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Effect of Direct-Current Firing Levels on Detonator Delay Times

By Karl R. Becker and J. Edmund Hay

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Report of Investigations 8613

Effect of Direct-Current Firing Levels on Detonator Delay Times

By Karl R. Becker and J. Edmund Hay

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EFFECT OF DIRECT-CURRENT FIRING LEVELS ON DETONATOR DELAY TIMES

by

Karl R. Becker[1] and J. Edmund Hay[2]

ABSTRACT

Detonators representing a sampling of various domestic commercial delay detonators were fired at various direct-current (dc) firing levels. Results of firings using well-below-recommended firing levels showed marked increases in delay times above the nominal values. There was also a marked increase in variation, to the extent that out-of-sequence firings would be essentially assured in any typical blasting round at these low firing levels. Within the range of recommended levels the effects of current increases were not considered to be of great importance relative to other overriding effects, such as the significant difference noted in average values of detonators from different lots having the same nominal delay. This effect, when combined with the normal variation noted among members from the same lot, would cause out-of-sequence firings with detonators from a neighboring delay period.

Where comparisons with results from another study were possible, it was found that both studies observed quite similar variations in delay times about the average values, and a lower probability of out-of-sequence firings for the shorter delay period groups. The criterion of the previous study for assessing the likelihood of observing out-of-sequence firings, when applied to the Bureau of Mines data, properly identified two neighboring delay period groups where out-of-sequence firings would occur.

INTRODUCTION

The accuracy and precision of delay times for delay detonators are important factors in multiple-shot blasting from the standpoint of blasting efficiency and safety. The time interval between shothole firings can affect blasting efficiency--for example, fragmentation of the rock and muckpile characteristics--as well as safety--for example, flyrock production, air and ground vibrations, and misfires from cutoffs.

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[1] Supervisory research physicist.
[2] Research supervisor.
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Winzer[3] determined the average delay times and variations for various domestic commercial millisecond (MS) series delay detonators. He concluded that sufficient errors existed to cause problems with poor fragmentation, as well as errors that might possibly make it difficult in complying with the Federal Regulations[4] on vibration control, which specify the maximum weight of explosives that can be detonated within any 8-ms period, given the distance of the blast from the nearest buildings. While the nominal intervals between members of MS delay series are a minimum of 25 ms, Winzer[5] indicated in a second study that the probability for observing "no crowding" (time intervals of the required 8 ms or greater throughout the complete blast) was low for many typical blast designs.

The Mine Safety and Health Administration (MSHA) and the Bureau of Mines are interested in any possible effects of delay time errors on safety. Therefore, to augment this body of information, Bureau of Mines personnel performed an experiment to gain information on the effects of firing currents on the accuracy and precision of delay times. While the work was not designed specifically to repeat or verify Winzer's findings, it was felt that some of the data might serve this end as well.

BACKGROUND

Two types of power sources recommended[6] for firing electric detonators are blasting machines and power lines. Most modern blasting machines are capacitor discharge (CD) types, and, providing they are in good operating condition, their current output does not depend upon human physical factors, as do the manually operated direct-current (dc) generators (for example, the rackbar and key-twist units).

Recommendations for minimum, as well as maximum, firing currents are also supplied by the manufacturers of detonators. Typical minimum values recommendend by Atlas Powder Co.[7] for their detonators are 0.5 A dc or ac for single-cap firings and 1.5 A and 2.0 A, respectively, per series for dc and ac parallel-series arrangements in multiple-shot blasting. Ten amperes is a typical maximum recommended current, especially for parallel circuits, to prevent a condition known as arcing that can damage detonators or cause them to malfunction.

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[3]Winzer, S. R. The Firing Times of MS Delay Blasting Caps and Their Effect on Blasting Performance. Martin Marietta Laboratories, Baltimore, Md., June 12, 1978, 36 pp.

[4]U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter VII--Office of Surface Mining Reclamation and Enforcement, Dept. of the Interior; Subchapter B--Initial Program Regulations, Part 715--General Performance Standards; Sec. 715.19(e)(2)(v)--Use of Explosives--Blasting Procedures.

[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, Tex., June 4-6, 1979, 10 pp.; available from S. R. Winzer, Martin Marietta Laboratories, Baltimore, Md.

