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SENSITIVITY OF EXPLOSIVE LOADED ORDNANCE (U)

Jacob Savitt

Explosiform, Inc.

TECHNICAL REPORT AFATL-TR-67-134

OCTOBER 1967

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FOREWORD

(U) This report "Sensitivity of Explosives Loaded Ordnance", by EXPLOSIFORM,INC., San Francisco, California was prepared under Air Force Contract No. AF 08(635)-5606, Project No. 2511. It describes studies of the effects of systems parameters upon the sensitivities of explosives and explosives loaded ordnance to shock and impact. The need for such information is becoming increasingly greater as more sophisticated conventional explosives ordnance items which employ delayed fusing for hard target penetration are required.

(U) This report contains no classified information extracted from other classified documents.

(U) The work was administered under the direction of Mr. Carl Kyselka and Lt. Jack Trossbach of the Air Force Armament Laboratory (ATWT), Eglin Air Force Base, Florida.

(U) The research program was conducted by EXPLOSIFORM,INC. under the technical direction of Mr. Jacob Savitt. Additional personnel who made significant contributions to the research effort were Mr. Robert E. Conover and Miss Carolyn Findley of EXPLOSIFORM,INC. and Capt. Nicholas Leone of DAD.

(U) This report covers work performed from 8 February 1966 to 28 April 1967.

(U) This technical report has been prepared and marked in accordance with the DOD Industrial Security Manual by the contractor.

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(U) This technical report has been reviewed and is approved.

fr Noble E. Brown
GEORGE P. BRENNER, Colonel, USAF
Chief, Weapons Division

UNCLASSIFIED ABSTRACT

(U) The effects of systems parameters upon the sensitivities of explosives and explosives loaded ordnance were studied by exposing simple steel-shielded systems to the direct contact detonation of large length-diameter ratio cardboard-confined cylinders of NITROGUANIDINE and TNT and to the impact of high velocity steel discs. The steel-shielded explosive appeared more sensitive when loaded at a high density than when loaded at a lower density. In addition, when initiating impulses were of longer duration, lower pressures were capable of detonating the acceptor explosives.

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SECTION I

INTRODUCTION

(C) Detonations of bombs delivered from very low altitudes must be delayed(1) until the aircraft delivering them are outside the lethal radii of the bombs. If the targets are soft and the speeds of the aircraft are slow enough so that impact velocities and pressures are low enough, these delays may be accomplished by the use of mechanical and/or electrical delay fuses and/or bomb retardation systems such as parachutes. However, if aircraft speed is very great, or if hard targets are involved,(2) the pressures developed in the bombs at impact may be very great. These pressures can be so great, that premature detonations will result, even though fuzes which can survive and function properly are used. These premature detonations have been found to be due to the inability of the main charge explosives to withstand the high pressures developed during impact.

(U) Sometimes premature detonations occur even at lower impact pressures because the bomb structure is mechanically not strong enough to survive impact and penetration. Bomb breakup(3) then results in localized pinching of thin layers of explosives or in other localized concentrations of energy sufficient to initiate self-propagating reactions which develop into vigorous deflagrations or detonations.

(C) The search for new and effective main charge explosives or explosives mixtures which are sensitive enough to be reliably detonated by ordinary explosives trains but insensitive enough to withstand hard target high velocity impact, with or without bomb breakup, has so far been unsuccessful.

(U) In order to optimize the design of explosives loaded ordnance to withstand high velocity impact, the sensitivity as well as the output of the main charge secondary high explosive must be known. How to measure this sensitivity is a major problem since the sensitivities and order of sensitivity of explosives depend overwhelmingly upon the characteristics of the entire system of which the explosive is only one part. Completely reliable measurements of explosives sensitivity can only be made when the explosive is loaded into the actual system of interest and tested full scale under actual conditions of use.

(C) For large bombs or other costly explosive loaded ordnance, this is not always economically possible. Only part of the economic problem is the high cost of the ordnance items. Sometimes the major cost of tests of impact sensitivity of explosive loaded ordnance is the cost of accelerating the ordnance to the impact test velocity. When we note that velocities of interest are of the order of 1000 or 1500 ft/sec and higher, we can see that aircraft or rocket sledtracks are required to bring ordnance weighing only a few hundred pounds to impact test conditions. Such tests(4,5) are very costly.

(C) Various alternative test systems have been suggested and tried. These include tests in which explosives samples are exposed to impact by falling weights(6) or to nearby detonations of other explosives(7,8), tests in which explosives are exposed to impact by bullets(9) fired from guns, tests in which explosives are exposed to impact by plates(10) or fragments accelerated by other explosives charges, tests in which explosives are loaded into modified small mortar shells and fired against controlled targets(11), and tests in which special idealized small scale containers are loaded with explosives and fired from smooth-bore guns(12) against controlled targets. None of these tests use complete or full scale bombs or similar explosive loaded ordnance.

SECTION II

THE DIRECT CONTACT DETONATION EXPLOSIVES SENSITIVITY TEST

(U) The direct contact detonation explosives sensitivity test(13) was first used to measure the sensitivities of small pressed pellets of explosives to explosives generated pressure pulses of short but controlled duration. The results of these tests indicated that meaningful and reproducible information could be obtained for ordering explosives with respect to their sensitivities to detonation by other explosives. Later(14), this test was used to measure the relative sensitivities of eight-pound cast bare charges of TNT, H-6, PICRATOL and TRITONAL to aid in choosing between them for use in an anti-bridge bomb which was designed to be delivered from a low flying high speed aircraft. This bomb was designed to impact and penetrate normal ground or road surfaces at supersonic speed without detonation or breakup to an optimum depth near a bridge abutment before detonation. This emplacement would result in maximum bridge damage per bomb expended.

(C) The direct contact detonation explosives sensitivity test indicated that the order of sensitivity was H-6, TNT, PICRATOL, and TRITONAL with H-6 the most, and TRITONAL the least, sensitive. These results were in agreement with full scale bomb impact sensitivity tests(1,3,4).

(U) More recent studies (15) of the effect of systems parameters using the direct contact detonation explosives sensitivity test indicated that the test could reliably and reproducibly detect effects of explosive loading density, size, and confinement upon critical pressures required for sample detonation.

(U) The test systems used for these studies are illustrated in Figures 1 and 2. In these systems, shock waves of varying peak pressure amplitudes are generated by the detonation of the cardboard confined long length-diameter cylinder of NITROGUANIDINE loaded to various densities. The sample explosives of interest are exposed to these calibrated shock waves and their sensitivities to them are observed.

(U) The peak pressure, P_s, of a shock wave which is transmitted into a sample exposed to the detonation of a NITROGUANIDINE charge in an arrangement like that of Figure 1 or Figure 2 is

$$P_s = 2P\rho_s U_s/(\rho_s U_s + \rho D) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where P is the detonation pressure of the NITROGUANIDINE, ρ_s is

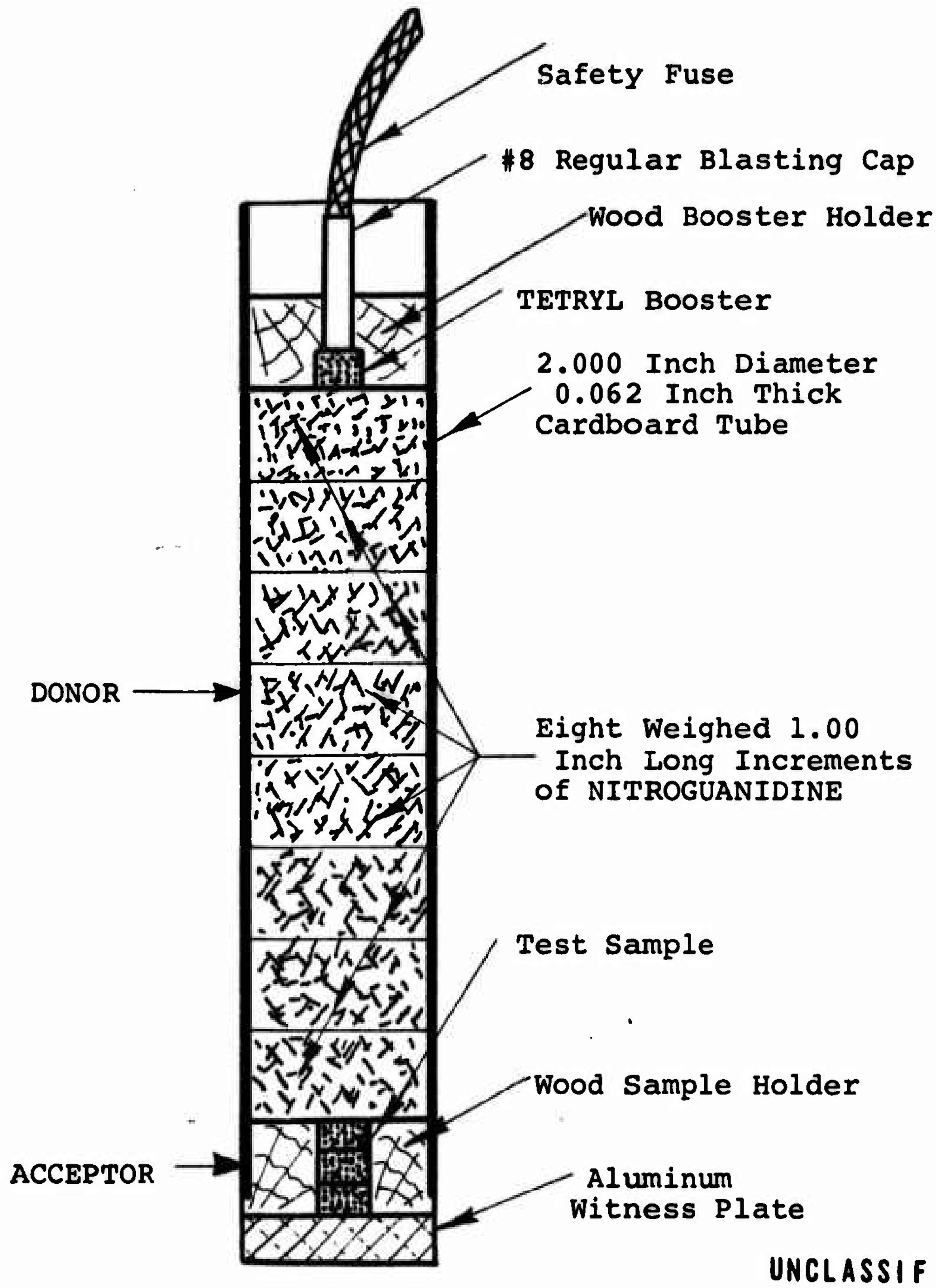

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Figure 1. Direct Contact Detonation Explosives Sensitivity System for Small Pressed Samples

