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THE BURNING BEHAVIOR OF TNT IN THE CLOSED BOMB

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ABSTRACT

This work shows that the physical structure of TNT breaks up during burning in the closed bomb. Combustion proceeds on fragments with a new surface-to-volume ratio.

The size, shape, and number of fragments is determined by the crystal pattern permitted to develop during the casting procedure. The intrinsic burning rate of TNT is very slow in relation to the rate of structural dissociation. Wax, the desensitizing agent used with TNT in the formulation Composition B, does not interact with TNT to modify its burning behavior.

INTRODUCTION

TNT burns in an anomalous manner. In contrast with the burning behavior of gun propellants, cast and

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pressed TNT samples react at a rate that is essentially independent of the initial geometrical configuration, i.e., surface area-to-volume ratio. Since TNT is used in large caliber explosive-filled projectiles, and is a major constituent of the explosive Composition B, it is important to understand its idiosyncracies in order to unravel the anomalous burning characteristics reported for it and for Comp B (ref 1).

This work identifies the major factors controlling TNT's burning mechanism and provides a foundation for subsequent evaluation of their role in the combustion behavior of Comp B. It is intended as a broad overview, with the conclusions providing guidelines for further study.

EXPERIMENTAL

Closed bomb data, in relation to gun propellant linear burning rate regression theory, provides the foundation for this work. The theory states that the burning rate is an intrinsic property of the formulation. Utilizing suitable techniques, the burning rate equation can readily be calculated from closed

bomb pressure-versus-time data. The method is routinely used to evaluate gun propellant formulations (ref 2).

If a sample burns only on its exterior surface after the entire surface area is simultaneously ignited, essentially the same constants are developed for the equation:

$$r = ap^n$$

for any known geometrical configuration. When the same constants are not developed for samples with different surface area-to-volume ratios (S_o/V_o), it means that the samples are burning on a surface area that is different from that predicted by linear regression of the initial surface area. This can happen through the fragmentation of the physical structure, penetration of burning into a porous body, or distortion of the surface area by massive melting.

When experiments are designed with specific goals, insight into unusual burning behavior can be gained from analysis of the quickness curve (dp/dt vs pres-

sure). These curves are particularly useful when used to compare the effect of controlled differences, i.e., surface area, density, crystal size, composition, etc. Based on the design of the experiment, valid inferences on the cause and effect relationship can be made.

Instrumentation

Details of the method are described in reference 1. Briefly stated, a heavy-walled vessel was provided with a closure, insulated firing electrode, and an exhaust valve. The pressure-versus-time data of a burning sample was sensed with a piezo pressure transducer, collected with a Nicolet Explorer III digital oscilloscope, and permanently stored on magnetic discs. The data was then easily retrieved and processed with a Hewlett-Packard HP-85 desktop computer for various listings and plots.

Procedure

Some results on cast and pressed TNT are reported in reference 1. These results and data on crushed TNT, flake TNT, and TNT cast with wax will be discussed in

more detail. This group of experiments was performed in a 201 cm^3 (12.27 in^3) bomb on single grain cylindrical samples. Questions stimulated by these experiments were addressed by a second group of experiments in a 252 cm^3 (15.38 in^3) vessel on samples burned under partial confinement in steel cups.

Precise cylindrical geometries were machined for cast TNT, pressed TNT, and TNT with wax. They were machined to provide two significantly different surface area-to-volume ratios for each sample. They were 2.54 cm (1.000 in.) diameter cylinders. One was solid and the other, a single perforated grain, contained a 0.953 cm (3/8 in.) diameter hole through the center. The lengths were adjusted to provide a constant mass, and were approximately 5 cm (2 in.) long. Crushed and flake forms of TNT were also tested. Each test was provided with massive thermal ignition by 5 grams of class 7 black powder. This was done to insure simultaneous ignition of the entire surface area.