[6]Atlas Powder Co. Handbook of Electric Blasting. Dallas, Tex., rev. ed., 1976, 93 pp.

[7]Work cited in footnote 6.

Other companies make similar, but not necessarily identical, recommendations. One reason for this is that the current sensitivities of different companies' detonators are nonuniform, varying, according to unpublished Bureau of Mines data, by a factor greater than 2.0. The companies fully recognize this and account for these differences in their recommendations for minimum firing levels and/or recommended design of the blasting circuit (given the total number of rounds). However, this nonuniformity represents, at least, a complication in the arrangement of detonators in the blasting circuit as well as a complication in the use of, or design of, new accessories for determining the condition of the blasting circuit for safe blasting.

EXPERIMENTAL PROCEDURES AND TECHNIQUES

The various current inputs applied to the detonators in this series of tests were currents in the range 0.5 to 0.7 A dc--well below recommended firing levels for multishot blasting circuits; 1.0 A dc; 3.0 A dc; and discharges from a 20-shot permissible blasting machine (Femco model SF-25-20)[8] using two different load values to yield peak currents of about 2.4 and 5.8 A.

The steady state dc firing levels were supplied by a Hewlett-Packard regulated power supply (model 6271B), and the firing levels were verified by using a digital ammeter. The condition of the blasting machine was checked once each day by using the REO BT-300 blasting machine tester, and also by oscilloscopic records of current profiles. The peak current values of 2.4 and 5.8 A were calculated using Ohm's law; however, these values were substantiated by the current profile records to within ±0.2 A.

The following delay detonators were surveyed:

1. Periods 1-6 of the Du Pont coal mine delay series, with nominal delay times of 25, 100, 175, 250, 325, and 400 ms.

2. Three nonconsecutive members (periods 1, 5, and 11) of the Hercules Superdet delay series, having respective delays of 0.9, 3.7, and 10.0 sec.

3. Five members of the Atlas Rockmaster delay series (periods 1, 5, 15, 20, and 36), having respective delays of 8, 100, 500, 1,000, and 3,000 ms.

The detonators tested were all recently purchased and were fired in the temperature range of about 15.5° to 21° C (60° to 70° F).

The technique used for obtaining the delay time measurements was simple, but time consuming. The detonators were fired one at a time using an ionization probe (twisted pair) attached to the base charge end of the detonator to sense the time of explosion. The probe consisted simply of two short lengths (6 to 8 in) of 28 AWG enameled copper twisted together in tight turns for a distance of 1 inch or less. These probes, properly made and attached to the detonator, previously had been found to respond without detectable error for

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[8]Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

measurements on a MS time scale. Upon explosion, these enameled insulated wires short out and discharge a capacitor, yielding a pulse for the measurement.

For a test, the detonator, with probe attached, was placed on top of a 1-5/8-inch-thick pine board. A similar board, weighted with a 4- by 4- by 1-inch-thick steel plate, was placed on top of the detonator. The particular current pulse that initiated the detonator was also used to trigger the sweep of an oscilloscope. The rise times of these pulses were, at worst, about 0.1 ms. Upon explosion of the base charge, the ionization probe shorted out, discharging a capacitor in a resistance-capacitance circuit whose output signal, in turn, was used to trigger a pulse generator whose output signal, in turn, was applied to the input of the scope. The pulse generator was used to provide a pulse of suitable duration for the sweep time used.

One major source of error in the measurements is from scaling distances on the oscillograms from sweep calibrations and delay-time measurements. With care and using a magnifying lens as well as a finely divided ruler, these errors are believed to have been kept within ±2 pct. Another possible source of error is from variations in temperature. While these trials were performed indoors in a heated room kept at about 19° C (≅66° F), it was found necessary, for fume abatement, to assist the exhaust system occasionally by opening a door to the outside, which reduced the temperature to 15° C (59° F). The detonators, however, were not stored in this room; they were stored in another room at a temperature of about 20° C and brought in individually just prior to the tests. But it is possible to conceive of an occasional error of about 3 pct, based on Winzer's data on temperature effects.

