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EVALUATION BY A MODIFIED CYLINDER TEST OF METAL ACCELERATION BY NON-IDEAL EXPLOSIVES CONTAINING AMMONIUM NITRATE

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Cylinder tests have been designed and conducted to study the effect of substitution of ammonium nitrate (AN) for RDX in a limited range of particle sizes and sources, to arrive at an appropriate design of cylinder tests for non-ideal explosives and to provide a basis for studying the basic mechanisms of these non-ideal explosives. Substitution of 20 and 40 parts of AN for RDX in Cyclotol 60/40 (i.e., Amatex 40/40/20 and 20/40/40, RDX/TNT/AN by weight) led to reduction of detonation velocity to 95% and 88.7% respectively and to 92% and 84.5% for the kinetic energy

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20. Abstract (Cont'd)

imparted to the metal wall for seven-fold explosive expansion from solid state. No particle size effect was found for Amatex 40/40/20; a slight effect may be present for Amatex 20/40/40. Recommendations were made for cylinder tests for non-ideal explosives with respect to length, diameter, wall thicknesses and material, pin mounting and spacings, optimum use of streak and framing camera, auxiliary measurements, explosive loading, safety, and necessary controls. The ratio of thin-wall to thick-wall velocity at corresponding wall displacements was essentially the same for the Amatex compositions as for the Cyclotol. This led to the conclusion that energy release in Amatex occurs prior to cylinder wall motion and is not altered thereafter. The significance of this observation for the non-ideality mechanism and further studies is discussed.

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INTRODUCTION

The metal accelerating ability of a variety of fast-reacting and composite explosives has been measured by means of cylinder tests (Ref 1-6). The essence of the cylinder test as first proposed by Lawrence Livermore Laboratory (Ref 1) is to use a one-inch-diameter, twelve-inch-long cylinder of explosive confined within a copper cylinder of the same length with a wall thickness of 0.1022 inch. The explosive is initiated at one end and the detonation wave propagates down the cylinder, causing the cylinder wall to expand. This expansion is measured by means of a streak camera in a plane perpendicular to the cylinder axis at a position about 7 to 9 inches from the initiation plane. The velocity of the expanding metal wall at the position where the explosive has expanded seven-fold with respect to its initial volume is used for a comparison of kinetic energy imparted to the metal by different explosives. Results are also obtained for larger diameters to study scaling where appropriate. It has also been shown (Ref 1) that calculations for ideal explosives with TIGER (or an equivalent computer program) of the energy change to the seven-fold point on the expansion isentrope provides the same relative measure of explosive performance as cylinder tests.

The objectives of the program described in this report were two-fold. The first objective was to design and evaluate a test configuration appropriate to measuring the metal acceleration with non-ideal explosives. A non-ideal explosive is one for which the product species at the end of the steady state detonation zone are not those of thermodynamic equilibrium based on the elemental composition of the explosive. Rate-dependent phenomena in these explosives require test design consideration of non-scaling, run-up distance, diameter effect, and enhanced role of rarefaction waves.

The second objective was to choose a non-ideal explosive medium which was of current interest to use for developing this cylinder test and simultaneously to carry out a plan of tests for evaluating the effect on performance of parameters of the explosive.

The role of the cylinder test for prediction of performance of explosives in munitions with respect to metal accelerating ability may be understood in terms of the diagram shown below.

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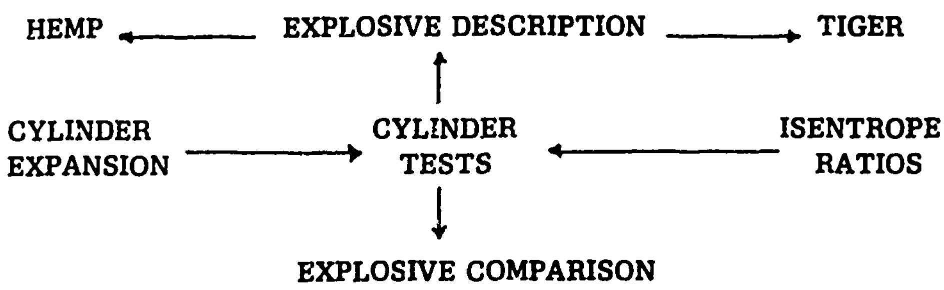

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METAL ACCELERATION IN MUNITIONS APPLICATIONS

Cylinder tests provide information for direct (downward arrow) comparison of explosives. The upward arrow indicates that the results of these tests also provide a means for calibrating an appropriate equation of state description of an explosive by using a two-dimensional wave propagation computer program such as HEMP (Ref 7) to predict the expansion of the cylinder and comparing these predictions with the results of the cylinder test (left loop). Verification of the derived explosive description in other situations such as with a different wall thickness serves to determine the domain of application of that explosive description. Cylinder tests can also be used (right loop) for comparison with the results of TIGER calculations of the change in energy from initial to final state along an isentrope for different explosives. This determines the validity of the use of TIGER for rela-rankings of explosives. These comparisons lead to predictions as to explosive performance when metal acceleration is the significant feature of munition applications. For the non-ideal explosives the cylinder test results have the additional important role of serving as a testing ground for hypotheses on the nature of the non-ideality. This report provides the experimental procedures and detailed results to involved scientists for use in this regard.

The reader will find it of value to refer to the Table of Contents to satisfy his particular interests on a first reading. Note that the results pertaining to the two objectives of this program are separately treated in the DISCUSSION.

PROCEDURES

Cylinder Test Configuration

Since ammonium nitrate containing non-ideal explosives would be expected to have a strong dependence on diameter in the one-to two-inch-diameter range and munitions containing non-ideal explosives would generally be larger than two inches in diameter, the cylinder test configuration was chosen to have a four-inch-diameter explosive charge. The copper wall thickness was scaled to 0.4 inch to be appropriate to this explosive charge diameter. However, since it was not readily feasible to provide a still larger diameter (e.g., 8 inches) to test the effect of scaling and since it was desired, as noted previously, to establish the range of validity of an explosive description deduced from a cylinder test, a second wall thickness half the previous (i.e., 0.2 inch) was included as an additional cylinder test. The two wall thicknesses represent two separate points on a scale of charge-to-mass ratios used in munitions (Table 1). The two values allow the limited extrapolation of these cylinder test results to the charge-to-mass ratio appropriate to the munition of interest.

In recognition of the need for a longer distance for a non-ideal explosive to establish a steady state detonation and the need for a longer disturbance-free expansion time because of the slower wall motion the overall cylinder length was increased from twelve to thirty-six inches. The location of contact pins for monitoring the run-up of the wave front and for measuring the velocity over the region where the radial expansion was measured by a slit camera are shown in Figures 1 and 2. The choice of slit position is intended to provide the longest possible expansion time free of rarefaction from either end. The far end of the explosive charge provided an opportunity to observe the emergent curvature of the wave front by using a second slit. (The DISCUSSION Section treats other possible design features for cylinder tests of non-ideal explosives.) Initiation was by a plane wave generator operating through a two-inch-thick Comp B booster (RDX/TNT 60/40 with 1% wax added) confined in a copper sleeve matching that of the cylinder wall. The end of the explosive cylinder closest to the riser (pouring end) was initiated by the booster so that the slit would be in the region of highest quality.

Table 1

Ratio of explosive mass (C) to metal mass (M) for munitions and cylinder test configurations

Munition	Explosive (lb)	Metal (lb) Less Fuze	C/M Ratio
60 MM Mortar	0.46	1.59	0.29
81 MM Mortar	2.03	5.12	0.40
105 MM Shell	4.60	25.60	0.18
155 MM Shell	15.4	77.80	0.20
175 MM Shell	31.0	113.8	0.27
500 Lb Bomb	192	308	0.62
750 Lb Bomb	380	355	1.07

Cylinder Test Values of C/M for RDX/TNT/AN Compositions

	Cyclotol 60/40/0	Amatex 40/40/20	Amatex 20/40/40
Thick Wall (scaled to standard LLL test)	0.418	0.403	0.391
Thin Wall (1/2 of standard)	0.836	0.807	0.783

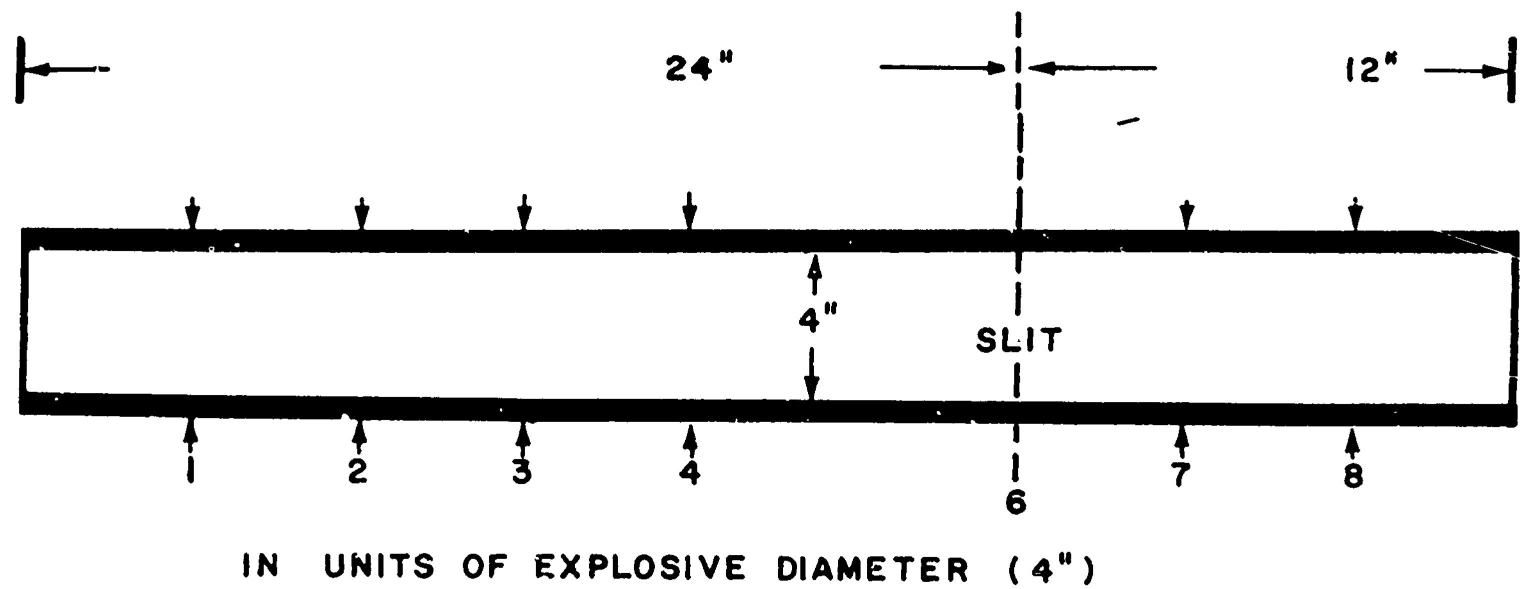

Fig 1 Nominal positions of slit and pins used for cylinder test of Cyclotol 60/40

