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The influence of some blasting techniques on the probability of ignition of firedamp by permissible explosives

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Abstract

The ignition of firedamp by permissible explosives is assessed by means of gallery testing conducted by the Bruceton up-and-down method. Six test series were made in order to analyze the influence of several blasting practices in long-holes coal blasting, namely: use of slotted PVC pipes, detonating cord, salt cartridges and double (top and bottom) initiation. The parameters of the distributions of the probability of ignition are determined by the maximum likelihood method; normal, logistic, lognormal and Weibull distributions have been used. Confidence bands for the probability points are obtained both from the asymptotic standard errors of the parameters and by a bootstrap-like technique. The four distributions used give similar results in a rather ample probability range; discrepancies in the probability points are within 2% and in the confidence limits within 10% in a range of probability [0.1, 0.9] in most of the cases. The use of detonating cord is found to affect significantly the probability of ignition; the double initiation does also have an influence though not statistically significant at a 95% level; the use of salt cartridges, in the amount tested, has little effect in the ignition probability; the use of PVC pipe shows no effect.

Keywords: Permitted explosives; Ignition probability; Bruceton test; Maximum likelihood; Bootstrap

1. Introduction

Methane forms an explosive mixture with air in proportions between 5 and 14% in volume, known as firedamp. The occurrence of firedamp is usually one of the major risks in underground coal mines. Methane is trapped in coal or rock, often in pockets within the veins, sometimes at a relatively high pressure, and may leak through the cracks towards the face where works take place. In gassy mines, there is always the danger that a mixture be formed which, if ignited, can cause serious damage and loss of life. There are many well-known methane ignition sources in mines [1], such as friction of cutting bits, open flames, electrical sparking and explosives. In particular, the firing of explosives in such mine works must always be undertaken with appropriate safety considerations.

The so-called permissible, or permitted, explosives are used in underground works where there is a risk of occurrence of flammable gases. They provide a lower temperature, shorter duration flame, with a lower probability of ignition of methane or coal dust than regular explosives. The evaluation of this and other critical safety-related properties is done by conducting elaborate tests [2–6] designed to model the explosive-gas interaction in controlled laboratory conditions usually carried out in government or independent institutions. As a result of such tests, explosives are classified in various safety levels or classes. Besides holding the "permissible" certification, explosives can only be used in potential firedamp conditions under strict firing prescriptions, mainly related with the charge to be fired per delay or per total round, and the allowable delay times, which depend on the class in which the explosive is rated and the type of working face where the blast is to be conducted [7–9]. Regulations in coal blasting generally restrict the amount of explosive to be loaded per hole. For instance, the Spanish regulation [7] states that no more than 2 kg of Class III explosive can be loaded per hole unless special permission is issued. Such restrictions are reasonable for typical drift blasting where holes are about 3 m long, but cannot be met in sublevel caving ring blasting with holes 10 or 20 m long; in such cases, blasting with higher charges per hole is carried out, under special supervision. Besides the increased amount of explosive, blasting with long holes may

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require some charging and priming techniques [10,11] that are not typically used with short holes: PVC casing to facilitate the charge preparation and blasthole loading; detonating cord along the charge to ensure continuity of the detonation; double (top and bottom) initiation to reduce the probability of a failed shot-hole, and inhibitor salt decks. This paper assesses the effect of these practices on the probability of ignition of a methane–air atmosphere.

2. Experimental design

2.1. The Bruceton method

A widely used method in tests where the result is binary (in our case, ignition or not of the firedamp atmosphere for a certain explosive charge) is the "Bruceton staircase technique" [12] also called "up and down" method. In it, the conditions of one test depend on the result of the previous one. If a "go" (ignition) is obtained when testing with a certain stimulus (mass of explosive charge), the stimulus is reduced by one increment, or step, for the next shot. If a "no go" (no ignition) is obtained, the stimulus is increased by one step. The test proceeds until a sufficient number of trials has been performed to obtain meaningful statistics. The size of the step is fixed and must be chosen so that the stimulus level can be increased or decreased incrementally. It is recommended that the step size be within about half and twice the standard deviation of the resulting ignition probability distribution [13].

The classical Bruceton analysis is based on a normal distribution of the test variable or stimulus level, though other distributions can also be used in the analysis of the data. The required number of tests is typically large, but it has been suggested that reliable results can be obtained for explosives tests with only 20 trials [14]. A minimum of 20 trials are also requested with this testing method for the approval of permissible explosives according to the U.S. regulations [3]. A stopping rule based on the number of trials or the number of reversals (shifts from a charge increase to a decrease or from a charge decrease to an increase; following the Bruceton procedure, a reversal must take place when there is an ignition after an increase in charge and when there is no ignition after a decrease in charge) is given in [13]: a minimum of 10 reversals with a zone of mixed results, or a minimum of 15 trials. In the present study, a minimum of 25 tests have been fired for each experimental condition.

Once an adequate number of tests have been performed, the results are typically analyzed to obtain the median value of the stimulus level, i.e., the stimulus level with a 0.5 probability of producing a "go" or a "no go", and the standard deviation. In fact, the Bruceton method is designed to estimate the median stimulus as the test sequence makes the observations concentrated around that stimulus level. For the determination of extreme stimulus levels, e.g. those required to give an ignition probability of 99% or higher, or 1% or lower, test designs other than the Bruceton should be used, such as OSTR [13], C-optimal [15,16] or D-optimal [17]; for such "all fire" or "no fire" tests, the ISO 14304 standard prescribes a minimum of 40 shots for the Bruceton sequence [18].