RESULTS AND DISCUSSION

Results of delay time measurements for Du Pont, Hercules, and Atlas delay series detonators are presented in tables 1, 3, and 4, respectively. Note that the data for the Du Pont detonators are for six consecutive (adjacent) members of the delay series having a constant delay interval of 75 ms. As such, more information may be obtained for the Du Pont detonators than for the Hercules and Atlas detonators, where isolated, nonconsecutive delay periods were chosen essentially as a "spot check."

The initial objective was to observe the effect of firing levels, or any other effects that might present themselves, on delay times and to determine if differences noted were statistically significant and had possible adverse effects on blasting. A secondary objective was to compare, where possible, aspects of these data with those from Winzer's studies.

Du Pont Detonators

The data in table 1 for the Du Pont detonators exhibit several fairly consistent features. In all cases the major effects of firing level on variation (standard deviation or spread), as well as the largest increases in delay times over those listed as nominal, are at the lower firing levels, especially at levels below the manufacturer's recommendations. In all but a few cases the average measured delay times exceeded the nominal values; this was less significant, generally, as the current was increased for each group.

TABLE 1. - Delay time measurements for Du Pont coal mine delay series detonators, ms

Firing current, A	Nominal delay	Average[1] delay	High value	Low value	S[2]
0.57-0.64 dc.....	25	[3]>268	>500	178	>126
1.0 dc...........	25	46.2	50.8	42.4	2.4
2.4 peak[4]........	25	39.3	52.2	30.3	6.5
3.0 dc...........	25	39.4	44.2	33.6	3.4
5.8 peak.........	25	32.9	37.6	26.8	3.8
1.0 dc...........	100	125.2	131.7	120.2	6.1
2.4 peak.........	100	109.7	113.3	106.2	2.3
5.8 peak.........	100	98.9	104.5	93.0	3.4
1.0 dc...........	175	208.6	219.5	187.6	10.4
2.4 peak.........	175	187.0	194.0	167.3	7.6
3.0 dc...........	175	192.4	198.2	189.0	3.0
5.8 peak.........	175	173.0	188.6	163.2	8.7
1.0 dc...........	250	251.7	264.2	234.6	10.0
2.4 peak.........	250	249.9	275.3	205.9	17.7
5.8 peak.........	250	248.7	273.4	227.8	15.3
0.7 dc...........	325	[5]427.6	463.0	330.9	44.6
1.0 dc...........	325	367.2	400.4	296.1	27.4
2.4 peak.........	325	371.8	395.9	335.5	22.4
5.8 peak.........	325	367.9	383.3	345.1	13.1
1.0 dc...........	400	423.6	449.9	381.6	22.6
2.4 peak.........	400	422.9	453.4	380.4	20.2
3.0 dc...........	400	414.0	437.4	380.9	20.1
5.8 peak.........	400	408.6	437.0	380.4	15.4

[1]Average of 10 trials unless noted otherwise.
[2]S = estimate of standard deviation of individual observations.
[3]6 trials.
[4]Peak indicates peak current using a CD type blasting machine.
[5]9 trials.

For example, for the nominal 25-ms detonators the average delay time was >268 ms when fired at 0.57 to 0.64 A; it dropped sharply to 46 ms, still almost double the nominal value, when fired at 1.0 A, and was still higher than the nominal value--at 32 to 39 ms--when fired at the recommended levels. A similar, but not so marked, result was obtained for the nominal 325-ms detonators. Average delay time was 427.6 ms when fired at 0.7 A dc (below the minimum recommended level) but was about 370 ms when fired at all the recommended levels, showing no further effect of current, though highly inaccurate (above the nominal value).

While some of the firing levels selected are well below those recommended by Du Pont, these levels were chosen to show what may occur if, for example, a faulty blasting machine is used.

While in most cases average delay times decreased as current levels were increased from 1.0 A dc to the 5.8-A peak (capacitor discharge), results of statistical tests for equivalence of averages indicated that the only statistically significant differences justified were among the nominal 25-, 100-, and 175-ms detonators. This means that any effect of current at recommended firing levels for the shorter delay periods should affect only the zero time of the blast, provided the effect translates all delay values equally without sufficient increase in variability. (Further discussion on blasting effects is presented later.)

