(4)

TECHNICAL REPORT BRL-TR-2970

BRL

1938 – Serving the Army for Fifty Years – 1988

TRAVELING CHARGE GUN FIRINGS USING VERY HIGH BURNING RATE PROPELLANTS

ROBERT E. TOMPKINS
KEVIN J. WHITE
WILLIAM F. OBERLE
ARPAD A. JUHASZ

DECEMBER 1988

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A203 307

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-TR-2970	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION US Army Ballistic Rsch Lab 6b. OFFICE SYMBOL (If applicable) SLCBR-IB	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
TRAVELING CHARGE GUN FIRINGS USING VERY HIGH BURNING RATE PROPELLANTS

12. PERSONAL AUTHOR(S)
Tompkins, Robert E., White, Kevin J., Oberle, William F. and Juhasz, Arpad A.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
TR	FROM Dec 86 TO Dec 87		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Traveling Charge, Ballistics, Combustion, Diagnostics, ~~VHBR~~ Guns, ~~XNOVAKTC~~ (JES)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A new class of experimental very high burning rate propellants (VHBR) has been formulated and studied for application toward the traveling charge concept. Combustion diagnostic work has been performed on various formulations to characterize the burning of these propellants under gun pressures. Results of the combustion diagnostics indicate that several of the VHBR propellant formulations could be used as a traveling charge gun propellant. These diagnostic results were also used as propellant input parameters for a traveling charge computer model, XNOVAKTC. Gun firings were performed for both conventional and traveling charge configurations. Comparisons are presented between the experimental firings and the computer predictions. Results indicate that the traveling charge concept can offer increased performance over conventional systems provided that the ignition and burnout times of the traveling charge can be controlled.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Robert E. Tompkins	22b. TELEPHONE (Include Area Code) (301) 278-6200 / 22c. OFFICE SYMBOL SLCBR-IB-B

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

ACKNOWLEDGMENTS

The authors would like to express their thanks to Mr. C. D. Bullock for his invaluable assistance in expediting the fabrication and delivery of the gun fixture and projectiles. Grateful appreciation is also expressed to Dr. I. W. May for his helpful discussions and support during the course of this work.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Interior ballisticians are often tasked with obtaining higher projectile velocities while simultaneously keeping gun pressures manageable. In line with these requirements, one of the approaches that has been investigated at the BRL is the traveling charge concept which was originally published by Langweiler[1] for an "Impulse Gun" in 1940. This concept is theoretically capable of producing muzzle velocities in excess of 2000 m/s without unacceptably high chamber pressures. Moreover, at very high loading densities, the velocity increase is not proportional to the charge, as more chemical energy must be used to accelerate the combustion gases. In the past four decades, there has been a great deal of effort expended toward this goal. (Please see references 2-8 for a partial listing.) One of the main problems in carrying out the concept was the low burning rates for conventional propellants. Recent advances in propellant technology has produced propellants offering properties that fulfill some of the high burn rate requirements of a traveling charge.

A simplistic view of the traveling charge concept is pictured in Figure 1. A traveling charge (TC) propellant is shown attached to the base of the projectile. The TC projectile is given an initial acceleration from a conventional booster propellant. The TC propellant then ignites after a slight delay to increase the down-bore base pressure on the projectile until muzzle exit.

In the late 1970's, the BRL initiated a propellant development effort in support of the traveling charge concept. The development effort resulted in propellants with apparent burning rates as high as 500 m/s as measured in closed bomb testing. Unfortunately, there were handling hazards associated with some of the faster burning formulations, interrupting gun firings. Subsequent efforts concentrated on research into safer formulations, combustion diagnostics, and theoretical interior ballistic studies. Rapid developments in these areas brought about the decision to reinitiate the traveling charge feasibility study.

Two important decisions have helped to move the project in the desired direction; rescaling of the TC gun fixture, and changes in the propellant combustion screening methodology. In earlier studies, combustion screening was done on 12.7-mm diameter samples while interior ballistic studies were carried out in a 40-mm gun. This required sample scaleup prior to ballistic testing. In the current approach, the gun was scaled down to permit use of the half-inch diameter samples in both combustion and interior ballistic tests. This eliminated any potential changes in combustion behavior associated with changing propellant diameter. It also minimized the time and cost of obtaining separate propellant samples for gun firings. The second important decision concerned combustion screening methods. In earlier combustion tests, samples were burned in the closed bomb using a small igniter charge. This is analogous to a traveling charge gun firing where the propelling charge consists entirely of the TC element. Interior ballistic computations,[5-8] however, indicated that optimum TC performance would most likely be achieved by using a conventional booster charge to initially accelerate the projectile/TC element. In such a scenario, the TC propellant would be burning under pressurization by the booster. To mimic this condition, a new closed bomb combustion test method was developed in which the VHBR propellant was pre-pressurized by the hot combustion products of a conventional granular propellant.

