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SSS-77-R-3148

DEVELOPMENT OF A NONPRIMARY-EXPLOSIVE, LOW-VOLTAGE ELECTRIC DETONATOR FOR USE IN MINING OPERATIONS

PREPARED FOR

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

BY P. B. RITTER & E. A. DAY

SYSTEMS, SCIENCE & SOFTWARE
P. O. BOX 1620
LA JOLLA, CALIFORNIA 92038

FINAL REPORT
ON
CONTRACT NO. H0366018

JULY 1977

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ABSTRACT

The feasibility of redesigning and adapting the all-secondary-explosive, low-voltage, electric safe detonator for use as a delay detonator has been demonstrated. Experimental results have shown that operational characteristics can be adjusted to allow direct competition of safe delay detonators with commercial delay blasting caps. Five different experimental delay period models have been developed and tested. Test results are given and results are evaluated.

Subsequent simplified and improved designs for practical and economical mass production are described. Design concepts to meet Bureau of Mines voltage withstand, incendivity, and spark sensitivity requirements are included. Recommendations are made for experimental procedures to ready the safe delay detonator for mass production and extensive use in mining and other industries.

I. INTRODUCTION

Successful all-secondary explosive, low-voltage electrical detonators were originally developed by Systems, Science and Software under contracts with the Air Force Armament Laboratories, Eglin Air Force Base.[1,2] Unique features of this development are subjects of a recent patent.[3] Following this work, techniques for including built-in time delays have been developed and are subjects of a second patent application.[4] The Safe Detonator Design concept is adaptable to numerous military applications and is being utilized in current experimental programs.

For many years, it has been the accepted practice to use a small quantity of primary explosives for the primer charge in all types of fuse-ignited and low-voltage electric blasting caps. The primer charge initiates a larger base charge consisting normally of a secondary explosive much less sensitive than the primary charge. Detonators utilizing primary explosives have always presented numerous safety problems in manufacturing, handling, storage, installation and use.

Detonators of the exploding-bridgewire type, employing only secondary explosives, can be used successfully for some applications and are commercially available. However, these require expensive high-voltage initiating sources and circuits, in themselves potential safety hazards. In addition, delay detonators of this type are unavailable since practical delay periods can only be achieved by electrically delaying the high-voltage initiating pulse.

The all-secondary explosive safe detonator works on a different principle from conventional detonators. The main charge, or base charge, can consist of the same quantity of secondary explosive as that used in ordinary blasting caps. Initiation of the base charge is brought about by the explosion of a small secondary explosive "acceptor" charge, which is in turn initiated by the high-velocity impact of a tiny metallic disc or "flyer". The flyer is the sheared-out center portion of a larger metallic disc called the "flyer plate". The very high pressure required for shearing and accelerating the flyer is provided by the burning (or deflagration) of a small quantity of secondary explosive in a very small steel-walled combustion chamber. This charge called the "donor" charge only burns, it does not detonate. Ignition of the donor charge is accomplished either directly by a low-voltage hot bridgewire for instantaneous types, or by a bridgewire-initiated pyrotechnic column for delay models. When pressure in the combustion chamber exceeds the strength of the flyer plate material, the flyer is sheared out and accelerated through a short barrel, impacting the acceptor charge at a minimum velocity of about 1mm/μsec.

The development and demonstration of a practical and reliable low-voltage secondary-explosive delay detonator has been the prime objective of this program for the U.S. Bureau of Mines. Another objective has been to demonstrate the feasibility of adapting the safe delay detonator design for use in all commercial applications which at present require the use of blasting caps. Concurrently with pursuit of these objectives, concentrated efforts have also been made to conceive, produce and test practical designs that can be operationally and economically competitive, yet inherently much safer than commercial blasting caps.

Preliminary phases of the safe delay detonator program included the study of electrical ignition and burning characteristics of pyrotechnic mixes commonly used for burning delay trains. Such a train is not normally ignited directly by a hot wire, but requires the use of an intermediate load of some easily-ignited material. This material usually produces gas in quantities capable of interfering with delay column burning rates, requiring the incorporation of a cavity in the detonator to act as an accumulation reservoir. However, the strict donor-charge confinement requirements associated with safe-detonator design preclude the presence of any sort of unfilled cavity in the combustion chamber. For these reasons, successful development of reliable means for direct hot-wire ignition of delay materials became vital.

While pyrotechnic studies were in progress, existing safe-detonator component designs were adjusted to provide a model with external dimensions and electrical characteristics more closely matching those of commercial delay blasting caps. These design adjustments required that a number of interacting parameters be changed simultaneously. Many experiments were required to achieve successful delay detonator performance. Additional tests were needed to establish loading techniques, delay material load combinations, and delay mix quantities suitable to produce five successful types of delay detonator.

Detonator component designs were standardized so that for nearly all applications, identical parts could be used for all types to be produced and tested. Detonators were manually produced in the quantities necessary for developmental testing as well as for filling Bureau of Mines proof testing requirements. Later design changes were conceived to facilitate automated mass production, enhance protection against extraneous electricity, and improve reliability.

II. PROCEDURE AND RESULTS

The Statement of Work for this program was subdivided into nine major tasks. Many aspects of tasks overlapped and often became interdependent. Tasks are discussed individually below, and experimental problems, solutions, results and suggestions for further improvements have been included.

2.1 ELECTRICAL REQUIREMENTS FOR IGNITION (Task 1)

An experimental program was planned to determine the ignition characteristics of "gasless" delay mixes having burning rates suitable for providing the five delay periods specified by the Bureau of Mines. These periods were 25 msec, 250 msec, 500 msec, 1000 msec and 3000 msec. Preliminary experiments were done with delay materials on hand. As tests progressed, requirements for other types of delay material were determined. Materials were selected from mixes per formula 189 (D-16, manganese-type delays) and formula 190 (slow-burning delays with tungsten) of Ellern [5] , which are subjects of specifications MIL-M-21383 (1958) and MIL-T-2313A (1973) respectively. The source for all delay materials was Pyrotechnics Specialties, Inc., Byron, Georgia.

Hot-wire ignition of most delay mixes proved to be unsuccessful or very unreliable in preliminary tests using the bridgewire and power supply currently utilized for instantaneous safe detonators. Slow-burning types were particularly difficult to ignite. However, one fast-burning tungsten delay mix (designated W-3 by S^3) was found to be reliably ignitable with the currently-used 0.002" diam. Nichrome* bridgewire, if loaded at 20,000 psi in direct contact with the bridgewire. Experiments with larger sizes of bridgewire also normally failed to ignite slow-burning types. Since ignition of W-3 was successful, it was decided to use W-3 as the delay column for the 25 msec model and as an ignition material for other models requiring slow-burning types. Tests showed that when W-3 is ignited, it can, in turn, readily ignite slow-burning mixes.

To meet the Bureau of Mines requirement to produce safe detonators with dimensions allowing interchangeability with representative blasting caps, it was necessary to reduce the diameter of previously proven safe detonator design. Figure 1 shows a typical previous design. However, some parameters such as body wall thickness, bridgewire diameter, header thickness, cavity length, barrel length, and acceptor-train length were not directly scalable. The developmental

*Trade name of W.B. Driver Co. for 80% Ni, 20% Cr. alloy.

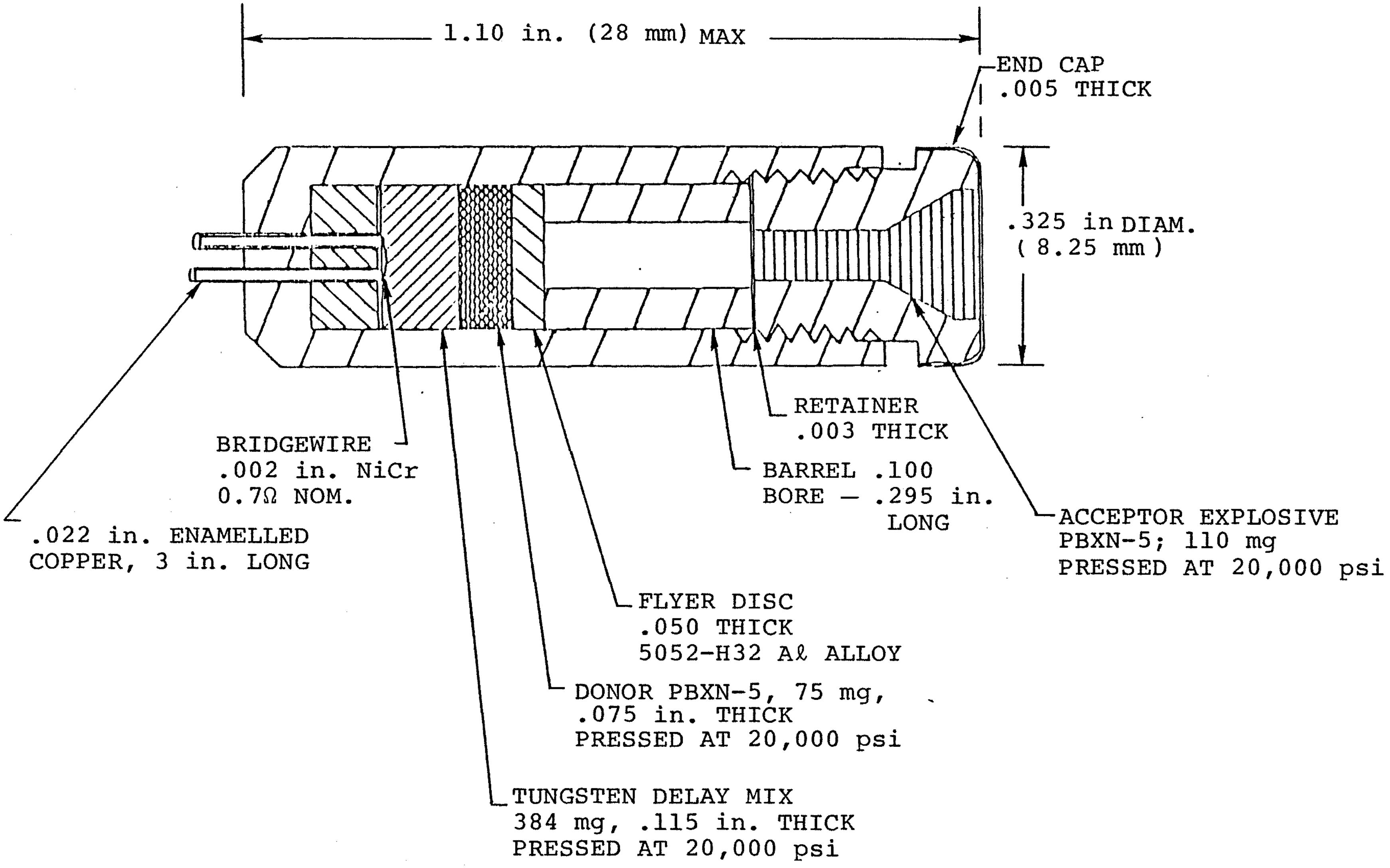


Figure 1. Nonprimary-explosive, 16-millisecond delay, low-voltage electric detonator.

program plan required redesign and proof testing of nearly all components. The outside diameter of the resulting successful model shown in Figure 2 has been reduced to 0.260". It is only slightly longer than a typical #6 blasting cap.

Redesign and miniaturization of the bridgewire header produced a model with the 0.002" diameter Nichrome wire shortened to about 0.050" and with nominal resistance decreased to about 0.4 ohm. To retain the strength necessary for cavity confinement, however, the header thickness of previous models was retained. Because of difficulties in working with the new miniaturized header, later detonator models were provided with a completely new and simplified header design as indicated in Figure 2. A substantial saving in assembly time and machining costs was realized after this header proved to be feasible. Reliable ignition of W-3 delay mix with the new header design was also successful.

