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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	ms	millisecond
ft	foot	μF	microfarad
g	gram	μs	microsecond
in	inch	Pa	pascal
J	joule	pct	percent
kV	kilovolt	pF	picofarad
mA	milliampere	s	second
mJ	millijoule	V	volt

ELECTROSTATIC SENSITIVITY, STRENGTH, AND NO-FIRE CURRENT OF SHORT-DELAY DETONATORS

By T. S. Bajpayee,[1] R. J. Mainiero,[2] and J. E. Hay[3]

ABSTRACT

The Bureau of Mines evaluated short-delay coal mine detonators manufactured by three domestic companies for electrostatic sensitivity, strength, and no-fire current level. Electrostatic sensitivity was studied in pin-to-pin and pin-to-case modes employing 10-kV potential. Strength of detonation was measured in the Bureau's underwater test facility. No-fire current was measured using a constant-current power supply unit. Test procedures and experimental data are included.

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INTRODUCTION

Data about safety characteristics of short-delay detonators are essential for safe blasting practices in underground coal mines. These characteristics are broadly classified in three groups:

1. Pyrotechnic characteristics such as accuracy of delays, absence of crowding and out of sequence firing, incendivity, thermal sensitivity, and strength of detonation.
2. Electrical characteristics such as ohmic resistance of the bridge wire and leg wires, safe firing current level and duration, sensitivity to stray currents and static electricity, and suitability for multiple blasting.
3. Mechanical characteristics such as impact sensitivity, resistance to traction of leg wires, waterproofness, and resistance to abrasion of leg wires.

The Bureau of Mines has been studying these characteristics under its Development of Safer Blasting Procedures and Improved Explosive Hazard Control Techniques program. This paper reports the results of a study of electrostatic sensitivity, strength of detonation, and maximum no-fire current for three brands of short-delay electric detonators typically used in underground coal mines.

ELECTROSTATIC SENSITIVITY

The potential danger of initiation of an electric detonator by electrostatic discharge is an ever-present problem in mines. An electrostatic charge is generated when two materials of different dielectric values move against each other. The quantity of charge generated depends on the degree of contact, freedom of electron movement, atomic structure of the materials, shape and size of the moving bodies, and other physical parameters.

The general sequence of events leading to initiation of a short-delay detonator by electrostatic charge is--

1. Generation of an electrostatic charge.
2. Transfer of charge to a suitable capacitor.
3. Accumulation of charge on the capacitor.
4. Transfer of adequate discharge energy to the detonator in pin-to-pin (P-P) or pin-to-case (P-C) mode from the capacitor.

During the last few decades, the Bureau has conducted extensive studies on the electrostatic sensitivity of detonators. A standard test setup for conducting electrostatic tests was developed. The unit is capable of delivering an electrostatic pulse at various energy levels up to 112.5 J at 30 kV. This setup is known to give reproducible results.

For testing short-delay electric detonators, capacitors are charged to a potential of 10 kV and subsequently discharged through the detonator to determine the energy values at threshold initiation level (TIL), the maximum energy level that would cause no initiations in five trials. In earlier work conducted by the Bureau with a broad spectrum of commercial detonators, TIL values ranged from 16 mJ to 350 mJ in P-P mode, and 36 mJ to 12.5 J in P-C mode. The energies referred to are stored energy in the capacitor. Commercial detonators provide antistatic protection and, in general, are less sensitive to electrostatic initiation in P-C mode than in P-P mode.

STRENGTH OF DETONATION

The effectiveness of a detonator in initiating an explosive charge depends primarily on the detonation energy of the base charge. The pressure in the shock front ahead of the reaction zone is considered as detonation pressure. It is difficult to measure detonation pressure directly, owing to its transient nature and exceedingly high magnitude. According to Fedroff (1),[4] the detonation pressure can be computed as the product of the density, detonation velocity, and particle velocity of any explosive

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[4] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

material. For the base charge of a detonator, the particle velocity is about 25 pct of its detonation velocity. Approximate values of detonation pressure are generally computed from the density and detonation velocity of the base charge.