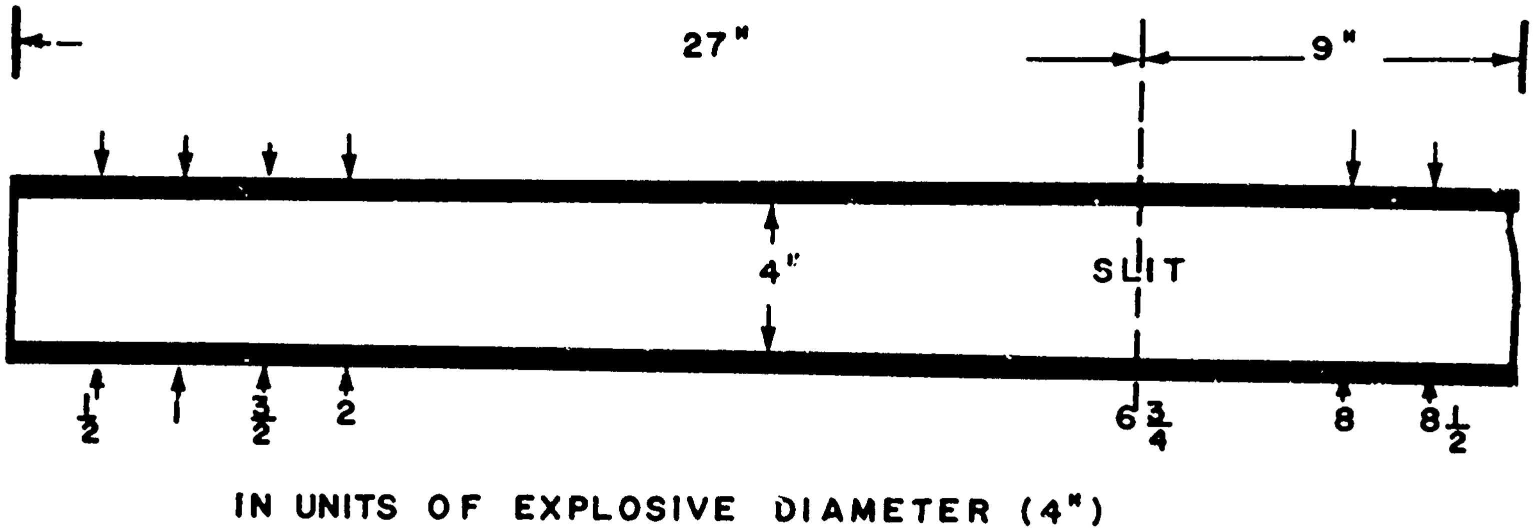

Fig 2 Nominal positions of slit and pins used for cylinder test of Amatex 40 and 20

Plan of Tests

Amatex explosives substitute ammonium nitrate for RDX in Cyclotol 60/40 RDX/TNT (by weight). The effect on metal accelerating ability of this substitution was studied in two steps: Amatex 40, RDX/TNT/AN (40/40/20) and Amatex 20 (20/40/40). This variation in composition is the ordinate in the plan of tests shown in Table 2. Another factor considered of great importance with respect to non-ideal explosives is the particle size distribution of the ingredients, which is here varied along the abscissa in three steps. In addition, two types of ammonium nitrate, designated T and C (further details are in Explosives sub-section), were pulverized to obtain the particle size fractions shown here.

The numbers within the test plan were assigned to each pair of cylinder tests (thick and thin wall) with the indicated combination of parameters. The test plan permits the following series of comparisons with respect to the parameters involved.

a. 1 vs 2 shows reproducibility of results for the same condition for both thick-wall and thin-wall cylinders.

b. 3 and 7 show effect of coarse ammonium nitrate substitution for RDX with 1,2 as reference.

c. 4 and 8 show the same effect for medium ammonium nitrate.

d. 9 shows the effect of fine ammonium nitrate only for one step in substitution for RDX. Additional ammonium nitrate could not be used because of the viscosity limitation for casting of Amatex 20.

e. 5, 6 are repeats of 4, 8 but use a different ammonium nitrate as source.

f. 7, 8, 9 and 6 (if the same as 9) provide a measure of the effect of progressive increase in surface area of ammonium nitrate in Amatex 40.

g. 3, 4 and 5 (if the same as 4) provide a measure of progressive increase in surface area of ammonium nitrate for Amatex 20.

h. Comparison in each case of thick-wall and thin-wall copper cylinder results provides a measure of the role of confinement on metal acceleration.

Table 2

Plan of tests*

RDX/TNT/AN		Ammonium Nitrate Particle Size Fraction Coarse	Medium	Fine
60/40/0	1,2			
40/40/20		7T	8T	9T 6C
20/40/40		3T	4T 5C	

*Each number represents a pair of tests one with a thick wall and one with a thin wall cylinder. The letters T and C refer to ammonium nitrate sources (see text)

i. There are second-order interaction effects between the above enumerated factors.

Copper Cylinders

In order to obtain the copper cylinders it was necessary to have a mill run made by a copper manufacturer of oversize tubes and to machine the final cylinders to the desired dimensions from these.

The specification used for purchase of the oversize tubes is outlined below.

Material	Oxygen-free high-conductivity (OFHC) electronic grade certified.
Treatment	Hard drawn, relief annealed to finish dimensions.
Length	40" + 1.00 - 0.00.
Camber	Maximum deviation from straight line of any and entire length of inside or outside 0.0625".
ID	3.75" $\pm$ 0.01.
Out of round	0.020" maximum.
OD	5.0" $\pm$ 0.01.
Eccentricity re ID	$\pm$ 0.050".
Transport	Wrapped and padded to prevent damage. Packed 4 to a box with wood separators, using minimum 3/4" lumber.

A total of 43 such tubes were furnished at a price of $6476 (18 were used for the tests reported here).

The samples were then machined to final dimensions in accordance with the specification outlined below.

Length	36 ± 0.06".
Thick-wall cylinders	ID 4.00 ± 0.004"; OD 4.820 ± 0.004".
Thin-wall cylinders	ID 4.00 ± .004"; OD 4.428 ± .004".
Hole	Straight within .008 over entire range.
Anneal	Non-oxidizing atmosphere after rough machining and at any other occasion.
Final hardness	50 Rockwell scale "F" maximum (with finished sizes).
Finish	16 finish called for on both the inside and outside and a 63 finish on the ends.

The cost of machining was $16,017.50 (for 21 thin wall cylinders and 22 thick wall cylinders). Nine of each were used for this series of tests.

Each cylinder was given an identification number and the end pieces cut off in machining were marked with the number. These end pieces were used for metallurgical controls and to provide a 2" length to confine each Comp B booster.

Explosives

An analysis of the Cyclotol 60/40 used, lot number HOL-SR-90-59, showed that the percentage ratio RDX/TNT by weight was 60.77/39.29. The TNT lot used for this composition by Holston Ordnance Works was VOL-1-2790. The RDX used was nominally Class A. The particle size distribution determined from the Cyclotol as furnished by Holston is shown in Table 3.

TABLE 3

RDX particle size distribution in Cyclotol 60/40 (HOL-SR-90-59) material*

US Standard Sieve	Sieve Opening (μ)	Cumulative Weight Percent Retained HOL-SR-90-59
35	500	0
45	[illegible]30	0.2
60	250	11.3
80	177	35.2
120	125	60.2
170	88	66.9
230	62	75.2
325	44	79.6
< 325	< 44	100.0

*Material as received from Holston at Picatinny Arsenal. Determinations made at both Los Alamos Scientific Laboratory and Picatinny Arsenal. Constituent material RDX/TNT, 60.77/39.29 wt %.

TABLE 4

Particle size distributions*

Range (Microns)	Thru/on	RDX	Ammonium Nitrate Coarse	Fine	
500-800	20/35	↑	34		
250-500	35/60	5.6	42		
177-250	60/80	23.4	24 ↓		
125-177	80/120	26.0		50	63
88-125	120/170	10.1		35	30
62-88	170/230	9.3			
44-62	230/325	6.6		15 ↓	7
< 44	325/PAN	19.0			

*Values are shown as sieve fractions. For RDX these are converted from cumulative particle size distribution data on samples of Cyclotol cast at Picatinny Arsenal as part of this program. For AN these are direct measurements on samples taken from material used in making Amatex compositions. The arrows and brackets combine sieve fraction (e.g., for RDX, 5.6 wt % on a U. S. Standard Sieve-60 Mesh).

The ammonium nitrate designated by the letter T in the plan of tests (Table 2) was pulverized using a hammer mill from high-density prills (MIL-A-50460) procured from Terra Chemical International, Inc. in an uncoated version. The material designated C in the test plan used ammonium nitrate pulverized from the Stengel process type manufactured by Commercial Solvents, Inc. The AN's were dried before and after pulverizing. The pulverized material was vibration screened through U. S. standard sieves. The coarse, nominally 20/60, indicates that it is the part of the pulverized material which passed through a number 20 U. S. standard sieve but was retained on a number 60 sieve. In the same sense, the fine, nominally 80/230, is the fraction which passes through a number 80 sieve but was retained on a 230 sieve. The third material, designated medium, contained equal parts by weight of the other two. Further sieve measurements were conducted on these fractions to establish the distribution that really existed. This was necessary because fractionation by sieving is not totally effective. The results are shown in Table 4. It can be observed there that residual fines existed in both the coarse and fine materials.

Loading of Cylinders with Explosives

Each composition was individually prepared in a preheated jacketed kettle and poured into the cylinders designated for that composition. Each copper cylinder was fitted with a base plate and a steam jacketed riser tube extending the explosive mix column 12". Heating of the cylinder was achieved through heat transfer from the riser. Mixture temperatures and cylinder temperatures were recorded for each pouring. Pouring temperatures varied from 178°F to 190°F, the latter for the more viscous melts. Typical measurements along the copper cylinder at the time of pouring were 185°F near the riser, 150°F halfway down, and 130°F near the bottom. A more uniform temperature can be achieved by using a thermally insulating jacket on the copper cylinder and a preheated base plate.

It was recognized from the start that the use of ammonium nitrate introduced severe problems with respect to moisture absorption. For this reason the pulverized ammonium nitrate was sealed and kept under heat and vacuum insofar as possible until introduced into the melt. The various compositions required were achieved by using Cyclotol 60/40 and adding the appropriate weights of TNT and ammonium nitrate for the designated mix. The order of introduction into the kettle was TNT, then Cyclotol, and lastly ammonium nitrate.

The kettle was held under vacuum for 15 to 20 minutes before pouring into the cylinder. Because the more viscous mixes were thixotropic manual vibration had to be used. After the mixes were poured heating of the riser was maintained for four to six hours. Then the source of heat was turned off and the mix was allowed to solidify overnight.

The following day the riser tube was removed and the loaded cylinder was sent to the Machine Shop for removal of the explosive riser section. Sequential sawcuts were made on the explosive riser, leaving a protrusion of approximately 1/16". This was later removed by "steam platen ironing," which process was also applied to the base. TNT was used where required as a filler. This process serves to provide an additional moisture seal of the ammonium nitrate in the composition and assures a smooth plane contact surface. The thin-wall and thick-wall cylinders were filled from the same melt, one immediately after the other. In addition to pouring into the 36" long cylinders, an additional 4" high cylinder (the section cut off during machining) was also loaded when enough mix was available. After cooling this 4" high section of explosive was removed from the short copper cylinder and used for control tests.

The copper cylinders were each sealed in a moisture barrier container after removal of the riser tube. They were taken out of the containers only for subsequent operations such as machining.

Controls

Before commencing this series of tests sample pieces of copper taken from 1" and 2" ID copper cylinders used for cylinder tests by Lawrence Livermore Laboratory had been obtained. These samples were examined with respect to longitudinal and transverse microstructure and their microhardness was measured. Three end pieces of the 4" ID cylinder of each wall thickness were selected at random and subjected to similar tests. Table 5 presents the results of these measurements. In general the thick- and thin-wall tubes appear to be similar in surface appearance, microstructure, and hardness and somewhat harder than the samples of the smaller diameter tubes.