The capacitor- discharge firing circuit shown in Figure 3 was used for all delay detonator tests except those requiring the use of the portable hand-held blasting machine (Excoa Permissible Maxi-Blaster). The firing capacitor was 1200μFd, and output current was determined by the charging voltage as well as by the total impedance of the output circuit which included the .11Ω current monitor resistor, the firing line, detonator leads, and the bridgewire. By recording the voltage drop across the .11Ω resistor while firing, records showing current flow vs time were obtained. Typical current risetime was about 5μsec and current flow records indicated bridgewire behavior and burnout time, and also provided information on the conductivity of delay mix combustion products immediately after ignition.

Preliminary experiments with a charging voltage of 45 volts produced high-order detonation of delay detonators with currents of 40 to 60 amps. Delay times, however, were erratic indicating variable delay-train burning periods. The difficulty was traced to probable disruption of delay mix columns by rapid vaporization of burning bridgewires. After the firing voltage was reduced to 22-1/2 volts, this difficulty was eliminated for subsequent tests. Voltage reduction decreased firing current to about 25 to 30 amps.

The burnout time for 0.002" Nichrome bridgewires with W-3 loading at 20,000 psi is typically from 60 to 130 microseconds with a current pulse of about 25 amps. Actual W-3 ignition takes place at some time before bridgewire burnout. Current flow drops sharply at burnout, but then recovers at about 1/2 the maximum amperage level as current continues to flow erratically through combustion products (See Figure 4).

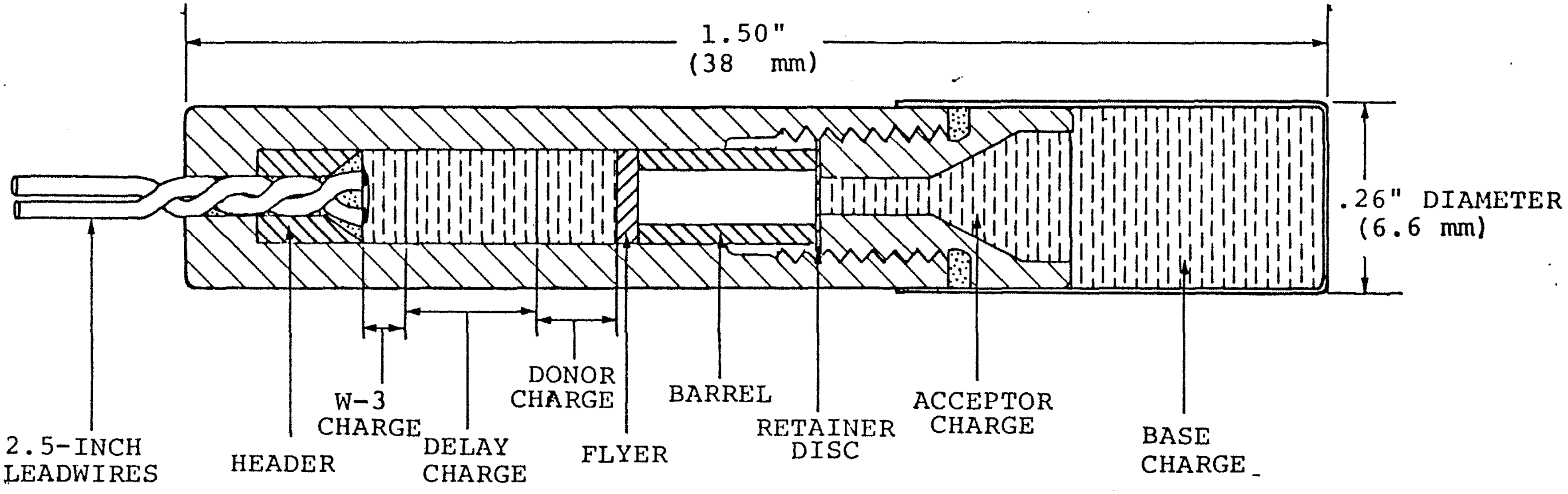


Figure 2. Safe delay detonator.

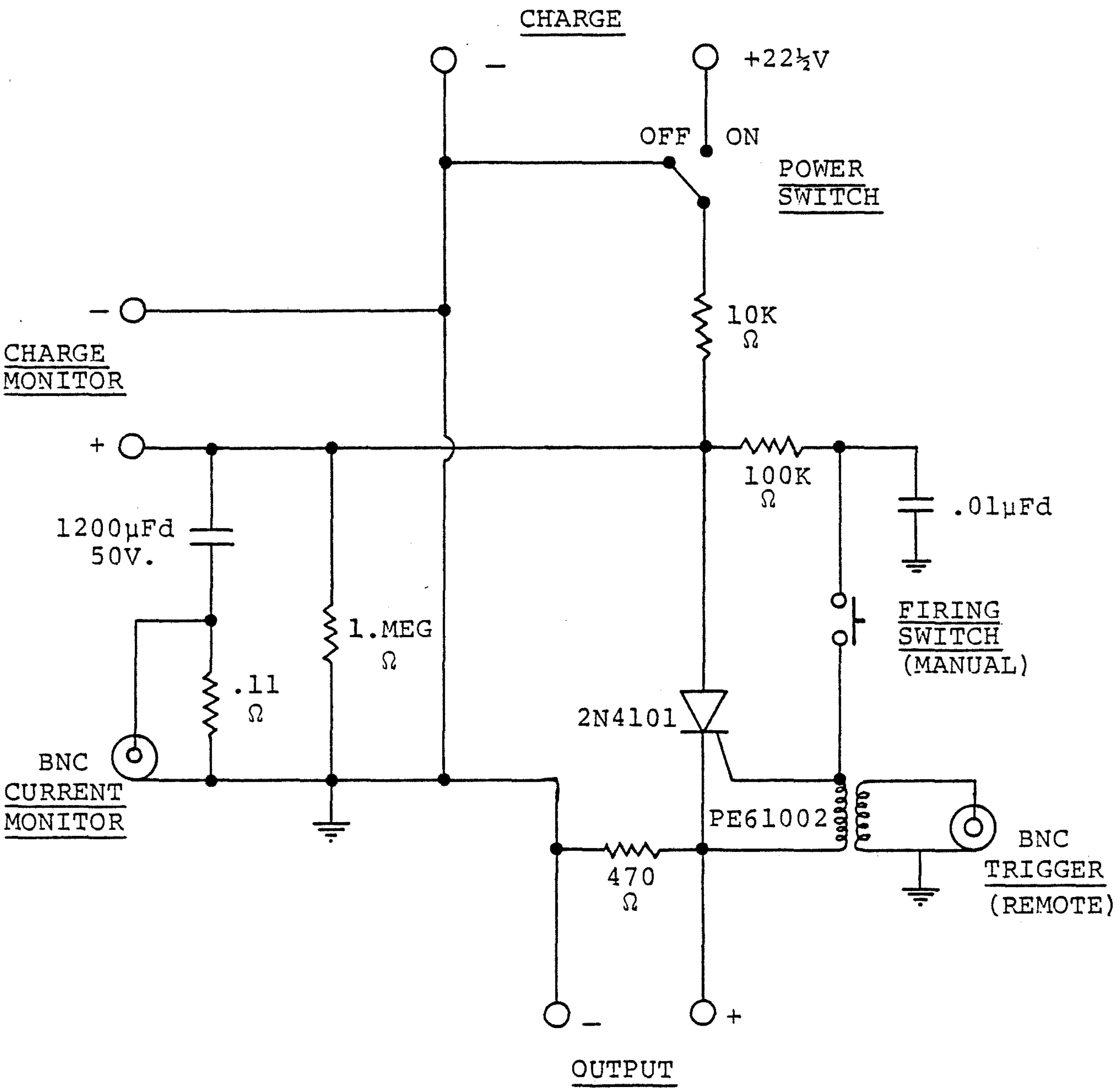
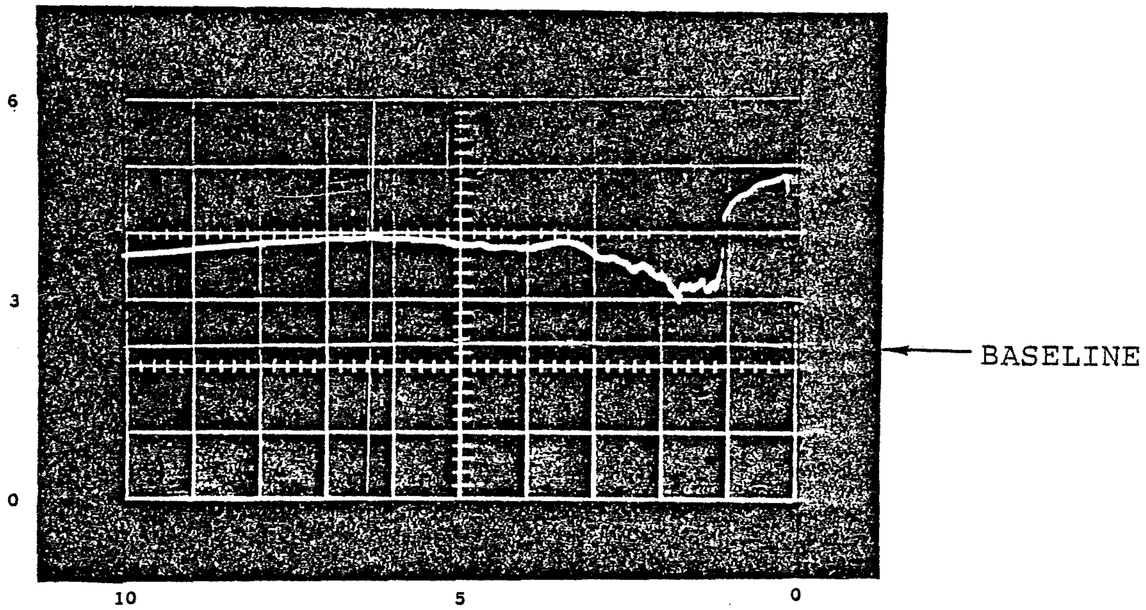


Figure 3. Firing circuit for safe delay detonators.



Vertical Scale = 9 AMPS/CM

Horizontal Sweep = 100 μSEC/CM, RIGHT TO LEFT

Figure 4. Typical current trace – safe delay detonator.

2.2 SUITABLE DONOR MATERIALS (Task 2)

Explosives tested as donor charges include RDX, PBXN-5, HMX, PETN and THKP (titanium hydride/potassium perchlorate). Although all materials listed have been used with success in safe detonators, availability, cost, ease of handling, and loadability play important roles in the selection of the most suitable type of a practical mass-producible delay detonator. PETN was selected as the best material after a period of preliminary testing. The type of PETN finally used in experimental models was the same grade used in 400-grain Primacord (Ensign & Bickford). In the required small diameters, this material was found to ignite reliably and predictably, and to accelerate flyers to velocities high enough for reliable initiation of charges loaded with the same material. Base charges were also loaded with this grade of PETN.

Loading pressures for all explosive charges and delay columns were standardized at 20,000 psi. The burning rates of delay mix columns vary with different loading densities. Therefore, it is vital to control loading pressures accurately. Loading was done with an air-powered press (Air-Mite, Model AP12). Each explosive and delay charge was individually preweighed to within ±one milligram of the desired weight (Mettler Macro-Balance, Model B5).

The total function time is defined as the period between the start of bridgewire current and the detonation of the acceptor charge. This period was measured with sub-millisecond accuracy by means of an electronic counter started by the firing pulse and stopped by the closure of a foil switch between the acceptor charge and a steel witness block. Depth of the witness block dent indicated high-order detonation of the acceptor. All preliminary tests were made using acceptor charges only; base charges were added to final test models.

With current pulses of from about 7 amps to about 30 amps, oscilloscope recordings of amperage vs time were made for about one millisecond after pulse rise time. These showed bridgewire burnout and subsequent diminished current flow through combustion products. With current pulses lower than 7 amps, sweep times were extended since bridgewire burnout times became longer with lower currents. When current tests of less than 3 amps were made using the portable hand-held blasting machine, 0.002" diam. Nichrome bridgewires failed to burn out within the built-in 6-msec cutoff time of the firing unit. These detonators were undamaged and were later successfully fired by current pulses of 3 amps or more.