RESULTS AND DISCUSSION

Test for Surface Area Burning, Cast TNT

The purpose of this experiment was to determine whether or not cast TNT burns by regression that is normal to its exterior surface. If this were the case, the two different geometries described in Experimental would generate the same constants for the linear burning rate equation. The quickness curve (dp/dt vs pressure), which provided the foundation for the calculation, must vary with respect to the surface area as a function of the volume fraction burned in order for the calculations to apply. The quickness curves for each of the two geometries were identical (fig.1, table 1). The solid and 3/8 single-perforated grains are represented, respectively, by the dotted and solid lines.

A common burning rate equation could not be generated for the two geometries. This can only mean that the physical structure has changed and generated a new surface area that is not represented by the original geometry. This can only be explained by the creation of a new common surface area from the initial geomet-

ries. This can happen through the complete breakup of TNT's physical structure, or through its deformation, as might occur through massive melting.

Test for Surface Area Burning, Pressed TNT

Essentially the same conclusions were drawn for pressed TNT as for cast TNT. The quickness curves for pressed TNT also show that a surface area alteration has taken place which produces similar burning of the two different geometries (fig. 2, table 2).

Even though the density of the pressed TNT (1.59 gm/cm^3) was slightly higher than that of the cast TNT (1.56 gm/cm^3), it should be noted that it burns at a considerably slower rate than the cast TNT. This is an important observation and will be addressed by subsequent experiments.

Crushed and Flake TNT Compared with the Solid Grain

Equal masses of crushed and flake TNT were also burned. Material from the same TNT casting was physically crushed into an aggregate of fine powder and small chunks. The flake TNT was thin oblong material

[approximately 0.953 cm x 0.079 cm (3/8 in. x 1/32 in.)] from whioh all the castings were made. Although their surface-to-volume ratios (S_o/V_o) were not determined, this ratio was two to three orders of magnitude greater than each machined grain. The ratio for the crushed form was estimated to be at least ten times greater than that of the flake form. Figure 3 and table 3 compare the quickness of crushed and flake TNT with the cast solid cylindrical grain.

All things (mass, composition, etc.) being equal, the quickness (dp/dt) is directly related to the surface area which is burning. This comparison shows that the crushed TNT, with a surface area on the order of a thousand times greater than that of the solid cylindrical form, burns only 20% faster. This strongly reinforces the conclusion drawn earlier, i.e., that TNT is changing its surface area through fracturing and /or melting of its physical structure.

Based on the tests performed thus far, and on the S_o/V_o relationship of the crushed and flake forms, one would expect the flake TNT to burn equally as

fast or slower than the crushed TNT. In spite of having a smaller initial surface area, the flake TNT, surprisingly, burned faster than its recast, crushed version. This suggested that the burning characteristics of TNT had been changed by the melting and recasting process. This point will be addressed by subsequent experiments.

TNT with 2.5% Wax Additive Compared with Cast TNT

The 1% wax additive in Comp B significantly affected its burning behavior (ref 1). In order to determine if this effect was due to an interaction of the wax with TNT, an attempt was made to mix an equivalent quantity (2.5%) directly into the TNT. This turned out to be very difficult. In the melt, the wax appeared to be immiscible with the TNT. To lock the wax within the casting, the mixture was homogenized and quickly cooled. The waxy feel of the machined casting and the difference in physical appearance indicated that a significant quantity of wax was locked in the casting.

Figure 4 compares the solid cylinder geometry of

cast TNT with the solid cylinder geometry of TNT with added wax. There was no significant difference in the results; TNT burned essentially the same with or without wax. The question of the role of wax in the combustion of Comp B will be addressed in a future communication.

In table 4, the two geometrical forms of TNT grains are compared. The same independence of geometry previously noted for cast and pressed TNT, is observed for TNT with wax.

Test for Melting or Fragmentation of TNT

The previous experiments show that the physical structure of TNT changes independently of the original configuration during burning. This experiment was designed to indicate whether this change is due to melting or fragmentation (breakup) of the physical structure. Equal masses of TNT were cast in open cylindrical steel cups that should permit burning on only one surface. The surface provided by one set of cups was 3.81 cm (1.5 in.) in diameter and the other was 1.91 cm (0.75 in.) in diameter (fig. 5). These samples were

ignited with 3 grams of class 7 black powder within a "Parr" high-pressure bomb.