The results of the first series of firings with the new closed bomb diagnostic conditions and a new 14-mm gun fixture were quite promising.[9] The closed bomb testing showed that most of the formulations tested would be able to withstand at least 360 MPa base-pressure without deconsolidating prior to ignition. Additionally, the testing showed that the burning time of the TC propellants can decrease by an order of magnitude when the pre-pressurization from the conventional propellant is increased from 180 MPa to 360 MPa. The combustion diagnostics allowed the selection of two formulations for ballistic testing. The initial series of conventional and TC gun firings showed that the pressure records and the velocity data within each type of firing were reproducible. The results from the ballistic firings were compared to results of calculations/simulations done with a recently developed ballistic computer code XNOVAKTC[10-11] that was used to interpret the physics of the gun firings. The comparisons showed good agreement for both conventional and traveling charge firings.

Extensive calculations were done to help guide the experimental program for a new series of firings.[12] Parametric studies indicate that the velocity gain from the traveling charge effect is greater as the charge-to-mass ratio is increased. However, the gain in velocity requires precise timing of both the ignition and burn out of the TC propellant.

The objective of this paper is to present the status of the experimental aspects of the traveling charge effort. The intent is to present progress that has been made and to show the obstacles that need to be overcome to obtain muzzle velocity improvements with no increase in breech pressure.

II. COMBUSTION DIAGNOSTICS

1. BACKGROUND

As was discussed in the INTRODUCTION, the intention in the traveling charge gun firings is to ignite and burn the TC propellant after the booster has reached peak pressure. Thus, combustion screening of formulations to find ballistic candidates should be carried out under conditions that will be encountered in the actual TC gun fixture. The test method discussed below was designed to meet this requirement. Based on projected velocities with a TC sample length of 25-50 mm in the 14-mm gun fixture, estimated sample burn times of 0.5 to 2 ms were sought.

2. EXPERIMENTAL

A closed chamber (210 cm^3) was modified with an insert containing a 13-mm hole to simulate the projectile-barrel configuration (Figure 2). The insert would provide heavy confinement on the sides of the sample to simulate the circumferential confinement of the gun tube expected in the ballistic tests. The sample was epoxied into the cavity. An ignition delay element (discussed in the next section) was attached to the surface of the TC to delay the start of combustion until after peak pressure. Silicone grease was used to fill in any remaining gaps on the front surface. Having been placed in the cavity, the sample was ignited with a booster charge (the same propellant that was used as a booster for the gun firings) located in the main chamber. The booster charge provided peak chamber pressures of 330 MPa. This pressure is similar to the maximum base pressure expected in gun firings. Burn times for the TC could then be found from the pressure histories (Figure 3). Other booster charges were used to obtain peak pressures between 180 and 350 MPa.

3. RESULTS

The purpose of these tests was to screen formulations to provide a number of ballistic candidate propellants and to devise a predictable TC propellant ignition delay device.

A representative list of formulations tested, that exhibited the desired burning times (0.5-2 ms) for our ballistic application, is given in Table 1.

TABLE 1. TRAVELING CHARGE FORMULATIONS

ID	BINDER	(%)	OXIDIZER	(%)	FUEL*	(%)	FORM
TMS-9	GAP	25	TAGN/HMX	24/41	H498	10	CAST
TMS-10	GAP	25	TAGN/HMX	23/37	H498	15	CAST
TMS-13	GAP	20	TAGN/HMX	26/44	H498	10	CAST
TMS-16	GAP	15	TAGN/HMX	30/50	H498	5	CAST
TMS-17	GAP	15	TAGN/HMX	28/47	H498	10	CAST
TC-14	KRATON	15	RDX	73	H466	12	PRESSED
TC-15	KRATON	10	RDX	78	H466	12	PRESSED
TC-16	KRATON	5	RDX	83	H466	12	PRESSED
TC-49	HYCAR	10	RDX	84	H498	6	EXTRUDED

* Proprietary boron-hydride compounds

Although all of the above samples had burning times between 0.5 and 2 ms, some of the formulations burned in such a manner as to give oscillations in the pressure record. Other formulations produced smooth pressure-time records. These were preferred for ballistic application.

