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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	Ω	ohm
A/ms	ampere per millisecond	pct	percent
J	joule	s	second
ms	millisecond	V	volt
mV/A	millivolt per ampere		

OVERLAP PROBABILITY FOR SHORT-PERIOD-DELAY DETONATORS USED IN UNDERGROUND COAL MINING

By T. S. Bajpayee,[1] Richard J. Mainiero,[2] and J. Edmund Hay[3]

ABSTRACT

The Bureau of Mines investigated coal-mine-type short-delay electric detonators marketed by three domestic manufacturers to determine the accuracy of delays and the probability of overlap between adjacent delay periods. The Winzer index was computed and compared with the probability of overlap. A close agreement between the Winzer criterion and overlap probability was demonstrated.

A permissible blasting unit capable of delivering a maximum firing energy of 4.0 J and a digital oscilloscope were used to measure the delay time with an accuracy of ±0.25 ms. Another oscilloscope and a pulse transformer were used to record firing current.

Experimental data indicated negligible overlap probability in detonators of shorter delay periods: periods 1 to 4, which correspond to 25 to 250 ms. However, a significant probability of overlap was detected in some detonators of longer delay periods: periods 5 to 9, which correspond to 300 to 500 ms.

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INTRODUCTION

Short-period-delay detonators are defined as follows: "'Short-delay electric detonator' means a delay-type detonator (blasting cap) the delay periods of which range in nominal value from 25 to 500 ms, and which will initiate (detonate) multiple charges of high explosives in succession with one application of the firing current" (30 CFR 25.2(e).)[4] From a productivity standpoint, the coal mining industry would prefer to incorporate nine or more delay periods within the 500-ms limit. However, increasing the number of delay periods within the 500 ms requires a decrease in the interval between adjacent delay periods, increasing the possibility of detonators' shooting out of sequence (overlaps). This situation led the Bureau to initiate a study of the accuracy of delay periods of short-period-delay detonators. Such data are essential to the study of safe blasting practices in underground coal mines. This research was conducted under the Bureau's "Generation of Hazard Criteria and Test Procedures for Explosive Products" program.

The accuracy and precision of commercially available coal mine delay detonators were investigated. Three separate lots of detonators of each delay period marketed by three domestic manufacturers were procured during the fall of 1982, fall of 1983, and summer of 1984 and tested.

Winzer[5] derived from statistical considerations a nondimensionalized critical parameter for estimating a satisfactory probability of "success" in delay blasting, i.e., that the later hole of an adjacent-period pair will fire at or later than a given time after the earlier hole. According to Winzer, a value for the Winzer index, S, of less than 3 indicates significant probability of overlap between adjacent delay periods.

The Winzer index, S, is given by

$$S = \frac{T_{(n+1)} - T_n - \tau}{[\sigma_n^2 + \sigma_{(n+1)}^2]^{1/2}}, \qquad (1)$$

where $T_{(n+1)}$ = average delay time for period (n + 1) detonators, s,

T_n = average delay time for period n detonators, s,

τ = required time interval between the firings of adjacent holes, s,

$\sigma_{(n+1)}$ = standard deviation for period (n + 1) detonators, s,

and σ_n = standard deviation for period n detonators, s.

The probability that two boreholes primed with adjacent-period detonators will fire within a given time interval relative to each other can be calculated from the knowledge of firing times, the mean firing times, and standard deviations of the firing times for each of the two periods. However, this time interval, the time requirement for the burden to move out sufficiently so that the subsequent shots do not fire in tight formation, is not precisely known. The most liberal assumption of this time is zero (see "Results and Discussion").

[4]U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter D--Electrical Equipment, Lamps, Methane Detectors; Tests for Permissibility; Fees; Part 25--Multiple-Shot Blasting Units; Subpart A--General Provisions; July 1, 1983.

[5]Winzer, S. R., W. Furth, and A. Ritter. Initiator Firing Times and Their Relationship to Blasting Performance. Pres. at 20th U.S. Symp. on Rock Mechanics, Austin, TX, June 4-6, 1979, 10 pp.; available from S. R. Winzer, Martin Marietta Lab., Baltimore, MD.

Overlap probabilities were computed as follows:

Let $p_n(t)\Delta t$ be the probability that a detonator of period n fires between times $(t - 1/2\Delta t)$ and $(t + 1/2\Delta t)$. Then the probability $P_{n+1}(t_1)$ that a detonator of nominal period n + 1 has already fired at time t is

$$P_{n+1}(t_1) = \int_0^{t_1} P_{n+1}(t)dt. \quad (2)$$

The probability $P_o(t_1)$ of an "overlap firing," i.e., that a detonator of period n fires between times $(t_1 - 1/2\Delta t_1)$ and $(t_1 + 1/2\Delta t_1)$, *and* that a detonator of nominal period n + 1 has already fired at time t, is the product of the above:

$$P_o(t) = P_n(t_1)\Delta t_1 \int_0^{t_1} P_{n+1}(t)dt. \quad (3)$$

The overall probability P_{oa} that overlap will occur is the integral of $P_o(t_1)$ over all possible times:

$$P_{oa} = \int_0^{\infty} P_n(t_1) \int_0^{t_1} P_{n+1}(t)dt\, dt_1. \quad (4)$$

It is assumed that the distribution of delay times is normal and that the standard deviation of the distribution is given to sufficient accuracy by the estimate of the standard deviation, i.e.,

$$\sigma_n = \left[\frac{1}{N} \sum_{i=1}^{N} (t_i - \bar{t}_n)^2 \right]^{1/2}, \quad (5)$$

where σ_n = the standard deviation for nominal period n,

N = the number of observations,

t_i = the observed firing times,

and $\bar{t}_n$ = the mean firing time for nominal period n;

$$\text{thus,} \quad P_n(t) = \frac{1}{\sqrt{2\pi}} \varepsilon^{-\frac{1}{2}\left(\frac{t - \bar{t}_n}{\sigma_n}\right)^2}. \quad (6)$$

The overlap probability claimed for any two adjacent periods n and n + 1 was obtained by inserting the corresponding values of $\bar{t}_n$, $\bar{t}_{n+1}$, σ_n, and σ_{n+1} into the expression given in equation 6 and integrating according to equation 4 by a straightforward second-order numerical quadrature.

A computer program was developed to compute the probability of overlap for samples of 20 detonators.

EXPERIMENTAL TECHNIQUE

Detonator delay periods were measured using a digital oscilloscope. The system was designed to test two detonators simultaneously. As shown in figure 1, the oscilloscope's trigger circuit was connected to the blasting machine so that the firing pulse would start the time measurement.

30 CFR 25.25[6] requires that a permissible 20-shot blasting unit should be capable of delivering adequate current to consistently fire twenty short-period-delay detonators through a series resistance of 150 Ω. This concept was utilized in designing the firing circuit. A Femco SF 25-20 permissible blasting unit[7] having maximum capacitor energy of 4.0 J was used in the tests. An external variable resistor was used to add resistance in series with the firing circuit, giving a total resistance of 150 Ω for testing the detonators.

[6]U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter D--Electrical Equipment, Lamps, Methane Detectors; Tests for Permissibility; Fees; Part 25--Mulitiple-Shot Blasting Units; Subpart C--Blasting Units Capable of Detonating 20 Short-Delay Electric Detonators; July 1, 1983.

[7]Reference to specific equipment does not imply endorsement by the Bureau of Mines.

A wide-band current transformer was employed to monitor the current pulse in the firing circuit. Figure 2 shows a typical firing current profile. The current transformer output was 100 mV/A of current flow in the circuit and was monitored with an oscilloscope. The peak firing current was 2.4 A and declined exponentially at an average rate of about 0.21 A/ms, as shown in figure 2. Figure 3 shows a typical firing voltage signature of the blasting unit. As each detonator fired, it shorted an ionization probe (twisted pair), which in turn caused a trigger circuit to send a pulse to the oscilloscope.

Three separate lots of detonators of each delay period for the three domestic manufacturers were tested. Detonators presented in appendix tables A-1, B-1, and C-1 were tested during the winter of 1982-83; those in tables A-2, B-2, and C-2 during the winter of 1983-84, and those in tables A-3, B-3, and C-3 during the summer of 1984. The pulses were recorded with an accuracy of ±0.25 ms. This technique had previously been shown to give reliable results on a millisecond time scale.