Special test units using 0.0015" diameter Nichrome bridgewires have been found to ignite W-3 successfully within the 6-msec cutoff limit when firing current is reduced to about 2 amps in a 150-ohm firing circuit. The 6-msec duration, minimum current required to burn out 0.0015" diameter bridgewires when loaded with W-3 at 20,000 psi has not yet been determined.

2.3 QUANTITY OF DONOR(S) REQUIRED (Task 3)

Experimentation revealed that maximum flyer velocity is adversely affected by both too much and too little donor explosive. Optimum quantitites differ for different explosives as well as for different diameters of the donor charge combustion chamber. For the safe detonator under development, a chamber diameter of about 0.125" is dictated by maximum outside diameter limitations and minimum wall strength requirements. The optimum quantity of PETN required to shear the 0.033" thick aluminum flyer disc and accelerate the .076" diameter flyer to one mm/μsec or faster is about 40 mg at this chamber diameter. The depth of this charge after 20,000 psi compression is approximately 0.1 inch. If the charge is reduced to 35 mg or less, deflagration sometimes fails to provide enough energy to produce the flyer velocity required. If the charge is appreciably above 50 mg, maximum flyer velocity again drops off. The reasons for this are thought to be related to premature shearing of the flyer before complete burning of the excess donor material. As a result, part of the energy normally transmitted to the accelerating flyer is expended in the acceleration of yet unburned excess PETN.

Another important factor found to affect detonator performance was discovered in this stage of development. With reduced outside diameter requirements, the decrease in case wall strength became a factor influencing flyer velocity. In our current design, the wall thickness has been reduced to about 0.060". During deflagration of the donor charge and acceleration of the flyer, chamber pressure approaches about 60,000 psi. For preliminary experiments, AISI 1215 free-machining cold-finished steel was used. It was found that the case walls were swelled and sometimes split in the area of the donor charge. Flyer velocities became erratic and inconsistent because part of the energy normally utilized for flyer acceleration was being lost when the case wall expanded. A solution was reached by making subsequent cases from AISI 4140 cold-finished chromium-molybdenum steel which has a much higher yield strength than 1215 steel. With 4140 steel, the case remains intact and the outside diameter remains essentially unchanged in the donor charge area after the detonator has been fired.

2.4 BLASTING MACHINE IGNITION (Task 4)

Successful ignition of both instantaneous and delay detonators has been accomplished by means of the Permissible Blasting Machine mentioned above. Initiation current requirements for instantaneous units were found to be somewhat lower than for delay units. This indicates that PETN is more easily ignited by a bridgewire than is the tungsten delay mix (W-3). The probable reasons for this are that the W-3 has a higher ignition temperature than PETN, and also has greater heat conductivity because of the tungsten particles.

At this point in the program, a concentrated effort was made to prove the current design could be made to work successfully. The development of the five required delay columns and their incorporation into the proposed design was postponed until design concepts were finalized and delay column timing accuracy proved. Continued proof firing with the Permissible Blasting Machine was deferred for incorporation into Task 6(f).

2.5 DESIGN OF DETONATORS WITH FIVE DELAYS (Task 5)

Based on results of previous tasks; designs were adjusted with the following objectives:

1. Simplification of current designs as much as possible without sacrificing performance.
2. Provision of dimensional changes as required to produce units interchangeable with corresponding delay blasting caps.
3. Standardization of designs to allow as far as possible, the use of identical components for all different delay units.
4. Adjustment of component design and design tolerances so that parts are readily and economically mass-producible by standard automatic screw-machine equipment.
5. Simplification and standardization of hand-loading and assembling techniques to make it practical to hand-produce the volume required for Task 6.

Special simple tools were made to provide means for faster and more accurate assembly and loading . With development of automation procedures, a much greater improvement in production can be realized, since hand-loading methods cannot compete favorably with automation for speed, precision and repeatability.

Bids by vendors for the mass production of safe-detonator components indicated that all parts for one detonator of the current design could be produced for less than 30¢ in quantitites of about 50,000 or more. Bids on components for a previously considered base-loaded and crimped model indicated its cost would be higher than for the top-loaded type. Experiments with the base-loaded type showed that with hand loading and crimping, reliability declined. This was probably caused by lack of precision in the crimping operation. The crimping procedure as done by hand tended to introduce a slight relaxation in charge confinement upon release of the crimping tool; this sometimes caused ignition failure. Automation would probably eliminate this problem.

Loading data for the five different delay detonator models developed and produced for Task 5 is given in Table I. Preliminary test-fire data is shown in Table II. Detonators tested at this time were usually fired immediately after loading. In no cases were they stored for more than 24 hours before being fired. Later tests on units of the 200-detonator lot which had been stored for about 4 weeks indicated time-dependent changes in delay time for some types. This is thought to be caused by slight readjustments of internal stresses in delay-column loads.

2.6 PARTS FOR TEST AND TEST EVALUATION (Tasks 6 & 7)

Task 6 of this effort consists of 8 subdivisions (a through h). Parts a, b, c, d, e, g and h list quantities of each type of delay detonator to be produced and sent to the Bureau of Mines for various testing procedures. Task 7 includes analysis and evaluation of test results following completion of Task 6(f) requirements by S^3. Forty of each type of detonator were produced; twenty-seven of each were shipped to the Bureau of Mines early in January 1977; six each were test fired by S^3 as required by Task 6(f). Most of the remainder were fired by S^3 for spot-check proof firing during the production period and for preliminary low-current-limit tests.

The firing circuit used for all performance test firing as specified in Task 6(f) was the hand-held Permissible Maxi-Blaster. This device is rated for use with a maximum of 20 detonators in a series circuit having a maximum total resistance of 150 ohms. It has an output rating of 400 volts peak and 3.8 watt-seconds @ 200 ohms. A typical set of performance curves for a Permissible Maxi-Blaster is shown in Figure 5. The firing circuit used for the 30 performance tests included a series resistor increasing its total effective resistance to simulate about 3000 feet of 18 AWG copper firing line (see Figure 6). Results for these tests are given in Table III.

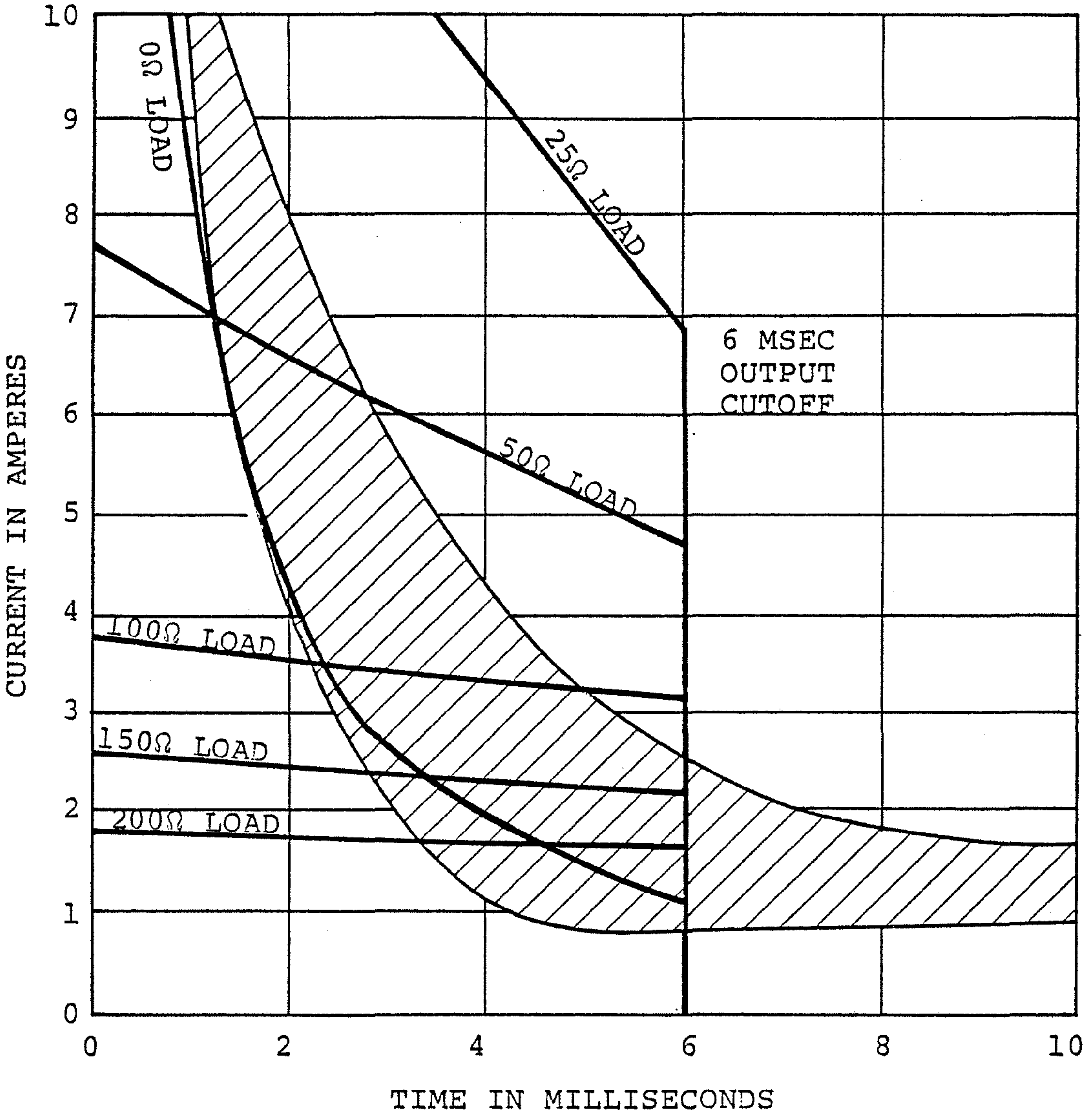
Table I. Safe delay detonator loading data.

DELAY (msec)	COLOR CODE	DELAY CHARGE MATERIAL		CHARGE WT(mg)	PRESSING INCREMENTS @ 20,000psi	DONOR CHARGE WT (mg PETN)	ACCEPTOR CHARGE WT (mg PETN)	BASE CHARGE WT (mg PETN)
		IGNITION	DELAY					
25.	Black	W-3	→	193.	4.	40.	110.	310.
250.	Red	W-3		135.	2.	40.	110.	310.
			M-1	40.	1.			
500.	Yellow	W-3		150.	3.	40.	110.	310.
			M-1	80.	2.			
1000.	Green	W-3		60.	1.	40.	110.	310.
			M-1	155.	3.			
3000.	Blue	W-3		75.	1.	40.	110.	310.
			W-2	206.	5.			

Note: W-2 = Tungsten delay with .06 in/sec nominal burning rate.
W-3 = Tungsten delay with 2.63 in/sec nominal burning rate.
M-1 = Manganese delay with .11 in/sec nominal burning rate.

Table II. Preliminary test-fire data for five types of safe delay detonators.

SHOT NO.	NOMINAL DELAY (MS)	MEASURED DELAY (MS)	AVERAGE DELAY (MS)	DEVIATION FROM NOMINAL (%)	DEVIATION FROM AVERAGE (%)
LD-274	25.	23.52	25.05	-5.9	-6.1
LD-279	25.	26.10		+4.4	+4.2
LD-280	25.	25.53		+2.1	+1.9
LD-294	250.	257.73	251.76	+3.1	+2.4
LD-295	250.	229.02		-8.4	-9.0
LD-296	250.	268.53		+7.4	+6.7
LD-297	500.	474.75	480.33	-5.0	-1.2
LD-298	500.	482.00		-3.6	+0.3
LD-299	500.	484.23		-3.2	+0.8
		(SEC)	(SEC)		
LD-310	1000.	0.93	1.05	-7.0	-11.4
LD-311	1000.	1.11		+11.0	+5.7
LD-312	1000.	1.10		+10.0	+4.8
LD-325	3000.	2.88	3.04	-4.0	-5.3
LD-326	3000.	3.03		+1.0	-0.3
LD-327	3000.	3.22		+7.3	+5.9



Shaded area represents firing current-time requirements for typical commercial blasting caps.