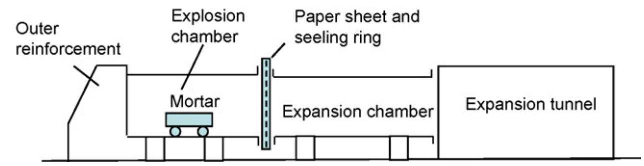

Fig. 1. Test gallery.

2.2. Gallery testing of permissible explosives

Regulations for the approval and use of explosives to be used under potential firedamp conditions are enforced in all coal-mining countries. The approval requires a certain capacity of no ignition of a methane atmosphere; the main instrument for testing this capacity is the test gallery [19,20]. The gallery used in the present work (Fig. 1) consists of a steel cylinder with one end permanently closed and the other end equipped with a light closing device such as a paper sheet and a sealing ring. Inside this closed cylinder, or explosion chamber, the explosive is positioned either within a mortar or freely suspended. After positioning the mortar and charging, the explosion chamber is sealed and filled with a methane–air mixture of 9% methane and the charge is fired. Whether or not ignition of the gas occurs is observed from a safe position.

Different mortars and test conditions can be set to give a higher or lower probability of ignition so that different safety grades of explosives can be defined. We have used in the present work the angle mortar (Fig. 2): a steel cylinder of 219 mm in diameter and 2 m in length with a right-angled groove; it is positioned in the explosion chamber against a steel plate at various distances and angles. Trains of several cartridges up to the full mortar length are placed in the angle and fired in the methane–air mixture.

2.3. Test series

The explosive tested was a permissible ion-exchange explosive (class III according to the Spanish classification [4]) in 32 mm diameter cartridges with a nominal cartridge mass of

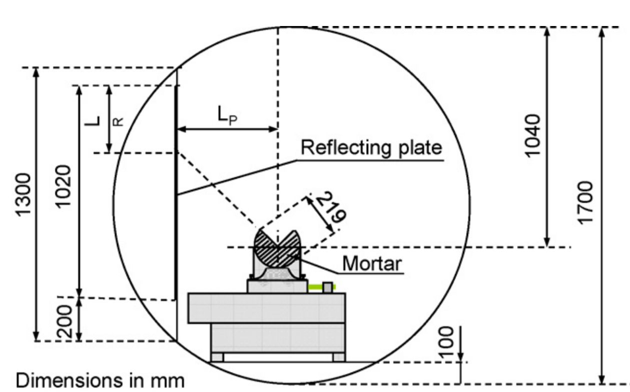

Fig. 2. Angle mortar test layout.

Table 1
Test series configuration

Series	Firing conditions	Distance to plate, L_P (cm)	Reflection length, L_R (cm)	Step (g)
1	Bare charge	47	32	215.2
2	PVC casing	47	32	214.5
3	PVC casing/detonating cord	47	32	214.9
4	PVC casing/detonating cord/salt	40	35	107.5
5	PVC casing/detonating cord	40	35	107.0
6	PVC casing/detonating cord/double initiation	40	35	107.2

215 g. Class III explosives are not required to pass the angle mortar test under the Spanish regulation; the Class III and angle mortar combination was selected in order to provide a significant probability of ignition for the statistical analysis with the different charging characteristics. Several trial shots varying the orientation of the mortar's angle and the distance to the reflection plate were done in order to obtain a configuration that assured a high enough ignition frequency for the range of explosive mass allowed by the length of the mortar and the resistance of the chamber. Table 1 lists the configuration parameters of the test series performed which are sketched in Fig. 3. The step values given in Table 1 are the mean weights of a cartridge or half cartridge in the corresponding series.

For the first test series, cartridges were placed in the mortar angle and initiated in one extreme of the charge. The step used in this series was one cartridge.

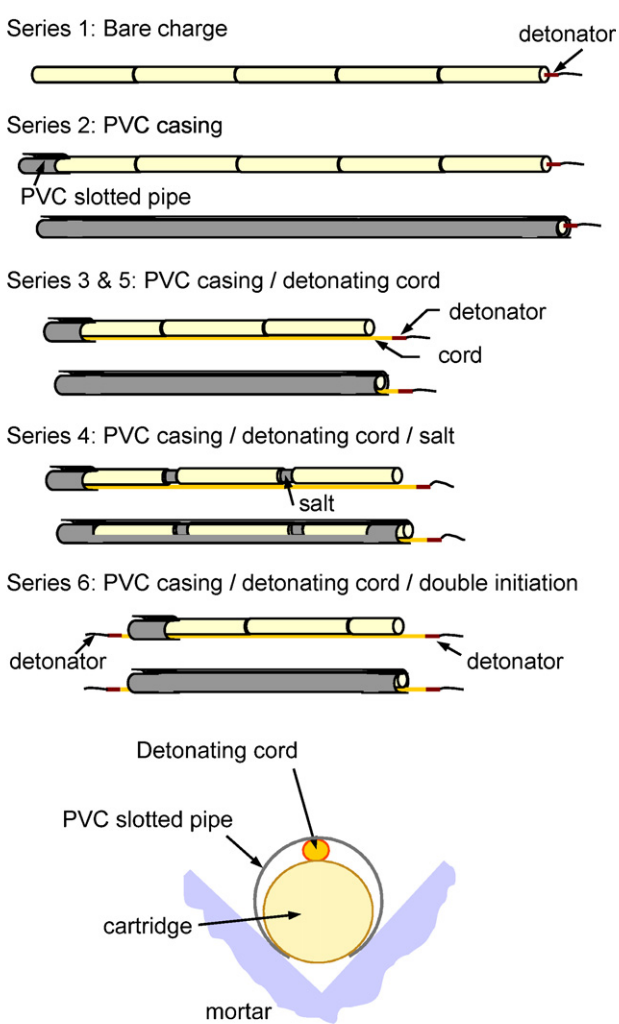

Fig. 3. Test series charge configurations.

