

The relative sensitivity of permissible explosives to dynamic pressure desensitization

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SYNOPSIS

Underground stress waves from detonations of borehole charges have the capacity to desensitize adjacent delayed borehole charges. Realistic simulation of this stress pulse-charge interaction was achieved with a novel destructible nozzled pipe fixture in which the explosive under test is subjected to the stress pulse generated by an explosive charge in an adjacent chamber, the amplitude and duration being controlled by the charge mass, chamber ullage, and connecting nozzle diameter. Five explosives types were tested, representing the major categories of permissible explosives in the U.S.A., viz., semi-gelatinous, water gel, emulsion, and granular sensitized with nitroglycerin and with a less sensitive nitrate ester mixture. Most of the explosives tested were desensitized under the recommended maximum pulse conditions of the fixture and by weaker stress pulses designed to match "worst-case" coal mine conditions.

INTRODUCTION

Dynamic pressure desensitization occurs when the underground stress wave from the detonation of an adjacent borehole charge results in the detonation failure of an unfired (recipient) borehole charge. Shock wave or quasi-static compression techniques have the wrong waveform characteristics for a reasonable simulation of the recipient borehole interaction. A destructible nozzled pipe fixture was developed that simultaneously generates the dominant waveform characteristics (pulse magnitude, pulse width, and the impulse). Therefore, the nozzled pipe fixture more realistically simulates the dynamic interaction of the underground stress wave with the recipient borehole charge. Preliminary tests at the working limits of the nozzled pipe fixture generally resulted in explosive desensitization. Only permissible mining explosives were tested for their susceptibility to dynamic pressure desensitization. Charge detonation was synchronized with, or delayed with respect to, the trailing edge of the stress pulse maximum. Some mining explosives subject to transient stress pulse interactions can undergo desensitization and partially recover, if the deformation process is reversible. For other mining explosives, the microstructure is less resilient and the desensitization more permanent.

Complex underground stress waveforms beyond the fracture radius of a detonated borehole charge show microsecond-type shock spikes superimposed on a wider millisecond stress pulse. Irreversible processes like fracture work, in conjunction with multimode nonlinear wave propagation, result in the rapid dissipation and conversion of shock spike (high-frequency) components of underground waves. For borehole separation

distances considered here, the stress wave (low-frequency) components have a higher impulse per unit area than do shock spikes. Though shock spikes regularly exceed the ultimate strength of the charge's microstructure, the stress waves determine the relative motion and mixing of the microstructure. Waveform decomposition analysis over a range of dynamic interactions illustrates how different mechanisms affect the malfunctioning of mining explosives.

In order of increasing pulse widths, Drimmer [1964] demonstrated the desensitization of military explosives when a detonation wave collides with an oppositely directed shock wave. For mining explosives, Mukerjee [1983] demonstrated that a subcritical shock wave traveling ahead of a supercritical (for detonation) wave will not desensitize the explosives if the wave retardation is less than 100 microseconds (0.1ms). The nozzled pipe fixture that simulates the underground stress waveform without shock spikes yields detonation failures, as discussed later. For still longer time frames, the quasi-static compression tests [Ruhe, 1982] resulted in the malfunction of mining explosives. Critical density, microstructure damage, sensitive-site reduction represent a few mechanisms that cause the explosive to malfunction. However, as is now obvious, the malfunction results depend on the stress-time profile and the delay interval until the charge detonator functions.

Though stress waveforms [Blasters' Handbook, 1977] for granite and diorite are somewhat multimodal, they represent a useful starting point for the stress-time pulse requirements for any simulator concept. The impulse, width-at-half-height (WHH), and the rectangular-pulse-equivalent-pressure (RPEP) were computed for the reported traces:

RPEP = IMPULSE/WHH. The duration (zero startup to zero return) is naturally longer than WHH. RPEP is normally comparable to the smoothed pulse maximum, though the difference is a function of wave shape. These pulse-shape requirements determined from the Blasters' Handbook [1977] provided the guideline design range ultimately fulfilled by the nozzled pipe fixture. Although no similar data in coal strata could be found, such measurements were made and are discussed here.