If TNT melts during burning, it is assumed that it will remain in the cup, and the burning will take place on the restricted surface area defined by the diameter of the cup. The rate of burning would be related to the ratios of the surface areas. The TNT in the large-diameter cup would burn faster than that in the small-diameter cup, and it should be possible to calculate TNT's linear burning rate.

If TNT were burning through a fragmentation process, it would be expected that the quickness curves would be, as previously observed, the same for the two geometries. The results are shown in table 5 and figure 6.

The reverse of what should happen for a melting mechanism was found to be the case. The sample with the smaller surface area actually burned faster. These results eliminate the melting mechanism as a possible explanation for the observations. It is therefore inferred that TNT burns predominantly by the deconsolida-

tion of its physical structure. Fragments are created at an extremely rapid rate in relation to the burning time of the fragments. This is suggested by the fact that the quickness curves for the two machined geometries (cast and pressed) are virtually identical. If the fragments were created at a rate that was within their total burning time, there would be a meaningful difference between the two curves.

The quickness curves for the TNT burned in the two cup sizes does not conform to that expected for the fragmentation mechanism. The two quickness curves were expected to be identical; instead, samples with the small surface area burned faster. Fortunately, before the burning it had been noticed that this casting, because of a slow rate of cooling, had permitted the growth of a long, needle-like crystal pattern. The larger-diameter casting had been fast-cooled. Its crystal pattern was not visibly structured.

Effect of Crystal Structure on the Burning of Cast TNT

It was serendipitously discovered that the crystal

structure developed in the casting process had a significant effect on the burning behavior of TNT. In order to further explore this observation, two groups of castings were made in the large-diameter cup. One group was permitted to cool rapidly, while the other was allowed to crystallize slowly over a period of several hours. Again, the rapidly-cooled castings had a visually undefined crystal structure, whereas the slowly-cooled samples had a radially-oriented pattern of long, thin crystals. The result of the burnings are shown in figure 7 and table 6. The TNT with the long, thin, needle-like crystal structure burned much faster than its unstructured counterpart.

The Effect of Density on the Burning of Pressed TNT

Although the densities were not comparable, it was observed in a previous experiment that pressed TNT burned significantly slower than cast TNT. In order to clarify the meaning of this observation, a spectrum of densities were pressed into the larger-diameter metal cups. The quickness of these samples was found to be related to the density (fig. 8, table 7); the quickness

increased as the density decreased. A good correlation was found between the maximum dp/dt and the density (fig. 9).

The fact that density increases with loading pressure means that there are voids (porosity) in the material, that become smaller with greater applied load. The fact that TNT can be pressed to higher densities than usually occur in good castings indicates that collapsible fissures are present in ordinary castings. It is quite possible that as the density of pressed TNT approaches its theoretical maximum density (TMD), the intrinsic burning rate of the composition would become measurable. This would be an interesting area for future study.

CONCLUSIONS

1. The physical structure of TNT breaks up during the burning process. Fragments are rapidly created with a new, unknown, surface-to-volume ratio. The rate at which the structure dissociates is much faster than the intrinsic burning rate of the dissociated material.

The net burning rate is determined by the rate at which the physical structure dissociates, the surface-to-volume ratio of the newly-created fragments, and the intrinsic burning rate of the composition.

2. The size, shape, and number of fragments is determined by the crystal and/or porosity pattern permitted to develop by the casting procedure.

3. Porosity was the major factor controlling the burning process in pressed TNT. Collapsible fissures (voids) that occurred naturally could exist in cast TNT. This was indicated by the fact that TNT could easily be pressed to higher densities than normally obtained in casting.

4. Porosity alone did not appear to provide a sufficient reason for the dissociation of the physical structure of TNT at the observed rapid rate. However, the existence of crystallinity implies that there are boundary layers between neighboring crystals, which provide cleavage paths for dissociation of the structure. The inferred, built-in porosity might be associated with these cleavage planes.