Table 2
Charge masses (g)

	Series #					
	1	2	3	4	5	6
No ignition	862	1274	1075	642	317	430
	845	1281	855	635	440	438
	1094	1063	1073	445	553	545
	1275	866	1062	637	635	634
	1067	1074	652	422	426	441
	1305	1284	652	434	426	528
	1496	1273	856	430	539	418
	1074	1296	859	622	427	224
	1089	1289	846	427	426	316
	1290	1074	871	428	537	420
	1301	1076	851	649	417	211
	1292	1288	855	641	555	315
	1494	1504		544	635	422
				520		
				530		
Total (m)	13	13	12	15	13	13
Ignition	1088	1515	1275	859	441	547
	1500	1511	1283	863	739	746
	1295	1302	1078	872	642	638
	1735	1290	1302	645	530	529
	1514	1072	1274	854	546	630
	1286	1531	1086	628	648	551
	1282	1478	847	664	547	548
	1500	1508	854	648	534	426
	1496	1488	1071	871	646	328
	1731	1289	1078	645	532	528
	1498	1269	1078	640	752	456
	1300	1701	1055	862	653	319
			1073	866		
				549		
				536		
				537		
				530		
				774		
				738		
				764		
				746		
				754		
				758		
Total (n)	12	12	13	23	12	12

In test series 2, the cartridges were enveloped in a PVC slotted pipe. The PVC casing improves the charge continuity and is very useful in practice, especially during the preparation of the charges and the loading of the holes.

In test series 3, the PVC casing was also used and the initiation was reinforced with permissible, 6 g/m detonating cord along the charge. Detonating cord is used under harsh conditions such as rock instabilities or wet holes, and when intermediate salt decks are employed, in order to ensure the propagation of the detonation along the charge. The cord positioning with respect to the charge and the mortar is shown in the lower diagram of Fig. 3.

The use of salt cartridges as an ignition inhibitor is a very common safety practice. Test series 4 was done using the PVC casing and detonating cord of series 3, and salt decks. The distance from the mortar to the reflection plate was reduced for this test series (see Table 1) in order to obtain enough ignition frequency. Several tentative shots were needed with different mortar positions and salt/explosive proportions in order to obtain a proper frequency for the statistical analysis. The salt/explosive proportion was finally 7% in length. The residual salt in the test chamber was cleaned up by means of an explosion when two consecutive no-goes were obtained. With an initial step of one cartridge, only three charge levels were obtained (with 2, 3 and 4 cartridges) so that 13 additional shots with intermediate charge weights (2.5 and 3.5 cartridges) were fired, whence the final step for this series was half cartridge. This procedure deviates from the Bruceton test but this is not relevant for the maximum likelihood analysis that has been performed, as will be seen in Section 3.

In order to study the influence of the salt in the ignition frequency, test series 5 was done with the same mortar configuration as series 4 but without salt. The charge set-up was equal to that in test series 3 but with the plate at a distance equal to test series 4. A step of half cartridge was used.

The last test series (no. 6) was done with PVC casing, detonating cord, salt decks and double initiation in the two extremes of the charge. The step for this test was also half cartridge.

3. Results

Table 2 gives the charge masses of all the shots for the six series. The detailed sequences of shots in each series are available from the authors. The analysis of the results requires the assumption of a probability distribution for the critical stimulus (a random hidden variable such that when the stimulus applied is lower than that there is no ignition and when it is greater or equal, there is ignition). In the present case, the stimulus for the ignition of the flammable atmosphere is the mass of explosive. The classical approach [12] of the Bruceton test in its origin was the normal distribution. The logistic distribution has also been commonly used for the analysis of quantal responses [21–23], giving more conservative values in the extremes range due to the longer tails of the logistic distribution as compared with the normal [22]. Both distributions are used in the present work. The lognormal distribution has also been tested for the analysis as a natural transformation of the data (already suggested by Dixon and Mood in their seminal paper [12]); unlike the normal and logistic, the lognormal distribution does not encompass a non-zero probability of ignition for negative stimuli. Where the aim of the test is to determine the median stimulus (that at which the probability of ignition is 50%), which is the main purpose of the Bruceton test, the choice of the distribution is relatively unimportant [21,24]. Wild and von Collani [25,26] dismiss the use of the Bruceton test for other than determining the 50% probability point and use a generalized, three-parameter Weibull distribution for describing the ignition probability, though the test conduct they describe is not the Bruceton's up-and-down. The Weibull distribution has also been tried in our analysis.

Let F be the cumulative probability distribution of the random critical stimulus. The probability of obtaining an explosion at a stimulus level x is that of the critical stimulus being less than x. For the various distributions used:

$$\text{Normal}: F(x) = \int_{-\infty}^{x} \frac{1}{\gamma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\gamma}\right)^2\right] \mathrm{d}x \qquad (1)$$

