+ S + 1R	2.38	3.04	2.53	3.22	2.61	3.42
5	4	1P + S + 1R + S + 1R + S + 1R+ S + 1R	3.18	4.06	3.38	4.29	3.48	4.56

* 2P + S + 1R means two cartridges (including one primer) at the bottom of hole, then one spacer, then one receptor cartridge.

Figure 6—Arrangement for firing explosive with spacer for fume analysis

conditions of decking using spacers in solid blasting. The DGMS stipulated that the effect of the proposed use of HDPE spacers for decking P_5 explosive in solid blasting should be studied under laboratory conditions before it can be considered for any trial in underground coal mines.

As experimental conditions in the standard laboratory method restrict firing of only 50 g of explosive, firing of two or more explosive charges with spacers in between them to simulate the proposed usage condition was not possible. However, to study the effect of spacers on toxic fumes generated by explosives, a known quantity of spacer material was kept in contact with 50 g of explosive, as seen in Figure 6.

Keeping in mind the maximum weight of spacers per 50 g of explosive not exceeding 4.56 g with spacers of 15 cm effective spacing length, as listed in Table V, the effect of spacers on the toxic fume quality of selected P_5 explosives was studied with different weights of spacers up to 6 g only. For each of the selected explosive, two trials were conducted with each weight of spacer. During each trial, four samples of gases were collected from different sampling points of the fume chamber to determine values of CO and NO_x in post-detonation fumes. The minimum, maximum and average values of CO and NO_x measured with different quantities of spacers for different selected explosives are listed in Table VI and Table VII respectively. The average values of CO and NO_x with different weights of spacers per 50 g weight of spacers are shown graphically in Figures 7 and 8 respectively[26].

In order to check whether differences in observed values of toxic gases in the post-detonation fumes of selected explosives were due to the use of different weights of spacers or due to noise of the experiment and whether they were statistically significant, analysis of variance (ANOVA) was carried out. For a selected explosive, the only variable factor was the weight of spacer used. Therefore, single factor ANOVA was carried out for each explosive. The sum of squares, mean squares, and degree of freedoms due to the variable and experimental error were calculated and then finally the F_0 value was calculated[27,28]. Table VIII and IX present the results of ANOVA carried out for CO and NO_x respectively.

Discussion and results

The results of the studies in Table VI and VII revealed that toxic fumes generated by emulsion P_5 explosive (Sample-D) under standard laboratory conditions were the lowest. This is

Table VI

Carbon monoxide generated by selected explosive with varying quantity of spacers

Weight of spacers	Sample-A				Sample-B				Sample-C				Sample-D			
	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev
0 g	30.5	32.8	31.56	1.01	20.2	26.0	22.72	1.83	21.6	26.8	24.24	1.60	19.1	24.2	21.12	1.89
2 g	30.9	36.6	33.66	2.22	26.7	32.1	29.52	2.11	24.2	30.1	26.52	2.09	21.1	27.0	24.60	2.18
3 g	33.8	38.3	35.64	1.49	28.5	36.3	32.16	2.67	26.9	31.8	29.64	2.02	22.3	29.3	25.32	2.33
4 g	35.5	41.1	38.52	2.10	33.5	38.6	35.76	1.87	29.8	35.3	33.72	2.00	27.0	31.8	29.64	1.84
5 g	38.8	44.9	41.76	2.32	32.8	38.1	34.92	1.97	33.8	39.1	36.00	1.98	28.6	34.1	31.08	2.07
6 g	41.7	48.7	45.48	2.28	35.9	41.1	38.40	1.77	34.5	40.8	37.32	2.04	29.3	34.8	31.92	2.10

Table VII

Oxides of nitrogen generated by selected explosive with varying quantity of spacer s

Weight of spacers	Sample-A				Sample-B				Sample-C				Sample-D			
	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev	Min	Max	Avg	Std dev
0 g	5.7	11.6	8.16	2.19	8.0	14.3	10.92	2.27	9.4	15.2	12.00	1.82	4.2	9.0	6.24	1.73
2 g	5.1	10.1	6.84	1.70	7.9	14.8	11.16	2.31	7.6	14.4	10.44	2.52	4.2	8.2	5.28	1.54
3 g	5.9	11.8	8.16	2.11	7.6	12.8	9.60	1.77	7.2	13.2	10.08	1.80	5.8	9.6	7.44	1.37
4 g	6.4	12.4	9.60	1.98	9.2	14.8	12.12	1.76	7.6	14.4	10.44	2.52	6.2	9.6	8.28	1.07
5 g	6.1	11.0	8.52	1.63	8.2	13.6	10.68	1.70	10.4	15.8	13.20	1.76	5.8	9.6	7.80	1.30
6 g	7.2	12.4	10.08	1.72	7.9	14.8	11.64	2.17	9.8	15.8	12.72	1.90	5.8	9.0	6.84	1.27