The results of the cylinder tests must be interpreted with respect to the density, composition, and voids incorporated in the castings. To obtain an indication of the extent to which the latter was included in the casting each of the loaded copper cylinders was radiographed. Although some voids and cracks were noted, no correlation was later found in such results as wall-breakup pattern that could be traced back to these defects.

TABLE 5

Knoop microhardness and Rockwell F (R_F) hardness for copper tubes

Wall	Sample No.	Section	Hardness: Average KHN	Average R_F	Minimum KHN	Minimum R_F	Maximum KHN	Maximum R_F	Range KHN	Range R_F
Thick	A5	Long.	65.4	*	59.3	*	75.8	65.2	16.5	**
		Trans.	77.2	66.7	62.7	*	102.2	82.6	39.5	**
	A15	Long.	76.9	66.2	63.2	*	100.0	81.5	36.8	**
		Trans.	64.4	*	44.2	*	81.0	69.2	36.8	**
	A17	Long.	67.9	57.8	60.4	*	81.2	69.5	20.8	**
		Trans.	70.6	61.0	64.4	*	82.6	70.7	18.2	**
Thin	B2	Long	71.2	61.5	62.6	*	80.0	69.0	17.4	**
		Trans.	66.6	*	60.7	*	76.6	66.0	15.9	**
	B8	Long.	82.5	70.5	75.0	64.7	88.7	74.8	13.7	10.1
		Trans.	76.6	66.0	64.4	*	93.3	77.7	28.9	**
	B10	Long.	70.9	61.3	61.1	*	81.0	69.2	19.9	**
		Trans.	74.0	64.2	64.3	*	78.0	[illegible]	13.7	**
1" Tube (LLL)		Long.	75.7	65.3	67.4	57.2	88.1	74.5	20.7	17.3
		Trans.	83.3	70.9	70.0	60.8	98.5	80.3	28.5	19.5
2" Tube (LLL)		Long.	82.2	70.3	68.4	58.9	97.6	80.1	29.2	21.2
		Trans.	69.0	60.0	58.1	*	78.4	67.6	20.3	**

*Below applicable range
**Not determinable

Core samples were obtained from the section of the riser closest to the top of the cylinder. This was considered to indicate the condition at the top of the cylinder. Core samples were also obtained from the separate 4-inch-high cylindrical castings previously described. Because of their short height these were considered to be indicative of the conditions at the base of the cylinder. In addition the density was obtained for the total 36" sample by weighing the copper cylinders before and after loading. The core samples described above were used as a basis of density and composition determinations. The results obtained from these determinations are given in Tables 6 and 7. Table 6 shows that the composition at the top of the cylinder, as indicated by the riser results, is RDX rich and TNT deficient. Bleeding out of TNT at the interface between the copper cylinder and riser tube had a strong effect. This bleeding will be corrected in future work by incorporating a sealing gasket in the riser tube. The 4" cylinder is closer to the nominal composition. Some TNT deficiency may be observed again for Amatex compositions in Table 7 (see under "Riser"). Note, however, that as TNT decreases in the Amatex compositions, part of the deficiency is compensated for by ammonium nitrate. Density results for the Cyclotol 60/40 in Table 6 show the higher density associated with the 4" casting and the lower associated with the riser region.

Densities in Tables 6 and 7 may be compared with computed maximum values using the compositions provided therein and densities of 1.82, 1.65, and 1.73 for RDX, TNT, and AN respectively. For Amatex 42/36/22 and 21/36/43 the computed values are 1.736 and 1.718 respectively. For these assumed compositions, one calculates from Table 7 that the 36" densities for Amatex 40 range from 92.7 to 95.1% of computed maximum values and for Amatex 20 from 91.2 to 93.3%. Percent values will be lower for densities in the riser section and higher for the 4" casting. It has been supposed that the latter most closely approximates the region of cylinder expansion observed by the streak camera.

Safety Considerations

It has been known for many years that ammonium nitrate can react with copper to form a salt (Tetrammino Cupric II) nitrate, which is reputed to have a sensitivity in the range of primary explosives (Ref 8 and 9). This was a matter of great concern since an accidental initiation of a cylinder containing 30 pounds of secondary explosive would lead to a most serious accident. The relevant reference was studied in great detail and additional inquiries were made. It was quickly established that there was no danger associated with the loading of the cylinder, i.e., formulating the

TABLE 6

Cyclotol composition and density measurements

<u>Composition Measurements</u> (Nominal 60/40)

	Riser[1]		4" Casting[1]	
	PA	LASL[3]	PA	LASL[3]
Thick	69.0/31.1			
		70.0/30.0		
	70.2/29.8			
			62.2/37.8	61.4/39.1
			64.2/35.8	62.6/37.4
Thin				
	66.1/34.0			
		64.1/35.9		
	65.6/34.5			

<u>Density Measurements</u>

	Riser[1]		4" Casting[1]		36"[2]
	Water	Mercury	Water	Mercury	
Thick	1.687	1.678			1.692
	1.656	1.676			1.694
			1.707	1.700	
			1.703	1.692	
Thin	1.691	1.679			1.694
	1.692	1.688			1.694

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[1] Three pellets from riser section adjacent to cylinder or from base of casting into a 4" high thick-wall cylinder from same melt

[2] From overall net weight and volume of 36" long loaded cylinder

[3] Los Alamos Scientific Laboratory results on samples furnished by Picatinny Arsenal. PA heading on results obtained at Picatinny Arsenal on other samples from the same sources (i.e. riser, etc.)

TABLE 7

Amatex composition and density measurements

	Riser[1]		4" Casting[1]		36"[2]
	Density	Comp	Density	Comp	Density
		Amatex 40, Nominal 40/40/20 (RDX/TNT/AN)			
Coarse	1.563	42.7/35.6/21.8			1.642
	1,589	42,4/35.8/21.8			1.647
Medium	1.528	41.6/36.9/21.5	1.673	40.4/39.4/20.3	1.639
	1.563	42.7/35.7/21.7			1.651
Fine	1.531	42.9/35.7/21.5	1.672	40.0/40.3/19.7	1.629
	1.561	42.3/36.6/21.2			1.623
Fine*	1.557	42.5/36.4/21.1	1.669	40.8/39.6/19.7	1.612
	1.535	41.5/37.8/20.8			1.609
		Amatex 20, Nominal 20/40/40 (RDX/TNT/AN)			
Coarse	1.490	20.8/36.4/42.9	1.604	19.6/40.3/40.1	1.579
	1.502	21.7/33.7/44.7			1.587
Medium	1.543	20.9/36.3/42.8	--	--	1.603
	--	--			1.602
Medium*	1.519	20.0/38.7/41.3	1.624	19.5/41.2/39.4	1.566
	1.543	20.6/38.5/41.0			1.574

[1] Three pellets from riser section adjacent to cylinder or from base of 4" casting from same melt

[2] Overall net weight and volume of 36" long loaded cylinder

*Pulverized Stengel type ammonium nitrate instead of pulverized prills. Upper and lower values of each pair are for thick- and thin-wall cylinders respectively.

mix in steam-heated open kettles posed no problems and at Picatinny no copper kettles or pails were used. However, ammonium nitrate and copper in the presence of moisture forms copper nitrate, which is the first step in the formation of the salt.

Since there would be ammonium nitrate and copper it was essential that the moisture content of the ammonium nitrate be reduced to an absolute minimum and the low level be maintained after loading the mixes. As stated earlier, the ammonium nitrate was dried prior to pulverizing and was kept in a dry state and vacuum heated and directly inserted while still hot in the rest of the mix. All of these steps were judged to have reduced the ammonium nitrate moisture concentration to a minimum value. After copper nitrate formed, the formation of the tetrammino cupric nitrate salt would require air, moisture, and a period of time exceeding two weeks and most likely of the order of months. The precaution was taken of moving as quickly as possible once the cylinders were loaded to have them radiographed and inserted in barrier bags which were evacuated and hermetically sealed.

It should also be mentioned that the cylinders were regularly inspected for evidences of blue corrosion products. In one case such products were found on the bottom and traced back to the presence of water used to clean the loading area. These were carefully removed and replaced with TNT in the ironing process. Although all these steps represented reasonable precautions, a final inspection was made by reopening a barrier bag on the sample that had shown some corrosion and been repaired just prior to shipment. The bags were reopened immediately on arrival at the testing site and another examination made for evidences of corrosion. Such monitoring was continued throughout the test period.

In the DISCUSSION section there is presented an alternate approach to conducting cylinder tests with copper cylinders on mixtures containing ammonium nitrate. For improved safety it is recommended that this method be followed in the future.

Experimental Arrangement at Field Site

The experimental arrangement is shown in Figure 3. The key points to be noted are that a double slit was used with a streak camera to record both the expansion and the end breakout on a single streak record. In addition simultaneous framing camera photography recorded the run-up