NOZZLED PIPE FIXTURE CHARACTERISTICS

Simulation of the rapid-charge compression from an underground stress wave requires severe but controlled dynamic conditions. Techniques utilized in rocket motor design, reaction rate mechanics, and shock wave attenuation precipitated a workable design, shown in Figure 1. The configuration utilizes a receiver chamber to house the sample charge, a connection nozzle, a generator chamber for the driver charge, and an exhaust nozzle. Machining, fabrication, and component costs were minimized by using a cylindrical symmetric configuration of commercial steel pipe fittings. The generator (upper) chamber houses the wrapped detonating cord for developing the driver gas. The receiver (lower) chamber is oriented downward, as shown, and houses the sample charge submerged in water. The exterior delay line determines the functioning time (delay time) of the shrouded detonator protruding into the sample charge.

Detonating cord is utilized in the generator chamber, since the shock wavelets are relatively incoherent, and this helps preserve chamber integrity. On the other hand, the cross-firing wraps of detonating cord function sufficiently fast so that fluctuations in the gas generation rate hardly influence the stress pulse developed in the receiver chamber. Flow contraction at the connection nozzle and rarefaction in the re-expansion zone (ullage of receiver chamber) substantially inhibit shock wave transmission. The cork washer on the bottom cap and the thermoplastic-and-cork piston further reduce shock wave transmission. The piston also inhibits the development of Taylor instability, whereby the reaction gas would form a penetration cavity in the water-and-charge zone. The water reduces the resulting flow work from the reaction gas and reduces (compared to air) the instantaneous stress gradient over the charge. The water region neutralizes (softens or masks) the mechanical reaction from different types of explosive charges. This water reservoir, therefore, helps to preserve the shot-to-shot reproducibility of the driver pulse, regardless of the explosive tested.

The original fixture design incorporated an unshrouded charge detonator with the result that malfunctions occurred from mechanical buckling of the charge detonator, and subsequent disruption of the

firing train. This undesirable complication resulted from the tremendous driving stress and rigid mechanical boundary condition at the bottom cap. The difficulty was resolved by shrouding the detonator with a steel pipe nipple to within 4 mm of the detonator tip. Detonator lead plate tests, 4 mm and 7 mm thick, yielded puncture and depression results quite similar to the normal tip-strength of bare No. 8 detonators.

Charge detonation with respect to the pulse maximum is precisely controlled with a detonating cord delay train. Roughly 7 m of detonating cord is required per millisecond of delay. Generation and propagation of the stress pulse require roughly 1 ms or an additional 7 m of detonating cord. For a given driver mass and fixture configuration, gauge measurements permit reproducible synchronization to within a quarter of a millisecond. Delay detonators or delayed firing circuits are utilized for longer delay times (>14 ms).

THE GENERATOR CHARGE

The design of the nozzled pipe fixture represents a number of structural and configuration compromises to develop the desired stress pulse, while minimizing shock transmission and reaction gas fluctuations. The fixture dimensions naturally influence the risetime, droop, and decay time of the stress pulse. On the other hand, the generator mass tends to affect the pulse magnitude more than the characteristic time constants. The generator charge consists of plastic-coated detonating cord wrapped in a coil and installed in the center of the generator chamber. The desired coreload mass M (grams) is related to the detonating cord length Z (centimeters) and the mass density G (grains per foot) specified by the manufacturer according to the relation;

$$M(g)/Z(\text{cm}) = G(\text{gr}/\text{ft})/470.4.$$

Plastic-wrapped 40-gr/ft detonating cord is recommended for the nozzled pipe fixture; 25 gr/ft was our second choice. For the identical charge mass, much higher coreload densities result in stubby charges that tend to fracture the generator chamber. Much smaller coreload densities are less efficient because of the relative sheath losses.

Two generators were designed with substantially identical internal dimensions, and hence had similar performance characteristics except for their maximum charge limits. The recommended working limit of the regular-duty generator was a charge mass of 4.7 grams (55 cm of 40-gr/ft detonating cord). The recommended working limit of the heavy-duty generator was a charge mass of 10 grams (117 cm of 40-gr/ft detonating cord).

WORKING LIMIT TEST RESULTS

To determine whether or not the fixture stress pulse range was sufficient to desensitize mining explosives, single-shot tests were conducted at the recommended working limits for the generator mass.