5. Wax did not interact with TNT to modify its burning characteristics.

RECOMMENDATIONS

There are several parameters associated with the deconsolidating burning mechanism that are combined in the quickness measurement. They are: the rate of structure dissociation, the average surface area of the dissociating fragment, and the intrinsic burning rate of the composition. Separated and measured, these data would provide a basis for understanding the deflagration aspect of the deflagration-to-detonation mechanism.

ACKNOWLEDGEMENT

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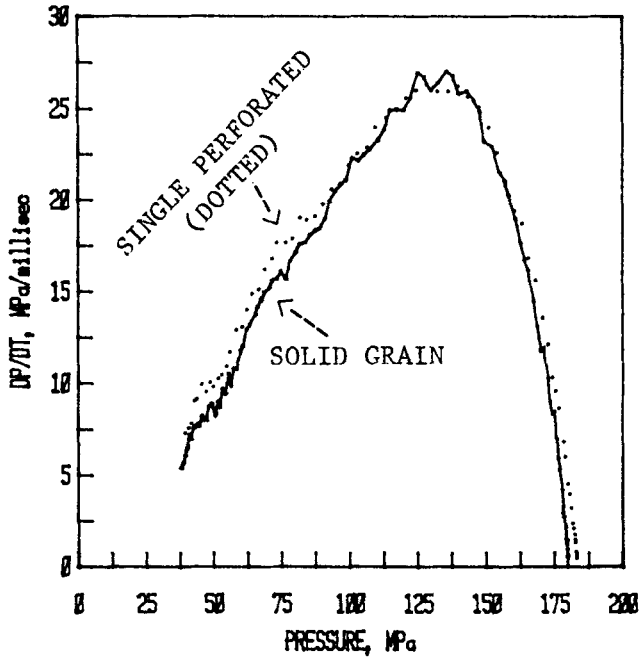

Figure 1. Cast TNT, test for surface burning (1.56 g/cm^3)

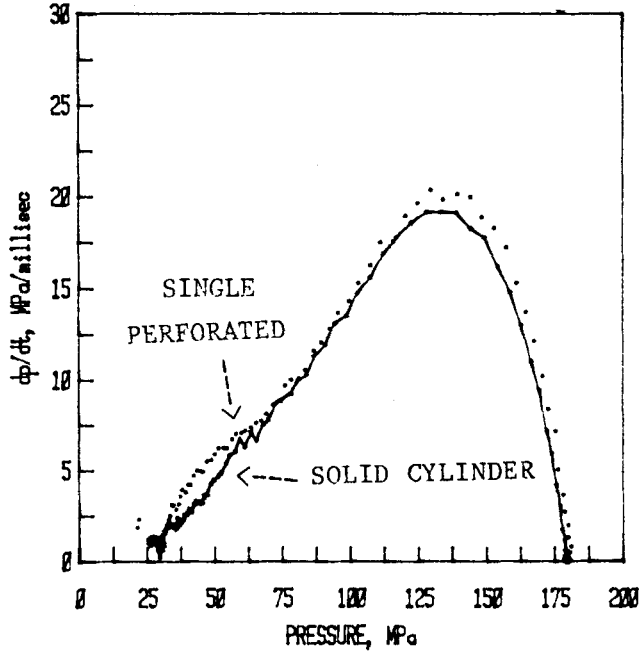

Figure 2. Pressed TNT, test for surface burning (1.59 g/cm^3)