Table 3
Parameters of the distributions of probability of ignition

Test series	Normal		Logistic		Lognormal		Weibull	
	μ	γ	μ	γ	μ	γ	γ	κ
1	1328.2	247.9	1329.4	150.3	7.183	0.193	1418.9	6.267
2	1317.3	206.8	1320.3	121.4	7.177	0.164	1392.6	7.753
3	980.7	150.8	982.1	90.6	6.879	0.156	1039.8	7.694
4	593.5	107.8	593.5	66.1	6.374	0.180	635.5	6.372
5	550.0	122.8	549.5	75.7	6.297	0.227	595.1	5.080
6	475.7	211.0	476.5	128.7	6.133	0.495	545.4	2.548
Test series	Median	S.D.	Median	S.D.	Median	S.D.	Median	S.D.
1	1328.2	247.9	1329.4	272.6	1316.7	261.4	1338.3	245.6
2	1317.3	206.8	1320.3	220.2	1308.7	218.6	1328.3	200.1
3	980.7	150.8	982.1	164.4	972.0	154.2	991.4	150.4
4	593.5	107.8	593.5	119.9	586.4	108.4	600.0	108.4
5	550.0	122.8	549.5	137.3	543.1	128.4	553.7	123.5
6	475.7	211.0	476.5	233.5	461.0	274.8	472.3	203.7

$$\text{Logistic}: F(x) = \frac{1}{1+\exp(-(x-\mu)/\gamma)} \quad (2)$$

$$\text{Lognormal}: F(x) = \int_0^x \frac{1}{\gamma x\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x-\mu}{\gamma}\right)^2\right] dx \quad (3)$$

$$\text{Weibull}: F(x) = 1-\exp\left[-\left(\frac{x}{\gamma}\right)^{\kappa}\right] \quad (4)$$

where the symbols μ and γ have been used for the location and scale parameters, respectively; for the Weibull distribution, κ is the shape parameter. The stimuli (explosive charge masses) and results (ignition/no ignition) are used to calculate the maximum likelihood estimates of the two parameters of each distribution. The likelihood function is the probability that the complete set of observations in each test series occurred. Since these events are assumed to be independent, the probability of observing the set is the product of the probabilities of the separate observations:

$$L(\theta) = \prod_{i=1}^{n} p_i \prod_{j=1}^{m} (1-p_j) \quad (5)$$

θ being the vector of the parameters of the probability distribution, (μ, γ) or (γ, κ); n and m are the total number of ignitions and no ignitions, respectively, of each test series, for which the charge masses are x_i and x_j to which the probabilities of the critical stimulus (mass) being less than them are $p_i = F(x_i)$ and $p_j = F(x_j)$, respectively. Note that, while the Bruceton test is done with a reduced number of levels (4–6 in the present work), the precise values of the masses in each shot (see Table 2) have been used in the likelihood function. This, in the more convenient logarithmic form, is:

$$L'(\theta) = \ln L = \sum_{i=1}^{n} \ln p_i + \sum_{j=1}^{m} \ln(1-p_j) \quad (6)$$

The maximum likelihood estimates (MLE) of the parameters are those that bring L or L' to a maximum. These are given in Table 3, from which the median and standard deviation of the critical charge mass can be calculated, also listed in Table 3. The distributions are shown in Fig. 4 in which the charge mass x_p for a probability p (probability points, or p-quantiles of F) is calculated by:

$$\text{Normal}: x_p = \mu + z_p\gamma \quad (7)$$

$$\text{Logistic}: x_p = \mu + \gamma \ln\left[\frac{p}{(1-p)}\right] \quad (8)$$

$$\text{Lognormal}: \ln x_p = \mu + z_p\gamma \quad (9)$$

$$\text{Weibull}: x_p = \gamma[-\ln(1-p)]^{1/\kappa} \quad (10)$$

where z_p is the normal standard p-quantile.

By inspection of Table 3 and the curves in Fig. 4, the following can, in principle, be observed:

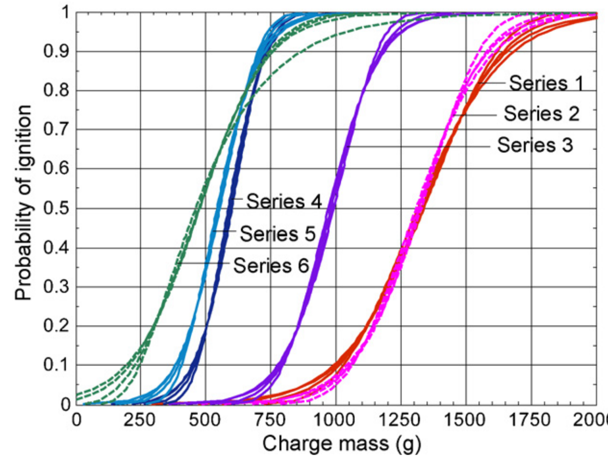

Fig. 4. Distributions of probability of ignition.

- The steps are always within 0.5 and 2 standard deviations. Using the standard deviations of the normal distributions, the step-to-standard deviation ratio is 0.87, 1.04, 1.43, 1.00, 0.87 and 0.51 for series 1–6, respectively.
- All the distributions give similar charge masses for a given probability of ignition in each series in the central zone (approximately the interquartile probability range [0.25, 0.75]); the agreement between the normal and the logistic distributions was already reported by several authors [16,21,24]. In the extremes (at probabilities less than 0.1 or greater than 0.9) the differences can be significant.
- The distributions of series 1 and 2 are very close, indicating a minor effect of the PVC casing in the probability of ignition.
- The inclusion of the detonating cord (series 3) has an important effect on the probability of ignition.
- The use of salt (at an amount of 7% in length) appears to have a small effect on the ignition probability, from the comparison of series 4 (with salt) and 5 (without salt).
- The double initiation seems to increase the ignition probability for probabilities below about 0.75.