Table 1. Working Limit Test Results

Charge Type	Generator Charge (g)	Reaction Result
Granular (NG)	0.0	DET
	4.7	NR
	10.0	NR
Granular (no-NG)	0.0	DET
	4.7	RUPT
	10.0	NR
Emulsion	0.0	DET
	4.7	W-DET
	10.0	NR
Semi-Gel (NG)	0.0	DET
	4.7	DET
	10.0	DET
Water-Gel	0.0	DET
	4.7	NR
	10.0	NR

Zero generator charge masses (no stress pulse) were run on charges that malfunctioned to confirm charge performance for water-submerged conditions during the nominal set-up time (roughly 20 minutes). Test results were categorized as no-reaction (NR), fixture rupture (RUPT), deflagration (DFLG), weak detonation (W-DET), or strong detonation (DET). When there were four or more cylindrical wall receiver-pipe fragments, the result was recorded as a strong detonation (DET). For two or three such fragments, the result was recorded as a weak detonation (W-DET). For a split-pipe or blown-off cap, the result was recorded as a tube rupture (RUPT) or a deflagration (DFLG). Tube rupture indicates there was still some unreacted explosive, while deflagration indicates no residual explosive. No-reaction (NR) was reserved for cases where the cylindrical pipe was intact and no reaction was observed. Explosives with nitroglycerin or explosive oil type sensitizers are designated NG.

With the exception of the semi-gel, all the explosives tested showed reduced performance or were totally desensitized. Further testwork with smaller generator charge masses determined the critical level for which the various explosives retained their detonability. The two granulars retained strong detonation characteristics for generator charge masses under and at 3.3 grams. The water-gel criterion was 2.2 grams and the emulsion criterion was 1.5 to 2.2 grams generator charge mass. In retrospect, the stress pulses thus far were not realistic simulations. The stress was 75% too high and the pulse duration 100% too short.

The working limit results and the reduced charge tests showed that most permissible mining explosives would be desensitized within the working range of the nozzled pipe fixture. Rationally content with the preliminary fixture design, our next imperative was to measure actual stress-time waveforms in coal strata under typical or worst-case conditions suggested by scheduled regulations.

COAL MINE CRITERIA

Realistic stress time waveforms for dynamic desensitization analysis were obtained with four shots in the Bureau of Mines Bruceton coal mine. Shooting conditions were discussed with MSHA (Mine Safety and Health Administration, U. S. Department of Labor) and worst case conditions permitted under Federal Coal Mine Regulations (CFR, 1983) were selected including shooting-off-the-solid. Two parallel boreholes were drilled 4.45 cm in diameter and 274 cm long with a horizontal center-to-center separation of 45.7 cm (minimum "burden"). The outside borehole closest to the drift wall(s) was charged with 1360 grams of water-gel explosive (maximum weight). Four resistance-type pressure gauges were submerged in separate waterbags and installed in the uncharged borehole at depths matching the charge column. Both boreholes were clay-stemmed to within 25 cm of the charge surface. Table 2 shows the impulse (WHH) and the rectangular pulse equivalent pressure (RPEP) for the seven worst stress pulses recorded during the four shots (four gauges each time); RPEP = IMPULSE/WHH.

The mean WHH is determined by averaging reciprocal WHH results. The last row of results determines the "in-water" criteria for setting up the simulator.

Coal mine tests [Mainiero, 1984] with multiple borehole charges and different time delays were fired under similar conditions, except that the boreholes were shorter and the distance from the collar to the charge was smaller. Malfunctions from no-reaction to weak reactions were noted for certain explosives, time delays, and hole separations. The charged borehole with zero time delay removed substantially more coal than observed in our criterion measurement tests. Nonetheless, the results [Mainiero, 1984] strongly suggest that the requisite conditions for marginal performance were created by stress waveforms similar to those recorded in the instrumented borehole tests. Utilizing the above results in Table 2, the nozzled pipe fixture was reconfigured to deliver similar stress-time waveform characteristics.