For effective initiation, the detonation pressure of the base charge should exceed the shock initiation pressure of the main explosive charge. A low detonation pressure may cause a low order of detonation reaction in the main explosive charge. The base charge of a detonator must have sufficient energy to initiate the detonation reaction in the main explosive charge and support it until the reaction becomes self-sustaining. The available energy of a detonator is a function of its mass, energy density, and other physical constraints.

There are various ways of determining the energy of a detonator. The underwater method (2) was used because it is equally applicable to explosives and detonators. The energy of the detonator during an underwater test is released as shock wave energy (shock energy) and also as energy expended by the gases in the reaction products, as they expand and perform mechanical work (bubble energy).

Shock Energy

When an explosive is detonated underwater, the shock produced by the detonation front is transmitted to the surrounding water as a pressure discontinuity followed by an exponential pressure decay. The pressure front moves radially outward as a shock wave in the water until its velocity decays to the sonic value. The shock energy of the detonator, Es, is defined as the integral of pressure, P, over the duration, t, of the shock pulse:

$$Es = \int P^2 \, dt. \qquad (1)$$

The limits of integration should be sufficiently wide to capture the entire shock front signature. The lower limit of integration typically starts from the beginning of the shock pulse. The shock front signature is generally manifested within 10 θ, where θ is the decay constant. The upper limit of integration seldom exceeds 10 θ, and in most cases integrating beyond 6 θ does not improve energy computation. The pressure signature is reduced to digital data, which are then squared and integrated to a time equal to 6 θ to obtain the shock energy. A computer program was developed to read the data from the oscilloscope, derive the equations for the exponential decay curve, and compute the shock energy relative to that of the standard detonator.

The shock energy of the sample detonator relative to that of a standard detonator, such as Hercules J2,[5] is defined as the ratio of Es (sample) to Es (J2) in the shock front. This is also termed "specific shock energy."

Hercules J2 was selected as a standard detonator for its consistency in strength and wide acceptance as a military standard. However, any other standard detonator may be selected.

Bubble Energy

On underwater detonation, an expanding gas bubble composed of reaction products under high pressure follows the shock wave. According to Cole (3), at first this gas bubble expands at a velocity in excess of that predicted by the internal bubble pressure, owing to the afterflow characteristics of the spherical wave. When the pressure in the bubble reaches hydrostatic equilibrium, the radius continues to expand because of the inertia of the moving water. Later, as the gas pressure falls below the equilibrium pressure (hydrostatic plus barometric pressures), the bubble radius begins to decrease, and this collapse continues until the rapidly increasing pressure of the gases in the bubble acts abruptly to reverse the water motion. As this process continues, the result is a series of pressure pulses. The time elapsing between the initial pressure peak and the

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[5] Reference to a specific product does not imply endorsement by the Bureau of Mines.

second, arising from the collapse of the gas bubble, is referred to as the bubble period. This period is related to the internal energy of the gas and the equilibrium pressure and is proportional to the cube root of the energy and the inverse five-sixths power of the pressure (3). For any given type of explosive, the bubble period, T, is

$$T = K \frac{Eg^{1/3}}{P_0^{5/6}}, \tag{2}$$

where T = bubble period, s,

Eg = bubble energy, J, and is a function of the charge weight, g,

P_0 = the equilibrium pressure (hydrostatic plus barometric), Pa,

and K = a proportionality constant.

From equation 2 it is evident that bubble energy is proportional to the cube of bubble period ($E \propto T^3$).

The bubble energy of the sample detonator, with respect to the standard Hercules J2 detonator, is termed the "specific bubble energy" and can be computed from the following equation:

$$\frac{E\ \text{sample}}{E_{J2}} = \left[\frac{T\ \text{sample}}{T_{J2}}\right]^3 \tag{3}$$

where E sample = bubble energy of the sample detonator, J,

E_{J2} = bubble energy of the standard J2 detonator, J,

T sample = first bubble period of the sample detonator, s,

and T_{J2} = first bubble period of the standard J2 detonator, s.

Bubble and shock energies of the currently available short-delay coal mine detonators were evaluated relative to those of the standard Hercules J2 detonator.