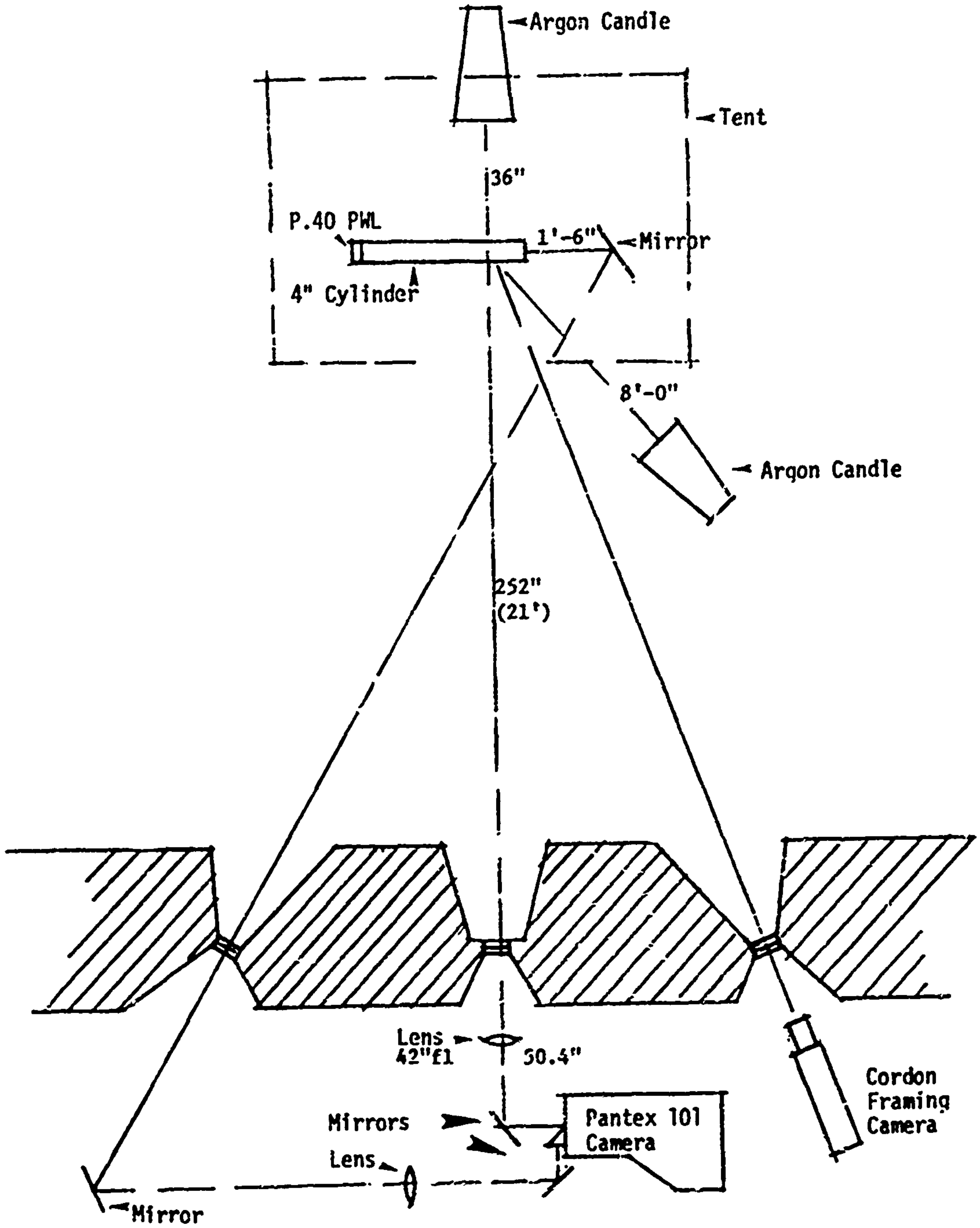


Fig 3 Cylinder test arrangement at firing site

and the expansion and breakup of the copper cylinder over the length surrounding the slit. These pins record the closing of the circuit between the copper cylinder and each pin as the initial wall expansion occurs at each pin position. Not shown in Figure 3 are the sets of pins used to record the passage of the detonation wave. Each set, located as shown in Figures 1 and 2, consisted of a ring holding six pins at each position. Thus a measurement from one position to the next would consist of six numbers representing the times of transit between corresponding pins on the circumference of the cylinder at each pin position. These pins were mounted in a plastic ring. Early framing camera photographs indicated that the mass of the plastic was adequate to induce early rupture of the copper cylinder during expansion. This led to the change in pin positions from those in Figure 1 to those in Figure 2. In this way the disturbance-free expansion time at the slit was maximized.

RESULTS

Pin Data

For each cylinder a set of pin data was obtained consisting of reference measurements of the spacing between pins and arrival times. Table 8 shows results for the case of Cyclotol 60/40 in a thick-wall copper cylinder. The pin spacings were measured in inches. The pin times are quoted in microseconds, representing the first displacement of the wall at the pin positions. From this data the velocities between corresponding pins are calculated (shown in millimeters per microsecond in Table 9. Numbers in this table are serial numbers of pins, not their position in explosive diameters.

Table 10 shows the mean value of propagation velocity in meters per second and the corresponding standard deviation of the individual pin span values (such as presented in Table 9) for Amatex composition studies. The pin positions are now expressed in terms of explosive diameter. Since the explosive diameter was always four inches, 1 to 2 can be simply interpreted as four inches to eight inches and 2 to 8 as eight to thirty-two inches. All measurements were made from the initiation end of the 36" long cylinder. Note the redundancy in that we have pin positions at 1, 3/2, and 2 diameters, but calculations for the spans 1 to 3/2, 3/2 to 2, and also the combination span 1 to 2. This last calculation was done to reduce the standard deviation in the region preceding the slit position.

TABLE 8

A typical set of pin data
(Cyclotol 60/40, thick-wall cylinder)

<u>Pin Spacings (inches)</u>

1-7	3.999	7-13	4.000	13-19	4.000	19-25	12.001	25-31	4.004
2-8	3.997	8-14	4.000	14-20	4.000	20-26	12.004	26-32	3.998
3-9	3.996	9-15	4.004	15-21	4.000	21-27	12.003	27-33	4.000
4-10	3.999	10-16	3.999	16-22	4.003	22-23	11.999	23-34	4.003
5-11	4.000	11-17	3.997	17-23	4.002	23-29	11.996	29-35	3.996
6-12	3.998	12-18	3.998	18-24	4.005	24-30	12.003	30-36	3.994

<u>Arrival Times at Pins (microsec)</u>

1	34.7807	7	47.5774	13	60.3819	19	73.3406	25	111.9803	31	--
2	34.8353	8	47.5792	14	60.4527	20	73.3887	26	111.9980	32	124.9590
3	34.7343	9	47.4921	15	60.4092	21	73.3209	27	111.9758	33	125.1009
4	34.7244	10	47.4473	16	60.3326	22	73.2555	28	111.9422	34	124.9630
5	34.7346	11	47.5030	17	60.3396	23	73.3006	29	111.9671	35	124.9972
6	34.7728	12	47.5449	18	60.4269	24	73.3778	30	112.0422	36	124.9669

TABLE 9

Propagation velocities (mm/μsec) calculated from Table 8
(Cyclotol 60/40, thick-wall cylinder)

1-7	7.93756	7-13	7.93471	12-19	7.84029	19-25	7.88891	25-31	NO TIME
2-8	7.96646	8-14	7.89218	14-20	7.85405	20-26	7.89710	16-32	7.83498
3-9	7.95579	9-15	7.87340	15-21	7.86883	21-27	7.88712	27-33	7.74089
4-10	7.98360	10-16	7.88298	16-22	7.86790	22-23	7.87802	23-34	7.80675
5-11	7.95714	11-17	7.90893	17-23	7.84282	23-29	7.88016	29-35	7.78953
6-12	7.95086	12-18	7.88303	18-24	7.85482	24-30	7.88519	30-36	7.84912
N =	6.00000	N =	6.00000	N =	6.00000	N =	6.00000	N =	5.00000
M =	7.95857	M =	7.89587	M =	7.85478	M =	7.88608	M =	7.80469
S =	.015488808	S =	.022486773	S =	.012027260	S =	.006802764	S =	.042451116

N = No. of measurements
M = mean velocity
S = standard deviation of individual values about the mean.

NOTE: The fourth set of data from the left provides the velocity for the slit position at which streak data were obtained on the radial expansion of the cylinder.

TABLE 10

Propagation velocities (m/sec) and deviations (N = 6) from pin data

Diameters	1/2 - 1	1 - 3/2	3/2 - 2	1 - 2	2 - 8	8 - 8 1/2
Amatex 20/40/40 (RDX/TNT/AN)						
Coarse	6821(35	6943(52	6972(13)	6962(29)	6947(4)	6935(22)
	6847(38)	6887(84)	7061(103)	6967(18)	6964(3)	6955(31)
Medium	7053(28)	7049(10)	7088(9)	7068(9)	7029(4)	7037(19)
	7027(27)	7027(26)	7078(56)	7053(18)	7029(10)	6975(109)
Medium*	6940(23)	7009(20)	7085(13)	7046(7)	7030(7)	7091(27)
	6956(25)	7013(29)	7042(25)	7029(15)	7055(9)	7070(22)
Amatex 40/40/20 (RDX/TNT/AN)						
Coarse	7404(74)	7527(71)	7582(22)	7554(32)	-	-
	7431(39)	7547(41)	7526(38)	7537(13)	7545(5)	7558(21)
Medium	7457(66)	7466(22)	7564(33)	7515(12)	7570(3)	7544(50)
	7442(57)	7581(37)	7567(37)	7574(14)	7585(2)	7578(21)
Fine	7339(77)	7464(56)	7475(23)	7470(31)	7554(4)	7602(46)
	7259(41)	7398(54)	7442(50)	7420(14)	7558(8)	7580(38)
Fine*	7419(59)	7468(6)	7506(17)	7492(13)	7499(6)	7548(43)
	7343(43)	7410(30)	7552(39)	7480(25)	7504(3)	7501(22)

*This mix used pulverized and screened Stengel process AN
Other mixes used pulverized and screened high-density AN prills.

Upper line of each set is for the thick-wall cylinder, lower is for the corresponding thin-wall cylinder. Positions are in multiples of explosive diameter (4") measured from the initiation end of the 36" long cylinder. The slit position of the streak record was at 6.75 diameters (27"). Standard deviations are for six sets of pins spaced around circumference of cylinder, not for cylinders. Only one cylinder corresponds to each line of data above.

Table 10 provides the data for examining the change in velocity with propagation distance, particle size, and wall thickness. If one examines for each horizontal line of data the two extreme left and right values, one observes that in almost every case they are either the same or there has been a small increase in velocity with the propagation. However, if one examines the last three columns to the right, it appears a reasonable conclusion that the velocity across the slit position was constant within the experimental error. This conclusion permits making comparison of the parameters of the experiment at the slit position as is done in Table 11. The latter also includes an estimate (see Tables 6 and 7) of the composition and density at the slit position. One can draw the following conclusions from Table 11:

a. The experimental reproducibility was measured using Cyclotol 60/40, the most uniform explosive. The detonation velocities of the two thin-wall cylinders differ by only 7 m/sec and of the thick-wall cylinder by only 14 m/sec. It follows that variations in observed detonation velocity for Amatex compositions may be attributed to the parameters involved.

b. The Amatex 40 and Amatex 20 velocities are lower, as shown near the bottom of the table. Substituting 20% and 40% ammonium nitrate for corresponding amounts of RDX in the Cyclotol leads to reduction in detonation velocity to 95 and 88.7% of that of the Cyclotol 60/40 (for loading densities achieved, which are close to anticipated production values).

c. There is no significant difference in velocities with respect to the wall thickness.

d. For Amatex 40, there appears to be no effect due to AN particle size within experimental error. (Note that this composition contains only 20% AN, that AN particle size variation was limited (Table 4), and that the density data (Table 7) is not sufficiently consistent to support density corrections to the detonation velocities (Table 11). At best, the latter corrections would lead to a very small (66 m/sec) effect for fine particle size.

e. In Amatex 40, for fine ammonium nitrate made from Terra source material the detonation velocity is higher than those for the Stengel process source material. No reason is known for this result and it may very well be due to variation in loading or density or composition.

TABLE 11

Detonation velocities and pin measurement standard deviation (N = 6) at slit position

	Cyclotol 60/40		Amatex 40/40/20		Amatex 20/40/40	
AN	Thick	Thin	Thick	Thin	Thick	Thin
None	7886 (7)	7900 (7) 7907 (5)				
Coarse				7545 (5)	6947 (4)	6964 (3)
Medium			7570 (3)	7585 (2)	7029 (4)	7029 (10)
Medium*					7030 (6)	7055 (9)
Fine			7554 (4)	7558 (8)		
Fine*			7499 (6)	7504 (3)		
Avg/SD/(N-1)	7898/10.7/2		7545/32.3/6		7009/43.0/5	
D_{re} 60/40	100%		95%		88.7%	
Composition	62/38		41/38/21		20.5/38/41.5	
Density	1.70		1.65		1.61	

*Stengel AN

Thick and thin headings refer to the two wall thicknesses of the copper cylinders. D_{re} 60/40 refers to the detonation velocity expressed as a percent of that for Cyclotol 60/40

f. For the Amatex 20 composition there is a slight increase in velocity associated with the change from coarse to medium particle size.