Figure 5. Permissible Maxi-Blaster performance curve. (From Excoa, Inc. Technical Data).

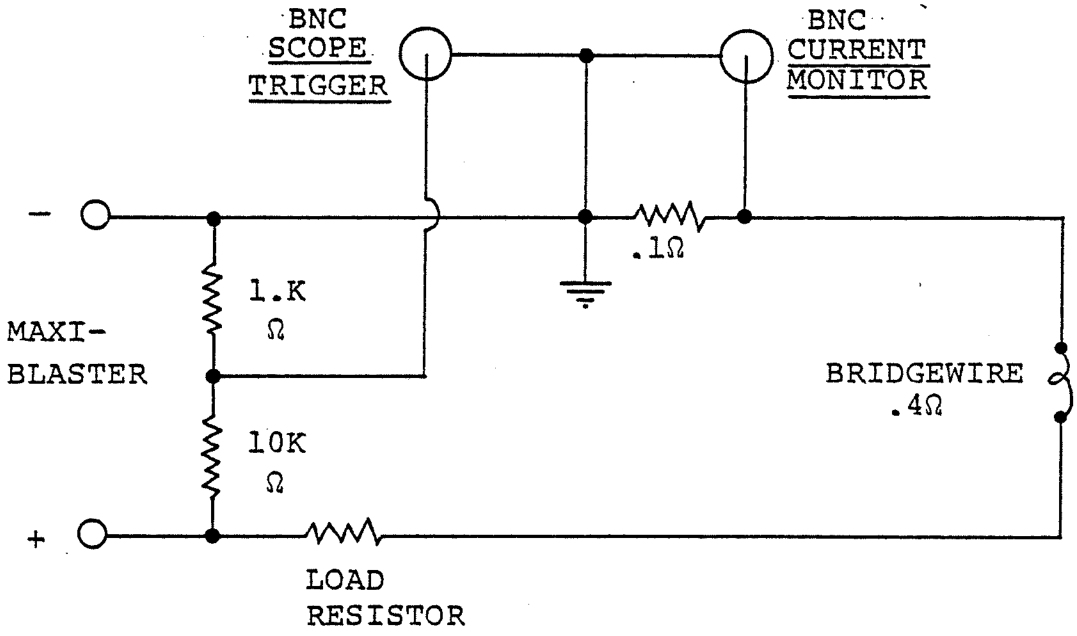


Figure 6. Test circuit for use with Permissible Maxi-Blaster.

For the 25 msec delay detonators, delays averaging 25.6 msec for six shots were measured. This was 2.4% longer than the nominal 25 msec delay, indicating a small increase in average delay time. Since these tests were made after the units had been loaded for a period of approximately four weeks, this small increase may have been caused by a small time-dependent readjustment of the W-3 delay column (The only delay material used in the 25 msec unit is W-3.) However, it also may be attributable to only the normal time-spread between individual loads. Apparently time-dependent changes in W-3 delay column loads is quite low, if it exists at all. The maximum deviation from the average delay of 25.6 msec for this group was 10.4%.

Results for tests with the 250 msec delay detonators indicate a marked time-dependent decrease in burning rate for columns loaded with M-1. M-1 is the S^3 designation for a manganese delay material used in the 250, 500, and 1000 msec delay detonators. In the preliminary time measurements for the 250 msec detonator made immediately after loading, delays were accurate to within 11% or less (see Table II). However, about 4 weeks after loading, an average increase in delay period of 22% was measured (see Table III). These results appear to indicate a time-dependent decrease in burning rate which may have been caused by a slight "relaxation" in particle compaction with a corresponding decrease in loading density. Assuming such adjustment of M-1 is a one-time occurrence taking place within a short period after loading, compensating adjustment can easily be made by decreasing the M-1 load weight from 40 mg to about 32 mg. The maximum deviation from the average delay time 304.8 msec was 6.5%

Based on results for the 250 msec detonators, a similar decrease in burning times for the M-1 columns in the 500 msec detonators might be anticipated. However, this was not the case. The 500 msec tests resulted in an average delay period of 517.2 msec, 3.4% above the nominal 500 msec. The maximum deviations from the average were 16.6% and 15.4% for two of the units, and the remainder were within 7.4% or less. From these results, one might conclude that the relaxation effect for M-1 columns is a phenomenon occurring for the most part with short or shallow columns. In longer columns the strength of the packed material is enough to resist such marked readjustment. An adjustment of M-1 load from 80 mg to 77 mg should compensate for the change in delay period.

Table III. Performance test-fire data for five types of safe delay detonators using Permissible Blasting Machine.

SHOT NO.	NOMINAL DELAY (MS)	MEASURED DELAY (MS)	AVERAGE DELAY (MS)	DEVIATION FROM NOM. (%)	DEVIATION FROM AVE. (%)	BRIDGEWIRE BURNOUT TIME (μSEC)	MAXIMUM CURRENT (AMPS)	INDICATOR DENT DEPTH (IN.)
LD-385	25.	24.5	25.6	-2.0	-4.3	490.	-	.031
LD-386	25.	27.8		+11.2	+8.8	350.	7.9	.037
LD-390	25.	23.0		-8.0	-10.4	445.	8.2	.036
LD-391	25.	26.6		+6.4	+4.0	370.	8.1	.036
LD-392	25.	26.3		+5.2	+2.8	370.	9.7	.035
LD-393	25.	25.5		+2.0	-0.4	-	8.1	.034
LD-394	250.	291.8	304.8	+16.7	-4.3	425.	7.9	.039
LD-395	250.	285.1		+14.1	-6.5	375.	7.2	.040
LD-396	250.	322.3		+28.9	+5.7	440.	7.3	.037
LD-397	250.	322.5		+29.0	+5.8	415.	7.5	.036
LD-398	250.	293.4		+17.4	-3.7	450.	7.9	.038
LD-399	250.	313.4		+25.4	+2.7	340.	8.1	.036
LD-400	500.	508.6	517.2	+1.7	-1.7	245.	8.1	.037
LD-401	500.	479.0		-4.2	-7.4	430.	8.1	.037
LD-402	500.	434.3		-13.1	-16.6	355.	10.7	.036
LD-403	500.	594.1		+18.8	+15.4	405.	10.7	.039
LD-404	500.	554.4		+10.9	+7.4	570.	8.1	.034
LD-405	500.	532.8		+6.6	+3.1	340.	7.9	.036
LD-406	1000.	1014.7	1064.2	+1.5	-5.0	370.	7.0	.036
LD-407	1000.	1022.0		+2.2	-4.2	385.	10.7	.037
LD-408	1000.	1014.2		+1.4	-5.0	365.	7.8	.036
LD-409	1000.	1026.0		+2.6	-3.8	430.	8.1	.037
LD-410	1000.	1115.6		+11.6	+5.1	380.	7.5	.035
LD-411	1000.	1192.8		+19.3	+12.9	365.	7.6	.038
LD-412	3000.	2334.4	2504.9	-22.2	-6.8	355.	8.4	.032
LD-413	3000.	2090.0		-30.3	-16.6	380.	8.4	.035
LD-414	3000.	2854.0		-4.9	+13.9	440.	7.8	.038
LD-415	3000.	2444.9		-18.5	-2.4	435.	7.5	.037
LD-416	3000.	2668.5		-11.0	+6.5	360.	8.7	.039
LD-417	3000.	2637.8		-12.1	+5.3	320.	7.7	.038

A similar decrease in M-1 burning time was measured for the 1000 msec delay detonator. The average delay period increaded to 1064.2 msec (+6.4%). This can be compensated for by decreasing the M-1 load 155 mg to 146 mg. Maximum deviation from this average was 12.9% for one unit, but 5.1% or less for the others.

Results for tests with the 3000 msec presented another surprise. Delay times for these units were substantially shorter than the nominal 3000 msec indicating a marked <u>increase</u> in burning rate after the four-week period. Since W-2 is used rather than M-1 in this model, this characteristic can be attributed to the behavior of W-2 when held in confinement. This may have been caused by a time-dependent breakdown of oxidized layers on the surfaces of W-2 particles while under compression. This process could bring about an increase in the heat conductivity in the delay material, resulting in a faster burning rate. The maximum deviations from the average delay time of 2504.9 msec were 16.6% and 13.9% for two of the six units and 6.8% or less for the remainder. Compensation to readjust to 3000 msec delay will require increasing the W-2 load from 206 mg to 247 mg. Table IV lists adjustments in delay mix weights to compensate for time-dependent delay-period changes measured in Task 6(f).

Very disturbing results were encountered with the three delay detonator experiments LD-389, LD-418, and LD-425. In these tests, donor charges were burned and flyers were blown, but the acceptor charges were not initiated. Sectioning the bodies of these units indicated that the difficulty appeared to be related in some way to a marked expansion and sometimes rupture of the end of the barrel sleeve adjacent to the acceptor charge. Referring to Figure 2, it can be seen that an approximately 0.060"-long extension of the 10-32 tap hole in the body beyond the end of the threads leaves nearly 50% of the upper end of the barrel without cavity-wall backup support. To facilitate screw machine production of barrel sleeves, the material chosen was Ledloy steel because of its easy machinability. Subsequent calculations show, however, that just prior to the time the flyer can be blown, the barrel sleeve end can be momentarily subjected to over 90,000 psi. This is well above the yield strength of Ledloy, although there remains a strong uncertainty whether the barrel can be deformed appreciably within the short shearing and acceleration period of the aluminum flyer. Any deformation of that end of the barrel before passage of the flyer could allow product gases to bypass the flyer and cushion its impact; or it might allow a slight tipping of the flyer and poor impact; or a small shift in barrel mouth position might make the impact point nonconcentric with the acceptor train.

Table IV. Delay-charge weight changes for delay adjustment.

Nominal Delay (ms)	Tungsten Delay W-3 (mg)	Tungsten Delay W-2 (mg)	Manganese Delay M-1 (mg)
25.	From 193. to 188.		
250.	135. (No change)		From 40. to 32.
500.	150. (No change)		From 80. to 77.
1000.	60. (No change)		From 155. to 146.
3000.	75. (No change)	From 206. to 247.	

Continued analysis of the situation has revealed that with this unforeseen lack of support at the acceptor end of the barrel, component tolerances are such that in some cases during loading, the loading pintle could have shifted from vertical enough to have pressed the upper surface of the donor charge with an appreciable tilt. This would have caused a corresponding tilt in the barrel and a loss of concentricity at the barrel-acceptor interface, since support by the body wall at that end of the barrel was missing. This possibility is considered to have been the most likely cause for the three failures.

Based on the analysis of test results for experiments LD-389, LD-418 and LD-425, the following improvements should be made in the safe delay detonator design.

1. Change the barrel sleeve material to one with a yield strength of 90,000 psi or greater.
2. Shorten the threads in the body to eliminate the unused portion.
3. Minimize the length of the unthreaded portion of the 10-32 tap hole.

In addition, the pressing pintle should be provided with a positive alignment fixture to assure that the upper surfaces of donor charges will be level.

2.7 COST/SAFETY TRADEOFFS (Task 8)

Concurrently with previous tasks, several other important efforts have been pursued. These include the following:

1. Conductivity tests with present safe delay detonator models.
2. Spark sensitivity studies and designs for simple and effective methods for incorporating antistatic air gaps in both current and future designs.
3. Efforts to isolate possible causes of incendivity problems along with the production of special test units to investigate means for eliminating potential incendivity sources.
4. Continued study of practical design changes to allow easier and more economical component manufacture, assembly and loading, yet adaptable to mass production methods.

2.7.1 Preliminary Bureau of Mines Tests

In August 1976, twenty 25-msec delay detonators were sent to the Bureau of Mines (Bruceton facility) for preliminary incendivity, impact, thermal, and spark sensitivity tests. The following test results were provided by the Bureau of Mines:

Incendivity Test [6]

One delay detonator was fired in an 8% natural gas/ air mixture; the gas mixture was ignited.