NO-FIRE CURRENT

The bridge wire of a detonator is a very fine resistance element that converts an electrical impulse to thermal energy (4). On application of a firing current, the bridge wire heats up and ignites the heat-sensitive ignition composition surrounding it. This in turn initiates the primary charge, through the delay element. The primary charge initiates the base charge. The thermal response of the bridge wire and the adjacent ignition material to the electrical pulse is very complex. For successful initiation, the magnitude of the firing current and its duration are critical. Depending on the magnitude and duration of the firing pulse, four possibilities (5) may arise: no-fire, uncertainty of firing, all-fire, and arcing. Recommendations for minimum, as well as maximum, firing currents are supplied by manufacturers of detonators. Ten amperes is a typical maximum recommended current, especially for parallel circuits, to prevent a condition known as arcing, which can damage the detonators and cause them to malfunction.

Becker (6) correlated delay times with firing current for a variety of domestic short-delay coal mine detonators. Results indicate an increase in delay time with reduction in firing current. The typical minimum firing current level recommended by manufacturers for a single cap is in excess of 0.5 A (6). No-fire current is defined as the maximum level of direct current that can be applied to a detonator without significant probability of causing an initiation. No-fire current is a function of application time. For short application periods, say up to 30 ms, no-fire current varies inversely as the application time. For longer application periods, beyond 1 s, the no-fire current does not vary with the application time. For the purpose of this study, no-fire current was determined with an application time of 10 s.

EXPERIMENTAL SETUP AND TEST PROCEDURE

ELECTROSTATIC SENSITIVITY

These tests were conducted in the Bureau's standard electrostatic sensitivity test apparatus (fig. 1), which consists of an energy storage unit and a detonator test chamber. Detailed descriptions of this apparatus are given by Mason (7) and Brown (8). The energy storage unit consists of a 30-kV power supply unit, isolation resistors, 10 storage capacitors ranging from nominally 200-pF to 0.25-μF capacitance, an electrostatic voltmeter, and a vacuum contactor for transferring the energy stored in the chosen capacitor to the detonator located in the test chamber.

The electrostatic sensitivity tests are performed at 10-kV potential, with variable capacitance, and with no appreciable series resistance in the discharge unit. Many electrostatic tests include a series resistance to simulate the finite resistance of the human body, usually conceived to be the "capacitor" in actual situations; this simulation is not the function of these tests. Two types of tests are performed on short-delay detonators: (1) pin-to-pin (P-P), in which the discharge occurs across the detonator leg wires, which are shortened to 3 in, and (2) pin-to-case (P-C), in which both 3-in-long leg wires are twisted together and attached to the high-voltage (positive) side, and the detonator's outer metallic shell is attached to the ground (negative) side. The results of the tests are expressed in terms of a TIL value, representing the highest capacitor energy level at which at least five consecutive noninitiations were observed. The stored energy levels at 10-kV potential ranged from 16 mJ to 12.5 J for capacitor settings of 200 pF to 0.25 μF, as shown in table 1. At some of the lower test energy levels, an adjustment was made in the energy to include the contribution from stray capacitance.

TABLE 1. - Stored energy levels of designated capacitors at 10-kV potential

Designated capacitor, μF	Stored energy level, mJ
0.25	12,500
.08	4,000
.04	2,000
.02	1,000
.01	500
.005	250
.002	[1]112
.001	[1]56
.0005	[1]36
.0002	[1]16

[1] These values represent the stored energy levels in the designated capacitor and also include corrections due to stray capacitance.

STRENGTH OF DETONATION

Strength of detonation is determined by firing one detonator at a time under water and measuring the bubble and shock energies. The experimental setup, as shown in figure 2, consists of an underwater cylindrical test chamber, two digital oscilloscopes, two water-resistant high-frequency dynamic pressure transducers, and a permissible blasting unit. The test chamber is filled with water, and a detonator is suspended in water at a depth of 4 ft. Pressure transducers are positioned 22 in from the center of the detonator. Weights are used to keep the pressure transducers and the detonator suspended in the water. Pressure transducers are four-element tourmaline gages, 3/8 in in diameter and designed for underwater use. Each tourmaline gage is connected to one digital oscilloscope housed in an instrumentation trailer through insulated coaxial cable and an amplifier unit. The oscilloscopes are triggered by the shock wave, and the dynamic pressure is displayed on the oscilloscope screen. The bubble energy is compared with that of the standard Hercules J2 detonator having an average base charge of 0.935 g PETN, using equation 3. The relative shock energy is also computed using equation 1. Standard