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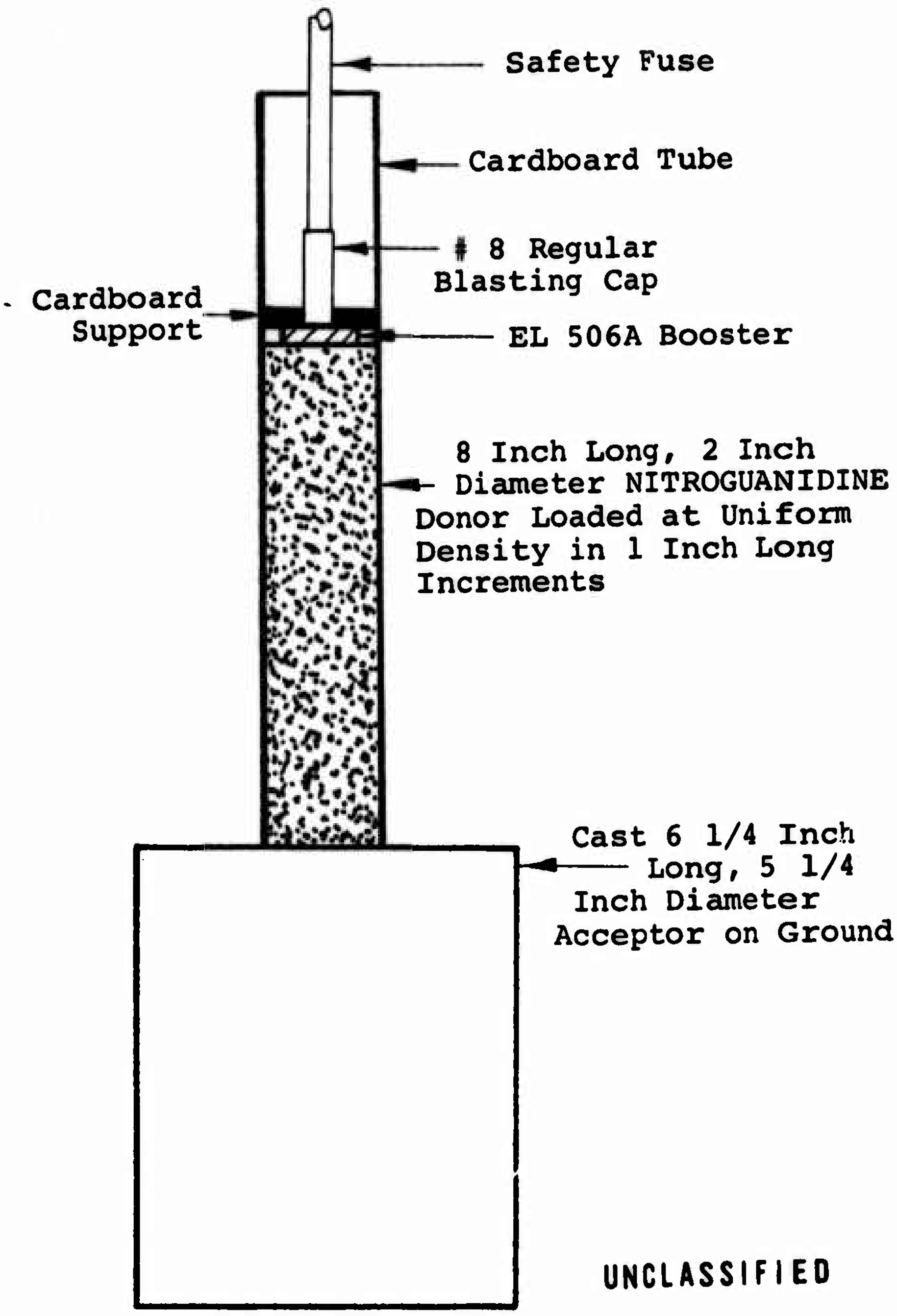

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Figure 2. Direct Contact Detonation Explosives Sensitivity Test System for Large Cast Samples

the density of the sample, U_s is the velocity of longitudinal compression waves in the sample, ρ is the loaded density of the NITROGUANIDINE, and D is its detonation velocity.

(U) When the units of ρ are expressed in gm/cc, the units of D in cm/μsec, and the units of P in kilobars,

$$D = 0.144 + 0.402\rho \quad \ldots\ldots\ldots\ldots (2)$$

and

$$P = 1/4\ \rho D^2 \quad \ldots\ldots\ldots\ldots (3)$$

(U) If the sample is steel (for example, the steel of a bomb case), P is the pressure of the shock wave transmitted into the steel case when NITROGUANIDINE loaded at a density equal to ρ is detonated in direct contact with the steel and the detonation wave strikes the steel at right angles to its surface.

(U) Since NITROGUANIDINE can be loaded to densities as low as about 0.1 gm/cc, detonation pressures as low as about one kilobar may be generated in it. By increasing the loading density and/or by using other appropriate C-H-N-O explosives, pressures greater than 100 kilobars may be generated without difficulty.

SECTION III

AN APPLICATION FOR THE STUDY OF THE SENSITIVITY OF EXPLOSIVE LOADED ORDNANCE

(U) NITROGUANIDINE systems similar to those shown in Figures 1 and 2 may be used to generate pressure pulses in full size steel bomb cases and in the cases of other explosives loaded ordnance items to simulate those experienced by such items when they impact with various targets of interest such as soils, rocks, concrete, and steel. It may thus be possible to use these NITROGUANIDINE generated pressure pulses to observe and measure the impact sensitivities of explosives loaded ordnance items such as bombs without dropping them from aircraft or hurling them against targets from rocket sleds. The results of such tests will of course be applicable only to those bombs which are designed to and which successfully can, penetrate their targets without mechanical breakup.

(U) Should air drop or sled impact tests confirm the validity of such simulations, it is highly probable that experiments with bomb segments or simulated or scaled bombs will yield data of useful reliability with even greater savings.

SECTION IV

PRESSURES GENERATED BY HIGH VELOCITY IMPACT

(U) When a high explosive loaded bomb strikes a target at a high velocity, high pressure shock waves are generated which propagate through the target and into the bomb. For such waves, the laws of conservation of mass and momentum require that

$$\rho_1/\rho_0 = U(U-u) \quad . . . . \quad (4)$$

and

$$P = \rho_0 Uu \quad . . . . \quad (5)$$

where ρ_0 is the density of the undisturbed medium, ρ_1 is the density of the medium immediately behind the shock wave, U is the velocity of the shock wave, u is the velocity of particles immediately behind the shock wave and P is the pressure immediately behind the shock wave.

(U) Two waves are generated at impact. One of these waves moves forward into the target; the other moves in the opposite direction into the bomb. If the amplitude of this shock wave is large enough, the bomb will be detonated.

(U) Given the relationships of Equations (4) and (5), the boundary conditions that the pressure and particle velocity must be continuous across the bomb-target interface, and the experimental relationship between pressure and particle velocity for the materials of bomb and target, it is possible to determine pressures generated in the bomb at impact by using simple graphical methods(16,17,18).

(U) The determination of pressures generated at the interface between a steel cased bomb and targets of tuff, grabbo rock and steel, when the velocity of impact is 500, 1000 and 1500 ft/sec, is shown in Figure 3 and illustrates the method.

(U) First the Hugoniot relationships, P = P(u), are plotted for the target materials of interest (i.e. for steel, grabbo rock and tuff); then the reverse Hugoniot relationship, P = P(v-u), is plotted for the steel cased bomb for the impact velocities, v, of interest.

(U) Tuff is low density volcanic rock. Grabbo is high density lava. These materials were chosen because P,u data was available for them and because their properties may bracket normal target terrain properties. Steel is not only the normal bomb casing, it is also the common target material of railroad tracks,

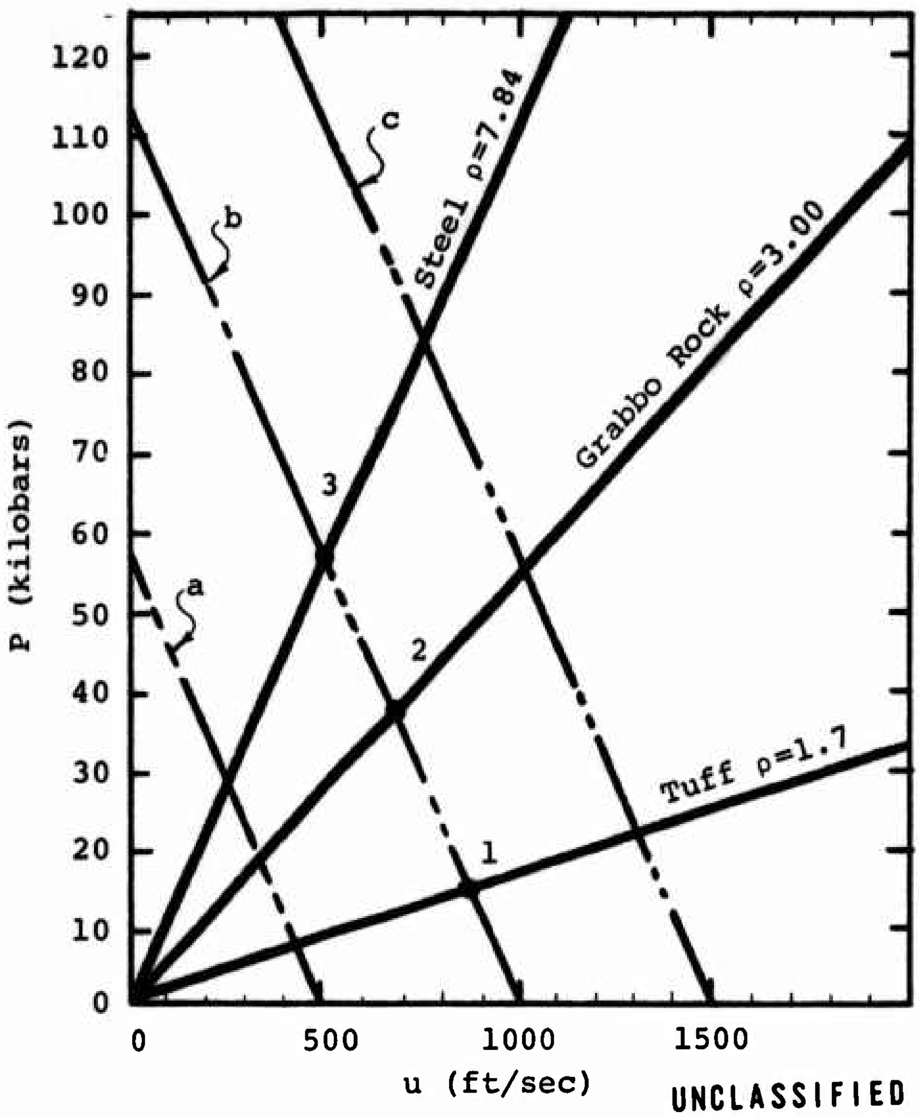

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Figure 3. Pressure - Particle Velocity Relationships

(Hugoniots for steel, grabbo rock, and tuff targets and reverse Hugoniots for steel-cased bombs impacting at a) 500, b) 1000, and c) 1500 ft/sec) bridges, etc. The data shown are extrapolations from higher pressure data obtained at LASL.

(U) P = P(v-u) is the reflection of the P = P(u) data in the P axis. It is identical to the P = P(u) reflection but is displaced parallel to itself on the u axis so that the P = 0 point is at u = v instead of at u = 0.

(U) At the intersections of the reverse Hugoniot for the steel bomb, and the Hugoniots for the targets, the pressures and particle velocities are the same in bomb and target. Thus, (see Figure 3) at an impact velocity of 1000 ft/sec, shock pressures of 15 kilobars (intersection point 1), 37 kilobars (intersection point 2) and 56 kilobars (intersection point 3), respectively, are generated in a steel bomb casing upon impact with tuff, grabbo rock and steel targets.

(U) The relationship between P_s, the magnitude of the shock wave pressure generated in a steel bomb case due to the direct contact detonation with it of NITROGUANIDINE and the density, ρ, of the NITROGUANIDINE may be determined by using Equations (1), (2), (3) and (5) and the P,u data for steel from Figure 3. (The magnitude of $\rho_s U_s$ may be determined from Equation (5) and the steel Hugoniot of Figure 3 and is equal to 3.74 gm/cm^2μsec.) The results of such calculations are shown in Figure 4. In this way we find that the direct contact detonation of NITROGUANIDINE test charges loaded at densities of 0.36, 0.56, and 0.69 gm/cc will simulate the pressures (i.e. 15, 37 and 56 kilobars, respectively, as calculated in the previous paragraph) generated in these bombs by their respective impacts with tuff, grabbo rock and steel at a velocity of 1000 ft/sec.