In addition, although the greatest amount of variation (standard deviation) was for the 25- and 325-ms detonators fired at current levels below 1.0 A, there is only a weak tendency, not a strong, consistent trend, towards less variation at firing currents in the range of recommended levels. (This is also discussed later in more detail.)

The inaccuracy of the nominal 325-ms detonators is not due solely to the effects of firing levels. This group of detonators produced average delay times about 45 ms above the nominal value (when fired at recommended levels), hence it crowded the nominal 400-ms delay time set of firings to the extent that some of the nominal 325-ms detonators exhibited longer delay times than some of the nominal 400-ms detonators. (See table 1 data for 1.0, 2.4, and 5.8 A for each set.) There are other examples that are not reflected in the table (since the table shows only the highest, lowest, and average values), such that 10 firings of the nominal 325-ms detonators had delay times longer than some of the firings of the 400-ms detonators, with eight of these occurring at 2.4 and 5.8 A. These out-of-order firings occurred despite a nominal interval of 75 ms, but since the detonators in this range studied by Winzer[9] had a nominal interval of only 50 ms (350 ms and 400 ms), it would still intuitively appear that his conclusion--that there is only a low probability of observing "no crowding" or out-of-sequence firing--is valid.

We tested this concept further by firing a separate group of nominal 325-ms detonators (having a different Du Pont lot designation on the carton) together with repeat firings of the detonators used in our first series of tests. Results (table 2) clearly showed marked differences between the two lots of 325-ms detonators. The average delay times were only about 320 ms for the new set (Du Pont lot 14Ju79-21152) but again were about 370 ms for the lot previously tested (Du Pont lot 21Ap78-3107). Sufficient crosschecks were made in the test sequence and current levels so as to demonstrate that this was indeed an effect of lot differences rather than of current level or firing date. The effect shown in table 2 is of sufficient magnitude to affect blasting.

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[9]Work cited in footnote 5.

TABLE 2. - Comparison of average delay times and standard deviations obtained from two different lots of Du Pont coal mine 325-ms detonators

Detonator identification		2.4-A peak		5.8-A peak	
Bureau key No.	Du Pont No.	Average delay, ms	S, ms	Average delay, ms	S, ms
C-2147E..............	21AP78-3107........	[1]371.8	22.4	[2]367.9	13.1
C-2126...............	14Ju79-21152.......	[3]320.2	18.0	[1]321.4	14.9

[1]Fired on Dec. 29, 1980.
[2]Fired on Mar. 19, 1980.
[3]Fired on Dec. 9, 1980.

Hercules Detonators

Data from the Hercules Superdet trials (table 3) show no statistically significant differences in average values for firing levels ranging from 1.0 A dc to the 5.8-A peak current pulse applied from the blasting machine. However, at much-below-recommended firing levels (0.30 to 0.35 A dc) for the nominal 3.7-sec detonator, the average delay time was about 4.63 sec, markedly higher than actual delay times of about 3.8 sec at all recommended levels. Hercules detonators had previously been found to have maximum no-fire currents ranging from 0.240 to 0.260 A, about half that of the Du Pont detonators; hence, lower currents were applied in these tests to demonstrate this effect.

TABLE 3. - Delay time measurements for Hercules Superdet delay series detonators, sec

Firing current, A	Nominal delay	Average[1] delay	High value	Low value	S[2]
1.0 dc............	0.9	1.08	1.23	1.01	0.065
2.4 peak[3].........	.9	1.13	1.32	1.01	.079
5.8 peak..........	.9	1.10	1.38	1.01	.105
0.30-0.35 dc......	3.7	[4]4.63	6.45	3.81	1.23
1.0 dc............	3.7	3.79	3.99	3.67	.102
2.4 peak..........	3.7	3.77	3.88	3.63	.096
3.0 dc............	3.7	3.76	3.90	3.65	.089
5.8 peak..........	3.7	3.80	3.93	3.64	.102
1.0 dc............	10.0	9.89	10.14	9.49	.22
2.4 peak..........	10.0	9.86	10.04	9.68	.13
5.8 peak..........	10.0	9.70	10.16	8.04	.64

[1]Average of 10 trials unless noted otherwise.
[2]S is estimate of standard deviation of individual observations.
[3]Peak indicates peak current using a CD type blasting machine.
[4]Average of 4 trials.