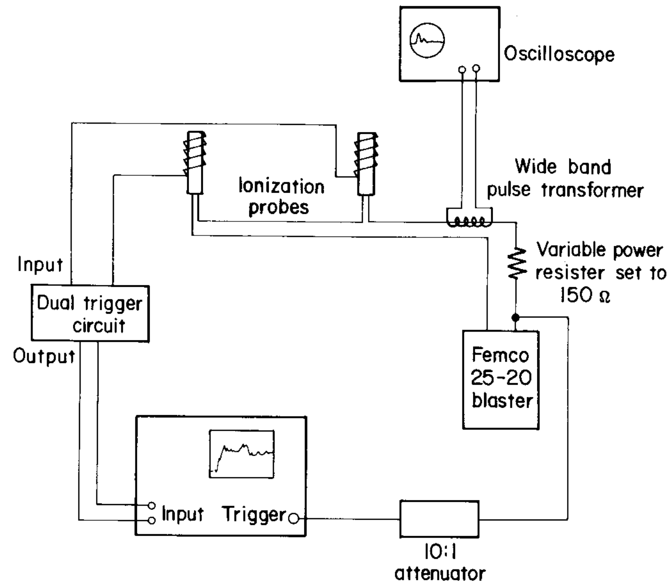

FIGURE 1. - Schematic diagram of experimental setup used for detonator delay measurement.

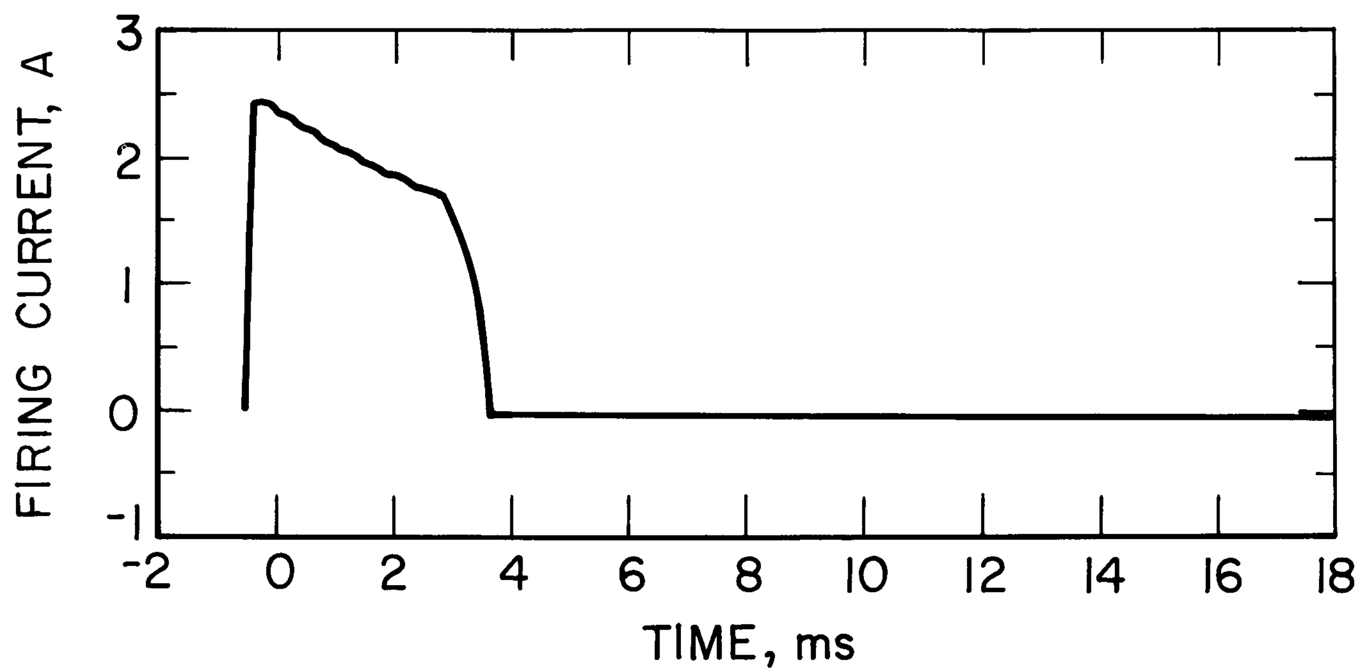

FIGURE 2. - Typical firing current profile.

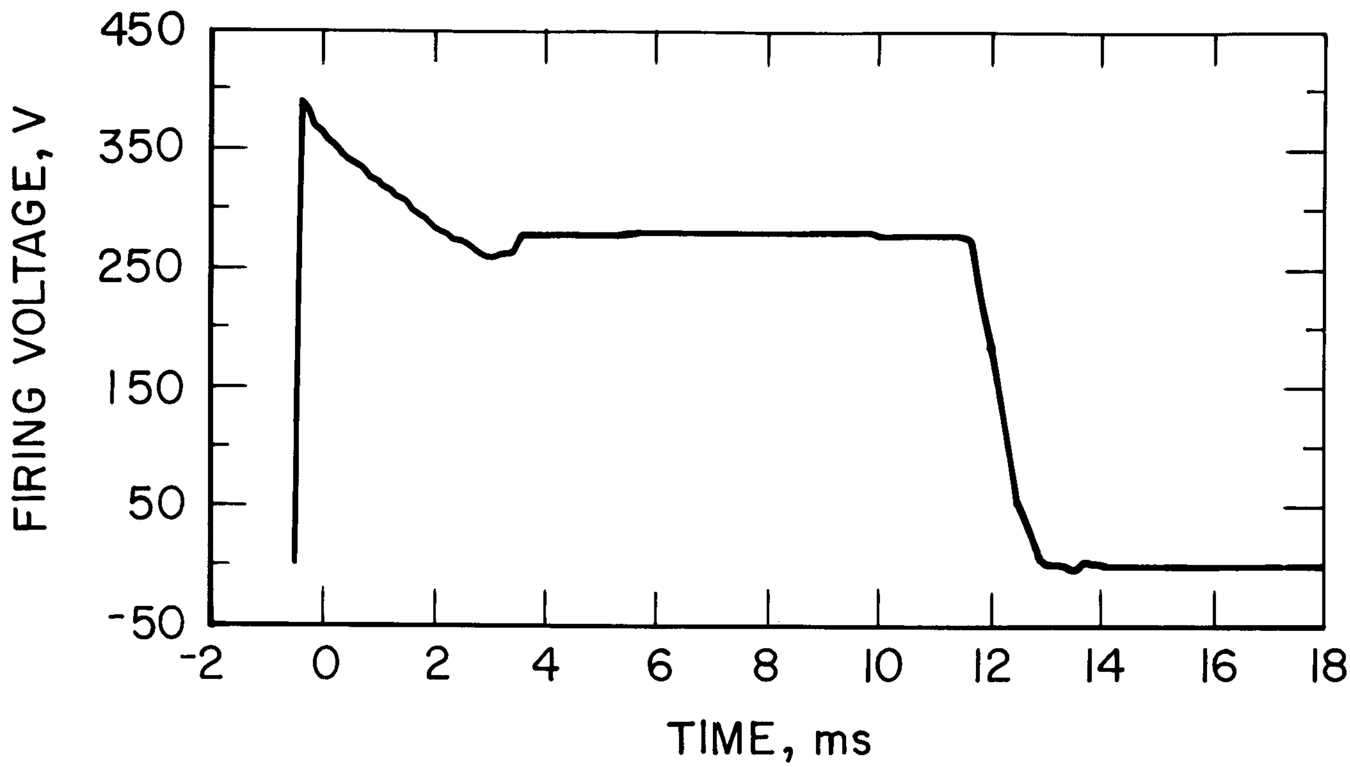

FIGURE 3. - Typical firing voltage signature.