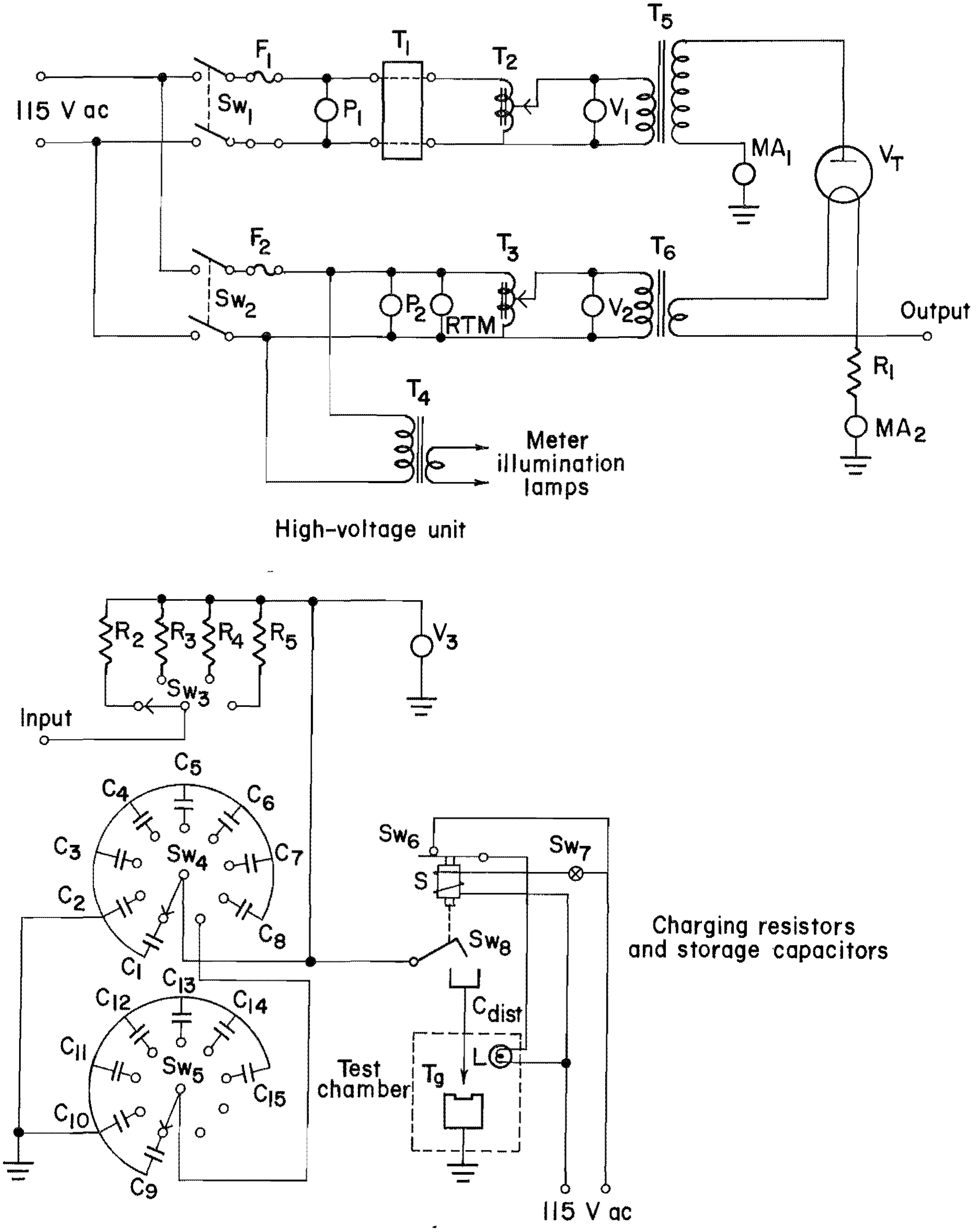

FIGURE 1. - Schematic diagram of electrostatic sensitivity test apparatus.