Comparison

Domestic coal mine delay detonators have N_{50}'s (Number of detonators required to ignite 8% natural gas-air mixtures) ranging from $1 < N_{50} < 3$; some foreign instantaneous detonators have N_{50}'s = 6 or 7.

Impact Test [6,7]

Impact tests were made using a 2.4 kilogram weight fitted with a 1/4-in-diameter striking pin for localized impacts on selected regions along the length of the detonator to determine the most sensitive spot. No initiations were observed at drop heights up to 120 cm.

Comparison

Conventional detonators can be initiated with a 2.4 kilogram weight dropped from a much lower height.

Thermal Test [7]

A delay detonator was heated at 0.5°C/min, and at 154°C the delay-donor charge combination ignited and actuated the flyer disc; the PETN base charge, which melts at about 140°C did not function.

Comparison

Commercial blasting caps detonate within the range of 121°C to 188°C.
An exploding bridgewire detonator did not explode at temperatures up to 240°C.

Spark Sensitivity Tests [6]

Spark sensitivity tests were made using 10 kilovolts with no series resistor. Both pin-to-pin and pin-to-case response was measured with the following results:

Pin-to-Pin

ENERGY	RESULT
16 mj	Negative
36 mj	Negative
56 mj	Negative
112 mj	Negative
250 mj	Positive

Comparison

Maximum no-fire energies or threshold initiation limits (TIL) for commercial blasting caps are from 20 mj to 250 mj. For exploding bridgewire detonators they are 1000 mj.

Pin-to-Case

ENERGY	RESULT
16 mj	Negative
36 mj	Negative
112 mj	Positive

Comparison

Maximum no-fire energies for commercial blasting caps are from 36 mj to 12,000 mj. For exploding bridgewire detonators they are 2000 mj.

2.7.2 Conductivity Tests

Conductivity measurements were made between legwires and the case. The tungsten delay mix W-3 is the only delay material in the currently-made safe delay detonator which contacts both the legwires (and bridgewire) as well as the inner surface of the case. For this reason, tests were made to determine if the conductivity of W-3 changes while loaded under 20,000 psi compression for a 10-week period. Measurements were made between legwires and case immediately after loading, and the resistance was found to be nearly infinite. After the 10-week period, however, resistance of the units had dropped and was from 50 to 60 ohms. When the detonators were test-fired, initiation and delay characteristics appeared not to have been appreciably affected by the increase in conductivity of W-3. It is suspected that soon after loading current paths through the tungsten particles are normally incomplete because of layers of oxidized material on particle surfaces. With aging while under compression, these surfaces appear to break down reducing the resistance to current flow. With a direct-current potential of 0.46 volts, current flows of about 8 milliamps were measured.

2.7.3 Insulating Coatings

Appreciable conductivity through the W-3 could have an adverse effect on spark sensitivity by eliminating the desired pin-to-case voltage withstand. As a solution to the problem, insulating coatings for the inner surface of the case were investigated. Several types of insulating paint were tried both by spray application and by dipping. Results were disappointing for several reasons. Paint layers usually were too thick and the layer thickness was not easily controlled. The paint tended to gather in corners and threads, interfering with header installation and acceptor installation. Variations in paint thickness also caused variations in delay train length with corresponding variations in delay periods for loads of equal mass. Installation of headers often damaged or scratched the paint layer, decreasing or destroying insulating properties of the layer. Another unknown was the possible chemical interaction of painted surfaces with delay mix materials and/or with donor charges. For these reasons, this approach was rejected in favor of commercially-available teflon or phenolic coating services. Coatings of chemically inert materials can be economically applied, and layer thickness can be held within close tolerances in production quantities.

A survey of commercial sources for the desired coating service revealed several good prospects, from which one was selected. One sample detonator case was coated with black teflon and several with phenolic in very thin layers (less than 0.0005"). Ultrathin layers were selected to allow assembly of currently available detonator parts without changing internal dimensions to accommodate the insulating layer.

Preliminary resistance tests with these parts show both materials to have excellent dielectric properties. For economic reasons, phenolic coatings are considered better than teflon for this application, since teflon coatings cost much more to apply. The layer of phenolic was found to break down at about 270 volts, indicating the need for a somewhat thicker layer. The coating should withstand more than 1500 volts, the potential selected as the breakdown voltage for the antistatic gap now in design stages for spark sensitivity improvement. Since thicker phenolic layers are required, component dimensions must be changed slightly to allow their incorporation into the design. The exact thickness of phenolic required is yet to be determined but will probably be about 0.002". To keep costs for this service at a minimum, the layer will be applied over the complete surface of the detonator body. When applied to the complete body, the coating will afford good rust-prevention and corrosion resistance for finished detonators. Phenolic coatings can be had in various colors, a convenient means for coding detonators with different time delays.

2.7.4 Incendivity Source Study

Incendivity tests by the Bureau of Mines have indicated that incendivity by frictional impact of aluminum alloys and rusted steel is proportional to the hardness of the aluminum alloy.[8] The flyer plates originally used in safe detonators were made of 6061 T6 aluminum alloy with Brinell hardness of about 95. Results of the tests mentioned above show that aluminum alloys with hardness of 95 are more than twice as incendive as those with hardness of only 60. Tests with safe detonators demonstrated that softer alloys will initiate PETN acceptor charges as effectively as will harder types. Consequently, flyer plate material for subsequent tests was changed to 5052-H32 aluminum alloy with a Brinell hardness of 60.

It is considered questionable whether the source of incendivity noted for the present safe detonator design can be the remnants of the aluminum flyer. Since the combustion cavity remains intact, the 0.076"-diameter aluminum flyer is driven back through the barrel and into the donor cavity by detonation of the acceptor train. After the acceptor charge and the base charge have detonated, remains of the flyer plate and the barrel sleeve (which also remains intact) can emerge from the cavity only after rebounding from the header end. This must occur at a comparatively low velocity, since at this time the case (still intact) has been sharply accelerated in the opposite direction. High-temperature delay-train and donor-charge products ejected at the same time are suspected as possible sources of incendivity.

In December, 1976, twelve special test detonators were assembled and shipped to the Bureau of Mines for additional incendivity tests. Delay charges were omitted from six of these to determine how much of the incendivity problem can be attributed to only delay-train combustion products. The remaining six detonators were loaded with standard 25 msec delay trains, but were provided with acceptor-charge sleeves and base-charge shells made of brass instead of steel. This was done to find out if high-velocity steel fragments may be causing incendivity.

The tests were made by firing the detonators in a methane/air mixture. High-speed photographs indicated that the omission of delay trains had little visible effect on the appearance of fireballs. Units with brass parts replacing steel showed a marked decrease in hot streaks from flying fragments. However, both types of detonator still ignited the methane/air mixture.

In January, 1977, four other special experimental detonators were assembled and sent for continued incendivity tests. Loading data for these detonators is given in Table V. In two of these units, the acceptor loads were omitted from the acceptor sleeves so that an attempt could be made to photograph flyer pellets and to study their possible incendive characteristics.

Omission of the acceptor loads also limited the size of the combustion-cavity vent aperture. Normally, after the acceptor has detonated, remnants of the acceptor sleeve are separated from the body, and venting occurs from an aperture the full diameter of the cavity (i.e., 0.129") after the barrel is ejected. With no acceptor charge, the acceptor sleeve and the body do not separate, and venting is limited to an aperture of about .052". Limiting the size of the venting aperture is thought to be a possible means for decreasing incendivity caused by ejected delay-train and donor-charge products.

In three of the four special detonators, aluminum flyers were replaced by epoxy/fiberglass flyers. This was done so that incendive characteristics of the two materials could be compared. In one of these three units, steel acceptor and base charge components were replaced with brass. Incendivity test results for the group of four special detonators are given in Appendix B, a summary of tests performed by the Bureau of Mines on safe detonators produced for this contract.

2.7.5 Header Design Development

Because of difficulties encountered in working with the new miniaturized header, a concentrated effort was made to simplify design and production. One approach was an attempt to make all-plastic headers. A small experimental four-cavity die was made by a local plastic molding firm, and a small quantity of trial plastic headers was obtained. Although several successful shots were fired with these headers, installation difficulties and erratic test results indicated the need for an extended development program if reliability were to be achieved. The plastic used was high-strength mica-filled epoxy (Furane No. 403-S3-40). Except under ideal conditions, however, plastic headers were still not strong enough (or backed up firmly enough) to sustain cavity pressures without frequent failures because of blowout and venting through legwire apertures.

Concurrently with experiments involving plastic headers, alternative designs for steel headers were considered. The previously used type of steel header consisted of a steel pellet 0.10" long penetrated by two 0.025" diameter legwire holes (see Figure 1). The top of the header was covered with a

Table V. Incendivity-test delay detonator loading data.

Detonator No.	Delay Period	Delay Charge		Donor Wt.	Flyer Material	Acceptor		Base Charge
		Mat'l	Wt.			Sleeve	Charge	
1	25 msec	W-3	193. mg	40. mg	5052-H32 Aluminum	Steel	None	None
2	↓	↓	↓	↓	Epoxy Fiberglass	Steel	None	None
3	↓	↓	↓	↓	Epoxy Fiberglass	Brass	PETN	PETN Brass Shell
4	↓	↓	↓	↓	Epoxy Fiberglass	Steel	PETN	PETN Steel Shell

NOTE: W-3 = Tungsten delay with 2.63 in/sec nominal burning rate.

0.010" thick fiberglass insulating disc separating the bridgewire from the flat steel surface. Legwires were epoxied into the two holes. Construction of this type of a header by hand methods was difficult and time-consuming.

A new and simplified twisted-lead header design proved to be feasible (see Figure 2). This type consists of a section of steel tubing 0.150" long with 0.047" inside diameter. A conical cavity is machined in the upper end of the tube. The legwires are first twisted in a simple fixture with a small circular loop on one end; the twisted wire is then inserted through the center hole and epoxied with the lower half of the loop seated in the conical cavity. After curing, the protruding half of the loop is clipped off, the upper surface is ground flat and the bridgewire is attached.

Substantial savings in assembly time and machining costs were realized with the new design. The header has also proved to be better than the previous all-steel type which would sometimes release individual legwires when fired, allowing slight venting. The twisted-wire and conical-cavity design traps legwires firmly and prevents legwire ejection.

2.7.6 Improved Safe Delay Detonator Design

A new safe delay detonator design is presented in Figure 7. A number of features have been incorporated to solve problems of conductivity and spark sensitivity as well as to improve component production and assembly. Suggested design changes have been conceived after a study of test results for the large number of experiments carried out in this delay detonator development program. The design has also been influenced by information accumulated on several other previous and concurrent safe-detonator experimental programs. Improvements incorporated are as follows:

1. The detonator is base-loaded but has the advantage of positive-threaded closure without the "springback" problem encountered with crimping.

2. The acceptor sleeve and the case are machined as a single piece to provide positive concentricity and alignment of barrel and acceptor train.

3. The barrel sleeve is supported and backed up for its full length by the case wall.

4. The one-piece construction limits venting of possible incendive materials (such as delay train and donor charge products) through an aperture much smaller than the full cavity diameter which

vents previous designs.

5. The removal of threads at the acceptor end strengthens the body in that area considerably, minimizing possibility of combustion chamber rupture or case/acceptor separation.

6. Any possible incendivity caused by aluminum from the flyer disc is eliminated, since the aluminum should be blown back into the combustion cavity by the acceptor detonation and effectively trapped.

7. The header is separated from the case wall by the insulating coating, and from the antistatic sleeve below it by an insulation disc. This prevents static discharges through the W-3 between the bridgewire and either the case or the header sleeve.

8. Base loading facilitates header sleeve and antistatic sleeve assembly and installation, which is considerably more difficult with top-loading designs.

9. Charge loading is no more difficult than with top-loading models, requiring only slight tooling modification.

10. Production of the header screw will be economical, since its design is nearly identical to that of a standard socket-head screw except with a hole through the center instead of a socket cavity.