RESULTS AND DISCUSSION

Measurements of actual delays arranged in an ascending order are given in appendix tables A-1, A-2, and A-3 for manufacturer A; tables B-1, B-2, and B-3 for manufacturer B; and tables C-1, C-2, and C-3 for manufacturer C. Tables 1, 2, and 3 summarize the appendix tables for manufacturers A, B, and C, respectively. They present salient data such as nominal delay time (T_n), average of 20 measurements (T_a), lowest (T_e) and highest (T_h) measured delay times, standard deviation (σ), ratio of standard deviation to average value (100 σ/T_a) (an estimate of dispersion of the observed data as compared to the average), and $(T_h-T_e)/\sigma$ (an indication of the spread in delay times, relative to standard deviation) for each delay period. Overlap probability and Winzer index for consecutive delay periods are also shown in tables 1, 2, and 3. Experimental data given in table 1 for the first lot of manufacturer A's coal mine delay detonator series (keys C-2360 and C-2379) indicate that--

1. Detonators of delay periods 1, 2, 3, and 4 show a Winzer index greater than 3 and have a negligible probability of overlap.
2. Detonators of delay periods 4 and 5 exhibit low overlap probability and have a Winzer index of 2.87.
3. The longest measured delay time of period 5 corresponds to the shortest measured delay time of period 6; the Winzer index is less than 3, and some probability of overlap exists.
4. For detonators of delay periods 6, 7, 8, and 9, the Winzer index is less than 3 and a significant probability of overlap exists.
5. The tendency of dispersion of data is quantified by ratios such as σ/T_a and $(T_h-T_e)/\sigma$. The σ/T_a ratios range from 1.87 to 7.12 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.26 to 4.74.

TABLE 1. - Summary of detonator delay measurement--manufacturer A

Delay period	Delay values, ms					$\frac{100\ \sigma}{T_a}$	$\frac{(T_h - T_e)}{\sigma}$	Overlap probability, pct	Winzer index
	Nominal (T_n)	Average (T_a)	Low (T_e)	High (T_h)	Std. dev. (σ)				
FIRST TEST SERIES, KEYS C-2360 AND C-2379									
1.......	25	35.1	29.4	38.8	2.5	7.12	3.76	Neg.	16.24
2.......	100	114.5	107.6	122.8	4.2	3.67	3.62	Neg.	9.15
3.......	175	183.0	170.2	193.8	6.2	3.39	3.81	Neg.	7.41
4.......	250	279.2	245.0	295.8	11.4	4.08	4.46	0.16	2.87
5.......	300	316.1	307.0	328.5	5.9	1.87	3.64	1.79	2.07
6.......	350	358.9	328.5	394.5	19.8	5.52	3.33	2.84	1.90
7.......	400	412.5	386.5	452.0	20.1	4.87	3.26	4.12	1.73
8.......	450	462.8	419.0	518.5	21.0	4.54	4.74	.24	2.78
9.......	500	536.6	502.0	567.0	16.2	3.02	4.01		
SECOND TEST SERIES, KEYS C-2469									
1.......	25	30.06	26.2	32.8	1.68	5.59	3.93	Neg.	19.46
2.......	100	102.46	95.8	108.6	3.32	3.24	3.86	Neg.	12.27
3.......	175	190.14	181.6	204.6	6.33	3.33	3.64	Neg.	7.40
4.......	250	277.64	253.4	292.6	9.98	3.59	3.93	8.16	1.39
5.......	300	296.83	276.0	313.5	9.51	3.21	3.94	Neg.	4.07
6.......	350	360.20	333.0	385.5	12.33	3.42	4.26	.38	2.57
7.......	400	440.03	409.0	536.0	28.52	6.48	4.45	17.89	.92
8.......	450	468.38	455.0	496.0	11.60	2.48	3.54	Neg.	3.26
9.......	500	520.95	502.0	541.0	11.21	2.15	3.48		
THIRD TEST SERIES, KEYS C-2552									
1.......	25	25.10	18.8	32.0	4.19	16.70	3.15	Neg.	15.97
2.......	100	104.27	100.8	110.0	2.65	2.54	3.47	Neg.	15.94
3.......	175	184.24	177.2	192.0	4.26	2.31	3.47	Neg.	8.78
4.......	250	255.23	244.0	267.4	6.89	2.70	3.40	0.29	2.63
5.......	300	293.99	271.5	319.0	12.97	4.41	3.66	Neg.	4.64
6.......	350	363.30	347.0	375.5	7.42	2.04	3.84	.01	2.99
7.......	400	401.25	382.5	423.0	10.32	2.57	3.92	Neg.	4.18
8.......	450	467.15	446.5	499.5	11.92	2.55	4.45	10.20	1.26
9.......	500	497.75	452.5	530.0	21.07	4.23	3.68		

Neg. Negligible.

TABLE 2. - Summary of detonator delay measurement--manufacturer B

Delay period	Delay values, ms					$\frac{100\ \sigma}{T_a}$	$\frac{(T_h-T_e)}{\sigma}$	Overlap probability, pct	Winzer index
	Nominal (T_n)	Average (T_a)	Low (T_e)	High (T_h)	Std. dev. (σ)				
FIRST TEST SERIES, KEYS C-2361 AND C-2372									
1.......	25	14.1	10.6	18.8	2.0	14.18	4.10	Neg.	3.62
2.......	100	61.7	31.0	82.0	13.0	21.07	3.92	Neg.	5.33
3.......	170	153.1	137.6	174.6	11.2	7.32	3.30	Neg.	6.76
4.......	240	253.7	242.0	271.6	9.8	3.86	3.02	Neg.	3.65
5.......	320	325.1	296.5	356.0	16.9	5.20	3.52	Neg.	3.47
6.......	400	406.8	379.5	442.5	16.4	4.03	3.84	Neg.	5.18
7.......	500	519.2	492.0	543.0	14.2	2.73	3.59		
SECOND TEST SERIES, KEYS C-2470 AND C-2475									
1.......	25	21.20	11.6	31.2	4.25	20.03	4.62	Neg.	6.96
2.......	100	90.38	65.4	102.0	8.98	9.94	4.08	Neg.	5.68
3.......	170	171.75	151.2	196.8	11.17	6.50	4.08	Neg.	5.02
4.......	240	255.37	238.8	274.6	12.35	4.84	2.90	Neg.	3.72
5.......	300	328.30	300.0	360.5	15.21	4.63	3.98	17.44	.94
5-1/2...	350	347.00	322.0	373.0	12.91	3.72	3.95	.09	2.87
6.......	400	403.70	378.0	425.0	14.96	3.71	3.14	Neg.	3.54
6-1/2...	450	480.83	453.0	511.5	15.80	3.29	3.70	18.51	.90
7.......	500	500.70	470.0	530.0	15.54	3.10	3.86		
THIRD TEST SERIES, KEY C-2575									
1.......	25	17.84	12.2	24.6	3.49	19.58	3.55	Neg.	6.55
2.......	100	80.18	66.2	99.0	8.85	11.04	3.71	Neg.	4.86
3.......	170	146.21	128.0	162.0	10.30	7.04	3.30	Neg.	6.92
4.......	240	235.89	222.0	256.0	7.88	3.34	4.31	Neg.	3.18
5.......	300	291.88	269.0	344.5	15.77	5.40	4.79	2.07	2.03
5-1/2...	350	331.73	316.5	359.5	11.63	3.51	3.70	Neg.	3.23
6.......	400	387.23	367.0	412.5	12.64	3.26	3.60	.08	2.86
6-1/2...	450	454.08	422.0	488.0	19.64	4.32	3.36	12.05	1.17
7.......	500	481.58	458.5	499.0	12.82	2.66	3.16		

Neg. Negligible.