On a MS time scale, the average values here can be expected to, and do depart more, from the nominal values than was the case for the Du Pont detonators; but the departures on a percentage basis are generally less. Hence, the accuracy here is at least as good as for the Du Pont detonators. Comments on precision are given later.

Atlas Detonators

Results from the Atlas Rockmaster trials (table 4) also exhibit no significant differences in average firing times, except at current levels of 1.0 A dc or less. Here again, at marginal current levels (0.35 to 0.40 A dc), the measured delay times were (for two trials) in excess of 500 ms for the nominal 100-ms delay detonators. At 0.5 A dc for the same group of detonators the average value (for four trials) was 136.1 ms, and variation was also much higher than normal. At higher current levels the delay times averaged about 102 ms, very close to the nominal value. Maximum no-fire currents, previously observed for Atlas Rockmaster detonators, are about 0.330 A.

TABLE 4. - Delay time measurements for Atlas Rockmaster MS delay series detonators, ms

Firing current, A	Nominal delay	Average[1] delay	High value	Low value	S[2]
1.0 dc	8	12.4	14.7	10.3	1.4
2.4 peak[3]	8	7.4	8.8	5.2	1.2
5.8 peak	8	7.9	9.5	6.0	1.3
0.35-0.40 dc	100	[4]>500	-	-	-
0.50 dc	100	[5]136.1	154.1	119.8	14.7
1.0 dc	100	102.9	107.7	97.8	4.5
2.4 peak	100	102.5	107.6	95.5	4.0
5.8 peak	100	101.1	109.7	90.8	6.0
1.0 dc	500	518.8	538.4	496.7	12.7
2.4 peak	500	520.6	541.8	487.1	10.8
5.8 peak	500	519.8	541.7	496.5	13.4
5.8 peak	1,000	1,030	1,060	1,000	23
1.0 dc	3,000	3,110	3,190	3,030	60
2.4 peak	3,000	3,110	3,180	3,050	52
5.8 peak	3,000	3,100	3,140	3,040	33

[1]Average of 10 trials unless noted otherwise.
[2]S is estimate of standard deviation of individual observations.
[3]Peak indicates peak current using a CD type blasting machine.
[4]Average of 2 trials.
[5]Average of 4 trials.

Relative Precision of Data

To gain some perspective on the relative precision of these three brands of detonators, table 5 shows ratios of the standard deviations to corresponding average values for the various sets of data. Each $S/\bar{t} \times 100$ value is the standard deviation expressed in terms of percentage of average value. These data indicate that:

1. Significantly poorer precision in delay times is observed at current levels below 1.0 A for all three brands of delay detonators. These

trials were for demonstration purposes only, and the $S/\bar{t}$ × 100 value of 26.5 obtained for the Hercules detonators should not be construed as indicating that Hercules detonators are less precise below 1.0 A than the other brands; this high value was obtained because these detonators were fired closer to their minimum firing currents than the one example each shown for Du Pont and Atlas detonators.

2. No significant, consistent effect of current input on precision is found in the recommended ranges; however, the lowest delay period tested in each company's delay series exhibited poorer precision than its higher delay period counterparts.

3. When these percentages (ratios) for each company's detonators are averaged over all firing levels and delay periods, grand average values of 5.8, 4.5, and 5.5 are obtained, respectively, for Du Pont, Hercules, and Atlas detonators. This is not interpreted as a significant difference among the various companies' detonators.

TABLE 5. - Comparison of $S/\bar{t}$[1] values among Du Pont, Hercules, and Atlas detonators

Nominal delay, ms	$S/\bar{t}$ × 100			
	Below 1 A	1 A dc	2.4-A peak	5.8-A Peak
Du Pont detonators:				
25	NT	5.2	16.5	11.5
100	NT	4.9	2.0	3.4
175	NT	5.0	4.1	5.0
250	NT	4.0	7.1	6.1
325	[2]10.4	7.5	6.0	3.6
400	NT	5.3	4.8	3.6
Average[3]	-	5.3	6.7	5.5
Hercules detonators:				
900	NT	6.0	7.0	9.5
3,700	[2]26.5	2.7	2.5	2.7
10,000	NT	2.2	1.3	6.6
Average[4]	-	3.6	3.6	6.3
Atlas detonators:				
8	NT	11.3	16.2	16.4
100	[2]10.8	4.4	3.9	5.9
500	NT	2.4	2.1	2.6
1,000	NT	-	-	2.1
3,000	NT	1.9	1.7	1.1
Average[5]	-	5.0	6.0	5.6