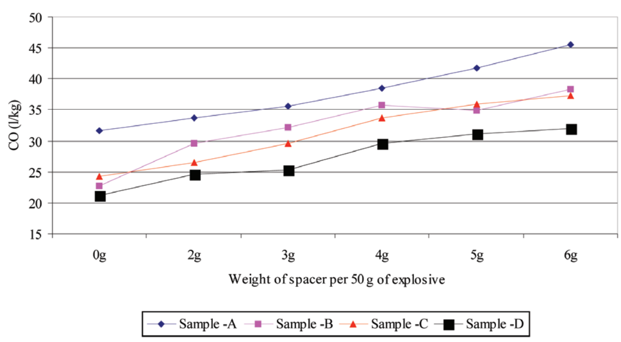

Figure 7—Average CO generated by selected explosives along with different weights of spacer

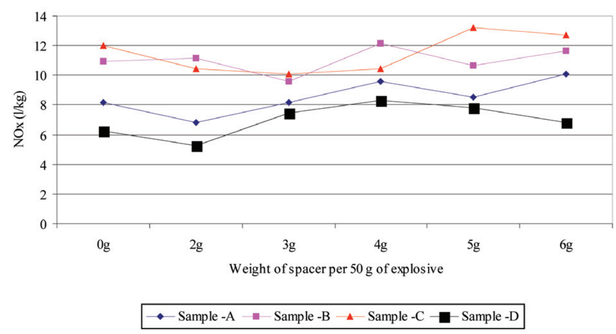

Figure 8—Average NO_x generated by selected explosives along with different weights of spacer

because of the higher surface area of contact between the oxidizer and fuel phases leading to a near ideal reaction in emulsion explosives. Although the other three explosives (i.e. Samples A, B and C) were slurry explosives, they were found to generate different levels of toxic gases in post-detonation fumes in standard laboratory conditions. This is because of the different compositions used by different manufacturers, which results in different oxygen balances of the compositions. The observed results were is in line with earlier findings[28]. However, toxic gases in post-detonation fumes generated by all four selected P_5 explosives under standard laboratory conditions without spacers (i.e. weight of spacer per 50 g explosive = 0 g) were within the statutory limits of 40 ℓ/kg for CO, 20 ℓ/kg for NO_x and 50 ℓ/kg for CO + NO_x.

Graphical analysis of toxic fumes in post-detonation fumes generated by different explosives with varying weights of spacers (i.e. 0 to 6 g per 50 g of explosives), in their contact revealed that the amount of CO generated by all four selected explosives increased linearly with the increase in the weight of spacer (Figure 7) because of oxygen negativeness of the HDPE spacers. There is an increase of about 2–3 ℓ/kg of CO per gramme of HDPE spacer used. Although there was variation in the average value of NO_x observed with different weights of spacers, no trend was observed for all four selected explosives with the increasing weight of spacers (Figure 8). Bhattacharyya[22] also observed a linear increase in CO and no effect on NO_x values in post-detonation fumes generated by Soligex, a nitro-glycerine based explosive, with varying amounts of wax-coated craft paper under two different laboratory conditions. From statistical analysis of the observed values of CO and NO_x using single factor

Table VIII

Results of analysis of variance for selected explosives for carbon monoxide values

Explosive source of variation	Sample-A		Sample-B		Sample-C		Sample-D	
	Use of spacer	Error	Use of spacer	Error	Use of spacer	Error	Use of spacer	Error
Sum of squares	1086.63	161.50	1243.80	180.58	1085.47	164.23	723.93	176.19
Degree of freedom	5	42	5	42	5	42	5	42
Mean Square	217.33	3.85	248.76	4.31	217.09	3.91	144.78	4.19
F_0	56.51		57.76		55.52		34.51	
$F_0 > F_{0.01, 5, 42}$	Yes		Yes		Yes		Yes	

Table IX

Results of analysis of variance for selected explosives for oxides of nitrogen values