TABLE 3. - Summary of detonator delay measurement--manufacturer C

Delay period	Delay values, ms: Nominal (T_n)	Average (T_a)	Low (T_e)	High (T_h)	Std. dev. (σ)	$\frac{100\ \sigma}{T_a}$	$\frac{(T_h-T_e)}{\sigma}$	Overlap probability, pct	Winzer index
FIRST TEST SERIES, KEYS C-2353 AND C-2375									
1......	25	23.5	17.4	44.4	5.7	24.26	4.74	Neg.	8.96
2......	100	105.1	93.0	117.4	7.1	6.76	3.44	Neg.	8.51
3......	175	185.9	175.0	196.6	6.3	3.39	3.43	Neg.	4.86
4......	250	248.3	228.4	268.6	11.2	4.51	3.59	Neg.	4.64
5......	300	319.2	299.5	338.5	10.4	3.26	3.75	0.07	2.90
6......	350	365.9	349.5	394.5	12.3	3.36	3.62	11.26	1.21
7......	400	399.1	371.5	448.0	24.6	6.16	3.11	1.24	2.24
8......	450	460.2	439.0	484.0	11.9	2.59	3.78	.03	2.95
9......	500	519.9	477.0	551.5	16.4	3.15	4.54		
SECOND TEST SERIES, KEY C-2473									
1......	25	22.77	19.4	29.8	2.56	11.24	4.06	Neg.	13.75
2......	100	107.46	96.8	119.4	5.60	5.21	4.04	Neg.	6.66
3......	175	186.91	171.8	210.4	10.53	5.63	3.67	Neg.	6.90
4......	250	288.19	266.6	312.0	10.22	3.55	4.44	2.42	1.97
5......	300	315.33	292.5	335.5	9.28	2.94	4.63	Neg.	3.22
6......	350	374.20	344.0	412.0	15.77	4.21	4.31	5.20	1.61
7......	400	426.28	370.5	474.5	28.14	6.60	3.70	5.08	1.64
8......	450	473.75	457.0	488.5	7.02	1.48	4.49	.04	2.93
9......	500	541.38	503.0	580.0	21.99	4.06	3.50		
THIRD TEST SERIES, KEY C-2586									
1......	25	24.05	20.2	28.4	2.40	9.99	3.41	Neg.	9.24
2......	100	111.38	95.2	126.8	9.14	8.21	3.46	Neg.	6.31
3......	175	187.05	173.4	204.8	7.77	4.16	4.04	Neg.	5.11
4......	250	249.52	232.8	274.6	9.43	3.78	4.43	Neg.	5.00
5......	300	323.83	300.0	344.0	11.50	3.55	3.83	6.32	1.52
6......	350	357.63	323.3	389.0	19.05	5.33	3.44	3.92	1.76
7......	400	403.43	373.0	442.0	17.77	4.41	3.88	1.56	2.14
8......	450	457.80	431.0	502.5	18.10	3.95	3.95	2.29	1.99
9......	500	508.73	469.5	546.5	18.04	3.55	4.27		

Neg. Negligible.

Data given in table 1 for the second lot of manufacturer A's coal mine delay detonator series (key C-2469) indicate that--

1. Detonators of delay periods 1, 2, 3, and 4 show a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 4 and 5 have a Winzer index less than 3 and a significant probability of overlap.
3. Detonators of delay periods 5 and 6 show a Winzer index greater than 3 and a negligible probability of overlap.
4. Detonators of delay periods 6 and 7 exhibit low overlap probability and a Winzer index of 2.57.
5. Detonators of delay periods 7 and 8 have a Winzer index less than 3 and a relatively high probability of overlap.
6. Detonators of delay periods 8 and 9 have a Winzer index greater than 3 and a negligible probability of overlap.
7. The σ/T_a ratios range from 2.15 to 6.48 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.48 to 4.45.

Data given in table 1 for the third lot of manufacturer A's coal mine delay detonator series (key C-2552) indicate that--

1. Detonators of delay periods 1, 2, 3, and 4 show a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 4 and 5 have a Winzer index of 2.63 and low probability of overlap.
3. Detonators of delay periods 5 and 6 show a Winzer index greater than 3 and negligible probability of overlap.
4. Detonators of delay periods 6 and 7 show a Winzer index of 2.99 and very low probability of overlap.
5. Detonators of delay periods 7 and 8 show a Winzer index greater than 3 and a negligible probability of overlap.
6. Detonators of delay periods 8 and 9 show a Winzer index of 1.26 and a relatively high probability of overlap.
7. The σ/T_a ratios range from 2.04 to 16.70 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.15 to 4.45.

Figure 4 shows the spread of delay times for the three lots of manufacturer A's detonators.

Data given in table 2 for the first lot of manufacturer B's delay series (keys C-2361 and C-2372) mainly indicate that--

1. Detonators of delay periods 1 through 7 exhibit a Winzer index greater than 3, and there is a negligible probability of overlap. (There are only seven delay periods within the 500-ms time span).
2. The σ/T_a ratios range from 2.73 to 21.07 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.02 to 4.10.

Data given in table 2 for the second lot of manufacturer B's delay series (keys C-2470 and C-2475) mainly show that--

1. Detonators of delay periods 1 through 5 exhibit a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 5 and 5-1/2 show a Winzer index less than 3 and a relatively high probability of overlap.
3. Detonators of delay periods 5-1/2 and 6 show a Winzer index of 2.87 and a low probability of overlap.
4. Detonators of delay periods 6 and 6-1/2 show a Winzer index greater than 3 and a negligible probability of overlap.
5. Detonators of delay periods 6-1/2 and 7 show a Winzer index less than 3 and a relatively high probability of overlap.
6. The σ/T_a ratios range from 3.10 to 20.03 pct, and $(T_h-T_e)/\sigma$ ratios range from 2.90 to 4.62.
7. Table B-1 in appendix B lists seven delay periods and table B-2 lists nine delay periods between nominal delays of 25 and 500 ms. Introduction of two more delay periods in table B-2 increased the tendency of overlap.

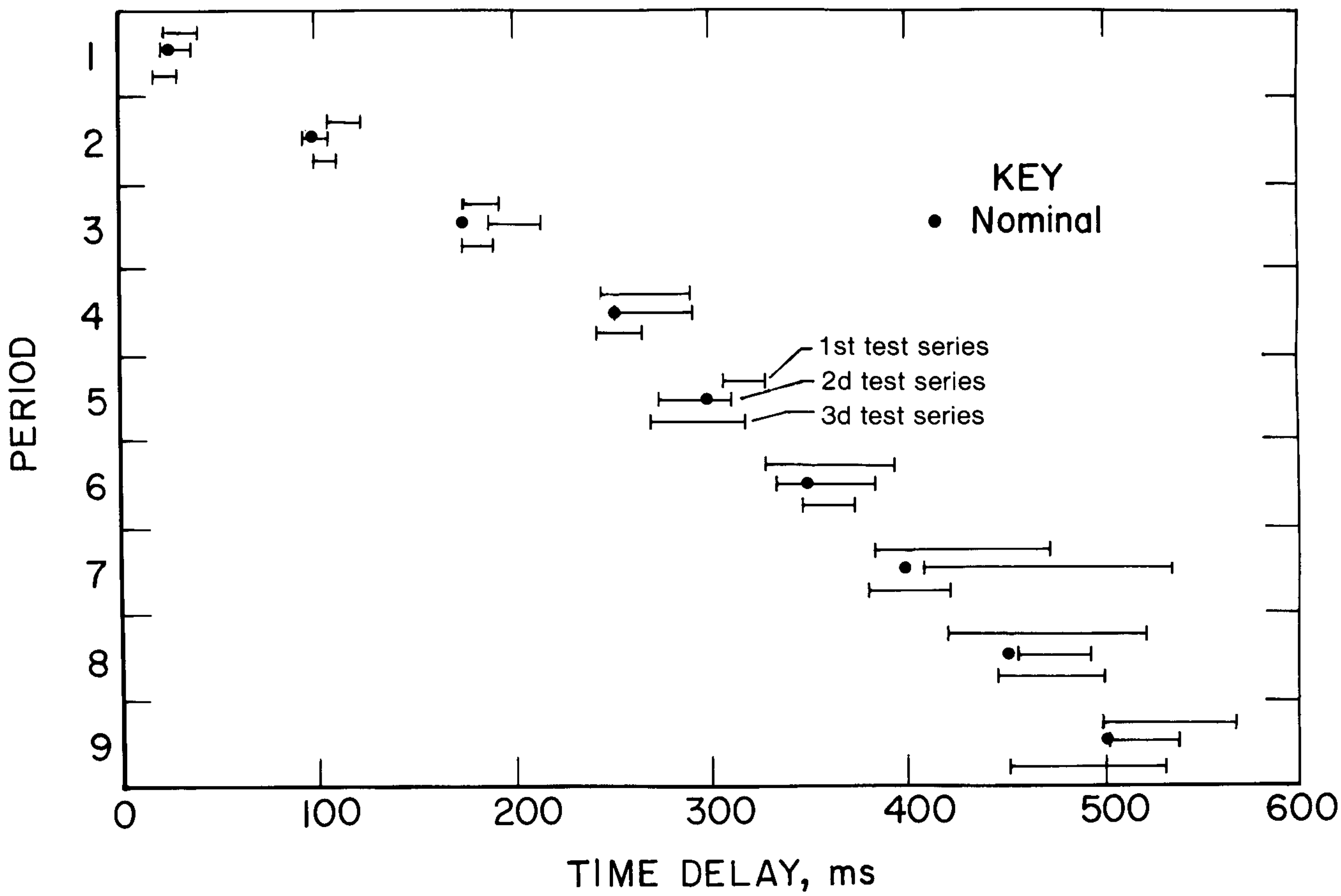

FIGURE 4. - Delay times for manufacturer A's detonators.