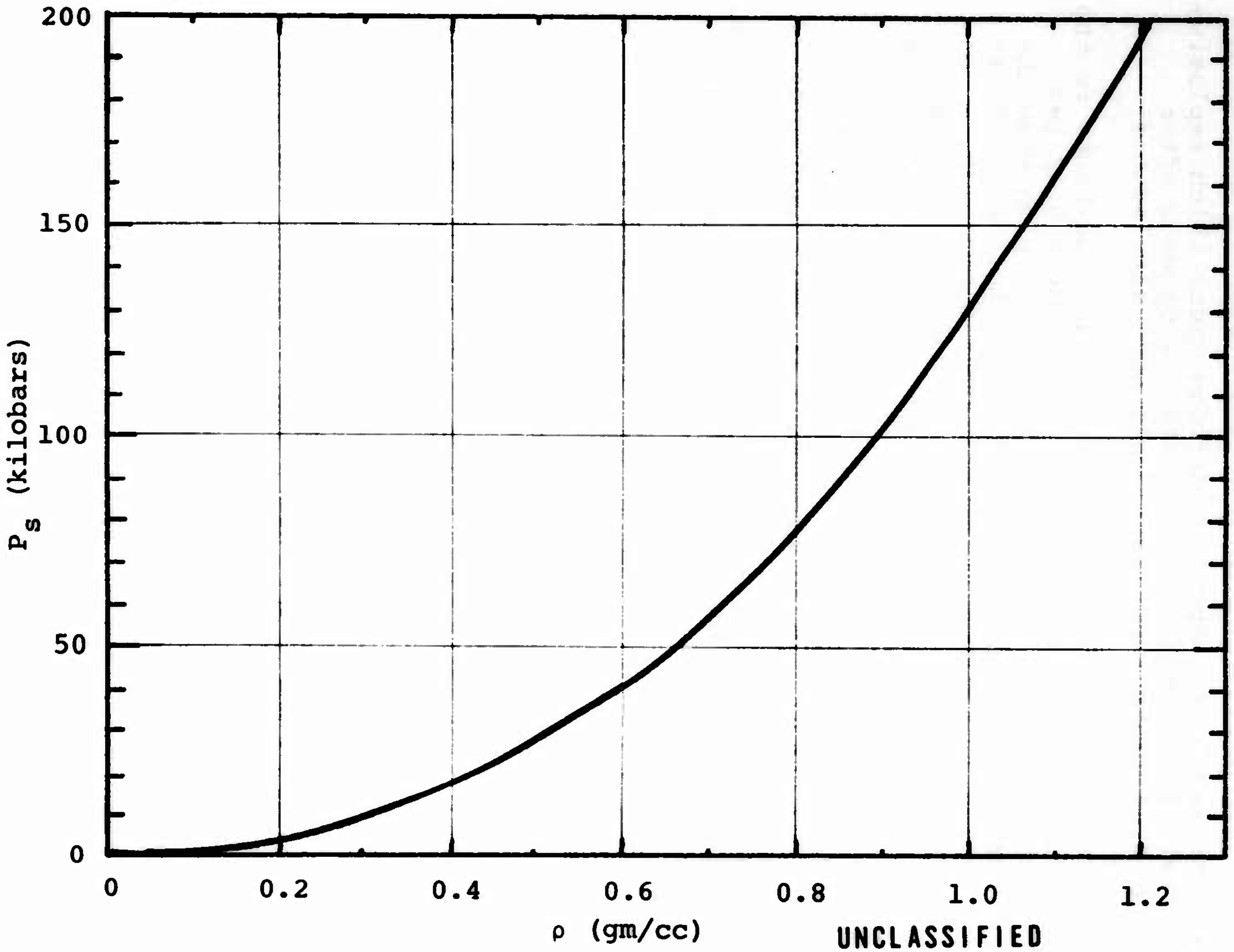

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Figure 4. Pressures, P_s, Generated in Steel by the Direct Contact Detonation of NITROGUANIDINE Loaded at Densities, ρ

SECTION V

THE PREDICTION SCHEME

(U) Predictions of the impact conditions under which explosive loaded steel cased bombs will detonate may be made after simple and straightforward experiments and calculations as follows:

A. Expose bombs or appropriately simulated bombs tc the direct contact detonation of NITROGUANIDINE test charges and determine the relationship between the magnitude of the NITROGUANIDINE generated pressure wave and the probability of bomb detonation.
B. Use the Hugoniot data for the bomb case and target materials of interest and determine the magnitudes of the pressure waves generated under various conditions of impact with these targets.
C. Hypothesize that the probability of detonation at impact is equal to the probability of detonation in the direct contact detonation sensitivity test when equal pressures are generated in the bomb case.
D. Test the hypothesis in C by actual impact tests.

SECTION VI

SCOPE OF EXPERIMENTAL STUDIES

(U) Because neither bombs nor warheads for the tests indicated in A and D of SECTION V were made available for testing, major program effort was devoted instead to the study of the effects of systems parameters upon the sensitivities of explosives and explosives loaded ordnance to shock and impact. The information from such studies will be required for the efficient design of experiments with full size explosives loaded ordnance items when these are made available for testing.

SECTION VII

BOMB CASE THICKNESS EFFECTS

A. Experimental Arrangement

(U) An exploratory investigation of the effect of bomb case thickness upon the response of the explosive to the pressure induced in a steel bomb case was conducted using the simplified acceptor systems shown in Figure 5.

(U) Two different methods were used to generate initiating pressure pulses in the acceptor system. In one, (see Figures 5 and 6) pressure pulses were generated in the acceptors by the direct contact detonation with them of large length-diameter ratio charges of TNT or NITROGUANIDINE loaded to various appropriate densities in accordance with the relationships of SECTION II. In the other, (see Figure 7) pressure pulses were generated in the acceptor systems in accordance with the relationships of SECTION IV, by exposing these systems to the impact of steel discs hurled at them by special explosive projectors.

(U) The projector system is shown in Figure 7. It consists of a large length-diameter ratio cardboard confined cylinder of pressed NITROGUANIDINE, which upon detonation at one end, projects a steel disc in contact with the other end in an axial direction. The velocity to which the disc is accelerated depends upon the mass and dimensions of the disc and upon the density to which the NITROGUANIDINE is loaded(19). The results of measurements of disc velocities as functions of the projector explosive loading density and disc thickness are presented in Table I and Figure 8.

(U) The acceptor system consisted of a "sandwich" structure which usually contained a 1/2 inch long by 1/2 inch diameter explosive cylinder between a C1018 steel barrier and a witness plate of similar material. Barrier and witness plates were 2 1/8 inches in diameter. The witness plates were 0.119 inches thick but the barriers were 0.018, 0.029, 0.055, or 0.119 inches thick.

(U) The samples were oriented "on end" or "on side" as illustrated in Figure 5 for direct contact detonation tests (see Figures 5 and 6) but only "on end" for impact tests. For impact tests, (see Figure 7) the projectile was initially approximately 3 1/2 inches from the acceptor.

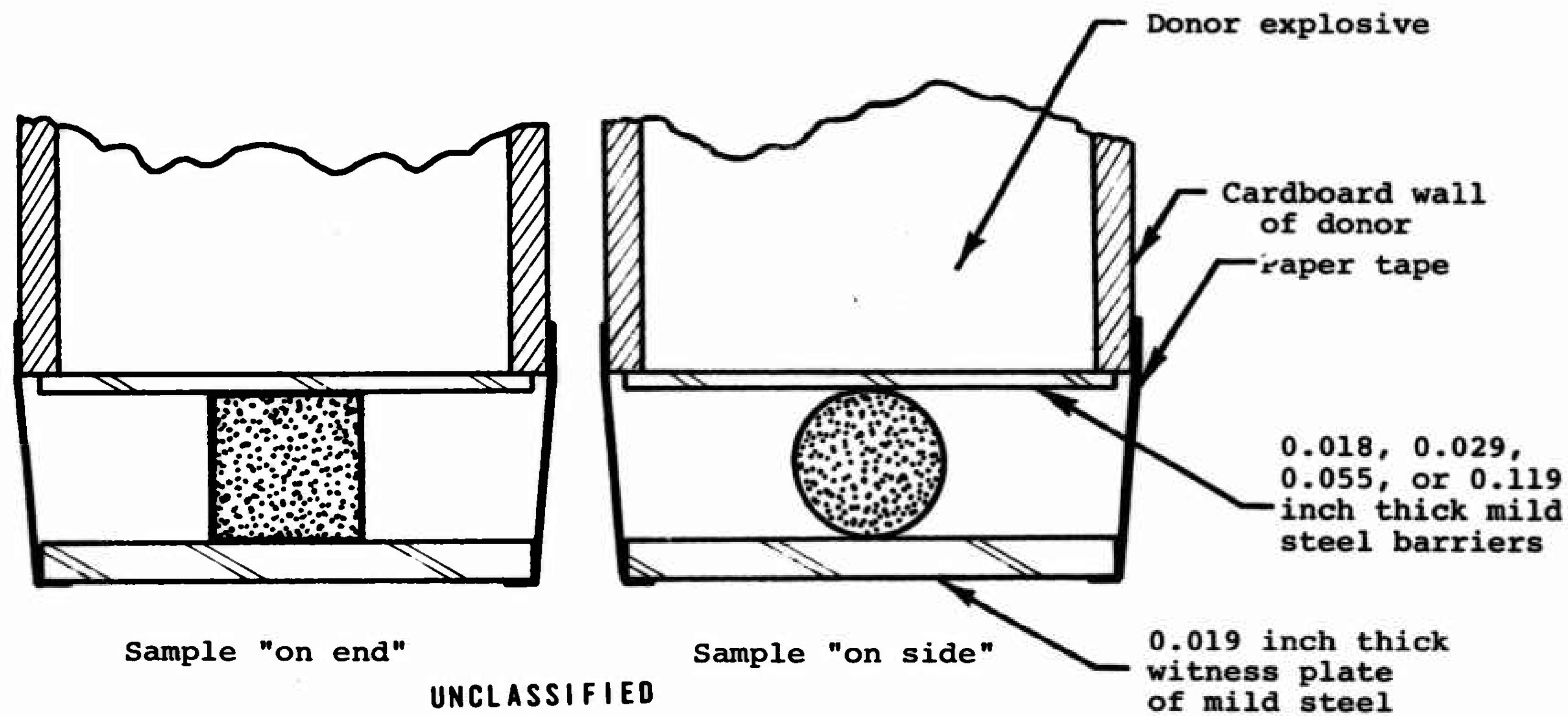

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Figure 5. Acceptor Systems

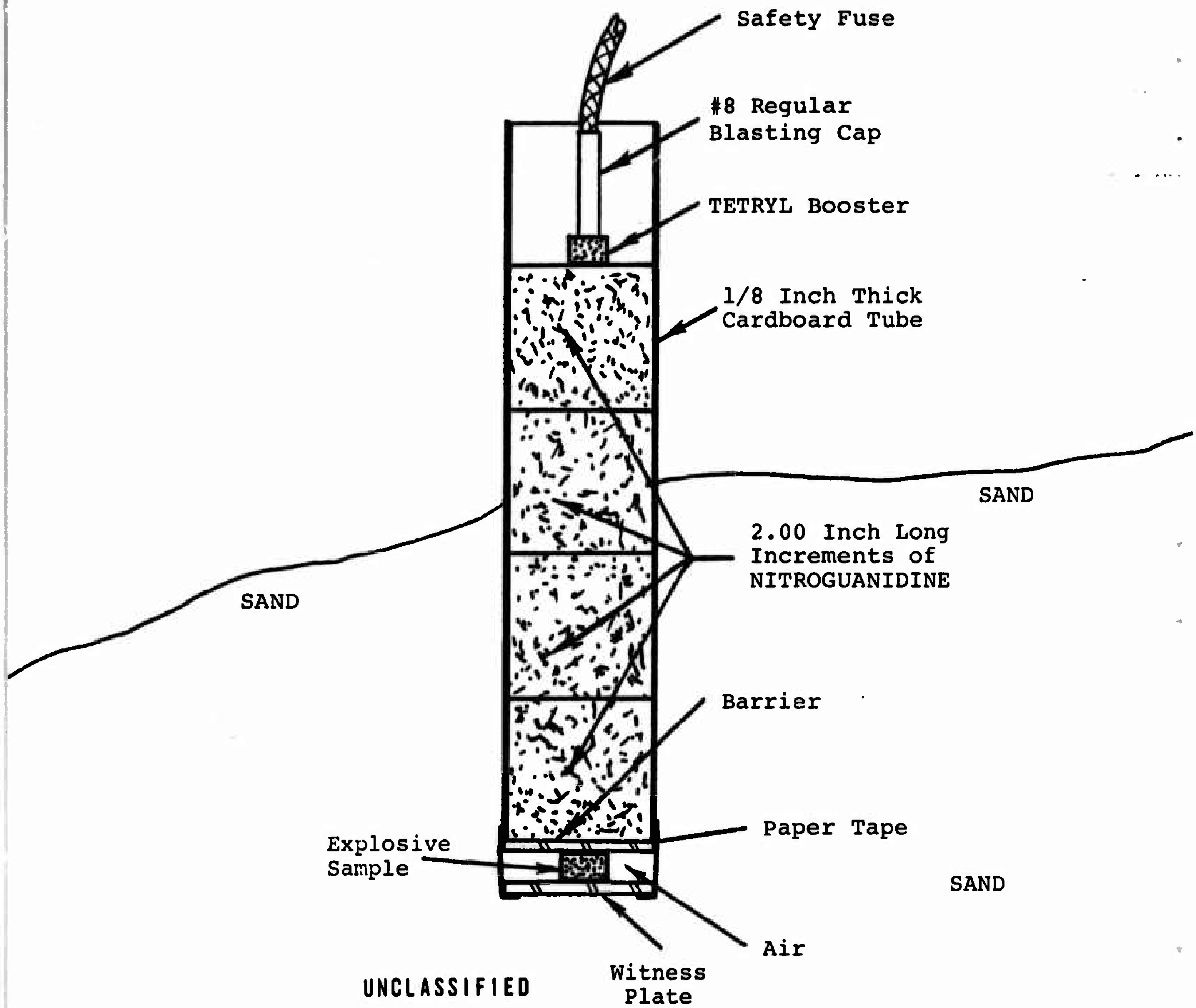

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Figure 6. Test Arrangement for Exploratory Studies