THE STANDARD "WORST-CASE" PULSE

Standard pulse waveforms were obtained by modifying the nozzled pipe fixture to yield the worst-case coal mine waveform

Table 2. Worst Stress Pulses From Coal Mine Shots. RPEP = IMPULSE/WHH

	Impulse (bar.ms)	WHH (ms)	RPEP (bar)
	113	1.350	84
	126	1.175	104
	186	0.475	393
	138	0.525	264
	62	0.250	248
	72	0.225	319
	206	0.425	484
MEAN	129	0.427	271

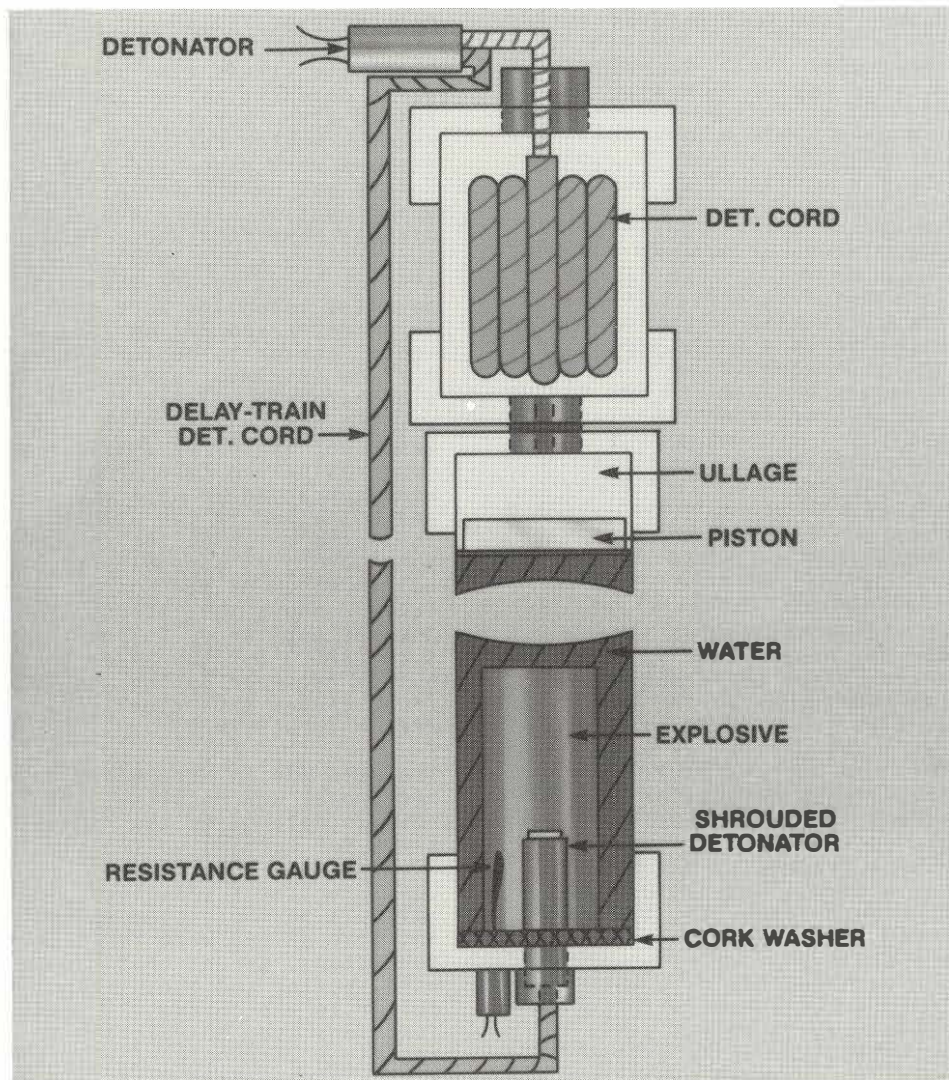


Figure 1. Nozzled Pipe Fixture

characteristics. The receiver chamber was filled with water only (no sample charge), corresponding to the criterion measurement conditions. The nozzled pipe fixture with a 17-cm receiver was reconfigured (nozzles, chamber, ullage dimensions) and the receiver pipe increased to 44 cm. The generator charge required to develop the simulation stress pulse was 4.0 grams. Reflected waves and reflected wave times were weaker and more dispersed in the 44-cm fixture, while the dominant (first) pulse had a more rectangular profile. The resulting waveform (first pulse) simulated the worst-case coal-mine criteria. Unfortunately, the updated hydraulic characteristics weakened the relationship between waveform characteristics and generator charge mass. Therefore, comparisons of data from dissimilar fixtures with similar driver charges are not warranted. The final configuration results were tabulated as means and relative deviation (standard deviation divided by the mean).