Explosive source of variation	Sample-A		Sample-B		Sample-C		Sample-D	
	Use of spacer	Error	Use of spacer	Error	Use of spacer	Error	Use of spacer	Error
Sum of squares	53.29	151.85	26.94	170.20	71.41	181.61	48.30	81.69
Degree of freedom	5	42	5	42	5	42	5	42
Mean Square	10.66	3.62	5.39	4.05	14.28	4.32	9.66	1.94
F_0	2.95		1.33		3.30		4.97	
$F_0 > F_{0.01, 5, 42}$	No		No		No		Yes	

analysis of variance, it can be observed that F_0 values obtained for CO for all selected explosive were much higher than the 3.49 (i.e. $F_{0.01, 5, 42}$), which signifies that the observed average values of CO for different weights of spacers were statistically significant and thus cannot be due to experimental error. On the other hand, F_0 values for NO_x were less than 3.49 in three out of four samples, which implied that observed variations in individual values can be assumed to be due to experimental errors.

The average values of NO_x generated by all four explosives were always found within the stipulated range even up to 6 g of spacers per 50 g of explosive. The average values of CO generated by Sample-B, Sample-C and Sample-D were found within the stipulated range of 40 ℓ/kg even with 6 g of spacer per 50 g of explosive. But, the average values of CO generated by Sample-A with a 5 g or 6 g spacer per 50 g of explosive were found to be higher than 40 ℓ/kg. Therefore, the maximum permissible weights of HDPE spacers, which can be used with Sample-A, should not exceed about 4.5 g per 50 g of explosive to maintain CO within the permissible limit. On the other hand, the use of PVC spacer up to 6 g alongwith 50 g of Sample-B, Sample-C and Sample-D were found to generate CO and NO_x within the permissible limits. Therefore, the maximum weights of a spacer that can be used with Sample-A and the other three explosives are 21 g and 28 g respectively, which is equivalent to spacers of about 15 cm and 25 cm respectively, even under the worst conditions of use of four spacers between five cartridges. As toxic gases generated by permitted explosives under laboratory conditions are more than those under actual usage conditions[23] and spacers of reduced weight per unit effective spacing length can be made by reducing density and the length of the end portions spacers of even longer lengths, if required, can be used without exceeding the permissible limits for toxic gases in post-detonation fumes.

Conclusion

All commercial explosives generate carbon monoxide (CO) and oxides of nitrogen (NO_x) in the post-detonation fumes. As per statutory requirements stipulated in India, CO and NO_x generated by permitted explosives under standard laboratory conditions should not exceed 40 ℓ/kg and 20 ℓ/kg respectively. Moreover, total toxic fumes, i.e. CO + NO_x, should also not exceed 50 ℓ/kg. Emulsion permitted explosive was found to generate fewer toxic gases in comparison to slurry explosives because of the higher surface area of contact between fuel and oxidizers phases.

Proposed use of HDPE spacers for decking P_5 explosives for improvement of blast performance in solid blasting in development faces of Indian underground coal mines was found to influence the generation of toxic fumes. It was observed that the level of CO increased linearly with an increase in the weight of HDPE spacer for all four selected explosive under laboratory conditions. But no trend was observed for NO_x values. Statistical analysis using single factor analysis of variance also revealed that the effect of use of an HDPE spacer is statistically significant for the generation of CO only. The observed difference in NO_x values were found to be not significantly different from a statistical point of view.

Based on the results of experiments conducted with different selected P_5 explosives along with varying quantities of spacers, it can be concluded that newly developed non-deflagrating Sample-A explosive, a slurry explosive composition with 16 cm air gap sensitivity in open unconfined conditions, can be used for air decking up to 15 cm in solid blasting using HDPE spacers of weight not more than 21 g without exceeding the permissible limits of toxic gases.

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Erratum

Paper entitled: **The effects of hot rolling process and the nitrogen and sulphur content on the mirostructural development of aluminium killed hot rolled low carbon strip steel,** by C.W. Siyasiya and W.E. Stumpf Published in the *Journal* of The Southern African Institute of Mining and Metallurgy, vol. 108, no. 8, pp. 481–489, August 2008.

Please note that there is an error in the footnote on page 481, in which we stated that the paper was first published at the SAIMM Symposium on Ground Support in Mining and Civil Engineering Construction. This is not correct: the paper was an original refereed paper, and had not been presented or published elsewhere.