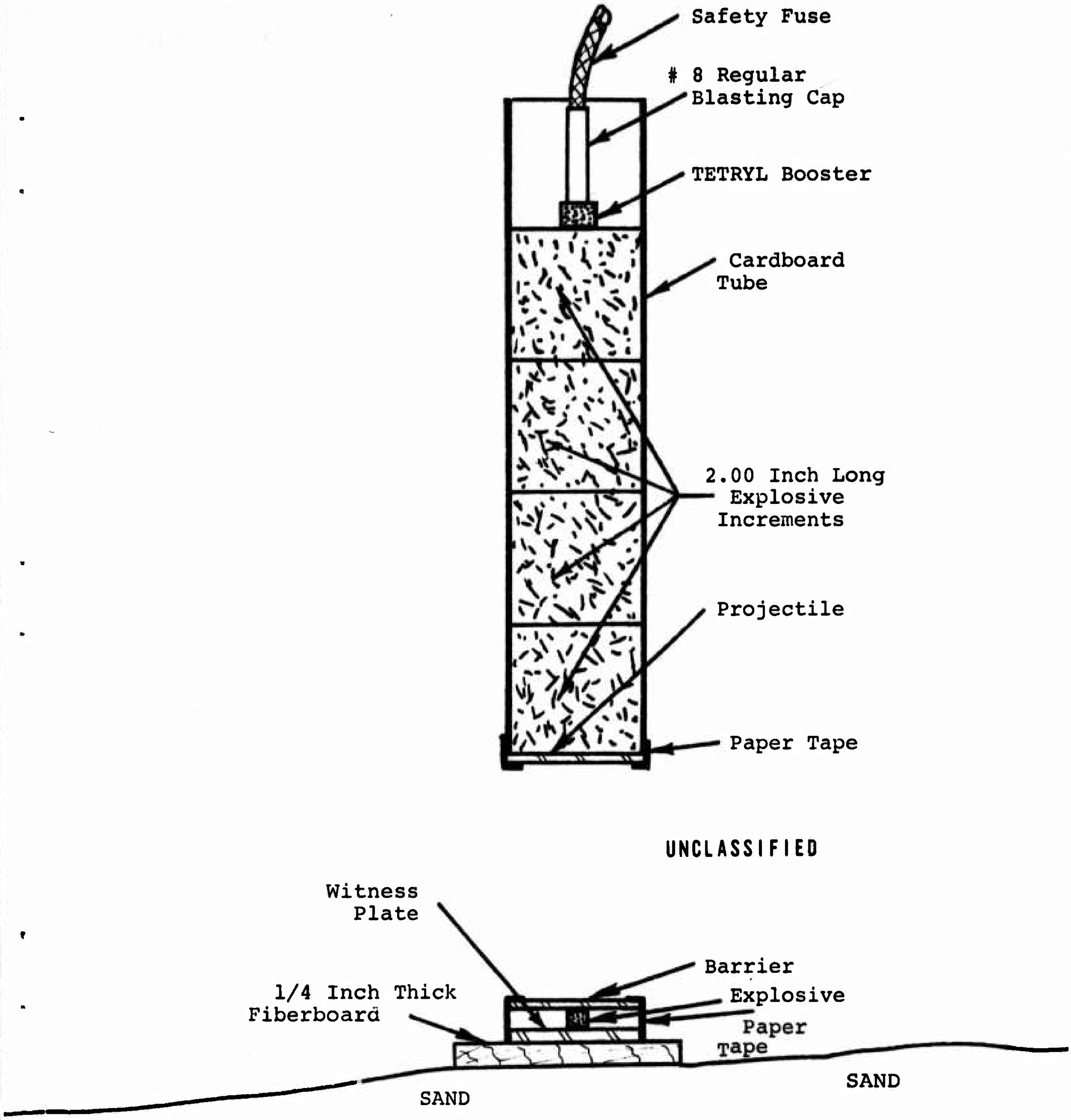

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Figure 7. Impact Test System

TABLE I. DEPENDENCE OF PROJECTILE VELOCITIES UPON NITROGUANIDINE LOADING DENSITY, ρ_{NQ}, AND PROJECTILE THICKNESS, a.

Shot No.	ρ_{NQ} (grains per increment)	a* (inches)	v (ft/sec)
53	300	0.119	773
54	400	0.119	966
55	300	0.119	860
56	400	0.119	980
57	500	0.119	1146
58	500	0.119	1147
59	600	0.119	1325
60	700	0.119	1454
62	1300	0.119	2415
78	600	0.373	432
82	1200	0.363	845
84	900	0.525	391
85	900	0.366	568
87	300	0.265	380
88	300	0.370	335
89	300	0.525	182
91	1200	0.495	563
92	1200	0.753	367
93	1200	0.266	1036
94	900	0.225	908
96	900	0.766	277
98	600	0.484	313
99	600	0.244	594
100	600	0.798	186
102	300	0.776	82
103	300	0.186	472
104	600	0.185	785
105	900	0.196	1030
106	900	0.182	913

* The 0.119 inch thick projectiles were 2 1/8 inches in diameter. All others were 2 1/4 inches in diameter.

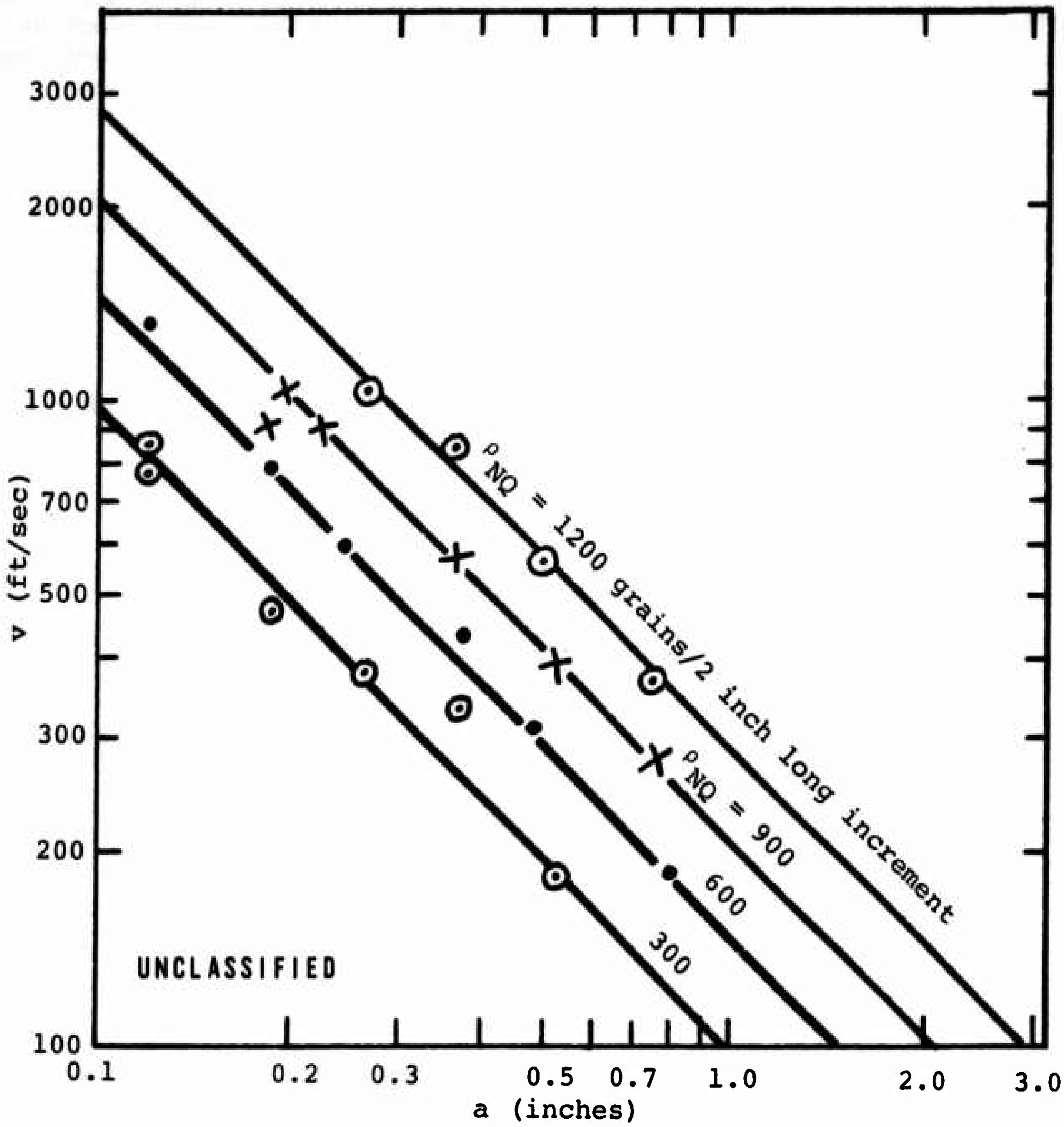

Figure 8. Variation of Projectile Velocity, v, with Projectile Thickness, a, and Projectile Explosive Density, ρ_{NQ}

(U) TETRYL which was used as the acceptor sample explosive for both direct contact detonation tests and impact tests was loaded at a density of 1.60 gm/cc. The cast materials were used as received from NOTS but were saw-cut to length with an accuracy of about ±1/16 inch.

B. Test Results

(U) The steel barrier discs of the acceptor systems of Figures 5, 6 and 7 simulate steel bomb cases. When donors loaded with TNT or NITROGUANIDINE at various loading densities ρ_{TNT} or ρ_{NQ} respectively, are detonated in direct contact with these acceptor systems, pressure pulses of magnitude P which depend upon the loading densities are generated in the barriers. The explosive samples react to these impulses in a variety of ways. These reactions depend upon the magnitude of P_s and upon the thickness of the simulated bomb case. The results of tests using the systems of Figures 5 and 6 are presented in Table II. Five different explosives samples were exposed. The compositions of the three uncommon plastic-bonded ones are given in Table III.

(U) Test results indicate that the vigor of the reaction of the explosive sample decreases when the barrier thickness is increased. In addition, these results indicate that the "on side" acceptor configuration is more difficult to detonate than the "on end" configuration.

(U) A comparison of pressures required, in the direct contact detonation test system of Figure 6 and in the impact system of Figure 7, to produce similar reactions in acceptors containing TETRYL samples is presented in Figure 9. The magnitudes, P_s, of the pressures which are transmitted into the 0.018, 0.029, 0.055 and 0.119 inch thick steel barriers of the acceptor system of Figure 6 and the sample reactions which result were taken from the data of Table II. The magnitudes, P_{s_i}, of the pressures which are transmitted into the steel barriers of the acceptor systems when these are hit by steel projectiles at velocities sufficient to cause similar sample reactions were taken from the data of Table IV.

(U) While it appears that pressures required to detonate the acceptor "high order" increase in a similar way with increasing barrier thickness for both the direct contact detonation and the impact test systems, very much higher pressures must be generated by disc impact in order to detonate the sample. This is consistant with the fact that the durations of the pressures generated by the impact of the very thin (about 1/10 inch thick) steel discs are very much shorter than those generated by the direct contact detonation system using long two inch diameter donors.