11. Integrity of the combustion cavity is further assured because the force on the header screw is only about 70% of that seen by the larger diameter acceptor sleeve in a top-loading model.

12. If closure by crimping procedure proves to have an economical advantage for mechanized mass production, the threads can be omitted and the header screw redesigned as a crimping plug.

With the base-loading approach, the header and antistatic components can be preassembled, aligned, sealed and pre-tested before installation into loaded detonators. Another small operation to be included in header production will be scoring the twisted lead slightly to remove a spot of insulation from each legwire where it passes through the antistatic washer. The legwire-to-washer gap will be about 0.010". The header will be insulated from the case by the phenolic

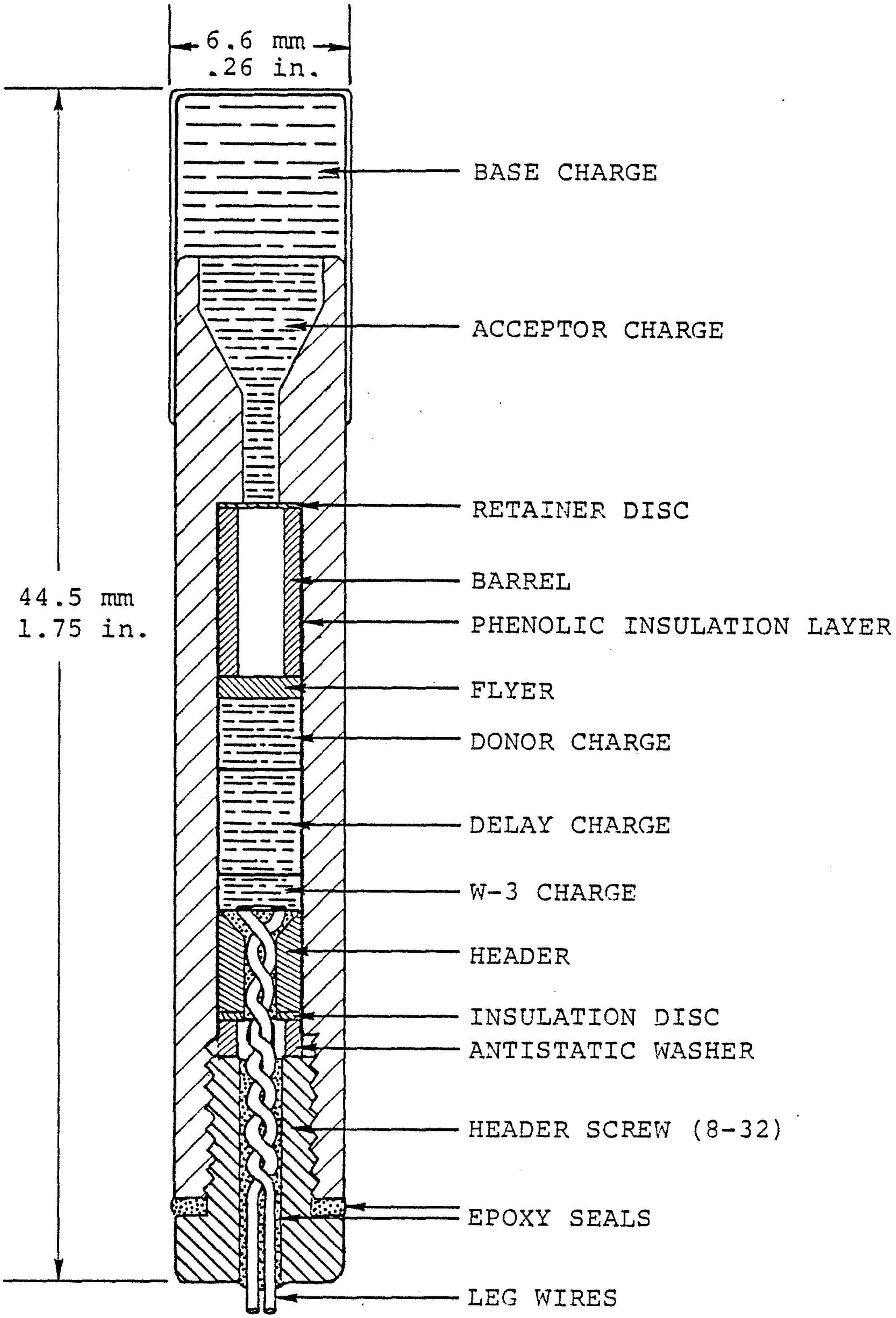


Figure 7. Safe delay detonator, #6 base-loaded.

coating and the insulation disc. The 8-32 threads should be tapped after the insulating coating has been applied to assure positive contact between antistatic washer, header screw, and case. The inside diameter of the cavity would be enlarged from 0.129" to 0.136" to accomodate the phenolic insulating layer. This dimension is ideal, since it is also the standard 8-32 tapdrill diameter. The addition of the antistatic washer and the header screw would increase the overall length of a #6 safe delay detonator to approximately 1.75 inches.

III. CONCLUSIONS AND RECOMMENDATIONS

All-secondary explosive, electric delay detonators with five different delay periods, as specified by the Bureau of Mines, have been successfully developed and tested under this contract. Most of the goals of the program have been achieved. In areas where proof testing procedures have indicated needs for improvement, means for satisfying those needs have either already been provided or feasible solutions have been conceived.

The present safe delay detonator design has dimensions compatible with existing blasting hardware, and electrical characteristics which can be adjusted to make it compatible with existing firing systems. Time delay requirements are attainable to somewhat better than 20%, and with mechanized loading processes this margin should be substantially reduced. As anticipated, the detonators are very ruggedly constructed and highly resistant to impact. Hazards avoided by elimination of primary explosives will allow simplification of loading, assembling, and handling equipment for mass production.

If not directly cost-competitive with existing delay blasting caps, the potential low cost for mass-produced safe detonators should still make them highly desirable because of inherent economical advantages connected with storage, transport, and handling.

The safe detonator should be less easily initiated than a conventional blasting cap in drilling operations such as might be required following the misfire of a buried charge. In such cases, initiation of the primary explosive in a blasting cap could easily occur if the cap is struck by the drill or heated by its proximity. If the safe detonator is struck by the drill, initiation of its secondary explosive charges would be somewhat more difficult. If the delay or donor charges were somehow ignited by penetration of the thick steel wall of the donor cavity, initiation of the acceptor charge by normal flyer impact would be impossible because of loss of confinement. Possible shock-initiation or ignition of the exposed base charge might be avoidable by the use of liquid coolant.

The following recommendations are made for follow-on efforts to ready the safe delay detonator for extensive use for mining and other commercial applications.

1. Assemble and test detonators with insulating coatings to prove pin-to-case voltage standoff capabilities.

2. Produce and incorporate antistatic gap components into test units to prove validity of safety gaps with spark sensitivity tests.

3. Assemble, load, and test units to prove significant reduction or elimination of undesirable incendivity characteristics.

4. Provide units for "drill back" tests to evaluate safe delay detonators in buried charge misfire situations.

5. Prove feasibility and reliability improvement to be gained by adopting base-loading concept; also show that design can be more economical for mass production.

6. Investigate mass-production methods and problems with potential manufacturers. Determine safest and most efficient and economical methods applicable to safe detonator production.

7. Study aging effects to determine time-dependent characteristics of safe delay detonators. These effects should be studied at ambient, low and elevated temperatures. Make any adjustments necessary to compensate for undesirable changes if they exist.

8. Measure airborne toxic emissions after firing delay detonators to determine if any (such as chromium VI) exist in hazardous quantities. This should be done in accordance with NIOSH criteria.

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APPENDIX A.

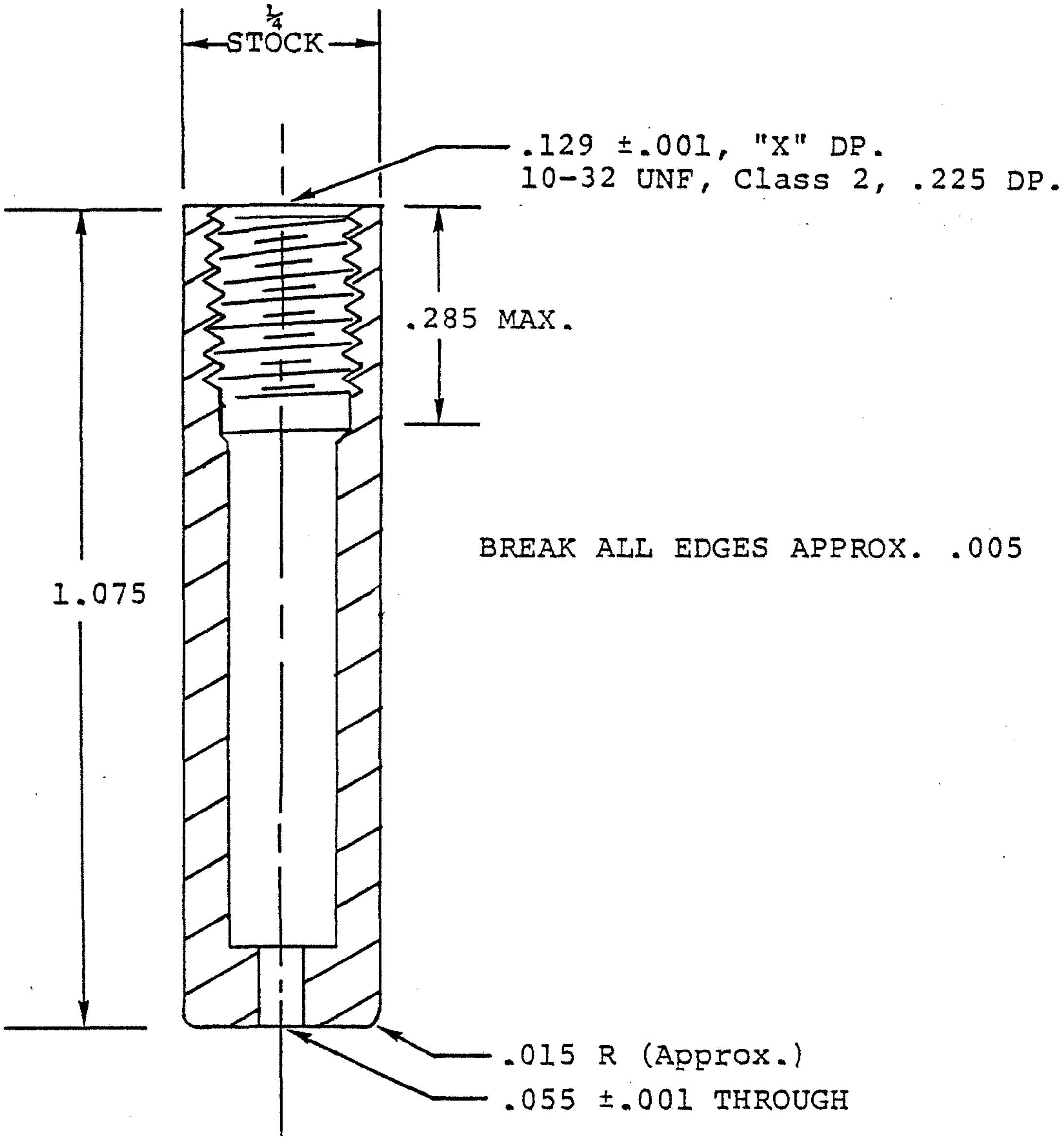
DESIGN DETAILS OF DELIVERED DETONATORS

Included in this appendix are sketches showing latest dimensions, tolerances, and materials for all machined components used for the five types of safe delay detonators developed and tested on this contract. Other materials used in their construction are also listed. Explosive and pyrotechnic loading materials and weights can be found on the loading data chart in the body of this report (see Table I).