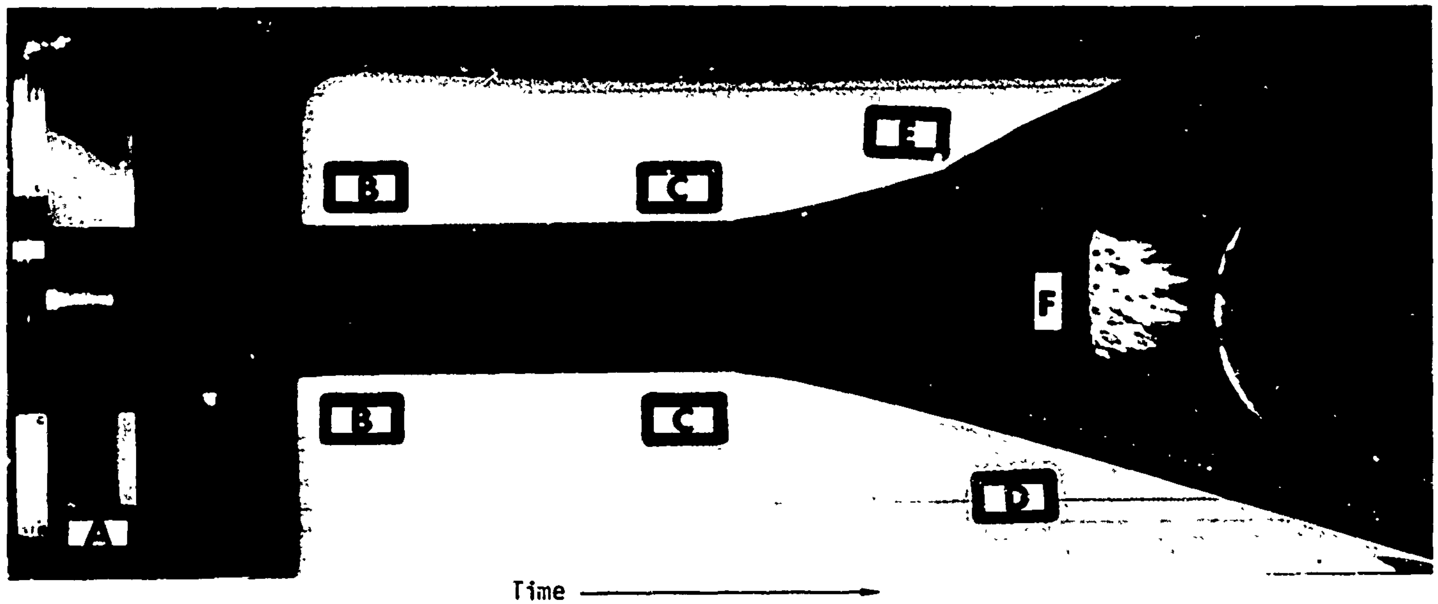
g. For Amatex 20 there is no change associated with the source of the ammonium nitrate.

The overall conclusion supported by this data in consideration of the fact that only single cylinders existed for each condition is that insofar as detonation velocity is concerned there is no significant effect due to particle size for the range used (see Table 4) or between the sources of the pulverized ammonium nitrate. However, there is a distinct effect on detonation velocity associated with the change in the quantity of ammonium nitrate substituted for RDX in Cyclotol 60/40. Detonation velocity was about 5% lower for Amatex 40/40/20 and about 11% for Amatex 20/40/40.

Radial Expansion of Cylinder at Slit Position

A schematic of a streak record is shown in Figure 4. Superimposed on the figure are designations for various regions in which coordinate data is recorded by means of a magnified projection of the original film. The coordinates are entered directly onto IBM cards in such a way that they can be furnished to a computer for subsequent analysis. Such data was obtained for each of the cylinders. It should be noted that the streak photograph provides two expansion records top (= right) and bottom (= left), one for each side of the cylinder. These records are not always of equal value. If a cylinder wall rupture occurs, the subsequent section of that expansion record cannot be used. Hence the analysis makes primary use of averages in the region where both sections are valid, but continues (with an overlap) with only one section when necessary. The data was carefully examined point by point and with use of framing camera records to limit data presented here to valid ranges.

The second point to note is that the original data is in the form of position, i.e., displacement of the cylinder wall, versus time. However, although this relationship is of interest in studying the effect of parameters, a greater interest exists in the wall velocity at particular expansions of the wall. To obtain wall velocity data, the expansion data is fitted by polynomials of various degrees; that polynomial with the best fit (smallest residual) is selected for further use in generating other relationships. The selected polynomial displacement versus time is differentiated to obtain the velocity. To get the velocity at a particular distance the time for



Legend

A - Still Picture; shows allignment fixture with scale and slit orientation on side and end of cylinder.

B - Run-up or zero motion part of trace.

C - First metal motion or "Jump-Off" of cylinder wall.

D - Record of cylinder wall expansion.

E - Cylinder wall rupture or jet.

F - Trace of cylinder end detonation front breakout.

Fig 4 Streak photo obtained from cylinder test

that distance is first found from the fitted polynomial by a root-finder routine and then that time is inserted in the differentiated polynomial to get the velocity. In all cases, a seventh, eighth, and ninth degree polynomial were tried and the seventh degree polynomial was found to provide the best fit.

To further define the region of validity of the data and of the use of the polynomials, original data and the polynomial fits were used to provide (through the computer and graphic outputs) plots of position, velocity and acceleration versus time. These were then examined with respect to region of realistic behavior of acceleration curves and with respect to concurrence of top (right) and bottom (left) results. The mass of data and the computer printout of the treatment of that data is too large to be included in this report but is available from the authors for examination by those directly involved in the subject. In addition to the treatment described above direct differentiation of the numerical data was tried and found not productive. Fitting of the data by "splines" was recognized as another approach but was not used. It is believed that the results to be presented would not be altered by a change in treatment of the data.

Effect of Parameters on Cylinder Expansion

The pertinent data is the velocity achieved as a function of time and displacement. The time factor gives a measure of the rapidity of the expansion whereas the velocity provides a measure of the energy transferred to the metal. The presentation is made in two tables, Table 12 is devoted to the thick-wall cylinders, and Table 13, devoted to the thin-wall cylinders. The displacements presented here may be divided by four to achieve corresponding displacement for the standard one-inch cylinder test. In that test a displacement of 19 millimeters represents a volume expansion of approximately seven-fold, and a displacement of 5 millimeters represents a volume expansion of approximately two-fold. The corresponding displacements to be used here are 76 and 20 millimeters. The full data is presented to facilitate studies on the non-ideal behavior of ammonium nitrate.

For thick-wall cylinders (Table 12) it is immediately obvious that the velocity decreases as RDX is replaced by ammonium nitrate. No significant difference appears to exist for Amatex 40 results or Amatex 20 results with respect to the particle size or source of the ammonium nitrate.

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TABLE 12

Cylinder data for thick-wall cylinders

AN	$(R - R_o)$*	8	12	16	20	28	40	60	76	104	128
		Cyclotol 60/40 (RDX/TNT)									
	u	1.103	1.232	1.316	1.380	1.461	1.534	1.608	1.645	1.692	--
	t	8.283	11.699	14.830	17.792	23.412	31.412	44.120	53.950	70.740	--
		Amatex 40/40/20 (RDX/TNT/AN)									
	u	1.058	1.179	1.264	1.327	1.414	1.491	1.557	1.587	1.629	--
Coarse	t	9.104	12.67	15.94	19.03	24.85	33.10	46.19	56.36	73.77	--
	u	1.055	1.185	1.262	1.311	1.382	1.464	1.523	1.558	1.595	--
Fine	t	8.945	12.50	15.76	18.87	24.81	33.23	46.55	56.93	74.70	--
	u	1.051	1.197	1.268	1.313	1.401	1.454	1.527	1.568	1.608	--
Fine**	t	9.137	12.67	15.91	19.01	24.90	33.34	46.74	57.07	74.67	--
		Amatex 20/40/40 (RDX/TNT/AN)									
	u	0.995	1.121	1.206	1.266	1.344	1.410	1.472	1.508	1.548	1.573
Coarse	t	9.632	13.40	16.83	20.07	26.18	34.88	48.74	59.47	77.78	93.16
	u	0.993	1.119	1.206	1.269	1.351	1.420	1.481	1.517	1.561	1.582
Medium	t	9.791	13.57	17.00	20.23	26.32	34.96	48.73	59.39	77.57	92.83
	u	1.016	1.128	1.215	1.276	1.354	1.415	1.469	1.509	1.564	1.573
Medium**	t	9.330	13.02	16.41	19.60	25.66	34.30	48.15	58.90	77.09	92.36

*$(R - R_o)$ is displacement in millimeters, u is velocity of outside of cylinder in mm/microsec and t is corresponding time in microseconds measured from first wall motion at slit position.

**Stengel process ammonium nitrate.

TABLE 13

Cylinder expansion data for thin-wall cylinders

	$(R - R_o)$*	8	12	16	20	28	40	60	76	104
					Cyclotol 60/40 (RDX/TNT)					
First	u	1.513	1.686	1.797	1.873	1.975	2.075	2.148	--	--
Cylinder	t	6.428	8.920	11.21	13.39	17.54	23.46	32.89	--	--
Second	u	1.533	1.705	1.806	1.878	1.986	2.083	2.175	2.210	2.271
Cylinder	t	6.292	8.753	11.03	13.20	17.33	23.14	32.51	39.80	52.32
AN					Amatex 40/40/20 (RDX/TNT/AN)					
Coarse	u	1.480	1.641	1.727	1.811	1.910	1.995	2.143	2.322	--
	t	6.771	9.321	11.69	13.80	18.09	24.23	33.93	41.11	--
Medium	u	1.489	1.657	1.752	1.812	1.906	2.000	2.109	2.153	--
	t	6.847	9.377	11.72	13.87	18.17	24.30	34.02	41.52	
Fine	u	1.446	1.610	1.721	1.800	1.903	1.991	2.077	2.119	2.167
	t	6.546	9.156	11.56	13.83	18.14	24.29	34.10	41.72	54.79
Fine**	u	1.477	1.638	1.709	1.754	1.856	--	--	--	--
	t	6.948	9.525	11.91	14.22	18.66	--	--	--	--
					Amatex 20/40/40 (RDX/TNT/AN)					
Coarse	u	1.350	1.512	1.617	1.689	1.783	1.874	1.983	2.040	2.092
	t	7.473	10.26	12.81	15.23	19.83	26.38	36.73	44.53	58.07
Medium	u	1.390	1.554	1.652	1.721	1.825	1.928	2.020	2.040	--
	t	7.632	10.34	12.83	15.35	19.85	26.23	36.33	44.20	--
Medium**	u	1.391	1.582	1.690	1.711	1.808	1.911	2.005	2.019	2.058
	t	7.192	9.872	12.31	14.65	19.19	25.64	35.81	43.75	57.52

*$(R - R_o)$ is displacement in millimeters, u is velocity of outside of cylinder in mm/microsec, and t is corresponding time in microseconds measured from first wall motion at slit position.

**Stengel process ammonium nitrate.

A similar examination of the data in Table 13 for thin-wall cylinders again shows the difference associated with the substitution of ammonium nitrate for RDX. The data for Cyclotol 60/40 which was replicated by the use of two thin cylinders shows excellent agreement, suggesting that any differences are associated with the explosive itself. Examination of the data shows no significant effect due to particle size of the ammonium nitrate. It is important not to be misled by a difference appearing only at a single displacement. The data with respect to the source of the ammonium nitrate is limited due to rupture of the thin-wall cylinders.