TABLE II. EFFECT OF STEEL BARRIER THICKNESS UPON PRESSURES, P_S, REQUIRED FOR REACTIONS OF EXPLOSIVES SAMPLES IN THE SYSTEMS OF FIGURES 5 AND 6 USING TNT DONORS

Acceptor Explosive		70/30 MPBX N101 E		70/30 MPBX N101 S				70/30 PBX N101 E	70/30 PBX N101 S		PBX N102 E	PBX N102 S	Cast COMP-B E L*	Cast COMP-B E S**
Barrier Thickness (10^{-3} in)		55	119	18	29	55	119	119	55	119	119	119	119	119
ρ_{TNT} (grains per increment)	P_s (kb)													
2100	208	X	X			X	⊠	X		⊠	X	⊠		
2000	188						Ø							
1950	178		X					X						
1800	150	X	⊠					⊖		⊖			X	Ø
1600	117	X		X	XX	⊠	Ø		X⊠					

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Key:

X = "high order" detonation, ⊠ = "low order" detonation, Ø = acceptor explosive completely consumed, ⊖ = acceptor explosive partly consumed, O = no explosive reaction

E means sample was "on end", S means sample was "on side"

L* means sample was a 3/4 inch diameter 1/2 inch long cylinder.
S** means sample was a 3/4 inch diameter 1 1/2 inch long cylinder.

TABLE II (CONTINUED). EFFECT OF STEEL BARRIER THICKNESS UPON PRESSURES, P_s, REQUIRED FOR REACTIONS OF EXPLOSIVES SAMPLES IN THE SYSTEMS OF FIGURES 5 AND 6 USING DONORS LOADED WITH NITROGUANIDINE

Acceptor Explosive		TETRYL E				70/30 MPBX N101 E	70/30 MPBX N101 S		70/30 PBX N101 S
Barrier Thickness (10^{-3} inches)		18	29	55	119	55	18	29	55
ρ_{NQ} (grains per increment)	P_s (kb)								
1300	82			X	X				
1200	69						⊠	⊠	
1100	57								
1050	52			X					
1000	47	X	XX	X	Ø				
900	38							⊠	
850	33			X					
800	29		X						
750	25			⊠					
700	22	X	⊠⊠	⊠⊠	ϴ		⊠		
650	19			⊠					
600	17		⊠				Ø		
550	13			Ø					
500	11	⊠	⊠	Øϴ	ϴ	Ø	ϴ	O	O
450	9			O					
400	7		ϴ						
300	4	⊠	⊠⊠	ϴ	ϴ		O		O
250	3		⊠						
200	2		Ø						

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Key: X = "high order" detonation, ⊠ = "low order" detonation, Ø = acceptor explosive completely consumed, ϴ = acceptor explosive partly consumed, O = no explosive reaction, E = sample "on end", S = sample "on side"

TABLE III. COMPOSITIONS OF PLASTIC BONDED EXPLOSIVES

Explosive	Composition
70/30 MPBX N101	70% RDX/ 30% Binder
70/30 PBX N101	70% HMX/ 30% Binder
PBX N102	59% HMX/ 23% Al/ 18% Binder

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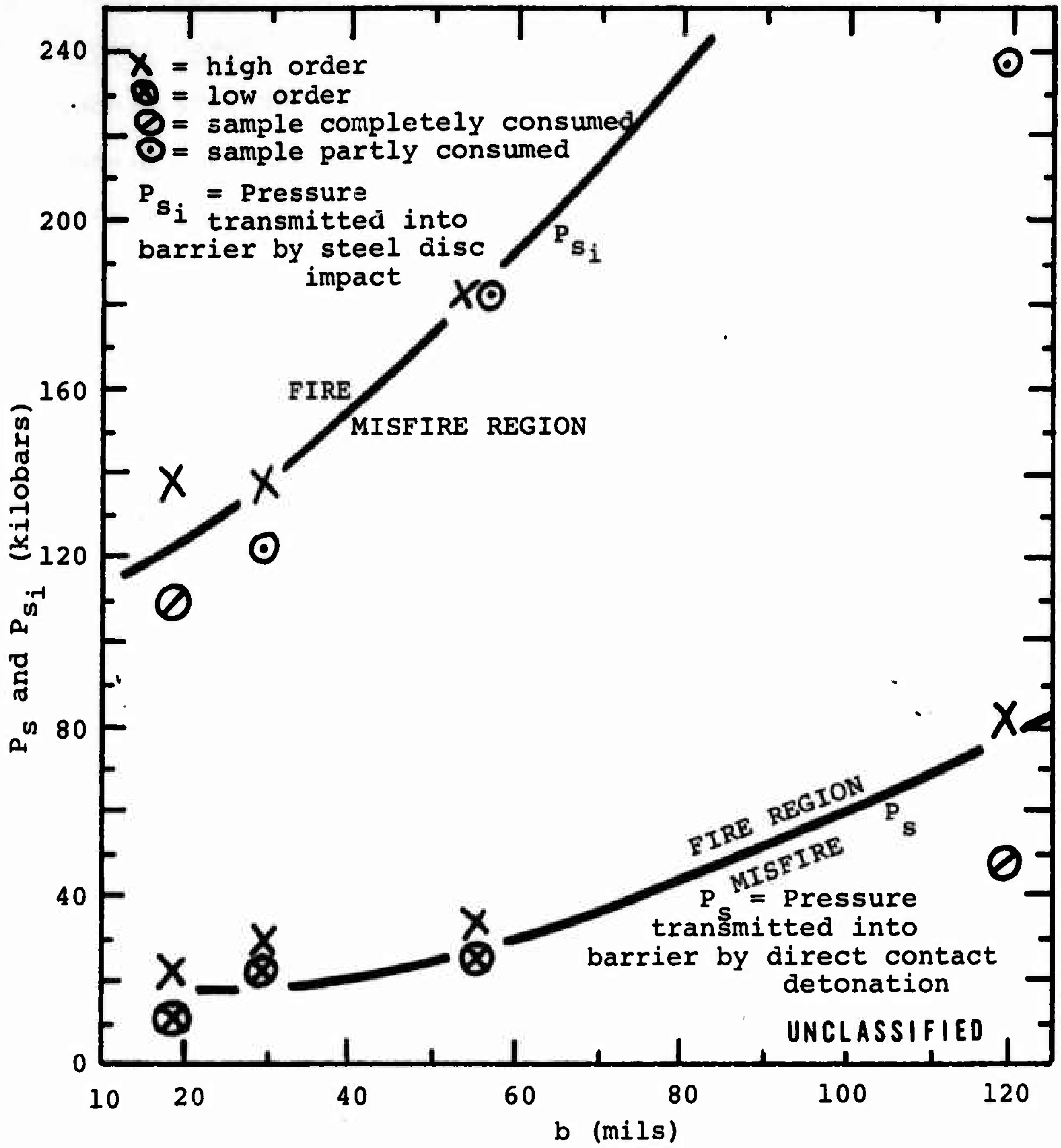

Figure 9. Effect of Steel Barrier Thickness, b, Upon Initiation Pressures P_s and P_{s_i} Required for High Order Detonation of Pressed TETRYL Pellets

TABLE IV. EFFECT OF STEEL BARRIER THICKNESS UPON PRESSURES, P_{s_i}, REQUIRED FOR REACTIONS OF TETRYL SAMPLES IN THE IMPACT SYSTEM OF FIGURE 7.

Barrier Thickness (10^{-3} inches)	Projectile Thickness (10^{-3} inches)	Projectile Velocity (ft/sec)	P_{s_i} (kb)	Acceptor Reaction
18	55	4250	237	X
18	119	2450	138	X
18	119	1950	109	Ø
18	119	1580	89	Θ
18	119	1450	82	Θ
18	750	383	22	O
18	750	312	17	O
29	55	4250	237	X
29	55	3250	182	X
29	119	2450	138	X
29	119	2150	122	Θ
29	119	1450	82	Θ
55	55	4250	237	X
55	55	3250	182	ΘX
55	119	2150	122	Θ
55	119	1750	98	Θ
55	119	980	56	⊠
119	55	4250	237	Θ
119	55	3250	182	Θ

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Key:
X = "high order", ⊠ = "low order, Ø = explosive completely consumed,
Θ = explosive partly consumed, O = no explosive reaction
P_{s_i} = initial peak pressure induced in steel barrier by impact of projectile

SECTION VIII

INITIATING IMPULSE DURATION EFFECTS

A. Introduction

(U) The duration of the initiating signal to an explosive system importantly effects the amplitude of the signal required to cause detonation. This has been found true for hot wire(20) initiation of primary explosives as well as for initiation by cook-off(21) and by impact by bullets(9). In all of these cases, the amplitude required for critical initiation decreases when the duration of the initiating signal increases.

(C) When unfuzed Mk 81 and Mk 82 bombs were loaded with H-6 (an explosive which is less sensitive than TETRYL in normal sensitivity tests) and thrown from rocket-propelled sleds against reinforced concrete targets, detonations resulted when the impact velocity(3) was as low as about 500 ft/sec. TETRYL in the system of Figure 7, however, required that impacting steel discs strike with a velocity of about 1000 ft/sec or more in order to detonate it. It thus becomes clear that the critical pressure required to detonate an explosives system by impact is a function of the duration of the pressure signal, that this critical pressure is less when its duration is longer, and that the magnitude of this critical pressure cannot be specified unless the duration is specified. A study of the effect of the duration of the initiating impulse upon the magnitude of the pressure required to initiate explosives confined in steel is thus necessary and was undertaken.

B. Experimental Arrangement

(U) Preliminary experiments were conducted with the test system shown in Figure 10. Steel barriers and witness plates which were recovered after these experiments are shown in the photograph of Figure 11. The distortions are indicative of the effects of peak pressure and duration of the initiating shock wave upon the acceptors.

(U) The donors were cardboard-confined cylinders of NITROGUANIDINE and had a length-diameter ratio of 3.0 or larger. The acceptors were sandwich structures of steel and pressed TETRYL. The barriers were 0.055 inch thick C1018 steel and the witness plates were 0.119 inch thick steel of the same material. The effect of pressure amplitude upon the reaction of the TETRYL system to it was examined by using 2.0 inch diameter donors loaded at the densities indicated in Figure 11 to produce shocks in the steel barriers varying from 4 to 47 kilobars in amplitude.