Data given in table 2 for the third lot of manufacturer B's delay series (key C-2575) indicate that--

1. Detonators of delay periods 1 through 5 exhibit a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 5 and 5-1/2 show a Winzer index of 2.03 and significant probability of overlap.
3. Detonators of delay periods 5-1/2 and 6 show a Winzer index greater than 3 and negligible probability of overlap.
4. Detonators of delay periods 6 and 6-1/2 show a Winzer index of 2.86 and low probability of overlap.
5. Detonators of delay periods 6-1/2 and 7 show a Winzer index of 1.17 and relatively high probability of overlap.
6. The σ/T_a ratios range from 2.66 to 19.58 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.16 to 4.79.

Figure 5 shows the spread of delay times for the three lots of manufacturer B's detonators.

Data given in table 3 for the first lot of manufacturer C's delay series (keys C-2353 and C-2375) show that--

1. Detonators of delay periods 1 through 5 have a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 5 and 6 exhibit a Winzer index of 2.90 and a low probability of overlap.
3. Detonators of delay periods 6, 7, and 8 exhibit a Winzer index of less than 3 and a significant to relatively high probability of overlap.
4. Detonators of delay periods 8 and 9 show a Winzer index of 2.95 and a low probability of overlap.

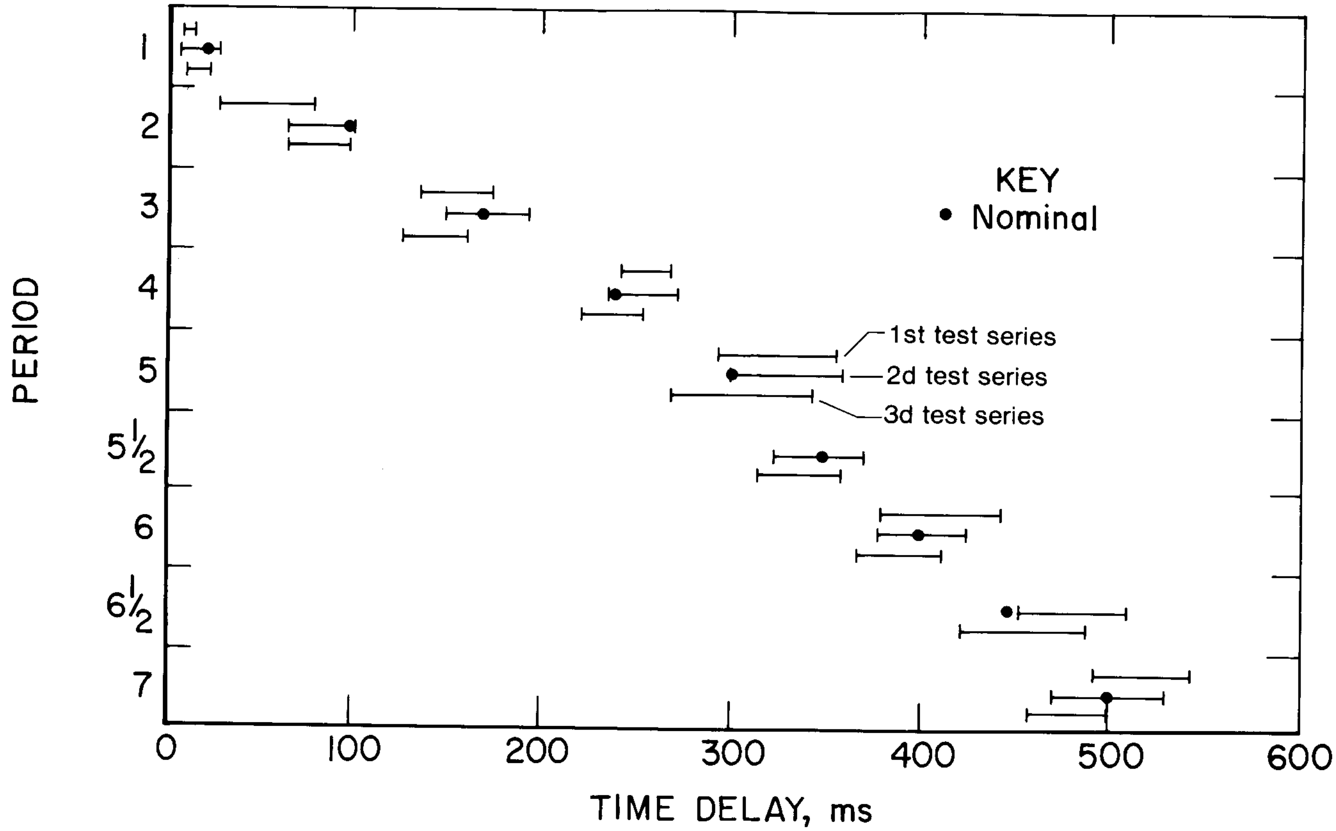

FIGURE 5. - Delay times for manufacturer B's detonators.

5. The σ/T_a ratios range from 2.59 to 24.26, and $(T_h-T_e)/\sigma$ ratios range from 3.11 to 4.74.

Data given in table 3 for the second lot of manufacturer C's delay series (key C-2473) indicate that--

1. Detonators of delay periods 1 through 4 have a Winzer index greater than 3 and a negligible probability of overlap.
2. Detonators of delay periods 4 and 5 have a Winzer index less than 3 and also exhibit a significant probability of overlap.
3. Detonators of delay periods 5 and 6 have a Winzer index greater than 3 and a negligible probability of overlap.
4. Detonators of delay periods 6 through 8 have a Winzer index less than 3 and also exhibit a significant probability of overlap.
5. Detonators of delay periods 8 and 9 show a Winzer index of 2.93 and a low probability of overlap.
6. The σ/T_a ratios range from 1.48 to 11.24 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.50 to 4.63.

Data given in table 3 for the third lot of manufacturer C's delay series (key C-2586) indicate that--

1. Detonators of delay periods 1 through 5 have a Winzer index greater than 3 and negligible probability of overlap.
2. Detonators of delay periods 5 through 9 have a Winzer index less than 3 and exhibit significant probability of overlap.
3. The σ/T_a ratios range from 3.55 to 9.99 pct, and $(T_h-T_e)/\sigma$ ratios range from 3.41 to 4.43.

Figure 6 shows the spread of delay times for three lots of manufacturer C's detonators.