All components are identical and interchangeable for the five detonator types except cases; the cavity depth of the case (see Sketch A1) is 0.850" for the 25 msec and 250 msec types, 0.900" for the 500 msec and 1000 msec types, and 1.000" for the 3000 msec type. Other variables were delay-charge material weights and color-coding anti-rust enamels as specified in Table I. Materials other than machined components along with applications and sources are given in Table A-I below.

Table A-I. Supplementary Parts

Material	Type	Use	Source
Epoxy	"5-minute" epoxy-polyamine resin	Header assembly & installation. Base charge. Shell seal.	Devon Corp.
Wire	24 AWG Magnet wire, #8064 polythermaleze enamel	Legwires.	Belden Corp.
Wire	0.002" diam. Tophet "A" Nichrome	Bridgewires.	Magnet Wire & Supply Co.
Paint	Anti-rust spray enamel Nos. 2701, 2705 2707, 2709, 2710, 2711	Rust prevention. Color Coding.	Montgomery Ward Co.

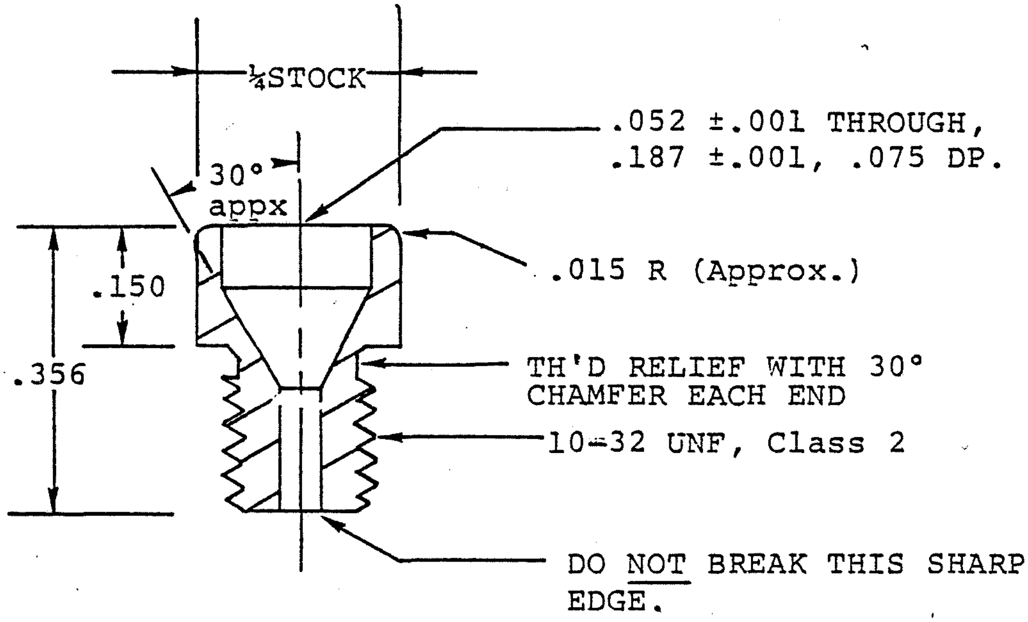


TOLERANCES: ±.005 except where noted.

MATERIAL: 4140 Cold Finished, Annealed.

NOTE: Bore "X" .850, .900, or 1.000 as specified.

Sketch A-1. Safe delay detonator case.

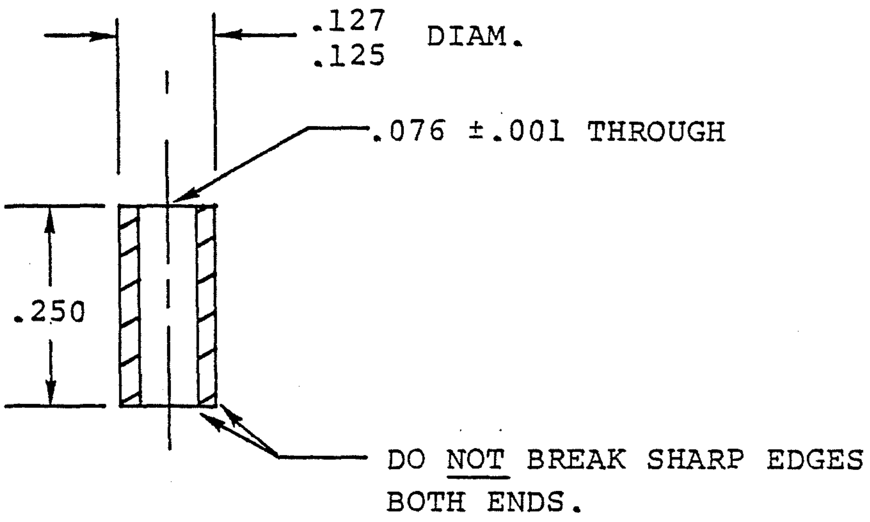


EXCEPT AS SHOWN, BREAK
ALL EDGES APPROX. .005

TOLERANCES: ±.005 except where noted.

MATERIAL: Ledloy A Cold Finished.

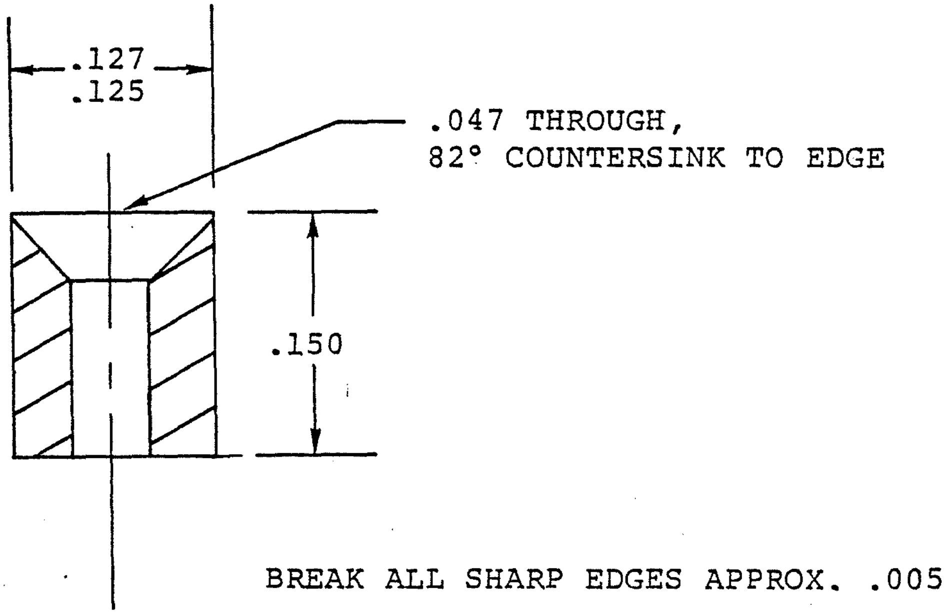
Sketch A-2. Safe delay detonator acceptor sleeve.



TOLERANCES: ±.005 except where noted.

MATERIAL: Ledloy A Cold Finished.

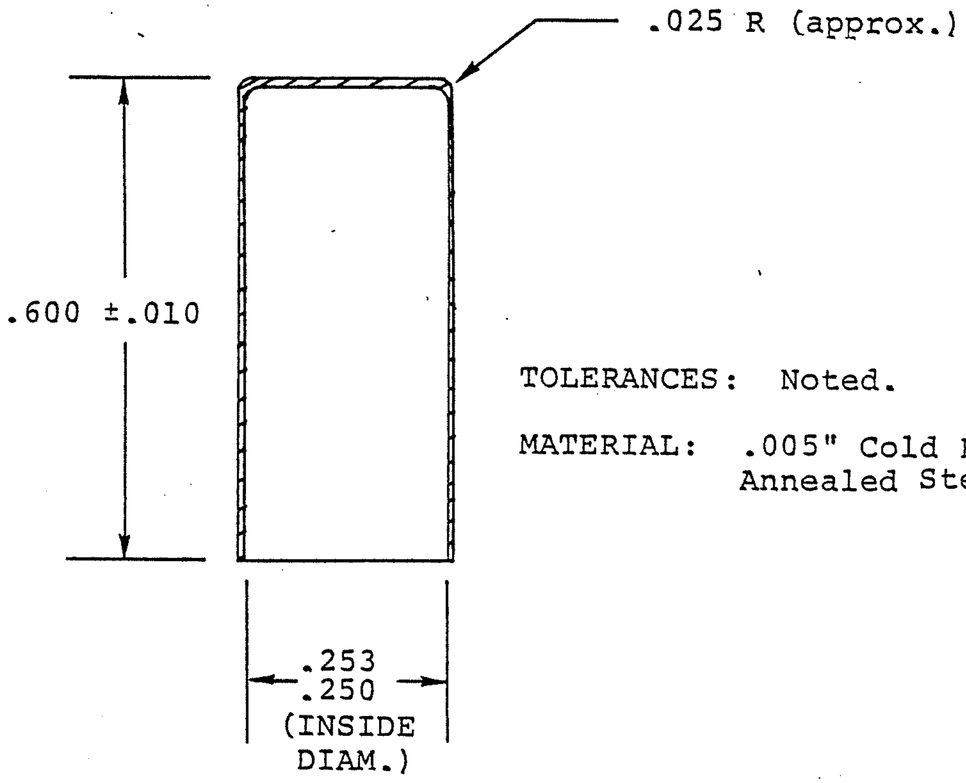
Sketch A-3. Safe delay detonator barrel sleeve.



TOLERANCES: ±.005 except where noted.

MATERIAL: Ledloy A Cold Finished.

Sketch A-4. Safe delay detonator header sleeve.



TOLERANCES: Noted.

MATERIAL: .005" Cold Rolled,
Annealed Steel.

Sketch A-5. Safe delay detonator base-charge cap.

APPENDIX B.

SUMMARY OF TESTS PERFORMED BY BUMINES ON VARIOUS S^3 COMPANY NON-PRIMARY EXPLOSIVE, LOW-VOLTAGE ELECTRIC DETONATORS

Karl R. Becker and Richard W. Watson

Introduction

Various mechanical, thermal, and electrical sensitivity tests, as well as incendivity tests, were performed on the S^3 Company experimental detonators. The Bureau received four separate groups of detonators which are identified below.

Group I (key no. 1811) - The initial group of twenty steel shell, 25 msec delay detonators containing W-3 ignitor mix (tungsten mix).

Group II (key no. 1833) - Consisted of two subgroups: (a) Six 25 msec delay detonators similar to those in Group I <u>except</u> the encasement around the base explosive was brass <u>rather</u> than steel; (b) Six instantaneous detonators similar to Group I detonators (steel shell) <u>except</u> that the ignitor explosive was PETN rather than W-3.

Group III (key no. 1851) - A group of various delay period detonators consisting of 27 each of 25, 250, 500, 1000, and 3000 ms delay; all utilized steel shells and the W-3 ignitor mix. Other differences were that the 25 msec items utilized the W-3 mix as a delay element as well, whereas the 250, 500, and 1000 msec items utilized M-1 delay mix; the 3000 msec item utilized a W-2 delay mix.

Group IV (key no. 1859) - Four 25 msec delay detonators all having steel shells and W-3 ignitor mix, but they differed in that they utilized different flyer materials and different acceptor sleeves and acceptor explosives as follows:

Detonator	Flyer Material	Acceptor	
		Sleeve	Charge
1	5052-H32Al	Steel	No charge
2	Epoxy fiberglass	Steel	No charge
3	" "	Brass	PETN
4	" "	Steel	PETN

Group IV detonators were used exclusively to study the poor incendivity characteristics exhibited by the earlier groups.

Experimental Techniques

(1) Drop weight impact tests - The detonators were impacted with a 2.4 kg drop weight in which a 0.635-cm-diameter (1/4-in) steel pin was inserted in the bottom face for impacts on selected localized regions along the length of the detonator to survey and find the most sensitive spot--ignition, delay, priming, or base explosive element. The results are expressed as a threshold initiation level (TIL), the highest drop height at which 5 nonignitions occurred; the interval used was 10 cm.