NT No trace.
[1]S = estimate of standard deviation; $\bar{t}$ = average delay time.
[2]These values were omitted in calculating the grand averages.
[3]Grand average 5.8.
[4]Grand average 4.5.
[5]Grand average 5.5.

Table 6 is a similar comparison, except between the Bureau's and Winzer's data where comparisons for the same nominal delay times were available. Winzer's data were from Du Pont's MS delay series detonators, whereas the Bureau study used Du Pont's coal mine delays; however, where nominal delay times are the same, both detonators use the same inner geometry and explosive train. Both establishments used the same designation Atlas delay series (Atlas Rockmaster MS series) detonators. For the Hercules trials, the Bureau used the Superdet delay series detonators while Winzer used the Millidet series; it is assumed that the detonator's geometry and explosive trains were identical for the one available comparison for the 900-ms detonators.

TABLE 6. - Comparison of $S/\bar{t}$[1] values between Bureau of Mines and Winzer's detonator trials

Nominal delay, ms	$S/\bar{t} \times 100$		
	BuMines data (n=10)		Winzer's data, current unknown
	2.4 A	5.8 A	
Du Pont detonators:			
25	16.5	11.5	15.8
100	2.0	3.4	5.0
175	4.1	5.0	3.1
250	7.1	6.1	3.4
400	4.8	3.6	4.6
Average	6.9	5.9	6.4
Hercules detonators:			
900	6.0	9.5	9.6
Atlas detonators:			
8	16.2	16.4	24.5
100	3.9	5.9	5.1
500	2.1	2.6	4.0
Average	7.4	8.3	11.2

[1] S = estimate of standard deviation; $\bar{t}$ = average daily time.

While one might interpret a lower variation for the Bureau's data for Atlas detonators, the comparison in table 6 exhibits remarkable agreement in individual and especially in average values, particularly for the more numerous data for Du Pont detonators. Thus, the distribution of individual values about the mean (variation) is taken to be the same for both sets of data.

Crowding

Despite the observed tendency for lower $S/\bar{t} \times 100$ values as the delay period increases, this should not be taken as an indication of less of a tendency for out-of-sequence firings for the longer delay periods, because the absolute magnitudes of departures from the mean value have a bearing on "crowding" as well. This is clarified better in the following paragraphs.

Winzer[10] found a critical parameter arising out of an analytical solution for probability of success to be

$$\frac{\bar{t}_{n+1} - \bar{t}_n - \tau}{[S_n^2 + S_{n+1}^2]^{1/2}}$$

The various quantities cited are identified in table 7. This parameter appears in the probability equations, and the term "success" can be defined as essentially a 100-pct probability that "no crowding" of given magnitude (for example, intervals of less than 8 ms, or out-of-order firings) will occur for a given set of different delay detonators used in a blasting round. To assure high probability of success for many typical blasting rounds, the value of this critical parameter should be at least 3.0.

TABLE 7. - Winzer's crowding criterion applied to Bureau of Mines data for Du Pont detonators

Nominal delay interval, ms	Winzer's index[1]		
	1.0 A dc	2.4-A peak	5.8-A peak
25-100	22.8	18.0	23.8
100-175	11.6	16.6	14.3
175-250	4.0	3.9	6.5
250-325	5.0	6.4	9.5
325-400	2.1	1.2	1.9

[1] $\frac{\left(\bar{t}_{n+1} - \bar{t}_n\right) - (\tau)}{\left(S_{n+1}^2 + S_n^2\right)^{1/2}} \gtrsim 3$ for high probability of success for observing no crowding or out-of-sequence errors.

NOTES.--(1) $\bar{t}_{n+1}$ and $\bar{t}_n$ are average delay times for period n+1 and period n detonators, respectively.

(2) τ is highest delay time value observed among period n detonators minus lowest delay time value observed among period n + 1 detonators.