Zero was used for the parameter τ in calculating the Winzer index, and delay periods were not considered to have overlapped unless a delay time for a longer

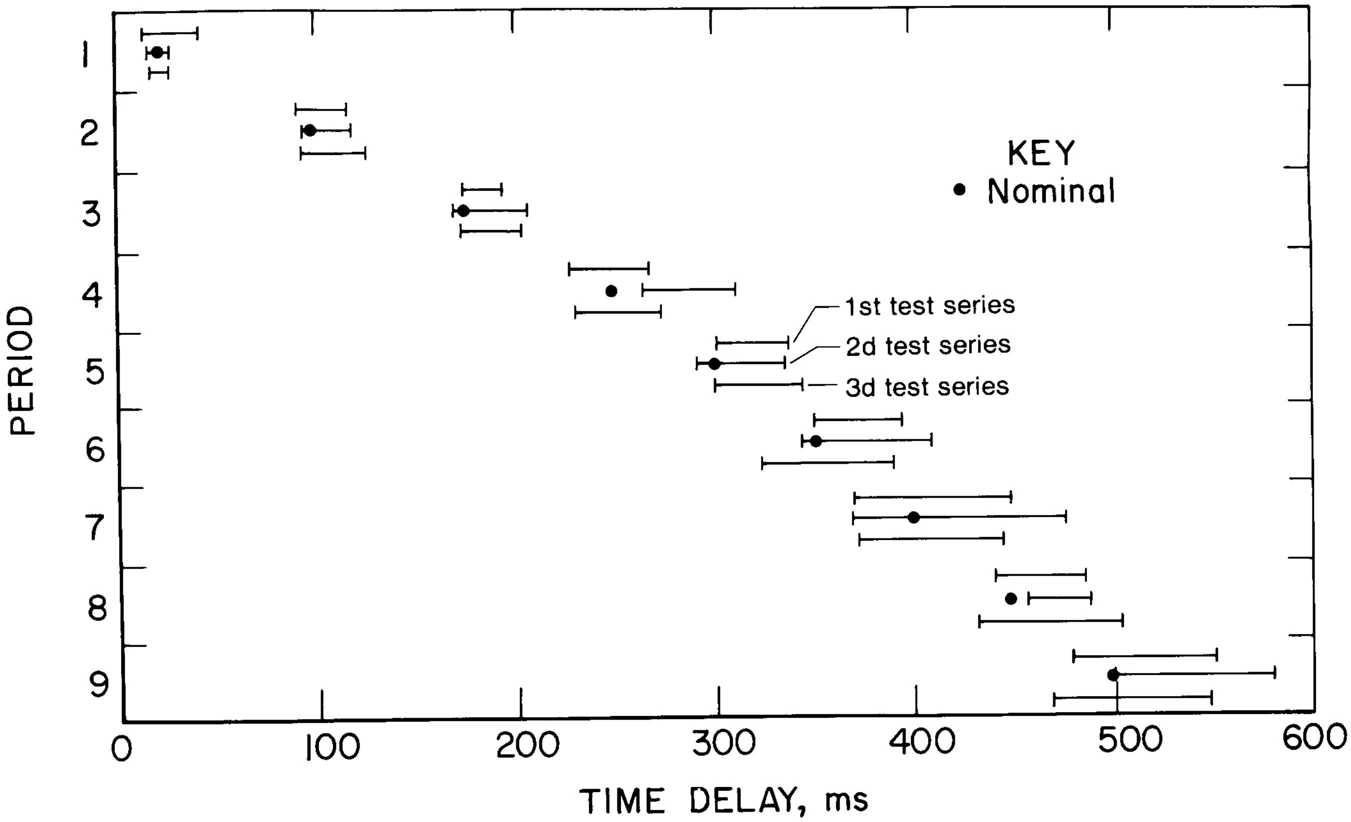

FIGURE 6. - Delay times for manufacturer C's detonators.

period detonator was actually less than that for a shorter period detonator of the same manufacturer (a criterion that is expressed as $\tau = 0$). However, it should be pointed out that this assumption is a mathematical convenience; since the "correct" value of τ is not precisely known, any finite value that it might be assumed to have would, at this point, be arbitrary, and the use of such a value in drawing conclusions would make the conclusions arbitrary as well. However, elementary calculations of the ability of explosives to significantly move the coal or rock at typical explosive-to-burden ratios indicate that appropriate values of τ are of the order of magnitude of 10 ms.

It should be observed that the results reported herein represent an attempt to survey the possibilities of overlapping time under field conditions and do not necessarily represent a critical evaluation of detonator quality control as such. Firing currents were chosen to be representative of field use conditions, which are not necessarily the same as those firing currents that will result in optimum detonator performance. In addition, the temperature at which the detonators were fired was not controlled, and since there is alleged to be a small temperature coefficient of delay time (of the order of a few tenths of a percent per degree Celsius), the reported firing times may vary somewhat from those that would be obtained under controlled temperature conditions.

The three brands of coal-mine-type delay detonators did not seem to differ greatly in delay accuracies; all showed a tendency toward overlap in the longer delay periods. Whether the overlap represents a hazard in delay blasting in underground coal mines is a difficult question requiring further study.

APPENDIX A.--DELAY TIMES FOR MANUFACTURER A'S COAL MINE DELAY DETONATORS

TABLE A-1. - Delay times for manufacturer A's coal mine delay detonators--first test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2379A	DP 2, 100-ms delay, key C-2379B	DP 3, 175-ms delay, key C-2379C	DP 4, 250-ms delay, key C-2379D	DP 5, 300-ms delay, key C-2360A	DP 6, 350-ms delay, key C-2360B	DP 7, 400-ms delay, key C-2360C	DP 8, 450-ms delay, key C-2360D	DP 9, 500-ms delay, key C-2360E
29.4	107.6	170.2	245.0	307.0	328.5	386.5	419.0	502.0
31.4	107.6	174.4	257.4	309.0	329.0	389.0	431.0	509.5
32.4	109.8	176.6	269.8	310.0	332.0	390.5	448.0	524.5
32.4	110.0	176.8	272.4	310.5	336.0	391.0	448.0	525.0
32.8	110.8	177.0	274.4	310.5	342.5	395.0	448.5	525.5
33.2	112.0	177.2	278.4	310.5	344.0	397.5	449.5	528.5
34.8	112.4	180.6	279.8	311.5	348.5	401.5	454.0	529.5
34.8	112.8	182.0	280.0	313.5	354.5	403.5	456.0	534.0
35.0	113.2	182.4	281.0	315.0	357.0	407.5	457.5	534.5
35.2	113.6	183.2	281.6	315.5	359.5	407.5	462.5	535.5
35.6	114.8	183.8	281.6	316.0	359.5	408.0	466.0	535.5
36.0	115.4	185.6	284.2	317.0	361.0	409.0	467.0	537.5
36.2	116.4	185.8	284.2	317.5	368.0	416.5	468.0	539.5
36.2	117.2	186.8	284.2	318.0	368.5	417.0	471.0	542.0
36.4	118.0	187.0	285.8	319.0	370.5	423.5	473.0	544.0
37.2	118.2	187.2	285.8	322.0	373.5	427.0	476.0	544.5
37.2	118.4	187.8	286.8	323.0	379.5	437.0	476.5	551.0
37.2	118.6	189.8	287.4	324.0	379.5	442.0	480.5	556.0
38.8	119.4	192.8	288.0	324.0	392.0	448.0	484.5	566.0
38.8	122.8	193.8	295.8	328.5	394.5	452.0	518.5	567.0

DP Delay period.

TABLE A-2. - Delay times for manufacturer A's coal mine delay detonators--second test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2469A	DP 2, 100-ms delay, key C-2469B	DP 3, 175-ms delay, key C-2469C	DP 4, 250-ms delay, key C-2469D	DP 5, 300-ms delay, key C-2469E	DP 6, 350-ms delay, key C-2469F	DP 7, 400-ms delay, key C-2469G	DP 8, 450-ms delay, key C-2469H	DP 9, 500-ms delay, key C-2469I
26.2	95.8	181.6	253.4	276.0	333.0	409.0	455.0	502.0
27.8	99.2	183.2	262.6	284.0	342.0	412.0	455.5	508.5
28.0	99.4	183.2	262.6	287.5	344.5	413.5	459.5	509.0
28.2	99.4	183.6	265.8	290.0	346.0	415.5	459.5	509.5
28.8	99.6	184.4	271.8	290.5	347.5	416.0	460.0	509.5
29.0	100.0	184.8	272.4	292.0	355.5	418.0	460.0	513.0
29.4	100.4	186.5	276.6	293.0	360.0	424.5	460.5	513.0
29.6	100.8	187.0	277.4	294.5	360.0	427.5	462.0	514.0
30.4	101.6	188.6	279.4	294.5	362.0	436.0	463.0	519.0
30.4	101.8	189.0	280.0	295.0	363.0	440.0	463.0	521.5
30.4	102.2	189.8	280.4	295.5	364.0	441.0	465.0	523.0
30.4	102.8	191.4	283.6	296.0	364.5	442.5	467.5	524.0
30.6	103.4	191.4	283.8	298.5	364.5	444.0	470.0	524.0
30.8	103.6	191.8	283.8	301.5	364.5	444.5	471.0	525.0
31.2	105.0	192.5	284.2	302.5	366.5	445.5	471.0	525.5
31.4	105.0	194.2	284.8	303.0	367.5	449.0	475.0	525.5
31.6	106.0	195.4	285.4	305.5	369.0	457.0	476.0	536.5
32.0	106.8	198.4	286.0	311.5	371.0	458.5	487.0	537.0
32.2	107.8	201.4	286.2	312.0	373.5	470.5	491.0	538.5
32.8	108.6	204.6	292.6	313.5	385.5	536.0	496.0	541.0

DP Delay period.