In Table 14 the relative energy transmitted to the copper for equal initial explosive volume, using as reference Cyclotol 60/40 is shown for Amatex 40 and Amatex 20 with variations according to the parameters of the experimental design. The values are given only for the 76-millimeter wall expansion, which corresponds approximately to a seven-fold explosive volume expansion over the loading volume, and the 20-millimeter wall displacement, which corresponds approximately to a two-fold volume ratio. These numbers were obtained simply by squaring the velocity values in the previous two tables at the stated displacement and then taking the ratio to the corresponding Cyclotol values and transforming this to percent. Examination of the data in Table 14 supports the conclusion that the substitution of 20% and 40% of ammonium nitrate for a corresponding quantity of RDX reduces the kinetic energy in the metal to about 91% and 84% of that for Cyclotol 60/40. Examination of the data for Amatex 40 suggests that there may be a very slight effect due to particle size when one goes to the fine particle fraction. Note that only 20 parts of AN are present in Amatex 40 and that the particle size range of AN in these experiments is limited (see Table 4). Note also the individual densities of the compositions (Table 7). In the Amatex 20, which contains 40 parts of ammonium nitrate, it was not possible to use fine ammonium nitrate due to viscosity limitations. One can only conclude therefore, that particle size had no effect on metal acceleration in going from coarse to medium ammonium nitrate. In both cases pulverized ammonium nitrate with the particle sizes used did not appear to have any dependence on the source of the ammonium nitrate. Examination of the data from all the displacements leads to the same conclusion.

The ratio of wall velocity (or square thereof) for a thin-wall cylinder to that for a thick-wall cylinder as a function of displacement depends on the energy release rate of the explosive involved and the mass per unit length of the explosive and of the cylinders. Table 15 shows this ratio for

TABLE 14

Relative energy (%) in copper for equal initial explosive volume referred to Cyclotol 60/40* (RDX/TNT)

		Amatex 40/40/20*		Amatex 20/20/40*	
Displacement	(mm)	20	76	20	76
AN	Wall				
Coarse	Thick	92.47	93.07	84.16	84.04
	Thin	93.29	**	81.14	85.21
Medium	Thick	--	--	84.56	85.04
	Thin	93.39	94.91	84.25	85.21
Medium***	Thick			85.36	84.15
	Thin			83.27	83.46
Fine	Thick	90.25	89.70		
	Thin	92.16	91.93		
Fine***	Thick	90.53	90.86		
	Thin	87.51	--		
Avg		91.37	92.09	83.79	84.52

*These are nominal compositions. The actual values are given in Table 7. Mean compositions (and densities) were by weight percent RDX/TNT/AN: Cyclotol 62/38 (1.70), Amatex 41/38/21 (1.66), and Amatex 20.5/38/41.5 (1.61). Individual densities have not been used to try to adjust the data to an equal density basis with respect to the AN particle size parameter.

**Value here would be erroneous due to wall rupture. Full curve must be used for comparison.

***Stengel process AN (others from Terra prills).

Blank space indicates data for these conditions as not part of plan of tests whereas a dash (--) indicates data not available for indicated comparison.

TABLE 15

Ratios of wall velocity squared for thin- to thick-wall cylinders with the same explosive

Displacement (mm)	12	16	20	28	40	60	76	Gurney*
				Cyclotol				
	1.916	1.878	1.852	1.848	1.844	1.829	1.805	1.699
	1.873	1.859	1.842	1.827	1.830	1.803	1.793	1.703
Avg	1.895	1.869	1.847	1.838	1.837	1.816	1.799	1.701
				Amatex 40				
Coarse	1.938	1.867	1.862	1.825	1.791	--	--	1.718
Fine	1.846	1.860	1.885	1.897	1.849	1.860	1.850	1.707
Fine**	1.930	1.840	1.774	1.785	--	--	--	1.709
Avg	1.905	1.856	1.840	1.836	1.820	--	--	1.711
				Amatex 20				
Coarse	1.820	1.798	1.780	1.760	1.766	1.815	1.805	1.724
Medium	1.929	1.876	1.838	1.824	1.844	1.860	1.808	1.712
Medium**	1.926	1.919	1.801	1.783	1.824	1.963	1.790	1.725
Avg	1.892	1.864	1.806	1.789	1.811	1.846	1.801	1.720
Overall Avg (all explosives)	1.897	1.862	1.829	1.819	1.822	1.838	1.809	
Number of Values	8	8	8	8	8	7	6	

*The ratios of $\frac{C/M}{1 + 0.5\ C/M}$ for thin to thick wall. The expression is part of the Gurney formula for cylindrical geometry. Overall net weights of explosive and copper of each 36" long cylinder were used for each C/M.

**Stengel process AN (others from Terra prills).

Cyclotol, Amatex 40 and 20 as a function of wall displacement. Note that the ratio decreases as the displacement increases with the same numerical trend for both Amatex 20 and Cyclotol overall: Cyclotol, 1.895 to 1.799; Amatex 20, 1.892 to 1.801. Cyclotol as an ideal explosive is considered to undergo an "instantaneous" transformation to equilibrium products releasing its energy within the detonation zone. The absence of a difference between Amatex 20 (40 parts AN) and Cylotol suggests that within the variance of the experiment there is no late release of energy by the AN. The significance of this behavior is treated further in the DISCUSSION.

In Table 15, the last column to the right provides the ratio of wall velocity squared for the thin- to thick-wall cylinders as calculated using the Gurney (Ref 10) expressions (see footnote to Table 15) for initial fragment velocities. For Cyclotol, which is an ideal explosive, the ratio at 76-millimeter displacement obtained experimentally does not coincide with the Gurney values, presumably because metal acceleration is not complete. It is reasonable to expect that the thin-wall cylinder is closer to its asymptotic velocity value than is the thick-wall cylinder. Hence, as the displacement continues, the wall velocity squared ratio should decrease further. The ratios for the Amatex compositions are too far from the Gurney values to permit any comparison that would provide information on the non-ideality.

Cylinder Wall Deformation and Rupture

In addition to obtaining a record of cylinder expansion at the slit position by a streak camera the expansion and rupture of each cylinder were recorded by a framing camera as the detonation progressed within the explosive. The photos presented in Figure 5 are typical of the results. They represent selected frames for five cylinders and also show in the upper right hand corner a still of a cylinder. This still photo corresponds to the configuration shown schematically in Figure 1. At the slit position there is mounted a fixture holding a mirror which is used for alignment purposes. Four pin-holding Lucite rings can be seen to the left and two to the right of the fixture. There is a barrier at each end to prevent smoke from the shot obscuring the region of interest. One can see the bare end of the explosive at the right and the plane wave generator at the far left. The cylinder is supported in the wood frame shown during the test. The photo to the left of the still is this cylinder as it expands during the propagation of the wave. The slit position is to the left of the pin holder seen in the photo. Off to the left can be seen the remains of the adjacent three pin holders. The two photos just below, i.e., in the center of the figure, are for Amatex 40 with fine ammonium nitrate taken from pulverized prills of the Terra Company (Mix 9 of Table 2). The two photos at the bottom of the figure are for Amatex 20 with ammonium nitrate of medium granulation from the same source (Mix 4 of Table 2). All the photos on the left side are of thick-wall cylinders and those on the right side are of corresponding thin-wall cylinders. All four lower photos have the wave front in approximately the same position along the cylinder. It is immediately apparent by the angles of divergence that the thin-wall cylinders expand to a greater extent in the same time frame. They also rupture at smaller expansions. All of the photos have been thoroughly examined and corroborate this statement. In the DISCUSSION section the possibility of change in wall thickness is treated. The center and lower photos had the arrangement of pin mountings shown in Figure 2, which is why the disrupted mountings are farther to the left. The bright region along the contour of the deformed cylinder is believed to be a reflection from the surface of the cylinder from the front lighting argon candle and the turning mirror (see Figure 3). No corresponding phenomenon is observed in the streak photographs. In future test programs it is believed this can be removed by placing a diffusing screen close to the cylinder, between it and the argon "candle." The center photo on the left displays a grid of black painted lines added as an experiment to observe the utility of such lines. They were not used in any analysis.

Wave-Front Profiles

The surface of the explosive farthest from the initiation was also viewed by the streak camera by imaging a slit running vertically through the axis of the explosive across this explosive surface. The experimental arrangement was previously described and shown in Figure 3. Presented in Figure 6 are the results for the thin-wall cylinders. The numbers correspond to the mix numbers in Table 2. Because the thin-wall results are essentially identical to those of the thick-wall, only the thin-wall data is given. In Figure 6, time is progressing downward; therefore the top or leading portion of each trace represents the first "break-out" of the detonation wave front, followed by the recording of the emergence of the full curved detonation front across the end of the cylinder. This curvature can be used, in principle, to study the nature of the detonation, a subject that has been left for future study. There is an additional feature found in these films. This is the existence of an optical precursor, which can be most clearly seen for Mix 4. As the first light appeared, it was followed immediately by a very short quenching after which the emission reappeared and continued. This optical precursor was not found for the Cyclotol mix

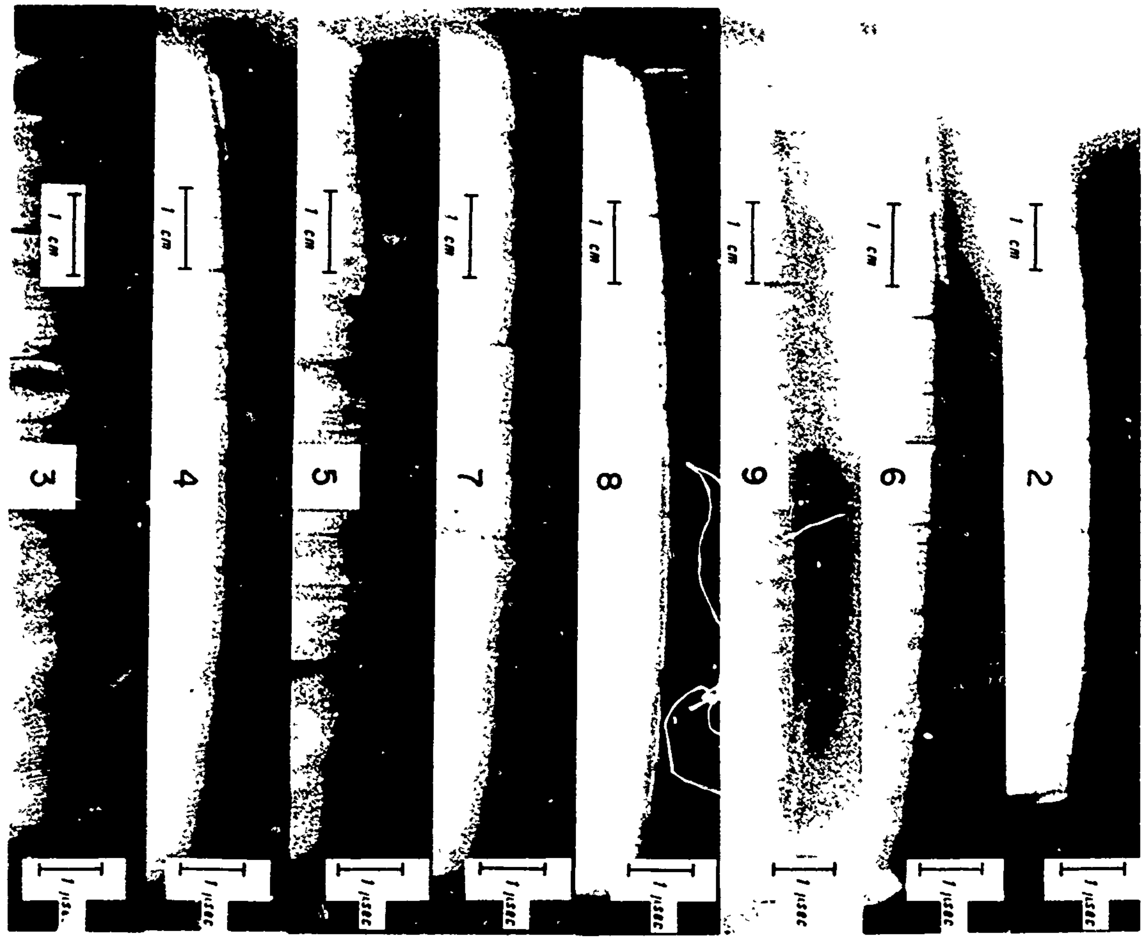

Fig 5 Framing camera photos of cylinder expansion (thick wall - left side; thin wall - right side; upper right - experimental arrangement)