(3) S_{n+1} and S_n are estimates of the population standard deviations of individual observations.

While other, more simplified parameters (or indices) can be constructed to indicate relative crowding tendencies, the parameter given above does contain all the essential elements (see table 7) that have a bearing on crowding, all normalized by the standard deviation, so that not too much weight is placed on high and low values.

[10] Work cited in footnote 5.

Note that the quantity $(\bar{t}_{n+1} - \bar{t}_n) - (\tau)$ would equal twice the nominal interval if all detonators in the two delay period groups exploded at their exact nominal values. While greater values for this expression would indicate an even greater departure from crowding for these two delay groups, it might not be desirable in the sense that a very high $\bar{t}_{n+1}$ might cause crowding difficulties between the n+1 and n+2 delay period groups.

Table 7 shows this parameter applied to Bureau of Mines data for Du Pont detonators. The table gives index values for each pair of adjacent delay period groups at several current firing levels. These data can be summarized as follows:

1. No consistent trend is observed, indicating less crowding tendency as current levels were increased from 1.0 to 5.8 amp.

2. The tendency for crowding increases substantially as the delay period increases.

3. Using the criterion that these values should be 3 or greater for high probability of success, the only indices less than 3 were the three values (at three current levels) for the nominal 325- to 400-ms sets, and as mentioned earlier these were the data sets for which 10 examples of out-of-order firings were observed.

Hence, while the exact value of the criterion of 3 or greater may be questioned, this criterion served very well to indicate problems in this case.

Had the nominal delay interval been only 25 ms between the nominal 175-ms detonator used in this study and the next highest delay period, as was the case in Winzer's study using the MS series detonators, then one could, assuming everying else being equal, conceive of possible serious crowding problems between 175- and 200-ms detonators. The index values would be one-third those obtained in table 7 (because the interval would be one-third as great), and the resulting values (of only 1.3, 1.3, and 2.2) would indicate a low probability for no out-of-sequence firings. It should, however, be pointed out that, while the criterion does appear to serve as a good indicator of possible crowding problems, the conclusions here are restricted to the case where 10 each of the nominal 325- and 400-ms detonators are used, and one cannot indiscriminately apply these conclusions to any or all blasting round designs containing a lesser number of these detonators.

In addition, while there were fewer indications of serious crowding in this study because the nominal interval was 75 ms, these data do essentially substantiate the results from the Winzer study in that serious crowding problems appear to exist, and they are more likely to be observed for detonators having longer delay periods.

SUMMARY AND CONCLUSIONS

The effect of inadvertently applying to detonators levels of firing current that are well below recommended levels would be to increase the average

delay times markedly above the nominal value, and more importantly, to increase the variation between members of the same nominal group to a point where out-of-sequence firings would be rampant. The consequences of this on efficient and safe blasting could be quite serious. The results of this study clearly demonstrated the importance of blasting circuit arrangements and circuit resistance measurements of sufficient accuracy to assure recommended current levels. In addition, it must be assured that firing sources, for example, blasting machines, be in peak operation condition to guarantee proper current levels.

Though average delay times and variations thereof tended to increase as the current was decreased, within recommended levels, the effect was not believed to represent a cause for concern relative to overriding effects observed; that is, a lack of precision that, when combined with lot-to-lot differences in accuracy, would result in out-of-sequence firings with detonators from an adjacent period.

Where comparisons were possible, it was observed that variations about average values in this study were quite similar to those observed in another study conducted by Winzer, providing a basis for greater confidence for substantiating one another's observations where they appear similar. Among these were that the likelihood for observing out-of-sequence firing was less for detonators in the lower end of the millisecond range. Since out-of-sequence firings were observed in this study for detonators having a nominal interval of 75 ms, it appears reasonable to concur that Winzer is correct in the conclusion (based upon MS delay series detonators having some delay intervals of only 50 and 25 ms) that the probability of success (no crowding to less than an 8-ms separation) for some typical blasts is low.

Most of the conclusions given were based on Bureau of Mines results with Du Pont detonators. Although data from Hercules and Atlas detonators were much more restricted, it would appear that the observations made for Du Pont detonators would apply to them as well, since variations observed were generally similar.

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