TABLE A-3. - Delay times for manufacturer A's coal mine delay detonators--third test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2552A	DP 2, 100-ms delay, key C-2552B	DP 3, 175-ms delay, key C-2552C	DP 4, 250-ms delay, key C-2552D	DP 5, 300-ms delay, key C-2552E	DP 6, 350-ms delay, key C-2552F	DP 7, 400-ms delay, key C-2552G	DP 8, 450-ms delay, key C-2552H	DP 9, 500-ms delay, key C-2552I
18.8	100.8	177.2	244.0	271.5	347.0	382.5	446.5	452.5
19.0	101.0	177.4	245.6	277.5	350.0	387.0	451.5	466.5
19.6	101.2	178.6	246.4	279.0	356.5	389.0	455.0	467.0
19.8	102.4	179.6	248.0	281.5	358.5	390.5	456.0	479.0
21.8	102.6	181.4	250.4	286.0	359.0	396.0	460.5	483.5
22.4	102.6	181.6	250.6	286.2	359.0	397.0	461.5	487.0
22.8	102.6	182.2	251.6	287.5	360.5	397.0	462.0	493.0
23.2	103.0	182.6	251.8	289.5	362.0	397.5	464.5	494.5
23.8	103.4	182.8	253.8	290.6	362.5	398.5	465.5	495.0
24.2	103.4	183.4	253.8	291.0	363.0	399.5	465.5	497.5
24.8	103.4	183.8	255.8	291.0	363.0	401.0	466.0	498.0
25.8	104.0	186.4	257.0	291.5	363.5	401.0	466.5	502.0
27.8	104.4	186.6	257.6	297.0	366.0	402.0	468.0	505.0
28.0	104.6	186.8	258.2	299.0	366.5	403.5	469.5	510.0
28.4	104.8	187.2	261.0	302.5	367.0	407.0	471.0	511.0
29.6	106.8	188.0	261.2	305.5	367.5	410.5	475.0	512.0
29.8	107.6	188.6	262.2	307.5	371.5	411.5	476.0	517.0
30.2	107.8	189.0	264.8	309.5	372.5	413.5	478.5	525.5
30.2	109.0	189.6	265.4	317.0	375.0	417.5	484.5	529.0
32.0	110.0	192.0	267.4	319.0	375.5	423.0	499.5	530.0

DP Delay period.

APPENDIX B.--DELAY TIMES FOR MANUFACTURER B'S COAL MINE DELAY DETONATORS

TABLE B-1. - Delay times for manufacturer B's coal mine delay detonators--first test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2372A	DP 2, 100-ms delay, key C-2372B	DP 3, 170-ms delay, key C-2372C	DP 4, 240-ms delay, key C-2372D	DP 5, 320-ms delay, key C-2361A	DP 6, 400-ms delay, key C-2361B	DP 7, 500-ms delay, key C-2361C
10.6	31.0	137.6	242.0	296.5	379.5	492.0
11.6	42.2	138.2	242.5	302.0	387.0	498.5
12.0	44.8	140.0	243.0	308.5	392.0	501.0
12.0	49.5	140.8	243.5	313.0	392.0	506.5
12.6	56.0	143.8	244.0	315.0	393.0	510.5
12.6	57.5	144.4	244.4	315.5	399.0	513.0
13.0	58.5	148.8	244.5	316.0	399.0	514.5
13.4	59.2	149.4	249.0	316.5	399.5	516.0
14.2	59.5	149.4	250.0	317.0	400.0	516.5
14.4	60.2	151.0	250.6	318.0	401.0	517.0
14.4	65.2	153.0	253.4	320.0	404.0	517.5
14.6	65.6	153.4	257.0	322.5	404.5	519.5
14.8	66.4	154.6	258.4	330.0	405.0	521.0
14.8	66.5	156.0	259.2	332.0	411.5	525.5
15.0	67.2	157.2	259.8	335.0	422.5	525.5
15.4	69.0	163.2	262.0	342.5	422.5	526.0
15.4	75.0	163.2	263.0	343.0	423.5	539.0
16.0	78.5	169.2	266.5	351.5	424.0	540.5
17.2	80.0	174.4	270.5	352.0	433.5	541.0
18.8	82.0	174.6	271.6	356.0	442.5	543.0

DP Delay period.

TABLE B-2. - Delay times for manufacturer B's coal mine delay detonators--second test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2470A	DP 2, 100-ms delay, key C-2470B	DP 3, 170-ms delay, key C-2470C	DP 4, 240-ms delay, key C-2470D	DP 5, 300-ms delay, key C-2470E	DP 5-1/2, 350-ms delay, key C-2475A	DP 6, 400-ms delay, key C-2470F	DP 6-1/2, 450-ms delay, key C-2475B	DP 7, 500-ms delay, key C-2470G
11.6	65.4	151.2	238.8	300.0	322.0	378.0	453.0	470.0
16.0	76.4	153.6	238.8	304.5	325.0	384.0	455.5	473.5
16.6	80.4	158.0	239.8	305.0	333.5	386.0	457.5	479.0
17.0	82.2	162.6	241.0	315.5	336.5	389.5	470.5	490.0
18.6	84.8	165.0	243.4	319.0	338.0	390.0	471.5	492.0
18.8	88.4	166.6	245.6	321.0	339.0	391.5	473.5	495.5
19.4	88.8	167.0	246.0	324.0	341.0	392.0	473.5	497.0
19.8	89.2	167.8	248.2	324.5	344.0	397.5	474.5	497.0
21.0	90.8	168.0	252.0	328.5	344.5	399.5	475.5	497.5
22.0	91.8	170.0	254.4	328.5	344.5	400.5	479.5	497.5
22.2	92.4	174.0	256.2	329.0	347.5	403.0	483.0	498.0
22.4	93.6	174.8	257.4	331.0	348.5	406.5	483.5	505.0
22.4	95.2	175.6	259.0	331.5	351.5	411.5	486.5	505.5
22.6	95.4	176.0	263.8	331.5	354.5	415.5	488.5	508.0
22.8	96.6	177.8	266.0	338.5	354.5	417.5	490.0	510.5
23.6	97.8	179.6	268.2	339.0	358.0	419.0	491.0	514.5
24.6	98.2	179.8	270.2	339.5	361.0	422.0	494.0	515.0
25.6	98.8	183.4	271.2	346.5	361.5	422.5	494.5	515.5
25.8	99.4	187.4	272.8	348.5	362.0	423.0	509.5	523.0
31.2	102.0	196.8	274.6	360.5	373.0	425.0	511.5	530.0

DP Delay period.

TABLE B-3. - Delay times for manufacturer B's coal mine delay detonators--third test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2575A	DP 2, 100-ms delay, key C-2575B	DP 3, 170-ms delay, key C-2575C	DP 4, 240-ms delay, key C-2575D	DP 5, 300-ms delay, key C-2575E	DP 5-1/2, 350-ms delay, key C-2575F	DP 6, 400-ms delay, key C-2575G	DP 6-1/2, 450-ms delay, key C-2575H	DP 7, 500-ms delay, key C-2575I
12.2	66.2	128.0	222.0	269.0	316.5	367.0	422.0	458.5
13.6	67.2	130.8	226.2	277.0	317.5	370.0	431.5	460.0
13.6	67.2	131.8	228.4	277.5	321.5	373.5	432.5	460.0
13.8	67.6	136.8	228.8	278.0	321.5	373.5	433.5	464.5
13.8	73.6	138.2	229.4	281.0	322.5	378.0	435.0	475.0
14.8	75.4	139.8	229.4	281.0	322.5	378.0	438.0	477.0
16.4	76.8	141.6	233.6	286.5	325.0	379.0	438.0	478.0
16.8	77.8	141.8	234.2	287.0	325.0	379.5	447.5	478.0
17.4	79.8	144.0	234.4	289.5	327.5	382.5	448.5	479.5
17.6	80.6	144.0	234.4	291.0	327.5	384.0	452.0	484.0
17.8	81.4	147.4	236.4	291.5	330.0	389.5	453.5	484.5
18.2	83.2	147.8	236.6	291.5	331.0	390.0	458.5	486.0
19.8	84.8	149.8	236.8	294.0	332.0	390.0	460.0	487.5
19.8	84.8	151.0	238.4	294.0	337.5	396.0	460.5	488.5
20.4	85.2	156.2	238.4	294.5	338.0	396.5	465.5	489.0
20.6	86.0	156.2	240.2	299.0	340.5	399.5	476.5	493.5
20.6	86.4	157.2	241.2	299.5	341.0	400.0	478.5	496.0
22.4	88.8	157.8	246.0	304.0	345.5	401.5	478.5	496.0
22.6	91.8	162.0	247.0	307.5	352.5	404.0	483.5	497.0
24.6	99.0	162.0	256.0	344.5	359.5	412.5	488.0	499.0

DP Delay period.