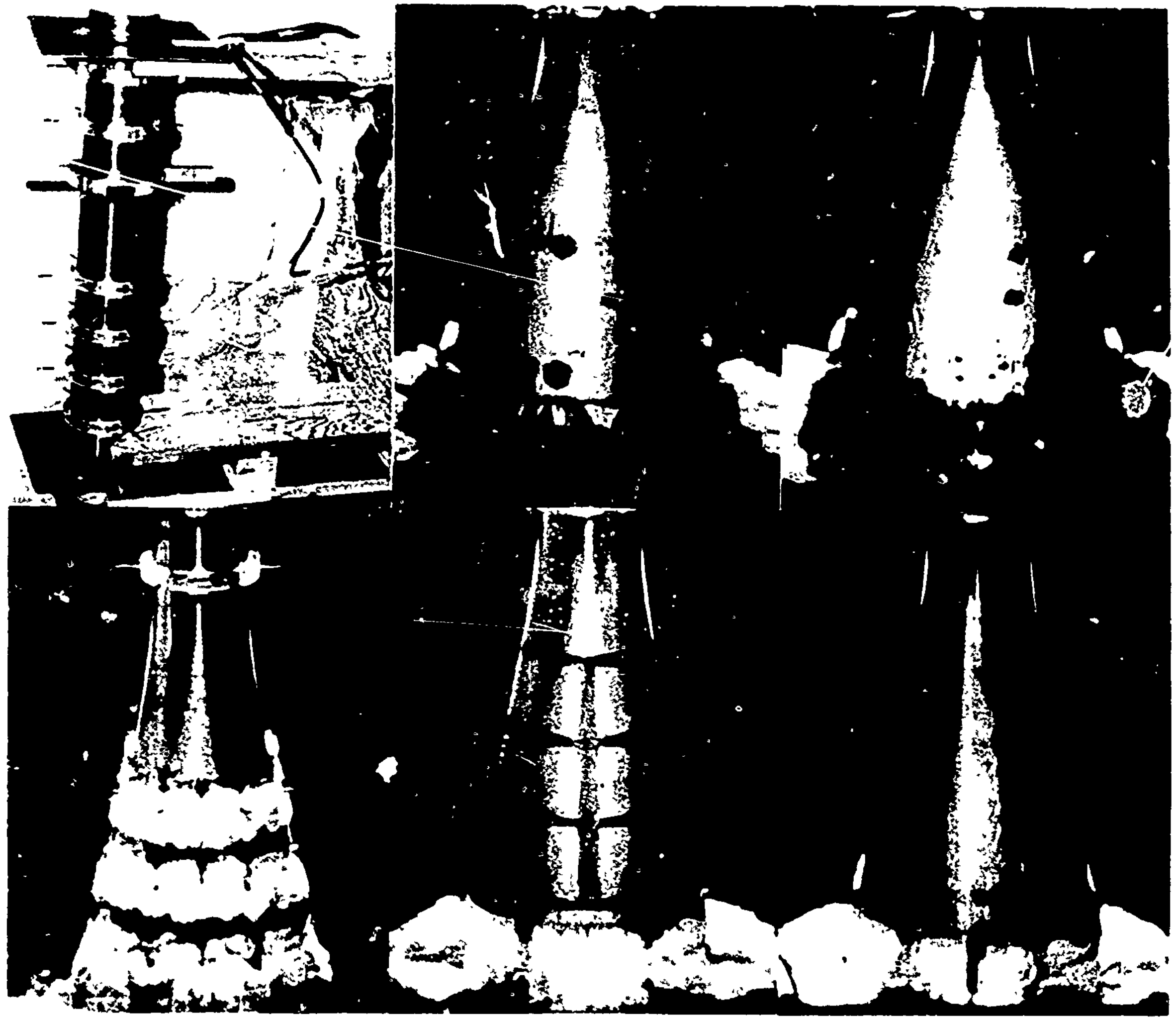

Fig 6 Streak records of propagation wave breakout from end of explosive cylinders for various conditions (see Table 2)

and was also not found for three of the other fourteen cylinders fired. It is not clear whether the optical precursor is associated with optical problems, the experimental arrangement, or is inherent in the explosive (Ref 11-15). It has been suggested (Ref 16) that the optical precursor consists of the first appearance of the detonation wave close to the surface viewed through the transparent TNT, followed by a quenching by the rarefaction upon arrival at the surface itself and then followed in turn by the viewing of the hot products for the balance of the Taylor wave. In the DISCUSSION section consideration will be given to other instrumentation which could be placed at the end of the explosive cylinder to further explore the nature of the propagation profile.

Computer Program Predictions

In the INTRODUCTION section of this report the role of cylinder tests with respect to metal acceleration in munition applications was presented. Full exploitation of the cylinder tests on non-ideal explosives reported herein should include making calculations with the TIGER computer program of the "isentrope ratios" between the explosives tested for comparison with experimental results. It should also include attempting to obtain an appropriate description of the explosive for use in hydrodynamic computer programs such as SIN and HEMP. Studies of this type are underway in other laboratories as well as this one and will be made the subject of separate reports.

DISCUSSION

Design of Cylinder Test for Non-Ideal Explosives

Cylinder Length and Pin Positions

The length of the cylinder is related to the need for disturbance-free expansion time at the slit position until the explosive volume has reached at least seven times the initial volume of the solid explosive. This disturbance-free expansion time is controlled by the rarefaction wave which follows in the explosive from the initiation end and by the rarefaction wave which starts from the terminal end back towards the slit after the detonation arrives at the terminal end. The maximum disturbance-free expansion time is obtained by equating these two times to find the optimum slit position. The calculation requires a knowledge of the detonation velocity, and of the sound speed and particle velocity in the expanding products. These are functions of the explosive under test and must be estimated. In addition, if the pin mounts are so massive as to introduce a perturbation in the flow, by causing cylinder rupture, or as to alter the cylinder expansion rate, it is necessary to use the pin position immediately preceding and following the slit to calculate the slit position. The disturbance-free writing time would be significantly shortened. (For future cylinder tests a design has been developed which reduces the mass of the pin mount to less than one-fourth of that used in these tests.)

From Table 12 we see that the disturbance-free expansion time required for Amatex 20 and 40 for a seven-fold expansion of explosive volume in a thick-wall cylinder ($(R - R_o) = 76$ mm) was about 60 microseconds. A calculation of the disturbance-free expansion time over the full cylinder length, assuming constant values for rarefaction wave and particle velocities, gave 50 microseconds. Considering that rarefaction waves and particle velocities in the axial direction are slowed by the expansion it is believed that the necessary 60 microseconds of disturbance-free expansion time was readily achieved for the slit position used. Such calculations clearly indicate that the cylinder length required when a four-inch-diameter explosive core is evaluated must be at least 36 inches long.

From Table 13 note that only about 45 microseconds is required for expansion of the thin-wall cylinder to 76 mm. In the thin-wall cylinders, wall ruptures frequently occur and the mass of the pin mounts would have a far greater effect. Using the Figure 2 pin mount configuration for the effective length influencing disturbance-free writing time, a calculation with constant values of rarefaction wave and particle velocities gave about 35 microseconds. Since these constant values shorten the calculated time, however, as stated, and since a disturbance generated by the pin mounts would require a period of time to start, it is believed that the thin wall was also not affected by the pin mounts. Examination of the framing camera results for rupture of thin-wall cylinders and the corresponding streak records has shown no evidence to suggest any effect. However, one can not entirely rule out a second-order influence on the expansion. The problem of wall ruptures can only be reduced by using a thicker "thin" wall with either the 4 inch or larger diameter explosive.

In future tests the spacing of the pins must also be changed from that of Figure 2. It may be observed in Table 10 that the variance associated with propagation velocities determined from pin data had a large value when the pin spacing between corresponding pins or between adjacent mounts was a half-diameter, that is, 2 inches. This variance was considerably reduced when the spacing between adjacent mounts was increased to one diameter, that is, 4 inches. However, the latter placed a pin mount too close to the slit position. It is believed that a compromise spacing of 3/4 diameter would be adequate. In addition it is not necessary to have four sets of pins preceding the slit position. For the recommended 4-inch-diameter, 36-inch-long cylinder the proposed pin positions stated in diameters are 1/2, 5/4, 2, with the slit at 6 3/4, 8, and 8 3/4. With a redesigned pin mount providing negligible loading on the cylinder, one could also consider adding an additional pin position at 2 3/4 diameters.

Diameter of Explosives and Wall Thickness of Cylinders

When scaled cylinder tests are done for two diameters containing ideal explosives, the radial dimensions are changed linearly (e.g. 1", 2", 4" explosive diameters correspond to 0.1", 0.2", 0.4" wall thicknesses and linear scaling factors are 1, 2, 4). It is indeed found that as long as one is not near a critical explosive diameter the radial expansion ratios $(R - R_o)/R_o$ and the corresponding times divided by their linear scaling factors are independent of initial diameter (see Ref 1, Table 1, for numerical example). Hence, measurements at a smaller diameter permit extrapolation of the results to a larger diameter. Additional experiments conducted at a larger diameter such as eight inches would be required to demonstrate whether scaling of results has been achieved. The practical difficulties associated with using such a diameter were sufficient to rule this out in this first series of tests. For non-ideal explosives this type of scaling would not be expected since one would expect significant energy release to occur behind the steady state detonation zone at a rate that depends on specific volume. With scaling not expected, the choice of diameter(s) for a cylinder test should be related to munition applications and to deriving information on energy release rates.

For the shells which are most important with respect to quantity used and potential for application of Amatex explosive fills the C/M ratios (see Table 1) are about 0.2 and the explosive diameters are not too far from the 4 inches used. However, the C/M for munitions does not represent a cylindrical configuration. The ratio for the central part of the munition (excluding base and nose metal and explosive in nose) would have a higher C/M. Hence the thick-wall cylinder (C/M about 0.4) is a better approximation to these munitions than Table 1 shows. For the bombs, the thin-wall C/M description derived from the cylinder test data of this report at both wall thicknesses can be used directly or in a computer program for calculations for the munitions listed.

The second objective of a cylinder test is to obtain research data which will give information about the non-ideality of the explosive in such a manner as to broaden the application of the data from the way in which the experiment was conducted. The 4-inch diameter was found adequate to rapidly achieve a steady state propagation velocity. Two wall thicknesses give information in two different time frames and may provide a means of verifying assumptions as to the basic mechanism leading to that non-ideality. The results for two wall thicknesses presented in Table 15 are considered in a later section for significance with respect to the nature of the non-ideality.

To increase the sensitivity of the cylinder test to obtain more useful research data, it would be necessary to go to shorter time frames. However, at smaller diameters with non-ideal explosives one encounters difficulties with critical diameter, initiation, and run-up distance. Keeping the 4-inch diameter but using thinner walls departs from C/M ratios of significance for munitions and leads to earlier wall ruptures than those already found marginal with the half-scaled value used in the tests. It would appear that some useful data might be obtained by adding to the thick- and thin-wall cylinders for 4-inch-diameter explosive described in this report, a 2-inch-diameter explosive with a thin wall cylinder which was scaled from the 4-inch thin wall used here. Success would depend on the factors enumerated and the nature of the non-ideal explosive.