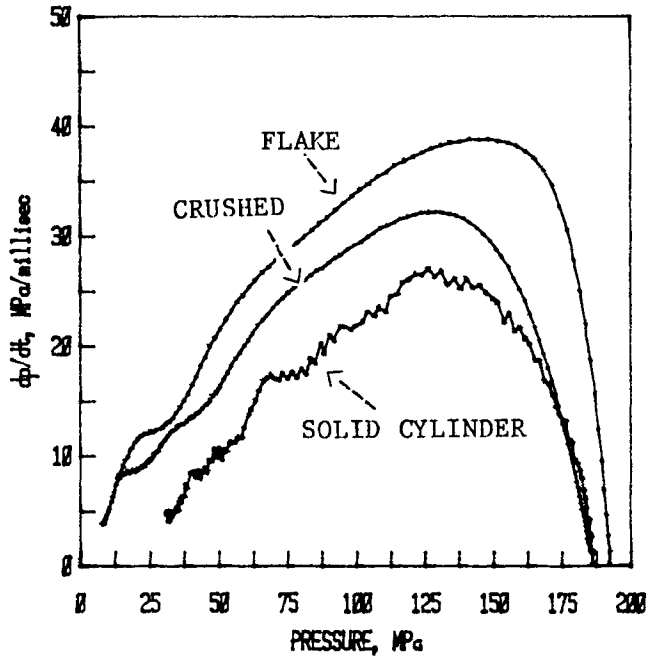

Figure 3. Crushed, flake, and solid TNT

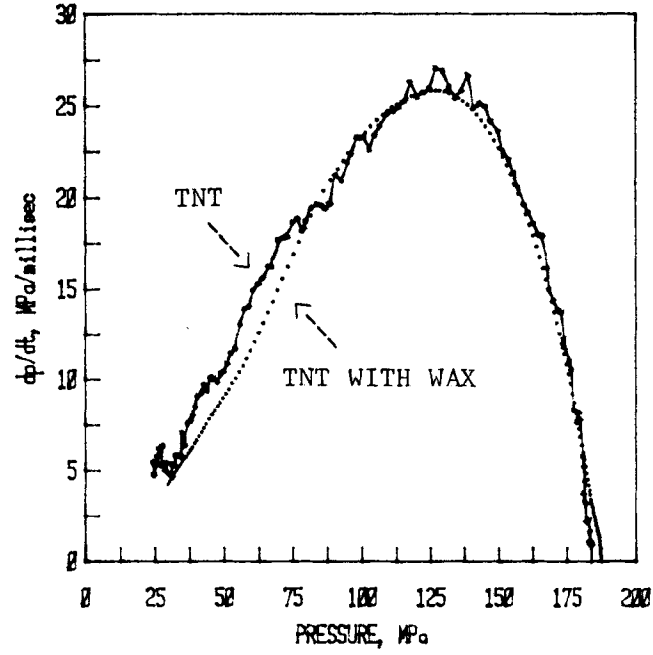

Figure 4. TNT, with and without wax

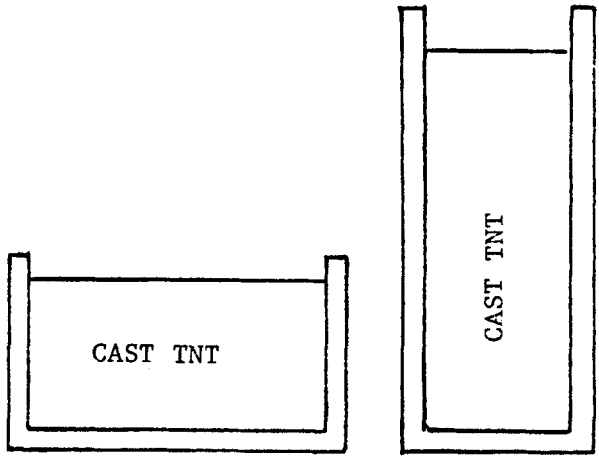

Figure 5. Restricted surface area cups

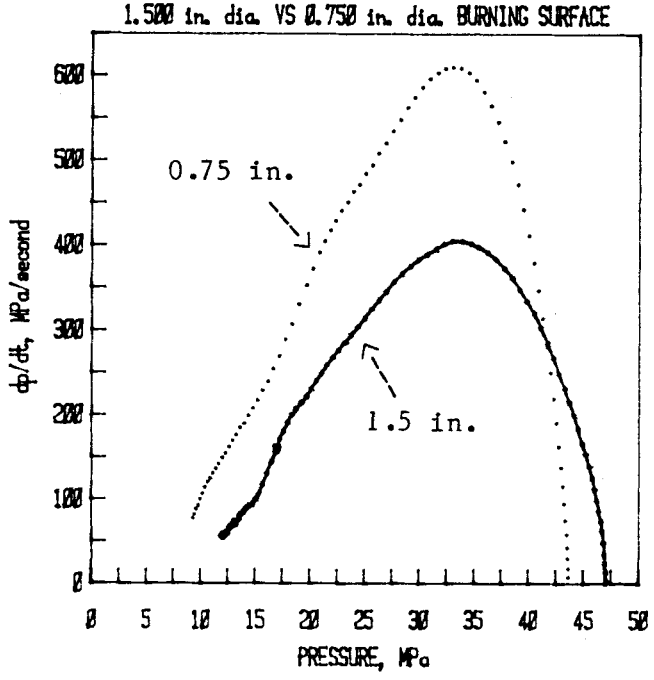

Figure 6. Fragmentation burning test

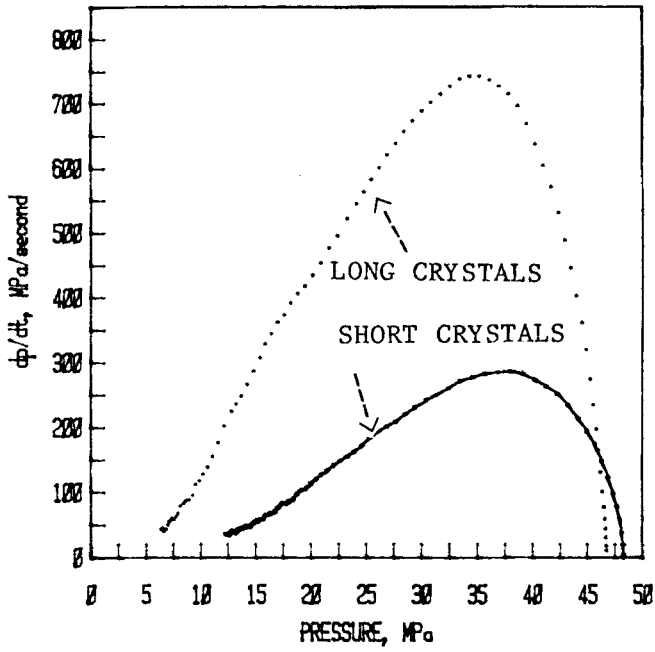

Figure 7. Crystal structure burning test

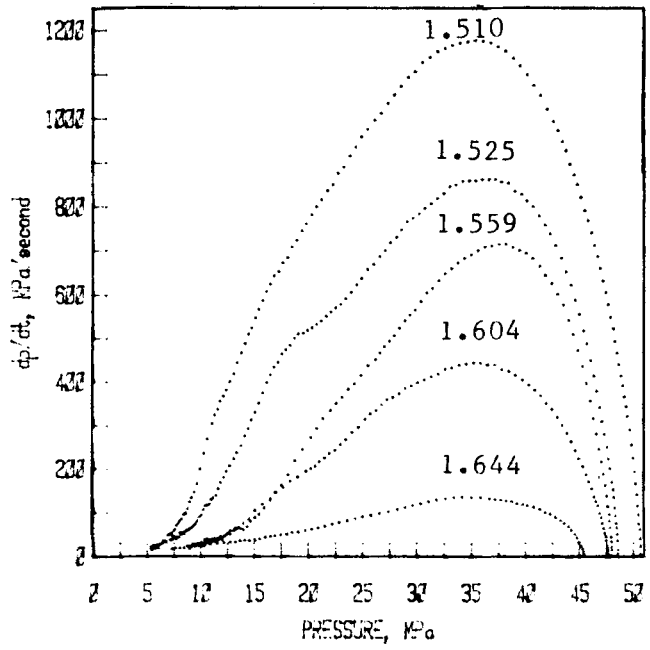

Figure 8. Density effect, pressed TNT

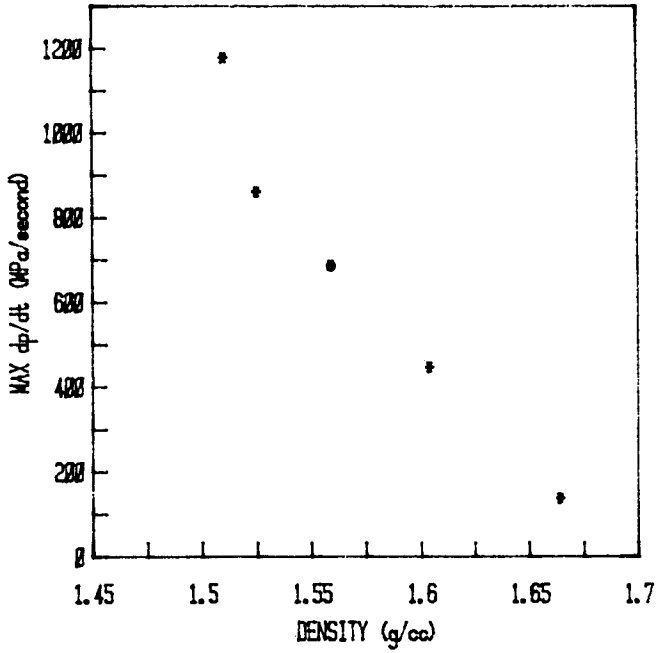

Figure 9. Density versus quickness correlation

Table 1. Surface Burning Test for Cast TNT

Pressure (MPa)	Quickness (MPa/ms)		
	#1	#2	#3
	Solid Cylinder		
30	5.57	5.59	5.56
40	7.80	7.83	9.31