In order to assess the significance of the variations observed, confidence intervals have been calculated for the x_p estimators. The standard error s_{x_p} can be obtained from the standard errors of the MLE of the parameters of the distributions – given their asymptotic normality – calculated by means of the covariance matrix (the negative inverse of the Hessian of the log-likelihood function in its maximum). Let $s_\mu, s_\gamma, s_\kappa$ be the standard errors of the estimators of the parameters of the distributions and cov(θ_1, θ_2) the covariances of the two parameters (θ_1, θ_2) of each distribution. From Eqs. (7)–(10), the standard errors of the probability point estimators are:

$$\text{Normal}: s_{x_p}^2 = s_\mu^2 + z_p^2 s_\gamma^2 \quad (11)$$

$$\text{Logistic}: s_{x_p}^2 = s_\mu^2 + \left\{\ln\left[\frac{p}{(1-p)}\right]\right\}^2 s_\gamma^2 + \ln\left[\frac{p}{(1-p)}\right] cov(\mu,\gamma) \quad (12)$$

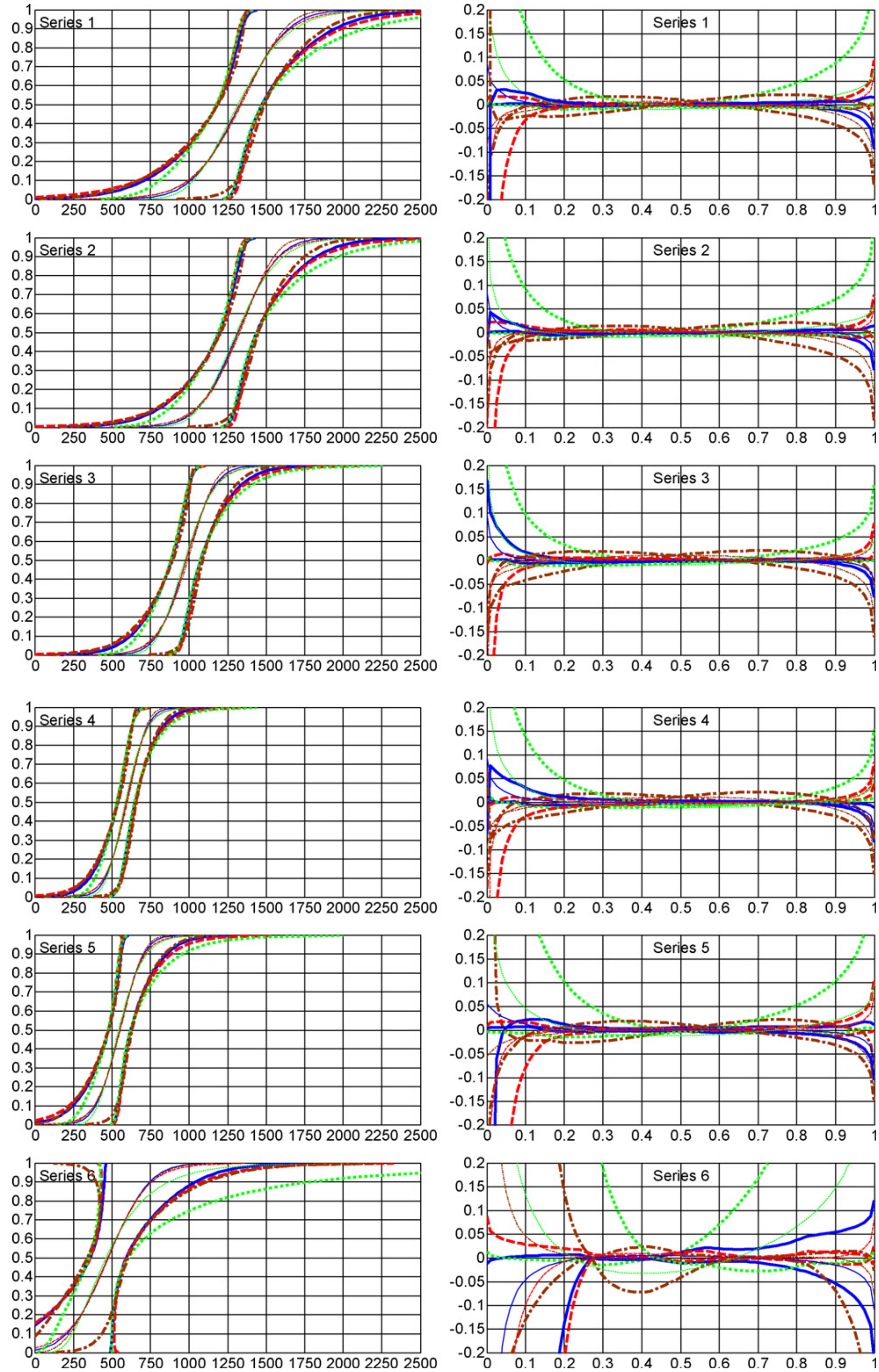

Fig. 5. Left graphs: probability distributions and confidence bands (abscissa: charge mass, g). Right graphs: relative differences in x_p and in confidence limits as calculated with the different distributions (abscissa: probability of ignition; ordinate: relative error). Solid lines: normal; dashed: logistic; dotted: lognormal; dashed-dotted: Weibull. Thin lines: x_p; thick lines: confidence limits.

$$\text{Lognormal}: s^2_{\ln x_p} = s^2_\mu + z_p^2 s^2_\gamma + z_p\, cov(\mu, \gamma) \tag{13}$$

$$\text{Weibull}: s^2_{x_p} = \left(\frac{x_p}{\gamma}\right)^2 s^2_\gamma + \left(\frac{x_p}{\kappa^2}\right)^2 \{\ln[-\ln(1-p)]\}^2 s^2_\kappa - \left[\frac{x_p^2}{\gamma\kappa^2}\right] \ln[-\ln(1-p)]\, cov(\gamma, \kappa) \tag{14}$$