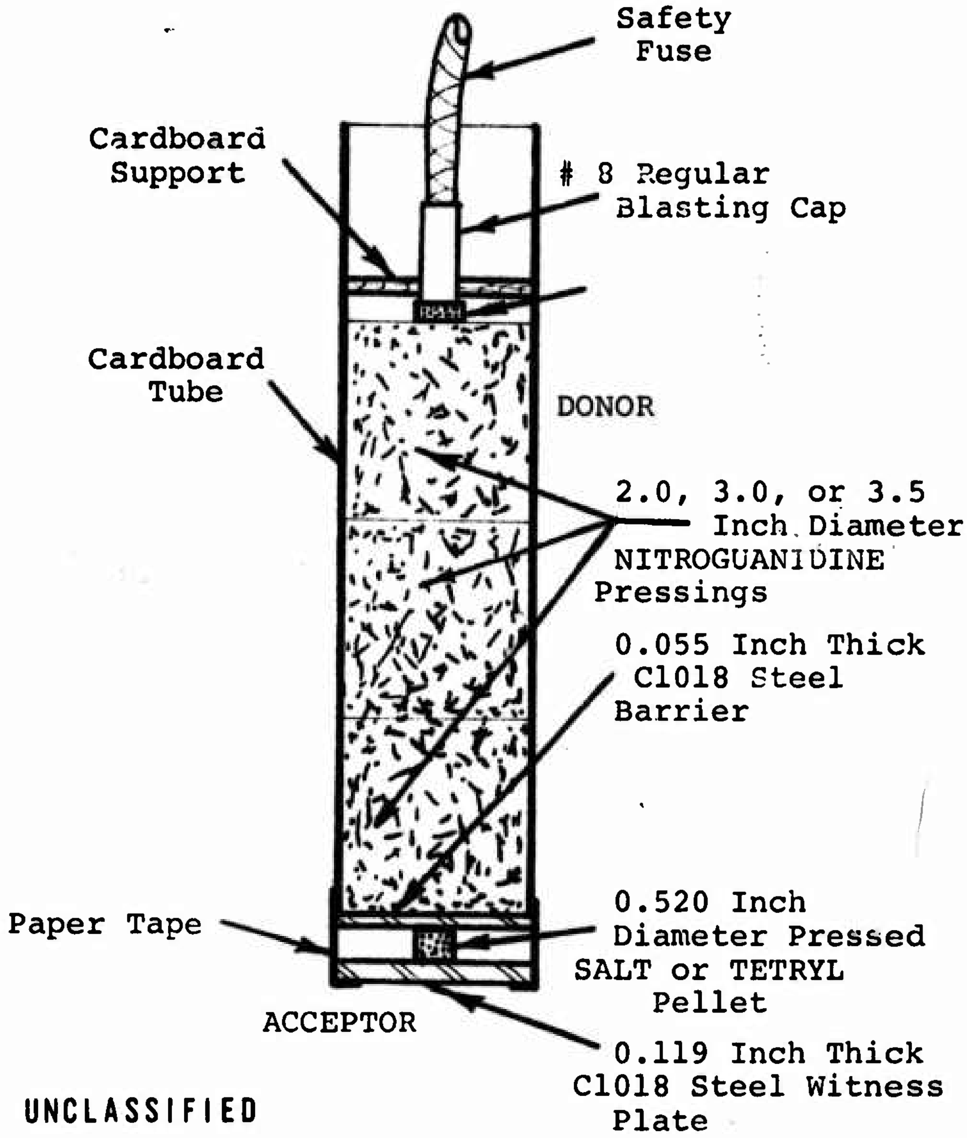

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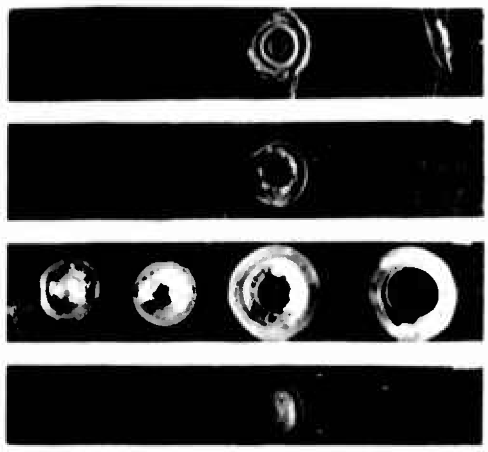
Figure 10. Preliminary Duration Effects Study System

d (inches)

2.0 2.0 3.0 3.5



ρ_{NQ} (gm/cc)	P_s (kb)
0.530	49
0.441	23
0.315	11
0.189	4

S T T T

Increasing Duration

UNCLASSIFIED

Key: S = Salt acceptor, T = TETRYL acceptor, d = Donor diameter, P_s = Peak pressure of wave generated in steel barrier, ρ_{NQ} = Density of NITROGUANIDINE in donor

Barriers were 0.055 inch thick mild steel. Donors were cardboard confined cylinders of NITROGUANIDINE which were at least three diameters long. These were detonated in direct end contact with the barriers. The camera looks down on the recovered barriers from the direction from which the detonation wave struck. The recovered witness plate is directly beneath the barrier. Acceptors were 0.520 inch diameter 0.500 inch long pellets pressed at 16,800 psi and sandwiched between the barrier plates and 0.119 inch thick mild steel witness plates.

Figure 11. Recovered Barriers and Witness Plates Illustrating Effects of Peak Pressure and Duration of Initiating Impulse Upon Pressed TETRYL Pellets

(U) The effect of pressure duration upon the reaction of the TETRYL system to it was examined by using 2.0, 3.0, and 3.5 inch diameter donors loaded at a density of 0.315 gm/cc to produce shocks in steel having a pressure amplitude of 11 kilobars. The durations increase with donor diameter and are nearly proportional to it. The vigor of the reaction of the TETRYL to these initiating shocks was judged by comparing the post-detonation distortions of the barrier and witness plates for the various donor conditions with each other and with distortions produced when common SALT instead of TETRYL was used in the acceptor system.

(U) Examination of the recovered barriers and witness plates clearly indicates that when the amplitude of the initiating impulse in the barrier is increased from 4 to 47 kilobars, the reactions of the TETRYL increase from very mild deflagrations, which only bulge and tear the barriers and witness plates, to vigorous high-order detonations which punch holes in the plates.

(U) When the duration of the 11 kilobar initiating impulse is increased by increasing the diameter of the donor charge, the vigor of the reaction of the TETRYL (as judged by the distortions to the barrier and witness plate) is significantly increased from a mild to a vigorous deflagration.

(U) The general effects described above were expected, but their usefulness for prediction capability is limited. More quantitative experiments to measure the effects of steel barrier thickness and donor diameter upon the applied pressure required to initiate detonation through the barrier were therefore designed. In addition, experiments were conducted with these same systems to measure the effects of acceptor loading pressure upon sensitivity, as well as to make measurements of comparative sensitivities of explosives. Test reproducibility was measured and the validity of the general scheme challenged by comparing test results for a system in which the NITROGUANIDINE donors were replaced by donors containing TNT.

(U) The experimental arrangements are illustrated in Figures 12 and 13. Two and three inch diameter systems were used. Except for donor, barrier, and witness plate diameters, these systems are identical.

(U) The donors are large length-diameter ratio cardboard-confined cylinders of NITROGUANIDINE or TNT. The acceptors are pellets of pressed TNT or TETRYL confined between mild steel barriers and witness plates. The critical pressures, P_s, required to be produced in the steel barriers at the surfaces farthest from the acceptor explosives to produce high-order detonations of the acceptors with probabilities of 50%, were

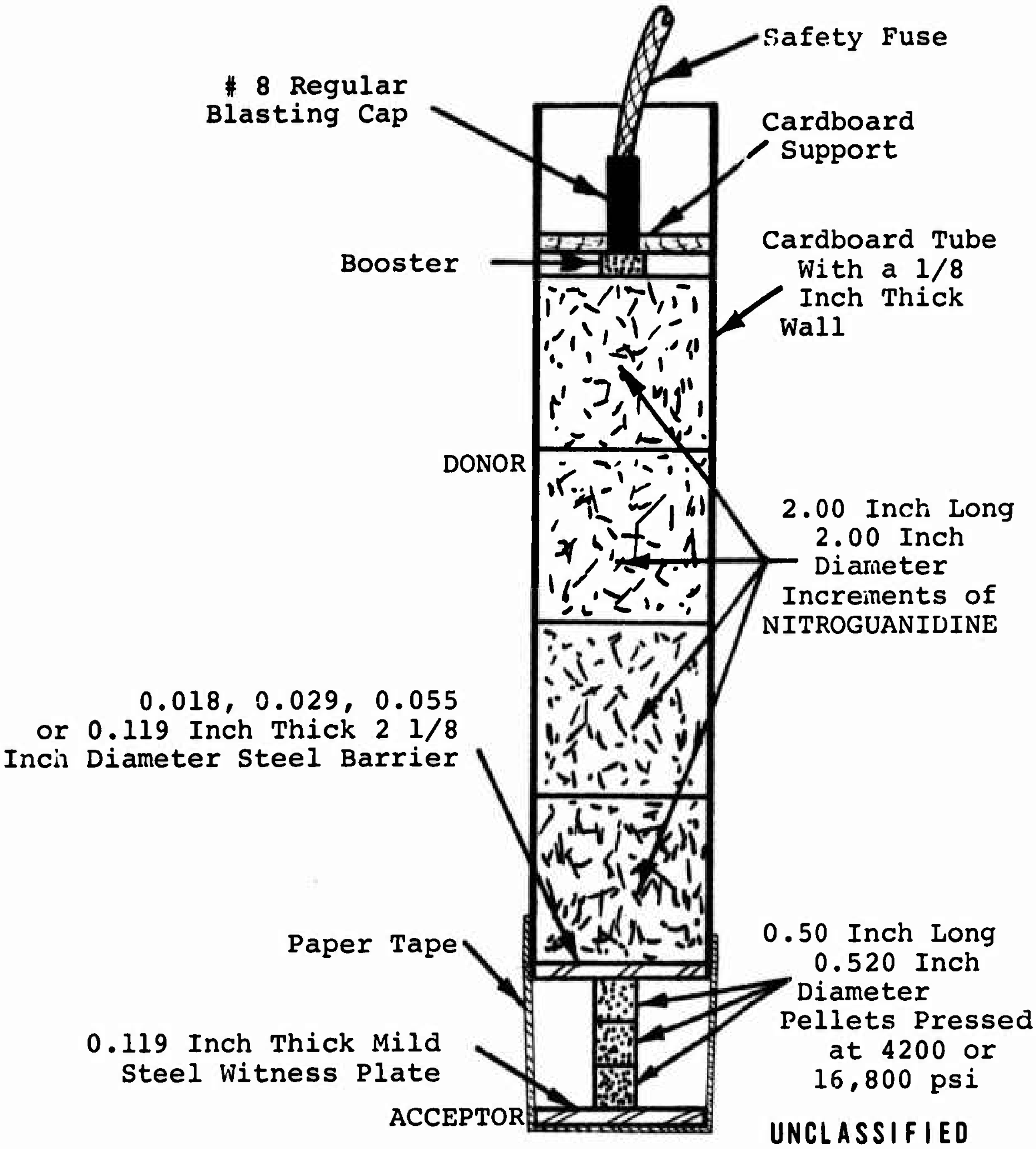


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Figure 12. Arrangement for Tests Using 2.0 Inch Diameter Donors

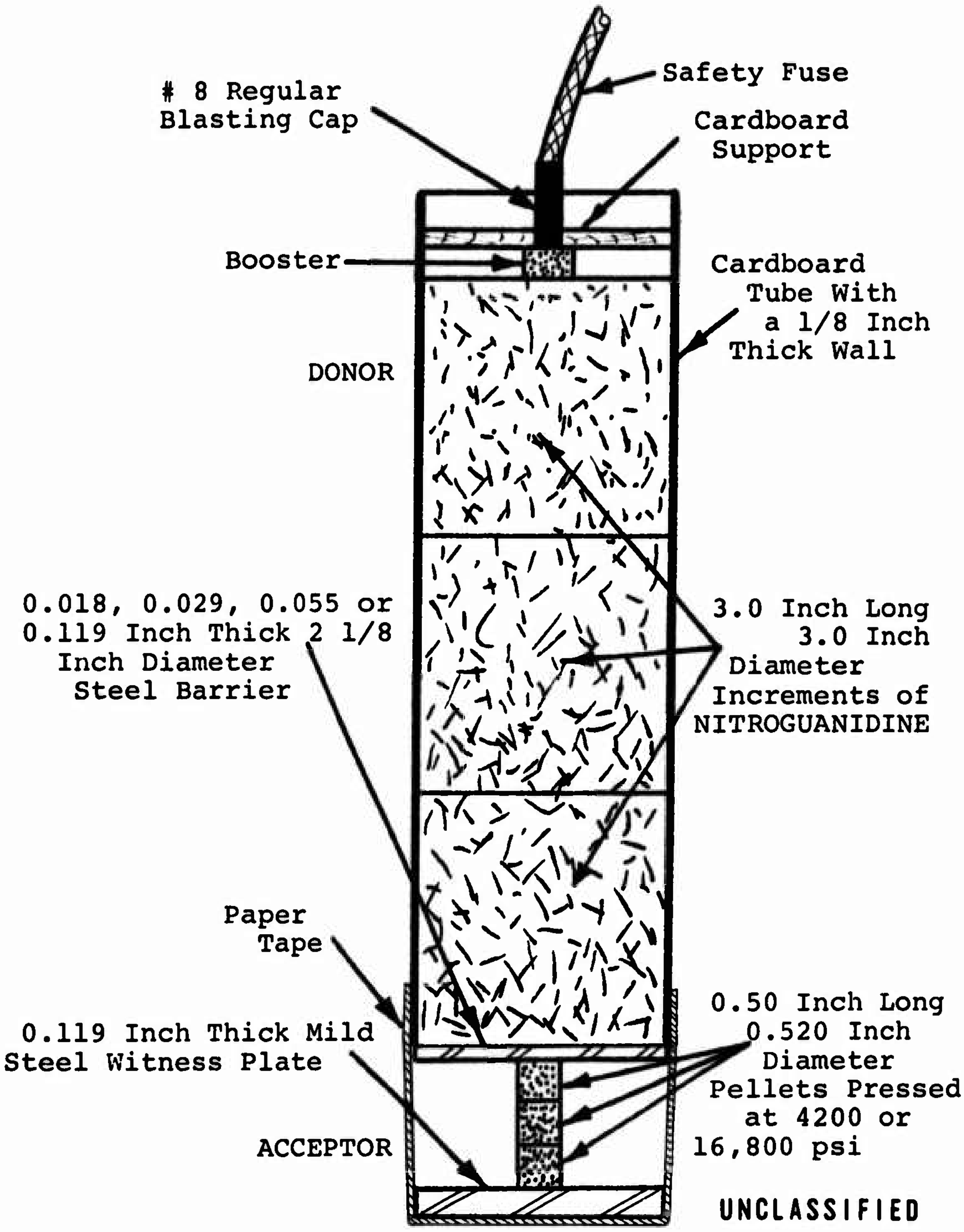

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Figure 13. Arrangement for Tests Using 3.0 Inch Diameter Donors

determined by conducting sensitivity tests in which Bruceton type staircase up-down procedures(22) were followed. Pressure inputs were varied by controlling the density to which the donor explosives were loaded. These densities were varied linearly so that pressure inputs were varied exponentially as illustrated in Figure 4. Test step sizes were 0.016 or 0.032 gm/cc.