50	10.82	10.05	10.51
60	14.64	13.14	14.31
70	17.32	16.65	17.07
80	19.36	17.82	18.51
90	20.63	19.59	20.49
100	22.99	21.99	22.69
110	24.32	23.25	24.32
120	26.14	25.39	26.53
	3/8 ID Single Perforated		
30	5.14	4.95	4.40
40	6.03	6.51	5.36
50	9.34	8.35	8.76
60	12.07	11.73	11.72
70	15.16	15.19	14.99
80	17.78	16.90	18.02
90	19.71	19.07	19.11
100	21.49	21.33	21.49
110	22.47	23.30	23.24
120	24.47	24.89	24.67

Table 2. Surface Burning Test for Pressed TNT

Pressure (MPa)	Quickness (MPa/ms)		
	#1	#2	#3
	Solid Cylinder Geometry		
	(Density = 1.59 g/cc)		
30	1.56	1.43	2.30
40	3.65	4.09	3.21
50	5.06	5.66	5.76
60	6.94	7.53	6.93
70	7.82	8.23	7.59
80	9.53	10.42	10.11
90	11.62	11.90	11.22
100	12.95	14.44	13.78
110	14.76	17.43	15.78
120	16.70	19.75	17.51
	3/8 ID Single Perforation Geometry		
	(Density = 1.59 g/cc)		
30	1.37	2.26	2.49
40	2.70	2.61	2.92
50	4.49	4.62	5.21
60	6.53	6.41	6.57
70	7.55	7.33	8.17
80	10.20	8.81	10.29
90	11.91	10.65	12.39
100	14.05	12.93	14.57
110	16.63	15.34	17.29
120	18.63	17.12	19.35

Table 3. Effect of an Increased Surface Area-to-Volume Ratio, Cast TNT

Pressure (MPa)	Quickness (MPa/ms)	
	#1	#2
	Crushed TNT	
30	9.96	10.69
40	12.09	13.16
50	13.99	15.96
60	16.81	19.21
70	19.89	22.42
80	22.77	24.99
90	25.30	27.11
100	27.52	28.89
110	29.35	30.18
120	30.62	31.05
	Flake TNT	
30	13.33	14.97
40	16.70	17.12
50	20.61	19.72
60	24.30	22.57
70	27.25	25.39
80	29.78	28.06
90	31.79	30.57
100	33.68	32.91
110	35.28	34.95
120	36.63	36.68