The mean impulse was 120 bar·ms with a relative deviation of 24%. The width-at-half height (WHH) was 520 μ s or 0.52 ms, with a relative deviation of 10%.

The rectangular pulse equivalent pressure (RPEP) was 230 bars, with a relative deviation of 7.3%. The resulting means compare reasonably well to the impulse = 129 bar·ms, WHH = 0.427 ms, and RPEP = 271 bars for the coal shots. The relative deviation of waveform parameters under simulation conditions were substantially smaller than the relative deviation of waveform parameters from the coal mine data. Further refinements to the fixture were not warranted. The database is still rather small and additional coal mine shots could yield somewhat different criteria. Nonetheless, the results provide magnitude estimates representative of the more severe blasting conditions consistent with MSHA regulations.

FIFTEEN-MILLISECOND DELAY SHOTS

There was considerable interest in test results for which charge detonation was delayed 15 ms, roughly half of the delay time of the first-period delay detonator. Maintaining coal mine simulation, eight permissible explosives were tested four times for statistically probable malfunctions. The results recorded in

Table 3. Dynamic Pressure Desensitization Results (15-ms Delay)

Explosive	Shot#1	Shot#2	Shot#3	Shot#4
Water-Gel Emulsion	W-DET RUPT	W-DET W-DET	W-DET RUPT	W-DET DET
Emulsion	W-DET	NR	NR	RUPT
Emulsion	W-DET	W-DET	RUPT	W-DET
Granular	W-DET	W-DET	W-DET	W-DET
Granular	DEFL	W-DET	W-DET	W-DET
Semi-Gel	W-DET	W-DET	DET	DET
Semi-Gel	DET	DET	DET	DET

Table 3 indicate that some explosives are desensitized more readily than others. The classification DET, W-DET, DFLG, RUPT, and NR, and no-reaction is the same as in Table 1. There were no other results except for two malfunctions where the shroud was not split (trifurcated or worse) in the usual fashion; the two questionable shots were redone. There was a fifth shot in each case for zero driver charge mass (no stress pulse); the results were strong detonations.

Taking the results in four groups, the semi-gels were the hardest to desensitize, the water-gels and granulars were next, and the emulsions were most prone to desensitization.

CONCLUSIONS

The nozzleed pipe fixture has successfully produced stress-time waveforms representative of the underground coal-mine stress waves from an adjacent borehole blast. The nozzle pipe fixture not only has filled the gap between shock-wave techniques and quasi-static techniques but most importantly enables us to study desensitization phenomena under realistic interaction conditions. Both the prototype configuration and the modified configuration generated sufficiently severe worst-case stress-time waveforms to totally or partially desensitize most of the permissible coal-mine explosives tested. Only one semi-gel continued to function normally. The nozzleed pipe fixture design and working range appear sufficiently flexible to study a range of coal mine blasting conditions, including worst-case adjacent borehole conditions (our interpretation); maximum charge 1.36 kg and minimum separation 45.7 cm. Our worst case criterion was determined by the seven strongest results measured in four shots in a coal seam with four pressure gauges in each shot. The mean impulse, width-at-half-height (WHH), and their ratio to the rectangular pulse equivalent pressure (RPEP) were 129 bar·ms, 0.427 ms, and 271 bars, respectively. The modified nozzleed pipe fixture yields a mean impulse, WHH and RPEP of 120 bar·ms, 0.520 ms, and 230 bars, respectively. Considering the large deviations of the experimental coal mine results, further adjustments were not warranted.

When the dynamic desensitization results from Table 3 are combined with those of Table 1, ignoring the zero driver masses cases, there are 42 results: 9 strong

detonations, 19 weak detonations, 1 deflagration, 5 tube ruptures, and 8 no-reactions. Tube ruptures probably occurred when some explosive close to the charge detonator functioned but the remote portion did not. They resembled no-reactions most closely. The desensitization was regarded as severe when there was residual unreacted explosive, which occurred for 31% of the shots. The weak detonations (and single deflagration) represent a milder form of desensitization which was observed for 48% of the shots. This was rather remarkable considering the restricted conditions (2 or 3 fragments) defining our results. The remaining 21% were recorded as strong detonations indicating that any desensitization was not critical to performance.