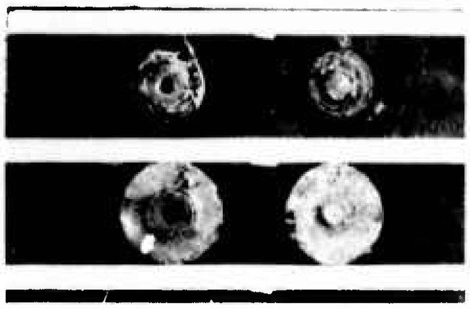
(U) For these tests, each shot was classified as a fire, X, or a misfire, O, in accordance with whether or not a hole was punched in the steel witness plate. Typical witness plate distortions by which fires and misfires were judged are shown in the photograph of Figure 14.

(U) If a misfire was obtained as a result of a test shot, the next shot was made with the donor loaded to a density one step size higher. This was repeated until a fire was obtained. The density was then decreased by one step size, and tests performed with continuously decreasing steps until a misfire was obtained. The entire procedure was continued and repeated in this manner until the test was completed. This procedure was followed for all of the tests. Typical data obtained from such tests is shown in Figure 15.

C. Test Results

(U) Test results which clearly show the effect of steel barrier thickness upon the critical pressures required to initiate detonation of the acceptors are presented in Table V and illustrated in Figure 16. These critical pressures increase in a regular and smooth manner as barrier thickness is increased. In addition, the manner of this increase does not appear to be affected by systems changes, that is, by changes in acceptor loading density or by changes in donor diameter. While this data does not prove that such critical pressures can be extrapolated with confidence, it does justify a continuing search for valid scaling relationships.

(U) The effect of initiating impulse duration upon the critical pressure required to initiate detonation is illustrated by the data presented in Table VI. In each of the seven systems in which critical pressures were determined and compared for 2 0 inch and 3.0 inch diameter donors, the required pressures are greater when the durations are shorter (i.e. when 2.0 inch diameter donors are used). We find this to be the case independent of acceptor explosive composition, acceptor loading density, and barrier thickness. Indeed, this is still the case even when the donor explosive is granular TNT instead of the usual NITROGUANIDINE. Furthermore, the ratios of the critical pressures for the 2.0 inch diameter donors to the 3.0 inch diameter donors for



2.0 Inch Diameter Donors

3.0 Inch Diameter Donors

Fire Misfire UNCLASSIFIED

Figure 14. Criteria of Fire and Misfire

d (in)	2.0	2.0	3.0
b (in)	0.018	0.029	0.029
P_L (psi)	16800	16800	16800
ρ_{NQ} (gm/cc)			
0.629		X	
0.613		X X X O X	
0.598		O O X X O O O	
0.582		O O	
0.566			X X
0.550			O O X X X X
0.535			O O O
0.519	X X		
0.503	X X X O O X X		
0.487	O O X O O X X		
0.472	O O O		

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Key:
d = donor diameter, b = barrier thickness, ρ_{NQ} = donor loading density, P_L = acceptor explosive loading pressure, X = fire, O = misfire.

Figure 15. Direct Contact Detonation Sensitivity Observations for Steel-Sandwiched Pressed 0.520 Inch Diameter Flaked TNT Samples.

TABLE V. EFFECT OF STEEL BARRIER THICKNESS UPON THE CRITICAL PRESSURE, P_s, REQUIRED TO INITIATE DETONATION THRU IT IN TNT WHEN USING NITROGUANIDINE DONORS.

P_L (kpsi)	b (mils)	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	$m_{99.9}$ (gm/cc)	$m_{0.1}$ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)	$P_s/P_{s_{18}}$
4.2	18	2.0	18	0.016	0.576	0.026	0.657	0.496	0.008	20.3	39	1.00
4.2	29	2.0	13	0.016	0.670	0.017	0.725	0.614	0.007	28.6	53	1.36
16.8	18	2.0	19	0.016	0.094	0.015	0.539	0.449	0.005	14.5	28	1.00
16.8	29	2.0	15	0.016	0.604	0.011	0.639	0.569	0.005	22.5	43	1.53
4.2	18	3.0	16	0.016	0.543	0.008	0.568	0.518	0.003	17.9	33	1.00
4.2	29	3.0	10	0.016	0.638	0.011	0.672	0.603	0.005	25.6	48	1.43
16.8	18	3.0	19	0.032	0.457	---	---	---	---	12.3	24	1.00
16.8	29	3.0	11	0.016	0.565	0.006	0.584	0.547	0.003	19.4	38	1.58
16.8	18	2.0	19	0.016	0.494	0.015	0.539	0.449	0.005	14.5	28	1.00
16.8	29	2.0	15	0.016	0.604	0.011	0.639	0.569	0.005	22.5	43	1.53
16.8	55	2.0	9	0.016	0.736	0.006	0.754	0.718	0.004	35.6	64	2.28
16.8	18	3.0	19	0.032	0.457	---	---	---	---	12.3	24	1.00
16.8	29	3.0	11	0.016	0.565	0.006	0.584	0.547	0.003	19.4	38	1.58
16.8	55	3.0	9	0.016	0.693	0.004	0.705	0.682	0.002	30.9	56	2.33
16.8	18	2.0	19	0.016	0.494	0.015	0.539	0.449	0.005	14.5	28	1.00
16.8	29	2.0	15	0.016	0.604	0.011	0.639	0.569	0.005	22.5	43	1.53
16.8	55	2.0	9	0.016	0.736	0.006	0.754	0.718	0.004	35.6	64	2.28
16.8	119	2.0	7	0.016	0.885	0.006	0.903	0.866	0.004	55.3	98	3.50

(SEE TABLE XI FOR DEFINITION OF SYMBOLS)

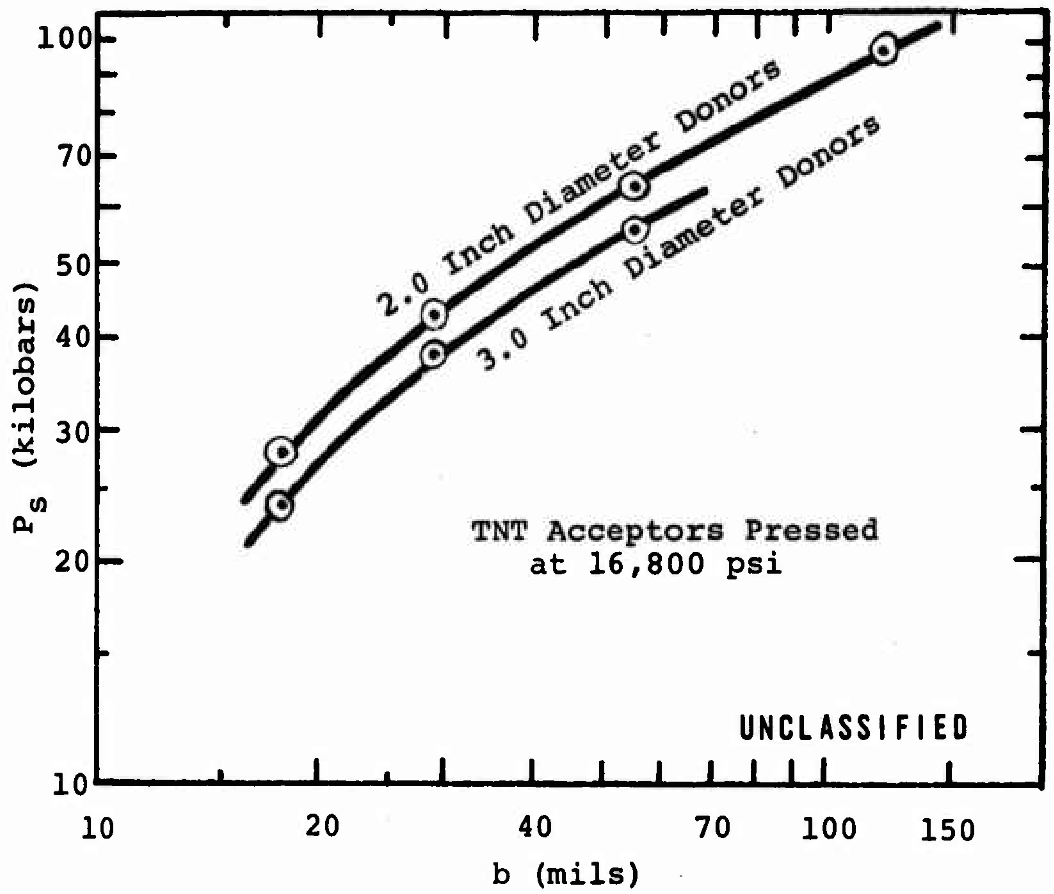

Figure 16. Effect of Steel Barrier Thickness, b, Upon the Critical Pressures, P_s, Required to Initiate Detonation of Acceptors of the Systems of Figures 12 and 13

TABLE VI. EFFECT OF DONOR DIAMETER UPON CRITICAL PRESSURE, P_s, REQUIRED TO INITIATE DETONATION THRU A STEEL BARRIER.

Donor	Acceptor	P_L (kpsi)	b (mils)	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)	$P_s/P_{s3.0}$
NQ	TETRYL	16.8	18	2.0	17	0.032	0.366	0.010	0.006	7.8	15	1.16
NQ	TETRYL	16.8	18	3.0	17	0.032	0.346	0.008	0.003	6.9	13	1.00
NQ	TNT	4.2	18	2.0	18	0.016	0.576	0.026	0.008	20.3	39	1.11
NQ	TNT	4.2	18	3.0	18	0.016	0.543	0.008	0.003	17.9	35	1.00
NQ	TNT	4.2	29	2.0	13	0.016	0.670	0.017	0.007	28.6	53	1.10
NQ	TNT	4.2	29	3.0	10	0.016	0.638	0.011	0.005	25.6	48	1.00
NQ	TNT	16.8	18	2.0	19	0.032	0.495	0.011	0.005	14.6	28	1.17
NQ	TNT	16.8	18	3.0	19	0.032	0.457	---	---	12.3	24	1.00
NQ	TNT	16.8	29	2.0	15	0.016	0.604	0.011	0.004	22.5	43	1.13
NQ	TNT	16.8	29	3.0	11	0.016	0.565	0.006	0.003	19.4	38	1.00
NQ	TNT	16.8	55	2.0	9	0.016	0.736	0.006	0.004	35.6	64	1.14
NQ	TNT	16.8	55	3.0	9	0.016	0.693	0.004	0.002	30.9	56	1.00
gTNT	TNT	16.8	119	2.0	10	0.016	0.835	0.004	0.002	41.8	76	1.19
gTNT	TNT	16.8	119	3.0	6	0.016	0.764	---	---	34.4	64	1.00

(SEE TABLE XI FOR DEFINITION OF SYMBOLS)

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corresponding systems do not appear to change significantly when the systems are changed. This is additional justification for the hope that simple scaling relationships may be found for such systems and that prediction capability can be developed.