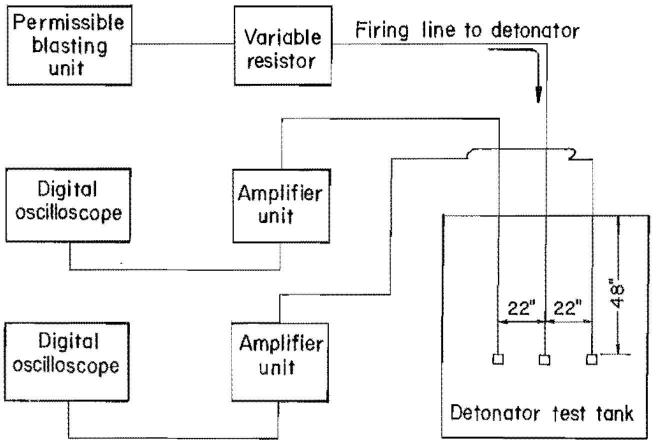

FIGURE 2. - Schematic diagram of experimental setup for detonation energy measurement.

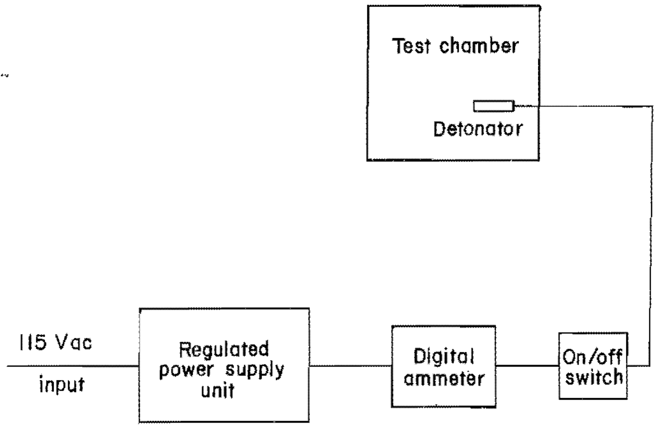

FIGURE 3. - Schematic diagram of no-fire current measurement.

Hercules J2 detonators are fired at the beginning and end of each working day, and the pressure profiles are recorded on digital oscilloscopes.

NO-FIRE CURRENT

The experimental setup shown in figure 3 consists of a constant-current regulated power supply unit, a digital ammeter, and a manual on/off switch. One detonator at a time is connected to the power supply unit, through the digital ammeter, and fired. The manual on/off switch is kept in the "on" position for 10 s to energize the detonator with the firing pulse. After 10 s the switch is turned to the "off" position. A new detonator is used in each trial. To start, a high firing current setting is used, which is capable of initiating the sample detonator under test. The current setting is changed in 10-mA steps. If an initiation occurs, the test is continued at the next lower current setting, and so on. The highest value of the current setting at which at least five consecutive noninitiations are observed is reported as the no-fire current.

RESULTS AND DISCUSSION

ELECTROSTATIC SENSITIVITY

Table 2 shows the TIL values in P-P and P-C modes for the three domestic manufacturers. The energies are reported as stored energy in the capacitor. TIL values in the P-P mode are generally lower than TIL values in the P-C mode. For manufacturer C, the TIL ranges from 36 mJ to 250 mJ in the P-P mode, and from 56 mJ to 2,000 mJ in the P-C mode. Manufacturer C's detonators show a higher TIL than manufacturer A's detonators in both modes. Manufacturer B's detonators show a similar TIL in the P-P mode, but a higher TIL in the P-C mode, compared with manufacturer A's detonators.