The nozzleed pipe fixture has a distinct advantage over field tests when the desensitization is marginal and standard (weak) detonations occur. The nozzleed pipe fixture distinguishes the reduced performance, whereas field tests would be difficult to resolve, since weak detonations fracture and move coal. Furthermore, the nozzleed pipe fixture has the design range to investigate problems involving severe desensitization. The severe desensitization results might explain the unreacted or partially burnt cartridges occasionally noted in mucking and recovery operations. Perhaps most importantly, the nozzleed pipe fixture is a useful tool with the potential for evaluating different types of explosive performance characteristics under a wide range of controlled conditions at a cost substantially smaller than corresponding field tests.

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LA SENSIBILITE RELATIVE DES EXPLOSIFS DE SECURITE A DESENSIBILISATION PAR PRESSION DYNAMIQUE

M.S. Wieland (Etats-Unis)

RESUME Dans le tir à retard, les ondes de contrainte produites par la détonation des charges dans les trous de mine peut désensibiliser les charges voisines. On a simulé cette interaction de pression - charge au moyen d'une tube à tuyère destructible dans laquelle on soumet l'explosif essayé à l'impulsion de pression produite par une charge d'explosif dans une chambre voisine, tant en contrôlant l'amplitude et la durée de l'effet par la masse de la charge, l'espace libre dans la chambre et le diamètre de la tuyère de liaison. On a étudié cinq types d'explosif.

RELATIVE EMPFINDLICHKEIT VON ZULASSIGEN SPRENGSTOFFEN BEI DER DYNAMISCHEN DRUCK-DESENSIBILISIERUNG

M.S. Wieland (USA)

ZUSAMMENFASSUNG Druckwellen von Detonationen von Bohrlochchargen können neben verzögerten Chargen desensibilisiert werden. Die Simulation dieser Druckimpuls-/Chargenwechselwirkung wurde mit einem zerstörbaren Düsenrohr erzielt, bei dem der geprüfte Sprengstoff dem von einer Sprengstoffcharge in einer benachbarten Kammer erzeugten Druckimpuls ausgesetzt ist, wobei Amplitude und Dauer von Chargenmasse, Kammerleerraum und Durchmesser der Verbindungsdüse bestimmt werden. Es werden fünf verschiedene Sprengstoffe geprüft.

ОТНОСИТЕЛЬНАЯ ЧУВСТВИТЕЛЬНОСТЬ ПРЕДОХРАНИТЕЛЬНЫХ ВЗРЫВЧАТЫХ ВЕЩЕСТВ К ДЕСЕНСИБИЛИЗАЦИИ ОТ ДИНАМИЧЕСКОГО ДАВЛЕНИЯ

M.C. Уиланд (США)

Волны напряжений от взрывания шпуровых зарядов способны десенсибилизировать соседние замедленные заряды. Это взаимодействие между импульсом напряжения и зарядом было моделировано с помощью разрушаемой трубчатой установки, снабженной соплом. В этой установке исследуемое ВВ подвергается импульсу напряжений, созданному взрыванием заряда в смежной камере. Величина и продолжительность импульса обусловлены весом заряда, величиной незаполненного объема камеры и диаметром сообщающего сопла. Было исследовано 5 типов ВВ.

安全炸药对冲击压力退敏作用的相对敏感性

M.S. 威厄兰德 (美国)

摘要: 钻孔装药的爆燃应力波能够降低毗邻定时炸药的敏感性。这种应力脉冲负载相互作用的模拟试验, 用的是—段不破坏的, 装上喷嘴的管子, 管中炸药受到毗邻的一个燃烧室中的炸药产生的应力脉冲的影响, 其范围和持续时间受装药量, 燃烧室缺量与连接喷嘴的直径的控制。进行了各种类型的爆炸试验。

認可内爆発物のダイミツク圧力減感への相対的感度

M.S. ウィーランド (アメリカ)

梗概: 試掘穴装薬の発火からの圧力波は、近くの発火の遅くなった装薬を減感することからできる。この圧力、振動、チャージ相互作用の模擬実験は一本の破壊可能な筒口パイプにより達成される。そのパイプの中には、テスト中の爆発物が、近くの部屋での爆発装置により起された圧力を受け入れるようにおかれ、振幅と時間は装薬質量、残室、と接続する筒口の直径によりコントロールされている。5種類の爆発物のパイプがテストされた。

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