At this point it becomes obvious that for further study it is more appropriate to conduct tests designed specifically for revealing the nature of the non-ideality rather than trying to extrapolate from cylinder tests. For example, one can use linear geometry where very thin plates are accelerated and study early energy release patterns.

On the basis of the above discussion, it appears that for non-ideal explosives the 4-inch thin wall (1/2 scale) configuration should be used in parallel with the conventional scaled 4-inch cylinder test. Larger explosive diameters should only be considered for those explosives where run-up detonation, critical diameter, and munition analogues make this necessary for meaningful results. For Amatex, no additional information on the nature of non-ideality can be hoped for by using larger explosive diameters; rather, specific experiments should be designed for that objective where appropriate.

Another possibility considered was to use aluminum instead of copper for the thin-wall case or even for both wall thicknesses. The problems envisioned with aluminum were chemical reactivity (with moisture leading to hydrogen evolution), inadequate ductility leading to early rupture, and a shock velocity in the wall greater than the detonation velocity, causing a wall precursor wave. As noted earlier, the hazard for copper reaction with ammonium nitrate required special precautions and some precautions may also be necessary for aluminum. Insofar as ductility is concerned, highly ductile forms of aluminum are available and the lower density of aluminum permits thicker walls for the same C/M as when copper is used. The overall results could be fewer early ruptures in the thin-wall case and the use of an even thinner wall in the cylinder test. However, the problem of the wall precursor for the Amatex explosives can not be ignored. The lowest propagation velocity measured was 6.8 mm/microsec. Using Hugoniot curves for the Comp B driver and the two metals, one calculates (for a one-dimensional case) maximum shock velocities of 5.4 and 7.4 mm/microsec for copper and aluminum respectively. Hence, aluminum cylinders would require a more precise resolution (perhaps by use of the HEMP program) of the possibility of a wall precursor.

Instrumentation of Terminal Face of Explosive Cylinder

The arrival of the wave front at the terminal face of the explosive cylinder provided a measure of front curvature and an optical precursor.

The variations in curvature with change in explosive composition were sufficiently small as to presage difficulty in the use of this data for further interpretation. However, the streak records are of sufficiently high quality to permit precise numerical analysis and this will be considered separately in the future.

The observed precursor has been tentatively hypothesized to be an optical phenomenon rather than a manifestation of detonation zone structure. However, further investigation is necessary to establish the validity of this hypothesis. The original streak records and associated data are of sufficiently high quality to permit establishing details of the profile in the form of density on film vs time. This, together with interpretations, will be considered separately in the future.

The results referred to in the previous two paragraphs pose the question of optimum instrumentation of the terminal face of the explosive cylinder. The objective of such instrumentation is to provide information on the structure of the detonation zone as a bonus of the cylinder test for non-ideal explosives.

The second slit used with the streak camera was inadequate to meet this objective. It could be improved by calibration of the film to convert density on the film to optical intensity. Use of narrow band filters over symmetrical parts of the slit might give information on particular spectral regions of interest and possibly lead to estimates of temperature profile. A vacuum environment would be needed to eliminate the air shock. Such time-resolving spectroscopy attempts are better done at higher turbine rates of the camera than are consistent with using the principal slit for cylinder expansion. Since use of the second slit still leaves almost the entire terminal face available, one can certainly consider other measurements (e.g., for pressure profile) that could be added to or used as a replacement for optical observation.

One or more miniature manganin gages (Ref 17) (gage rise time less than 25 nanosec, active area 1 mm sq) could be modified for plane-wave measurement to provide pressure-time from the front to gage disruption. The 1/8" (3 mm) inpedance-matched base permits pressure recording by the gage element for a comparable depth into the detonation zone. The overall dimensions of about an inch permit placing more than one gage on the terminal face of the explosive cylinder. The problem with these measurements is that special pulsed power supplies which require triggering must be used and that voltage measurements from the gage must be made with a high speed oscilloscope. The addition of such equipment to the already complex cylinder test instrumentation poses field site problems.

The peak pressure could be measured by the shock electric effect (Ref 18) which uses a stack of Lucite disks, with small gaps between them terminated by a metal plate. As the shock goes through the gap, ionization is picked up by the metal electrode and appears as a pulse on the scope. The initial velocity in the Lucite is obtained by extrapolation and is used to deduce the peak pressure at the Lucite explosive interface. Optical observation with the streak camera of the progress of the wave in the stack of Lucite disks is also possible. Another method uses an axially symmetric electromagnetic probe (Ref 19) to monitor detonation pressure and reaction zone length.

The velocity imparted to one or more "flyer" plates contacting the terminal surface of the explosive cylinder can also be measured by high speed camera techniques. The velocity reflects an integration over part of the pressure profile depending on thickness of the flyer plate.

In the next series of cylinder tests consideration will be given to using some of the described methods for the terminal face to see if any merit regular use for cylinder tests on non-ideal explosives.

Loading and Assembly for Cylinder Tests

The technique used for loading the copper cylinders with explosives was direct casting into the cylinder. For some explosives, such as liquids or slurries, the direct casting method with vertical orientation for firing is the only way. For solid explosives one can first make a set of shorter castings, oversize in diameter, in a multiple mold. These are then remote machined to close tolerances and slip fitted into the copper cylinder. This method reduces the range of variation in explosive density and composition over the length of the cylinder but does result in a sawtooth function of these parameters and interfaces between cast sections. With proper attention to detail, prior availability of multiple molds, and precision remote machining capability this seems to be a preferable method. It also has the advantage that the explosive need not be in contact with the copper until shortly before the firings, thus eliminating hazards due to formation of (Tetrammino Copper II) nitrate. In addition machining eliminates any effects due to "ironing" with TNT.

On the other hand assembly of individual machined castings involves sliding friction and static hazards and should be done under an approved SOP. Disassembly in the event of change in plans or a misfire must be done remotely and involves, depending on the explosive, sufficient risk to merit remote destruction of the item as the only safe operation. Of course, steaming out the explosive, under an approved SOP, would salvage the copper cylinder, but lose the explosive charge.

The procedure used for these tests of casting directly at one location and shipping to a different installation for tests is not recommended. The entire operation should be done at one installation in the shortest time span possible. For slurries the time span may have to be shorter, with loading done at the test site to avoid segregation. The appropriateness of time of loading for slurries in relation to firing time and method of loading must be chosen with consideration of the manner in which the explosive would be used in practice.

Costs of Tests

For each non-ideal explosive composition one would require at least two cylinders, one thick wall and one thin wall. Parameter variation within explosives (e.g., particle size) must be considered as generating additional explosives for evaluation. If one assumes that tests of many explosives are provided for jointly so that procurement, planning, testing, and overhead costs are reduced, a reasonable expectation of costs per explosive composition is listed in Table 16.

Non-Ideal Explosives Containing Ammonium Nitrate

Nature of the Non-Ideality

The cylinder tests on Amatex 20 and 40 have provided percentage decreases in detonation velocity and metal acceleration associated with substitution of AN for RDX. The results include cylinder expansion data and also indicate that the fraction of available energy released is approximately constant during the expansion phase. Various hypotheses on the non-ideality of these explosives can be inserted in computer programs and the predictions compared with the experimental results. Such quantitative considerations are appropriate at this time.

One may immediately ask whether the results represent the full potential of the ammonium nitrate. To check this, calculations can be done for a Chapman-Jouguet detonation using computer programs such as BKW or TIGER and permitting all elements in the composition to fully react to equilibrium product species. Such calculations indicate that higher detonation velocities and metal acceleration could occur than has been reported herein or found in munition performance tests. Furthermore, the fact that the fraction of available energy released does not change during the expansion suggests that the energy release to the point achieved occurs early and then does not continue; i.e., "freezing" of some intermediate composition products is occurring either in the detonation zone or in the early part (top 1/3 roughly) of the isentrope from the Chapman-Jouguet plane. This hypothesis makes it possible to rule out any continuing (non-freezing) process as the source of the non-ideality. Thus, diffusion limitation over the time span of the cylinder expansion is ruled out, but not as a mechanism participating in the "freezing." Experiments are needed to establish the nature of the early product compositions for explosives containing AN and the kinetics of the possible decomposition routines, including freezing of species. Computational efforts with TIGER using a variety of product

TABLE 16

Estimated cost of non-ideal explosive cylinder test*

Copper Tubes (2)	$ 300
Machining Copper Tubes (2)	750
Explosive (1) (with pulverizing and screening)	250
Loading, Assembly and Quality Control (2)	1000
Field Site Firing (2)	2500
Analysis of Results (2)	500
Test Report	1000
Planning and Guidance	3000
Total	$9300

*Prorated for one explosive composition at 4" diameter, 36" length in one thick-wall and in one thin-wall copper cylinder. Values have been rounded and should be considered only as estimates appropriate to the 1972-73 time frame of costs. The (2) above is to stress that cost shown is for two copper cylinders (one thick, one thin wall).

hypotheses have not been successful to date but are continuing. Detonation calorimeter experiments re freezing (Ref 20) are being planned and experiments are under consideration, using time-resolved spectroscopy to observe propagation profiles of these explosives in transparent confinements and to observe combustions and detonations terminating in a vacuum chamber.

Particle Size Distributions in Amatex Explosives

The finest sieve fraction of AN used was 80/230, which corresponds to 62 to 177 microns. This limitation was imposed by viscosity in casting. For larger quantities of AN as in Amatex 20 only half of the AN could be in this size range. It is of both theoretical and practical interest to know whether as the particle size of the AN is further reduced, the energy release properties are improved. For this purpose experiments on pressed compositions using much finer AN are required. Cast Amatex compositions could use finer AN by use of surfactants, removal of RDX fines, and using AN of spherical shapes with selected particle size distribution. The added cost would have to be considered in relation to the possible benefits.

Significance of Results for Other Ongoing Programs

The problems encountered in casting the Amatex compositions were communicated to those involved in interim type qualification studies and were useful in choice of particle size of the ammonium nitrate. The demonstrated independence of performance results on the practical range of particle sizes of ammonium nitrate for economical casting permitted a decision based on loading factors. The quantitative measure of degradation of detonation velocity and metal acceleration with substitution of AN for RDX has been valuable in discussions on the merits of alternate fills for munitions. The experimental modifications made for these cylinder tests of non-ideal explosives and the consequences have been communicated informally to other scientists doing related studies.

FUTURE WORK

A second series of cylinder tests should be conducted to follow through on the suggestions made in this report for the optimum design of a cylinder test for non-ideal explosives. The non-ideal explosive(s) chosen for evaluation should again provide information for other ongoing programs and for understanding the nature of non-ideality. In this regard, consideration should be given to including a slurry-type explosive so as to encounter the new problems posed by this non-solid type.

Further work should be done with the data provided by these experiments. These studies would include:

a. Comparison with TIGER and HEMP (or equivalent) computer program predictions and calibration of descriptions of the explosive.

b. Interpretation of curvature of wave emergence and precursor from terminal end of explosive.

c. Pursuit of hypotheses on the non-ideality of Amatex compositions.

d. Correlation with forthcoming (LASL, LLL) results on explosives containing ammonium nitrate and other explosives.

The availability of one dozen each of the thick-wall and thin-wall copper cylinders obtained as part of this program but not used and the experience gained in this study will serve to reduce the cost of the future work described above.

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