And the confidence intervals at a $1-\alpha$ significance level are:

$$x_p \pm t_{N_S-1,1-\alpha/2} s_{x_p} \tag{15}$$

for the normal, logistic and Weibull distributions, and:

$$\ln x_p \pm t_{N_S-1,1-\alpha/2} s_{\ln x_p} \tag{16}$$

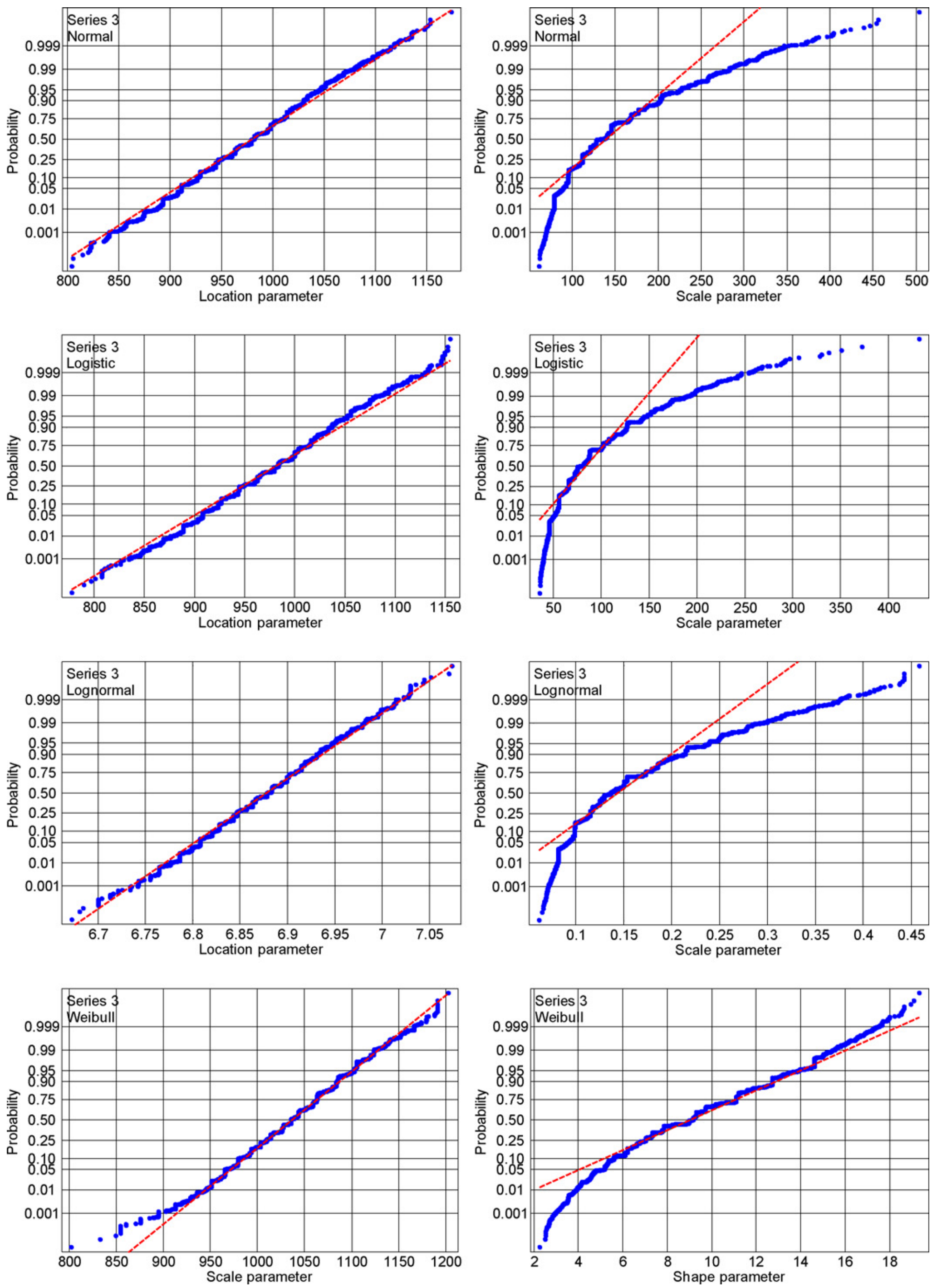

Fig. 6. Normality plots of the parameters of the distributions for series 3.

for the lognormal; t is the Student's $1-\alpha/2$ quantile and N_S-1 degrees of freedom, N_S being the number of shots in each series.

The 95% confidence bands ($\alpha=0.05$) are shown in Fig. 5 for the six series (left plots); the four distribution functions are plotted. The differences in x_p and in the confidence limits obtained with the different distributions are plotted in the right graphs; the medians of values of the four distributions are used as reference:

$$\frac{x_p-\mathrm{med}(x_p)}{|\mathrm{med}(x_p)|} \tag{17}$$

and similarly for the confidence limits.