(2) Thermal test- The detonators were heated in a 5.1-cm-diameter (2.0-in) sand-filled pipe from ambient temperature 100°C at an average rate of 1.0°C/min and thereafter at a rate of 0.5°C/min until they exploded. The results are expressed as an average explosion temperature usually derived form 3 trials.

(3) Electrostatic tests - The energy of a charged capacitor was discharged (via a vacuum switch) into the detonator. The circuit parameters used were a constant 10 kV potential, variable capacitance, and no series resistance. Two types of tests were performed: (a) pin-pin, in which the discharge occurred across the detonator lead (leg) wires; (b) pin-case in which both detonator lead wires were twisted together and attached to the high-voltage lead (positive) and the detonators outer case (shell) was attached to the ground (negative) side. Usually the results are expressed as a TIL energy based upon 10 trials (10 different detonators), however because of the limited number of detonators available, the procedure for S^3 Company detonators was to perform 5 trials at some relatively low energy and repeat this procedure with the same detonator at successively higher energies until it initiated; the TIL energies specified are thus one energy level lower than the level at which they initiated. Tested in this manner, the previous pulses could conceivably have a dudding effect on the detonator, however no marked dudding effects have been observed in tests with another commercial detonator.

(4) Constant current initiation level test - The detonator bridgewire circuit was simply subjected to a constant current level for ten seconds; the current level was increased in successive steps to find the level of initiation.

(5) Tests with a Femco (SF-25-20) 20-shot blasting machine - Single detonators were placed in a circuit with the blasting machine using different values of series resistance (150, 100, and 50 ohms). The data are expressed as

the number of initiations observed per number of trials performed at each of the resistance values. The peak currents were also observed through the use of a current viewing resistor (≈1.0 ohm) and an oscilloscope.

(6) Incendivity tests - This test provides an estimate of the number of detonators that when fired will ignite an 8-pct natural gas-air mixture. Normally, at least five ignitions and five nonignitions are observed to determine the N_{50} values. Because of the highly incendive characteristics of the S^3 Company detonators, all tests were single detonators. The inside of the gallery was also lined with wood because the detonators steel shell impinging on the steel walls might conceivably cause sparks to ignite the gas-air mixture.

(7) Rock drill tests - In this test, a 1-3/4-in-diameter by 8-in deep hole was drilled in a 14-in cube of sandstone. A 1-1/4-in-diameter by 4-in-long simulated charge (sand contained in a dynamite wrapper) with a live S^3 detonator positioned in the bottom of the charge was inserted in the borehole. A model S-58 Gardner-Denver sinker rock drill, having a 1-3/8-in-diameter by 18-in-long carbide bit, was lowered in the hole (via suspension cables) on top of the simulated charge. During the drilling procedure, there was no tension on the suspension cables and drilling pressure or load was by virtue of the weight of the drill and bit. Data are expressed in terms of the number of initiations observed per number of trials; the drilling time was recorded as well.

Experimental Results

(1) Drop weight impact trials (Table 1) - Initial tests performed on Group I detonators consisted of impacts upon four detonators; two were impacted in the ignitor (also delay)-donor region and two were impacted in the base charge region; all tests were performed at the maximum drop height of 120 cm and no initiations were observed. In fact, the impacts on the ignitor-donor region produced little or no deformation of the thick steel incasement in this region. Additional impacts were also performed at 120 cm drop height on six detonators in delay Group III; they were impacted in the same areas as indicated for Group I detonators. None of these detonators initiated as well. Thus, the TIL value for S^3 detonators is >120 cm. For comparison, previous results for impacts on a variety of conventional, commercial detonators produced TIL values ranging from 15-90 cm drop height. One unconventional high voltage exploding bridgewire (EBW)

detonator that utilized no primary explosives also produced a TIL >120 cm.

(2) Thermal tests (Table 1) - Results of a test with one of the Group I detonators indicated an ignition occurred at 154°C; apparently the ignitor and driver elements ignited and the flying plate mechanism was actuated, however the PETN base charge, which would be in the melted state at this temperature, did not detonate. For comparison, a variety of other conventional commercial detonators exploded in the temperature range 121-160°C and the high voltage EBW detonator did not explode at the maximum attainable temperature of 240°C.

(3) Electrostatic tests (Table 2) - The data indicated a consistent pin-pin TIL value of 112 mj for all detonators utilizing the W-3 tungsten mix as an ignitor element; the Group II instantaneous detonator containing PETN as an ignitor element however was somewhat more sensitive, producing a TIL value of 36 mj in the P-P mode. Data for detonators tested in the pin-case mode also indicated a more sensitive result for the instantaneous (PETN ignitor element) detonator; here the TIL value was less than 4 mj. The TIL values for all other Group I, II, and III detonators utilizing the W-3 ignitor element produced TIL values ranging from <15 to 36 mj.

For comparison, results for other conventional commercial detonators showed TIL values ranging from 20-250 mj (pin-pin) and ranging from 36 mj - >12.5 j (pin-case). The EBW detonator yielded a pin-pin TIL value of 1 j; no pin-case tests were performed on the EBW detonator.

(4) Constant current initiation level tests (Table 3) - Two 25 ms and one 250 ms detonators from Group III could not be initiated at the maximum available current of 1.5 amps applied for 10 sec, not even in repeated tests with the same detonator; other members of this delay series would also probably not initiate in this test since they also utilized the same W-3 ignitor element. For comparison, results of similar tests with six other conventional commercial detonators showed firing levels (at the 99.9-pct probability level) ranging from 0.32-0.59 amps.

(5) Blasting machine test (Table 3) - In tests with Group III detonators, the data indicate that the W-3 ignition mix cannot be initiated in conventional blasting machine circuits having a total series resistance of either 150 or 100 ohms. Peak currents were about 2.2 and 3.3 amps, respectively. In a 50 ohm circuit, the S^3 detonators initiated in 9 out of 10 trials; the peak current was about

5.8 amps. For comparison, a well-known coal mine designation detonator which is known to be relatively insensitive compared to other commercial detonators initiated consistently (6/6) in the 150 ohm circuit. Thus the S^3 detonator, while relatively safe from the hazard of stray currents, cannot be fired with existing blasting machines if the total circuit resistance is near the design limits for the machine.

(6) Incendivity tests (Table 4) - Tests were performed on a total of 13 detonators drawn from the four groups; single detonators were used in each test and with one exception all the detonators ignited the gas-air mixtures. The trial with the Group I detonator showed that the original basic design was incendive. The trials with Group II(a) detonators showed that utilization of a brass, rather than a steel shell, around the base charge section was not sufficient to measurably reduce incendivity, while tests with Group II(b) indicate no improvement through the use of PETN rather than the W-3 as an ignitor element. The Group III trials showed that all members of the delay series were equally incendive and the trials with Group IV detonators suggested that the combined effects of using an epoxy fiberglass (rather than aluminum) flyer disc and using no base charge reduced the incendivity somewhat; the detonator with these features was the only one that did not ignite the gas-air mixtures. Taken together, these tests indicate that the flyer incendive characteristics of the S^3 detonator is one of the problem areas of this basic design and further development is indicated.

(7) Rock drill tests - All five of the 25 ms, Group III detonators tested initiated in this test. The drilling times required for initiation ranged from 7 to 10 sec; the average time was 7.6 seconds. Initiation was evidenced by the fact that the operator was able to detect an audible report and an examination of the recovered detonator remains showed that the encasement surrounding the base charge was completely fragmented. For comparison purposes, 3 different coal mine designation detonators from 3 different manufacturers also initiated consistently in these tests, however the average drilling times to initiation were less; they ranged from 4.2 to 7.0 seconds.

Table 1 - Results of mechanical and thermal tests

DROP WEIGHT IMPACT TEST

Ignitor-driver region			Base charge region		
Detonator	Drop height (cm)	Result	Detonator	Drop height (cm)	Result
25 ms; Group I (1811)	120	no go	25 ms; Group I (1811)	120	no go
25 ms; Group I (1811)	120	no go	25 ms; Group I (1811)	120	no go
25 ms; Group III (1851)	120	no go	25 ms; Group III (1851)	120	no go
500 ms; Group III (1851)	120	no go	250 ms; Group III (1851)	120	minor reaction[1]
3000 ms; Group III (1851)	120	no go	1000 ms; Group III (1851)	120	no go

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THERMAL TEST

Detonator	Explosion Temperature (°C)
25 ms; Group 1	154°C

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[1] Indicates a minor decompositon of some PETN material that did not propagate throughout the base charge. This is a common observation for PETN base charges of other detonators when impacted at high drop heights.

Table 2 - Results of electrostatic tests

Detonator	Results, TIL (mj)	
	Pin-Pin	Pin-Case
25 ms; Group I (1811)	112	36 < TIL < 112
Instantaneous; Group II(a) (1833)	36	<36 and <4 (5kV test)
25 ms; Group II(b) (1833)	112	36
25 ms; Group III (1851)	112	16
250 ms; Group III (1851)	112	16
500 ms; Group III (1851)	112	<16
1000 ms; Group III (1851)	112	36
3000 ms; Group III (1851)	112	16

Table 3 - Results of constant current and blasting machine tests

CONSTANT CURRENT TESTS

Detonator	Current applied for 10 sec (amps)	Result # of initiations/# of trials
25 ms; Group III (1851)	0.5	0/1
25 ms; Group III (1851)	0.75	0/1
25 ms; Group III (1851)	1.0	0/1
25 ms; Group III (1851)	1.5	0/5 (2 different detonators)
250 ms; Group III (1851)	1.5	0.5 (same detonator)

BLASTING MACHINE TESTS
(Femco SF-25-20)

Detonator	Total series resistance (ohms)	Peak Current (amps)	Result # of initiations/# of trials
25 ms; Group III (1851)	50	5.8	4/5 (5 different detonators)
250 ms; Group III (1851)	50	5.8	5/5 (5 different detonators)
25 ms; Group III (1851)	100	3.3	0/20 (4 different detonators)
250 ms; Group III (1851)	100	3.3	0/15 (3 different detonators)
25 ms; Group III (1851)	150	2.2	0/10 (2 different detonators)

Table 4 -
Results of incendivity tests for <u>all</u> groups of S^3 "ultrasafe" detonators received to-date

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Forward - All detonators fired in 8-pct natural gas-air mixture.

Detonator	Ignitor	Delay	Results
I. Original group of 25 ms delay, steel shell items (#1811)			Ignition (one trial with single detonator)
II. Second group received consisting of: (A) six, 25 ms delay with brass shell and (B) six, instants with steel shell (#1833)			
A - 25 msec, brass shell; W_3 ignitor			Ignition (one trial with single detonator)
B - Instant; steel shell; PETN ignitor			Partial ignition, single detonator (base charge did not initiate)
B - Instant; steel shell; PETN ignitor			Ignition; single detonator
III. Third group; 27 each of 5 different delays; various ignitor - delay combinations; aluminum flyer used throughout; steel shell			
A - 25 ms	W_3	W_3	Ignition (one trial with one detonator)
B - 250 ms	W_3	M_1	Ignition (one trial with one detonator)
C - 500 ms	W_3	M_1	Ignition (one trial with one detonator)
D - 1000 ms	W_3	M_1	Ignition (one trial with one detonator)
E - 3000 ms	W_3	W_2	Ignition (one trial with one detonator)

(continued)

IV. Fourth group just 4 detonators having different flyer-sleeve combinations; 25 ms; W_3 - W_3 ignitor-delay (#1859)

Flyer Mat'l	Sleeve	Base Chrg	
A - 5052-H32Al	steel	None	Ignition (one trial - one detonator)
B - Epoxy fiberglass	steel	None	Non-ignition (one trial - one detonator)
C - Epoxy fiberglass	brass	PETN	Ignition (one trial - one detonator)
D - Epoxy fiberglass	steel	PETN	Ignition (one trial - one detonator)

Table 5 - Results of rock drill tests

Detonator	Result # of initiations/# of trials	Drilling Time (sec)
25 ms; Group III (1851)	5/5	7, 10, 7, 7, 7 (average-7.6)