APPENDIX C.--DELAY TIMES FOR MANUFACTURER C'S COAL MINE DELAY DETONATORS

TABLE C-1. - Delay times for manufacturer C's coal mine delay detonators--first test series, arranged in ascending order and by designated nominal delay, millseconds

DP 1, 25-ms delay, key C-2375A	DP 2, 100-ms delay, key C-2375B	DP-3, 175-ms delay, key C-2375C	DP-4, 250-ms delay, key C-2375D	DP 5, 300-ms delay key C-2353A	DP 6, 350-ms delay, key C-2353B	DP-7, 400-ms delay, key C-2353C	DP 8, 450-ms delay, key C-2353D	DP 9, 500-ms delay, key C-2353E
17.4	93.0	175.0	228.4	299.5	349.5	371.5	439.0	477.0
18.2	93.0	176.2	230.2	304.0	350.0	373.0	442.0	502.5
19.0	94.2	177.6	232.2	308.5	350.5	374.0	447.0	503.0
20.2	99.4	179.2	239.6	309.0	351.5	376.5	448.0	505.5
20.8	100.0	180.2	240.6	311.5	353.5	379.5	451.0	510.5
20.8	100.2	182.8	242.6	312.5	356.0	380.0	455.5	512.0
21.0	101.2	183.6	244.4	313.0	361.0	384.5	456.0	513.0
21.4	104.4	184.0	245.0	313.5	363.0	385.0	457.0	515.5
21.8	105.2	184.6	246.4	316.5	363.0	385.5	457.5	517.5
22.2	106.4	184.6	246.8	317.0	365.5	386.5	460.0	518.5
22.6	107.0	186.2	248.6	321.0	366.5	389.5	460.0	519.0
22.8	107.0	187.8	249.2	322.0	369.0	392.0	460.0	523.5
23.0	107.4	188.2	250.6	323.5	370.0	403.0	461.0	526.0
23.6	108.0	189.6	252.2	324.5	371.0	408.0	463.5	529.0
24.0	108.6	190.6	252.4	326.0	372.5	414.5	464.5	531.5
24.4	108.6	191.6	259.4	328.0	373.0	429.0	473.0	533.5
25.0	111.2	192.0	260.6	329.0	373.0	433.0	474.0	534.5
28.8	113.2	192.4	263.2	330.5	377.5	433.5	475.0	536.5
28.8	117.0	195.4	264.8	335.5	388.0	435.5	476.5	537.0
44.4	117.4	196.6	268.6	338.5	394.0	448.0	484.0	551.5

DP Delay period.

TABLE C-2. - Delay times for manufacturer C's coal mine delay detonators--second test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2473A	DP 2, 100-ms delay, key C-2473B	DP 3, 175-ms delay, key C-2473C	DP 4, 250-ms delay, key C-2473D	DP 5, 300-ms delay, key C-2473E	DP 6, 350-ms delay, key C-2473F	DP 7, 400-ms delay, key C-2473G	DP 8, 450-ms delay, key C-2473H	DP 9, 500-ms delay, key C-2473I
19.4	96.8	171.8	266.6	292.5	344.0	370.5	457.0	503.0
19.6	101.0	172.2	274.6	304.5	351.0	379.0	462.5	506.5
20.2	101.4	176.6	274.8	306.5	358.5	390.0	466.5	508.5
20.4	102.0	176.6	280.6	309.5	362.0	400.0	468.0	528.5
21.0	102.0	178.6	281.2	310.0	364.0	405.5	469.0	530.0
21.4	102.2	178.8	282.0	310.5	364.5	408.5	471.0	531.0
22.0	105.0	179.0	284.2	312.0	365.0	409.5	471.0	531.5
22.4	105.2	180.2	285.0	312.0	370.0	416.0	471.5	537.0
22.4	106.8	184.4	285.8	312.5	370.0	429.5	472.5	537.0
22.4	107.6	184.6	286.8	313.5	371.5	432.0	476.0	537.5
22.4	108.0	185.4	290.2	316.0	372.0	434.5	476.0	539.0
22.6	109.0	189.8	292.0	317.5	374.0	434.5	476.0	541.0
22.6	109.6	190.8	292.8	318.0	381.5	435.5	477.0	544.5
22.6	110.2	192.0	294.2	319.5	384.5	439.0	477.0	545.0
22.8	110.6	193.6	294.8	320.5	385.0	447.5	478.5	552.5
23.6	110.8	195.2	295.4	320.5	386.5	448.0	478.5	556.5
24.4	112.6	197.2	295.5	321.5	387.5	454.5	479.0	569.0
26.0	114.4	199.4	295.6	327.0	389.5	456.5	479.0	574.5
27.4	114.6	201.6	299.6	327.0	391.0	460.5	480.5	575.0
29.8	119.4	210.4	312.0	335.5	412.0	474.5	488.5	580.0

DP Delay period.

TABLE C-3. - Delay times for manufacturer C's coal mine delay detonators--third test series, arranged in ascending order and by designated nominal delay, milliseconds

DP 1, 25-ms delay, key C-2586A	DP 2, 100-ms delay, key C-2586B	DP 3, 175-ms delay, key C-2586C	DP 4, 250-ms delay, key C-2586D	DP 5, 300-ms delay, key C-2586E	DP 6, 350-ms delay, key C-2586F	DP 7, 400-ms delay, key C-2586G	DP 8, 450-ms delay, key C-2586H	DP 9, 500-ms delay, key C-2586I
20.2	95.2	173.4	232.8	300.0	323.5	373.0	431.0	469.5
20.4	101.0	175.0	241.2	309.0	326.5	375.0	434.5	483.5
21.6	102.6	175.8	241.6	310.5	338.5	383.0	435.5	486.0
21.6	103.2	176.2	241.8	310.5	342.0	386.5	438.5	497.5
22.0	103.8	182.8	242.0	311.0	342.5	388.0	442.5	499.5
22.6	104.6	183.9	242.2	319.0	344.0	393.0	446.5	503.5
22.6	105.2	185.0	243.8	319.0	345.5	396.0	447.5	504.0
22.8	105.2	186.8	244.6	322.0	346.5	400.5	449.0	504.5
23.4	107.0	187.0	245.8	325.0	349.0	401.0	449.5	505.0
24.0	110.8	187.6	248.8	325.0	353.5	404.0	460.0	505.5
24.0	112.0	188.4	249.0	325.5	360.5	404.0	461.0	505.5
24.6	112.6	189.2	249.4	325.5	363.0	404.0	461.5	511.0
24.8	112.6	189.6	250.6	326.5	368.0	404.5	462.0	512.0
24.8	113.0	189.8	253.0	328.5	372.5	410.5	464.5	515.0
25.2	118.6	190.2	253.6	328.5	374.5	415.0	467.0	516.5
26.2	121.6	192.8	256.2	333.5	376.5	416.5	472.5	517.0
26.2	123.0	193.0	257.4	336.0	377.0	421.0	476.0	525.5
27.6	124.2	193.2	259.0	338.5	378.5	422.5	477.0	528.0
28.0	124.6	196.4	263.0	339.0	381.5	428.5	477.5	539.0
28.4	126.8	204.8	274.6	344.0	389.0	442.0	502.5	546.5

DP Delay period.

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