In general, the differences in the results by the various distributions appear to be small except in the extremes. In the range of probability [0.1, 0.9], the x_p values from the different functions differ by a few units percent, lognormal and Weibull generally being the more discrepant; the discrepancy in the confidence

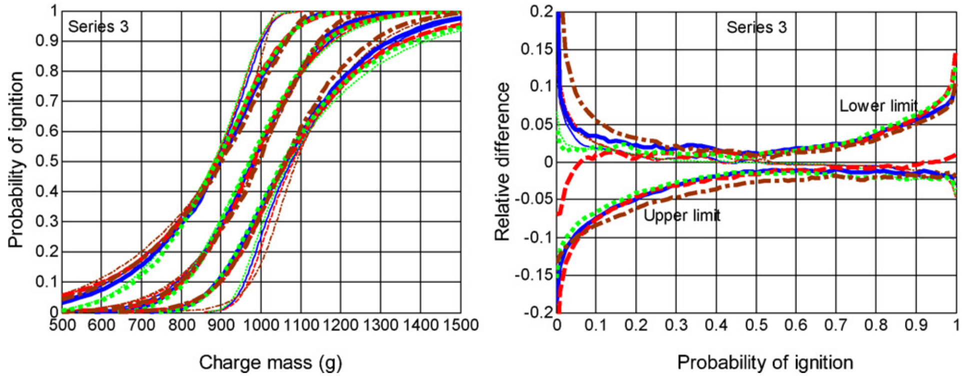

Fig. 7. Left graph: probability of ignition and confidence bands for series 3; thin lines: asymptotic; thick lines: bootstrap. Right graph: relative difference between the asymptotic and bootstrap calculations; thin lines: x_p; thick lines: confidence limits. The same line types as in Fig. 5 are used for the different distributions.

limits is generally within 5% in the range [0.25, 0.75] in most of the series (all but no. 6, where the lognormal's upper confidence limit differs quite significantly) and is still limited to 10% in the range [0.1, 0.9]. This indicates that the Bruceton test results are quite robust in this range, out of which the x_p values are much distribution-dependent and their confidence bands very wide.

In order to assess the normality of the parameters of the distributions and of the probability points, confidence intervals of these have also been obtained by a bootstrap-like procedure [27]. For each series, 40,000 simulated replicates of the test were generated using the distributions with the parameters determined from the real tests (Table 3). Random generation of samples typically used in bootstrapping cannot be directly applied since the stimulus applied in each shot of a test depends on the result of the previous shot. For each shot, random critical stimuli (charge masses) following the four distributions were generated to decide a go or a no-go, depending on such number being smaller or greater than the mass of explosive at the level of the shot, and proceed with a decrease or increase of the mass accordingly. The step and the number of shots in the simulated series were the same as in the real ones. Some deviations from the random evolution of the simulated tests were required: (i) both the normal and logistic distributions have non-zero probability for negative critical stimuli but replicates were not allowed

Table 4
Influence of firing characteristics

Parameter				
PVC casing 1 vs. 2[a]	Detonating cord 2 vs. 3[a]	Distance to plate 3 vs. 5[a]	Salt 4 vs. 5[a]	Double initiation 5 vs. 6[a]
Difference at a 95%				
NO	YES	YES	NO	NO
p-Values	Interval	Interval	*p*-Values	*p*-Values
i-1) *t*-Test, errors asymptotic				
p_{min} = 0.66–0.77	0.13–0.975	0.01–0.999	p_{min} = 0.30–0.33	p_{min} = 0.11–0.20
$p(x_{50})$ = 0.91–0.93	0.14–0.96	0.025–0.99	$p(x_{50})$ = 0.33–0.35	$p(x_{50})$ = 0.25–0.28
	0.09–0.93	0.001–0.975		
	0.15–0.99	0.01–0.999		
i-2) *t*-Test, errors bootstrap				
p_{min} = 0.66–0.77	0.06–0.99	0.01–0.999	p_{min} = 0.26–0.28	p_{min} = 0.11–0.19
$p(x_{50})$ = 0.89–0.94	0.08–0.975	0.025–0.999	$p(x_{50})$ = 0.26–0.30	$p(x_{50})$ = 0.20–0.24
	0.025–0.96	0.001–0.99		
	0.07–0.999	0.001–0.999		
ii-1) Bands overlap, asymptotic				
–	0.24–0.89	0.06–0.975	–	–
–	0.24–0.86	0.08–0.96	–	–
–	0.20–0.82	0.01–0.91	–	–
–	0.28–0.93	0.07–0.975	–	–
ii-2) Bands overlap, bootstrap				
–	0.15–0.96	0.025–0.99	–	–
–	0.17–0.92	0.06–0.975	–	–
–	0.10–0.90	0.001–0.95	–	–
–	0.17–0.975	0.04–0.99	–	–

[a] Series compared.

to have negative explosives masses, and (ii) in order to ensure the existence of MLE [28,29], the replicate series must have at least 4 levels; should only three or less levels be present at the end of a replicate, additional shots were simulated until a fourth level appeared.

For each replicate, the maximum likelihood parameters of the distributions were determined and from these, probability points. The median and the 0.025 and 0.975 quantiles of the 40,000 data so obtained are the central value estimate and the 95% confidence limits, respectively.

The assumption of normality of the parameters of the distributions can be checked from the results of the replications. Both the Kolmogorov-Smirnov and the Lilliefors tests reject the hypothesis of normality for both parameters of all the distributions at a 95% confidence level. Normality plots (given, as an example, in Fig. 6 for the parameters of series 3) show that the deviation from normality is not severe for the location parameters of the normal, logistic and lognormal, and for the scale parameter of the Weibull, but it is so for the scale parameters of the normal, logistic and lognormal and the shape parameter of the Weibull, albeit normality could still be accepted in the interquartile range. This is the reason why the asymptotic confidence intervals are not much different from the bootstrap ones in the interquartile range. As an example, Fig. 7 shows the probability distributions for series 3 and the confidence bands for the four functions both from the normal assumption and from bootstrap. The right graph shows the relative differences of both methods:

$$\frac{x_p^{B} - x_p^{A}}{1/2\left|x_p^{A} + x_p^{B}\right|} \tag{18}$$

The differences in the x_p values obtained with the asymptotic method, x_p^A, and with bootstrap, x_p^B, are of the same order than the discrepancies in x_p from the various functions (compare the right graphs of Figs. 5 and 7), i.e., a few units percent except in the extremes. As in the comparison of the various functions, the discrepancy in the confidence limits is larger than in the x_p values but it is also limited. Bootstrap confidence limits are generally narrower than the asymptotic ones.