(U) The effect of the loading density of the acceptor explosive upon the critical pressure required for its initiation through steel barriers is illustrated by the data in Table VII. In each of the four systems studied, the critical pressure required to be generated in the steel barrier discs by the detonation of the donors is greater for those acceptors which were loaded at a lower density than it is for those which were loaded to a higher one. This is a surprising result and is the reverse of what was expected. Indeed, it is the reverse of what was observed when no steel barriers were used(15). In such a case, (see Figure 1) the critical pressure required to be generated in the bare acceptor by the direct contact detonation with it of the donor is less when the acceptor density is less. The reason for this reversal is not clearly understood.

(C) When we compare the system of Figure 1, however, with that of Figures 12 or 13, we may note that we are concerned in the case of the first system, with the transfer of energy directly between explosives whose shock impedances match fairly well. In the case of the systems which contain barriers, on the other hand, we must deal, instead, with the transfer of energy from high impedance steel barriers to low impedance acceptor explosives. In such cases the transfer of energy from steel barrier to acceptor explosive is much more efficient when the acceptor is loaded at a high density than when it is loaded at a low one. This acts in the direction of making a high density explosive appear to be more sensitive, in such a system, than one loaded to a lower density. It is possible that this may also be the case with respect to the responses of explosives which are loaded into bombs and other explosives loaded ordnance which are subjected to impact. It may be that such ordnance may be made less sensitive to impact if the explosives in them are loaded (at least near the walls) at lower densities.

(U) When the barrier systems of Figures 12 and 13 are used to measure the sensitivities of TETRYL and TNT, we find (see Table VIII) that their relative sensitivities are the same in each system. In the 2.0 inch diameter system, the critical pressure required to detonate the TNT is 1.87 times that required to detonate the TETRYL. In the 3.0 inch diameter system, the comparable ratio is 1.85. When TNT and TETRYL are loaded under the same conditions (i.e. at 16,800 psi) and tested(15) in the system of Figure 1, that is without the steel barrier, the comparable ratio is 1.91. This suggests, that even if quantitative

TABLE VII. EFFECT OF ACCEPTOR LOADING PRESSURE UPON SENSITIVITY OF EXPLOSIVES TO INITIATION THRU STEEL BARRIERS FOR NITROGUANIDINE DONORS AND TNT ACCEPTORS.

P_L (kpsi)	b (mils)	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	$m_{99.9}$ (gm/cc)	$m_{0.1}$ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)	$P_s/P_{s16.8}$
4.2	18	2.0	18	0.016	0.576	0.026	0.657	0.496	0.008	20.3	39	1.39
16.8	18	2.0	19	0.016	0.494	0.015	0.539	0.449	0.005	14.5	28	1.00
4.2	29	2.0	13	0.016	0.670	0.018	0.725	0.614	0.007	28.6	53	1.23
16.8	29	2.0	15	0.016	0.604	0.011	0.639	0.569	0.005	22.5	43	1.00
4.2	18	3.0	16	0.016	0.543	0.008	0.568	0.518	0.003	17.9	33	1.37
16.8	18	3.0	19	0.032	0.457	---	---	---	---	12.3	24	1.00
4.2	29	3.0	10	0.016	0.638	0.011	0.672	0.603	0.005	25.6	48	1.26
16.8	29	3.0	11	0.016	0.565	0.006	0.584	0.547	0.003	19.4	38	1.00

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TABLE VIII. COMPARATIVE SENSITIVITIES TO INITIATION BY NITROGUANIDINE DONORS THRU 0.018 INCH THICK STEEL BARRIERS OF TNT AND TETRYL PELLETS PRESSED AT 16,800 PSI.

Acceptor	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	$m_{99.9}$ (gm/cc)	$m_{0.1}$ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)	$P_s/P_{s\,TETRYL}$
TETRYL	2.0	17	0.032	0.366	0.010	0.397	0.335	0.006	7.8	15	1.00
TNT	2.0	19	0.016	0.494	0.015	0.539	0.449	0.005	14.5	28	1.87
TETRYL	3.0	17	0.032	0.346	0.008	0.371	0.322	0.003	6.9	13	1.00
TNT	3.0	19	0.032	0.457	---	---	---	---	12.3	24	1.85

(SEE TABLE XI FOR DEFINITION OF SYMBOLS)

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predictions cannot be made regarding the response of explosive loaded ordnance to impact, relative sensitivities, as determined in idealized simplified test systems, may still serve as the basis for valid qualitative predictions. That is, relative sensitivities in simplified systems and relative sensitivities in full-scale systems may be expected to be the same.

(U) One cornerstone of the structure of the prediction scheme of SECTION V is the assumption that the pressures developed by the direct contact detonation of NITROGUANIDINE with steel cased bombs and those developed by the impact of bombs with targets or with projectiles will have the same effect upon the explosives in the bombs if the magnitudes of these pressures are the same. We have already seen in SECTION VIII, however that this is not necessarily so when the durations of these signals are not the same.

(U) Another cornerstone of the structure is the assumption that the relationships of SECTIONS II, III and IV, which are used to determine the pressures generated in the steel bomb cases by the direct contact detonation with them of NITROGUANIDINE donors, are correct. These relationships should, of course, also be correct if TNT donors were used instead of donors containing NITROGUANIDINE. In such a case, Equation (2) relating loading density and detonation velocity for NITROGUANIDINE, must be replaced by the comparable one for TNT, namely

$$D = 0.178 + 0.332\rho \quad . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

(U) An indirect test of these relationships was performed by comparing critical pressures which are required to be generated in 0.119 inch thick steel barriers in order to detonate TNT acceptors with NITROGUANIDINE and with TNT donors. The results of these tests are presented in Table IX. It is clear from these results that the pressures, P_s, differ when TNT instead of NITROGUANIDINE donors are used. Since the validity of Equations (1) thru (6) has been firmly established(23), it may be that the durations of the signals generated by the TNT and the NITROGUANIDINE donors are different. If this is so, it appears that the durations of signals generated by the TNT donors are longer than those generated by donors containing NITROGUANIDINE.

(U) During the course of the experimental test program, four different independent measurements were made of the critical pressure required to initiate detonation in TNT pellets thru 0.018 inch thick steel barriers. The results of these tests are presented in Table X and are a measure of the reproducibility of the test system of Figure 12. Reproducibility is extraordinarily good.

TABLE IX. EFFECT OF DONOR EXPLOSIVE COMPOSITION UPON CRITICAL PRESSURE, P_s, REQUIRED TO INITIATE DETONATION IN PRESSED TNT PELLETS THRU A 0.119 INCH THICK STEEL BARRIER.

Donor	P_L (kpsi)	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	$m_{99.9}$ (gm/cc)	$m_{0.1}$ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)
NQ	16.8	2.0	7	0.016	0.885	0.006	0.903	0.866	0.004	55.3	98
TNT	16.8	2.0	10	0.016	0.835	0.004	0.847	0.823	0.002	41.8	76

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TABLE X. TEST REPRODUCIBILITY FOR NITROGUANIDINE DONORS AND TNT ACCEPTORS

Test No.	P_L (kpsi)	b (mils)	d (in)	N	h (gm/cc)	m (gm/cc)	σ (gm/cc)	$m_{99.9}$ (gm/cc)	$m_{0.1}$ (gm/cc)	σ_m (gm/cc)	P_m (kb)	P_s (kb)
1	16.8	18	2.0	19	0.032	0.495	0.011	0.530	0.460	0.005	14.6	28
2	16.8	18	2.0	13	0.016	0.493	0.013	0.533	0.454	0.005	14.4	28
3	16.8	18	2.0	19	0.016	0.494	0.015	0.539	0.449	0.005	14.5	28
4	16.8	18	2.0	9	0.016	0.492	0.006	0.510	0.474	0.004	14.4	28

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(SEE TABLE XI FOR DEFINITION OF SYMBOLS)

TABLE XI. SYMBOLS

m is the donor loading density for which the probability is 50% that the acceptor will detonate.

σ and σ_m are, respectively, the standard deviations from m, for single and mean observations.

$m_{99.9}$ and $m_{0.1}$ are, respectively, the donor loading densities for which the probabilities are 99.9% and 0.1% that the acceptors will detonate.

P_m is the donor detonation pressure for which the probability is 50% that the acceptor will detonate.

P_s is the amplitude of the pressure wave which is generated in the steel barrier when the donor detonation pressure is P_m.

$P_{s_{18}}$ is the value of P_s when the barrier is 0.018 inches thick.

$P_{s_{3.0}}$ is the value of P_s when the donor diameter is 3.0 inches.

$P_{s_{16.8}}$ is the value of P_s when the acceptor explosive is loaded at 16,800 psi.

$P_{s_{TETRYL}}$ is the value of P_s when TETRYL is the acceptor explosive.

NQ is NITROGUANIDINE, TNT is flaked TNT, gTNT is grained TNT.

P_L is the loading pressure of the acceptor explosive

d is the donor diameter, b is the steel barrier thickness

N is the number of test shots in a Bruceton type test

h is the step size in a Bruceton type test

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P_{s_i} is the initial peak pressure which is induced in a steel barrier when it is struck by a high velocity steel projectile

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

(U) The sensitivity of a steel enclosed explosive to shock and impact has been found to depend not only upon the magnitude of the impulse which is generated at the outer boundary of the steel, but also on the duration of that signal.

(U) Cardboard confined charges of NITROGUANIDINE and TNT have been found useful and convenient for generating shocks of varying amplitudes and durations in steel enclosed explosives by detonating them in direct contact with the steel. Pressures required to detonate explosives thru steel barriers in this way have been found to increase in a regular manner when the barrier thickness is increased. When the duration of this pressure is increased, its effect upon the explosive is increased.

(U) Simple correlations between pressures required to detonate steel-shielded explosives by the direct contact detonation of NITROGUANIDINE with these shields and by impact with them of free-flying thin steel discs were not found because the durations of the signals generated in these two ways were not the same.

(U) The sensitivities, to detonation by shock and impact, of the simple steel-shielded explosives systems studied, decrease when loading densities are decreased, and when the thickness of the steel shield is increased. This suggests similar behavior for explosives loaded ordnance.

(U) The magnitudes of changes in sensitivity resulting from changes of explosives geometries, loading conditions, and environment can be very large, and are of great practical interest. Indeed, it has been found that the measured sensitivity of the explosives tested may be changed by changing any of these parameters of the system of which the explosive is a part. Since such changes are also capable of inverting the order of sensitivity of a series of explosives, an understanding of these effects is essential for the understanding of the phenomena and meaning of sensitivity. This understanding is, in turn, required for the development of a sensitivity prediction capability.

(U) Since explosives are used in ordnance systems under many very different conditions of geometry, loading density, and confinement and since the sensitivities of these explosives systems have been shown to depend not only upon the physical and chemical characteristics of the explosives themselves, but also upon characteristics of the inert system of which the explosives are but a part, the study and understanding of the interaction of explosives with their environment is essential for the safe, effective and efficient use of explosives in ordnance.

(U) It is recommended that studies of the effects of systems parameters on explosives sensitivity be continued. These should include studies of the effect of the duration of the initiating impulse on the response of explosives, sensitivity comparisons of pressed and cast explosive charges, and studies of density, diameter and temperature effects in highly confined systems. In addition, it is recommended that sensitivity tests be conducted to find correlations between direct contact detonation sensitivity test results, results from standard air-gap and barrier sensitivity tests, and results from high velocity impact tests.

(C) It is recommended that heavy-walled shells or bombs be loaded with high and low density charges of explosives and impacted against hard targets to check the prediction, based upon the results of tests reported herein, that lower density loaded items will be better able to withstand high velocity impact.

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13 ABSTRACT

(U) The effects of systems parameters upon the sensitivities of explosives and explosives loaded ordnance were studied by exposing simple steel-shielded systems to the direct contact detonation of large length-diameter ratio cardboard-confined cylinders of NITROGUANIDINE and TNT and to the impact of high velocity steel discs. The steel-shielded explosive appeared more sensitive when loaded at a high density than when loaded at a lower density. In addition, when initiating impulses were of longer duration, lower pressures were capable of detonating the acceptor explosives.

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