Table 4. Test for Interaction of Wax with TNT

Pressure (MPa)	Quickness (MPa/ms)		
	#1	#2	#3
	Solid Cylinder Geometry (Cast with 2.5% Wax)		
30	4.28	4.87	4.80
40	6.53	8.02	8.24
50	9.36	11.54	11.49
60	11.34	13.07	14.34
70	15.41	14.20	15.27
80	19.19	17.24	17.38
90	21.71	20.59	20.46
100	23.53	23.30	23.43
110	25.05	25.42	25.63
120	26.29	26.86	26.90
	3/8 ID Single Perforation Geometry Cast with 2.5% Wax		
30	2.73	2.41	1.74
40	7.75	5.98	4.12
50	12.17	9.42	8.24
60	15.57	12.16	13.26
70	17.21	13.74	16.22
80	17.84	15.86	18.59
90	19.66	19.44	20.76
100	22.16	33.01	22.82
110	24.33	35.10	24.65
120	25.61	25.88	26.08

Table 5. Test for Deconsolidation of Cast TNT

Pressure (MPa)	Quickness (MPa/ms)	
	#1	#2
	1.500 Inch Diameter Cup	
10.0	35.5	37.6
12.5	61.9	66.5
15.0	109.3	107.3
17.5	176.7	159.0
20.0	231.9	211.5
22.5	274.4	260.2
25.0	316.8	311.1
27.5	353.8	354.9
30.0	381.6	392.4
32.5	405.4	418.0
35.0	408.9	426.0
37.5	382.2	419.2
40.0	335.9	388.6
	0.750 Inch Diameter Cup	
10.0	103.6	104.5
12.5	162.0	243.6
15.0	210.0	283.6
17.5	276.1	320.3
20.0	423.0	348.3
22.5	443.5	397.8
25.0	477.4	448.8
27.5	529.3	390.6
30.0	598.3	530.9
32.5	629.1	556.2
35.0	611.5	558.6
37.5	556.8	516.1
40.0	444.2	414.0

Table 6. Effect of Crystal Structure on Burning of TNT

Pressure (MPa)	Quickness (MPa/ms)	
	#1	#2
	Short Crystal Structure	
10.0	29.5	26.2
12.5	45.9	34.2
15.0	79.2	54.2
17.5	113.0	84.1
20.0	159.5	113.7
22.5	198.8	148.7
25.0	246.3	178.9
27.5	291.8	205.6
30.0	324.9	236.5
32.5	349.9	261.5
35.0	369.3	281.4
37.5	359.9	290.4
40.0	344.1	277.7
	Long Crystal Structure	
10.0	123.1	67.7
12.5	220.5	138.5
15.0	292.6	241.2
17.5	385.0	327.8
20.0	432.8	394.0
22.5	506.8	471.6
25.0	574.8	553.7
27.5	637.8	645.7
30.0	684.9	714.1
32.5	740.7	769.0
35.0	745.0	825.3
37.5	732.5	849.5
40.0	662.6	839.0

Table 7. Effect of Density on Burning of Pressed TNT

Pressure (MPa)	Quickness (MPa/ms)				
	1.510 (g/cc)	1.525 (g/cc)	1.559 (g/cc)	1.604 (g/cc)	1.664 (g/cc)
10.0	204.4	95.1	18.7	32.5	25.7
12.5	391.5	196.7	52.5	55.0	32.6
15.0	542.5	327.6	84.6	103.8	38.8
17.5	546.3	461.3	163.9	152.7	51.2
20.0	772.4	520.6	265.9	197.9	62.3
22.5	863.7	571.1	349.2	244.2	76.3
25.0	960.6	641.5	420.2	309.6	91.4
27.5	1041.1	712.8	495.8	360.7	104.2
30.0	1113.7	781.0	571.3	400.3	120.3
32.5	1157.1	828.5	645.3	426.6	132.8
35.0	1177.7	860.8	688.4	446.6	136.8

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