4. Discussion

The influence of a given firing characteristic can be derived from the relative position of the confidence bands of the pair of series in which that characteristic was different. Such comparison is dependent on the probability of ignition. The following two criteria have been used:

(i) A t-test of comparison of the x_p values of two series, using as standard errors: (i-1) the asymptotic normal, and (i-2) those estimated from the width of the bootstrap confidence bands:

$$s_{x_p} = \frac{x_p^{B+} - x_p^{B-}}{2t_{N_S-1,0.975}}$$

where x_p^{B+} and x_p^{B-} are the bootstrap confidence limits of x_p.

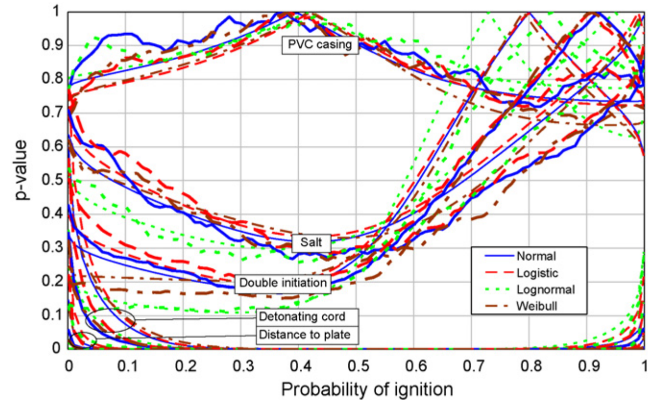

Fig. 8. p-Values for the t-test comparing pairs of series for which a firing characteristic changes. Asymptotic (thin lines) and bootstrap (thick lines) standard errors are used. The higher the p-value the less influential the characteristic is.

(ii) The overlapping of the confidence bands: the x_p values in two series are different if the lower confidence limit of the greater x_p is greater than upper confidence limit of the smaller x_p. Both (ii-1) asymptotic and (ii-2) bootstrap confidence intervals have been used.

The results of the comparisons are summarized in Table 4. For each pair of series describing the effect of a firing characteristic, the range of probability at which the series are different is given if such difference exists at a 95% significance level; the four ranges given correspond from top to bottom to normal, logistic, lognormal and Weibull. When difference cannot be stated at that level across the whole probability range, the minimum p-value, p_{min}, and the p-value of the comparison of the median charge masses, $p(x_{50})$, in the t-tests are given (ranges of the values for the four distributions). The p-values are plotted as a function of the probability of ignition in Fig. 8. The higher the p-values the closer the two series are and the less influential the firing characteristic assessed is.

The different criteria and distributions give similar results with discrepancies only in the extremes. The distance to the reflection plate appears to be very influential in the results, as expected. Of the firing characteristics, the use of detonating cord reduces the charge mass with statistical significance for a wide range of probability of ignition. For a 0.5 probability, the charge mass with detonating cord is 26% less than without it.

The influence of the PVC casing is negligible, as the high p-values tell. The use of salt appears to have some effect as expected, increasing the charge mass for a given probability of ignition (8% for a 0.5 probability), though such influence cannot be stated at a 95% level (at least with the amount of salt used in the tests, 7% in length). The double initiation, finally, decreases the charge mass for a given probability of ignition (about 14% for a 0.5 probability) though, again, the p-value is never less than 0.05.

5. Conclusions

The Bruceton method has been used to determine the probability of ignition of firedamp under several firing conditions applied in underground coal blasting with long holes. The variables assessed are the casing of the charge in a PVC slotted pipe, the use of detonating cord along the charge, the inclusion of salt decks and the double priming in the top and bottom of the charge when detonating cord is used. A total of six series were conducted, five of them with 25 shots and one with 38.

Four distributions have been used to describe the probability of ignition of a certain charge mass: normal, logistic, lognormal and Weibull. Their parameters have been determined from the test results by the method of maximum likelihood. Confidence bands of the probability points have been determined from their standard errors, calculated both from the assumption of normality of the parameters of the distribution and by a bootstrap method with 40,000 random replicate tests of each series.

The different distributions are similar for each series except in the probability extremes; the x_p values from the different functions differ by a few units percent in the range of probability [0.1, 0.9]; the confidence bands differ by less than 10% in that range. Similar discrepancies have been found between the results from the asymptotic normal and the bootstrap calculations, all of which provides consistency to the comparisons within that range of ignition probability. Differences between the various distributions can be large out of that range, which confirms the inadequacy of the Bruceton method for the determination of all-fire and no-fire charges. The effect of the various firing techniques on the ignitability of firedamp is as follows:

- The casing of the charge with a PVC slotted pipe, useful in practice for the charging of the holes, does not have an influence on the ignition probability.
- Detonating cord increases the probability of ignition with statistical significance of 95%; for an ignition probability of 0.5, the charge mass is reduced by a 26% when detonating cord is used.
- The influence of salt is very limited in the amount used in the present study (7% salt/explosive length ratio). In spite of an increase of 8% in the mass at an ignition probability of 0.5, the use of salt in this quantity cannot be considered an influential parameter at a 95% confidence level.
- The double initiation increases the probability of ignition, the charge mass being on average 14% smaller than with one-end initiation for a 0.5 probability of ignition. However, as with the use of salt, the influence cannot be stated at a 95% confidence level.

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