STRENGTH OF DETONATION

Table 3 lists the specific bubble and shock energies expressed as percent of standard Hercules J2 detonator. The energies represent the average of at least two trials. Manufacturer C's detonators exhibit the greatest bubble and shock energies. For any given type of detonator, as seen from tables 3 and 4, the dispersion of shock energy data points is wider than that of the bubble energy data points. In table 4 the quantity 100 σ/μ expresses the dispersion of data points relative to their average. This value ranges from 1.60 to 4.20 for specific bubble energy and from 9.06 to 9.57 for

TABLE 2. - Electrostatic sensitivity of short-delay detonators

Delay period	Nominal delay, ms	TIL value, mJ	
		P-P mode	P-C mode
MANUFACTURER A			
1	25	36	112
2	100	36	112
3	175	36	112
4	250	36	112
6	350	36	112
7	400	36	112
8	450	36	112
MANUFACTURER B			
1	25	56	250
2	100	36	112
3	170	36	250
4	240	36	112
5	320	36	250
6	400	36	112
7	500	36	500
MANUFACTURER C			
1	25	250	2,000
2	100	112	250
3	175	112	250
4	250	112	500
5	300	250	250
6	350	36	250
7	400	112	500
8	450	112	56
9	500	112	500

TABLE 3. - Bubble and shock energies of short-delay detonators

Delay period	Nominal delay, ms	Specific energy, pct	
		Bubble[1]	Shock[2]
MANUFACTURER A			
1	25	54.9	48.7
2	100	50.7	49.7
3	175	49.9	53.4
4	250	52.0	49.9
5	300	55.4	58.7
6	350	54.5	43.8
7	400	56.7	53.7
8	450	52.8	57.6
9	500	53.2	55.4
MANUFACTURER B			
1	25	54.9	43.5
2	100	55.4	39.4
3	170	56.2	42.0
4	240	58.5	45.4
5	320	57.6	52.0
6	400	58.0	43.1
7	500	58.0	51.0
8	600	58.0	45.5
MANUFACTURER C			
1	25	70.5	71.5
2	100	73.2	64.3
3	175	72.6	63.4
4	250	72.6	79.9
5	300	71.8	64.1
6	350	70.5	80.0
7	400	70.0	68.3
8	450	71.0	71.8
9	500	70.5	65.0

[1] Specific bubble energy is expressed as percent of bubble energy of standard Hercules J2 detonator.

[2] Specific shock energy is expressed as percent of shock energy of standard Hercules J2 detonator.

TABLE 4. - Dispersion of bubble and shock energy data, percent

Manufacturer	Av (μ)	Std dev (σ)	100 σ/μ	Manufacturer	Av (μ)	Std dev (σ)	100 σ/μ
Specific bubble energy:				Specific shock energy:			
A.............	53.24	2.24	4.20	A.............	52.32	4.74	9.06
B.............	57.08	1.37	2.40	B.............	45.24	4.33	9.57
C.............	71.40	1.14	1.60	C.............	69.81	6.54	9.37

specific shock energy. Owing to wide dispersion of shock energy data points, bubble energy is generally used to compare the strength of different detonators.

Bubble energy also correlates well with the detonation energy measured in the classical Sand Bomb Test Apparatus. Tests so far conducted by the Bureau indicate a coefficient of correlation of 97.25 pct.

NO-FIRE CURRENT

Table 5 shows the no-fire current levels of short-delay detonators for the three manufacturers. The highest value of the current setting at which at least five consecutive noninitiations were observed is reported in this table. Detonators of manufacturer A consistently exhibit the highest values of no-fire current, in the range of 440 to 590 mA. This represents good stability against stray currents. Detonators of manufacturer B indicate no-fire current ranging from 240 to 270 mA, which is generally adequate against stray currents normally encountered in underground blasting situations. Detonators of manufacturer C show a no-fire current ranging from 320 to 350 mA; again this is generally adequate against stray currents.

TABLE 5. - No-fire current levels of short-delay detonators

Delay period	Nominal delay, ms	No-fire current, mA
MANUFACTURER A		
1	25	590
2	100	500
3	175	500
4	250	520
5	300	490
6	350	500
7	400	440
8	450	480
9	500	560
MANUFACTURER B		
1	25	270
2	100	240
3	170	240
4	240	260
5	320	260
6	400	250
7	500	240
MANUFACTURER C		
1	25	330
2	100	320
3	175	330
4	250	330
5	300	340
6	350	350
7	400	340
8	450	340
9	500	350

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