The shape of the pressure-time curve can be a useful diagnostic for analyzing propellant combustion. If the end-burning cylindrical VHBR samples were to burn in a laminar one-dimensional manner then the pressure time curve should be nearly linear or, if there is a conventional pressure dependence, the slope should be increasing with time. It is obvious from Figure 3 that this is not the case. In fact, the slope, over the section indicated at (C), is decreasing with time. This is consistent with the model reported earlier[13] that VHBR samples burn porously followed by a deconsolidation where a large number of particles burn regressively. This would result in a pressure-time curve with a decreasing slope. As will be seen later, the interior ballistic code assumes a laminar, one-dimensional burn for the traveling charge. To compensate for the observed burning phenomenon described above, adjustments to the burning rates will be required. More will be discussed on this subject in a later section dealing with interior ballistic calculations.

Aside from achieving an acceptable burn time for the propellant, an ignition delay element is required for proper functioning of the TC concept. The goal of a predictable ignition delay device was not attained. Various thicknesses of NOSOL 463 were tried in an attempt to use a propellant that would burn through in a controlled fashion. Unfortunately, the results were not predictable or reproducible. After many tests, the decision was made to use small circles of masking tape as the ignition delay element. This was simple to attach to the TC sample and as reproducible as any other delay element tested.

As a result of the combustion tests, sample TC-49 was selected for gun firings. The ignition delay device used was a small circle of masking tape.

III. BALLISTIC FIRINGS

1. BACKGROUND

As mentioned in the INTRODUCTION, previous gun firings had shown reproducible ballistic results from the 14-mm fixture. The traveling charge results also exhibited down bore pressure increases and accelerations that coincided with the burning of the TC. The conventional firing pressure histories were in good agreement with those predicted by XNOVAKTC but the TC velocity results were lower than those calculated. The TC velocity differences (experimental vs. computed) were attributed to an abnormally high down-bore resistance profile due to TC combustion and to excessive gas blow-by around the obturator.

Interpretation of the results from previous firings indicated that the projectile should be modified to decrease the down-bore resistance and to improve the obturation. The computer modeling effort being used to understand the physics of the TC ballistics event also indicated that the percent increase in velocity possible from the traveling charge is greater at increased charge-to-mass ratios. These results prompted a redesign of the projectile to improve obturation and decrease the projectile mass so that the next series of firings would be carried out with higher charge-to-mass ratios and improved obturation.

2. EXPERIMENTAL

A schematic of the gun fixture, with pressure port locations, is shown in Figure 4. The bore diameter is 14 mm. The smooth-bore barrel length is 2900 mm. A conventional propellant, to be ignited in the 100 cm^3 chamber, provides the initial acceleration to the projectile.

A sketch of the projectile used for this series of shots is shown in Figure 5. The overall projectile length, when using a 50-mm sample of TC propellant, is 104 mm. The nominal mass of the unloaded projectile is 14.3 grams. The 9.6-g TC sample was epoxied into the rear cavity of the projectile (Figure 5). The ignition delay element, described in the previous section, was attached to the exposed end of the TC. The rear of the sample was located at the entrance of the tube such that a chamber volume of 100 cm^3 was maintained for all test firings.

The booster propellant used for the gun firings was a non-deterred, unrolled small arms ball propellant. A non-deterred propellant was chosen in order to simplify the interior ballistic calculations. A description of the propellant is given in Table 2.

TABLE 2. BOOSTER PROPELLANT CHARACTERISTICS

Manufacturer..Olin, WC 615, X-4179
Type..........non-deterred, un-rolled ball propellant
Ave. grain diameter.......0.72 mm

Ingredients	Wt. %
Nitrogen of NC	13.16
NC	59.94
NG	37.86
Dibutylphalate	0.28
Diphenylamine	0.49
N-Nitroso Diphenylamine	0.81
Water	0.46
Total volatiles	0.51

Thermochemistry at 0.2 g/cm^3

Temperature (K)	3680
Impetus (J/g)	1165.4
Molecular wt (g/mole)	26.25
Co-volume (cm^3/g)	0.966
Gamma	1.2155

Derived burning rate equation, $r(mm/s) = 2.259\ P^{0.863}$

A 34-gram booster charge with a 1.5-gram igniter of black powder was chosen for all tests. A schematic of the booster-chamber configuration is given in Figure 6. Axial ullage was reduced as much as possible in order to minimize pressure waves. When an inert simulant was used in place of the TC, the total projectile weight was 21.5 grams. This gave a charge-to-mass ratio of approximately 1.6.

Data acquisition is done on analog tape, which is later digitized and reduced by the BALDAS (Ballistic Data Acquisition System) data reduction code. The gun pressures are measured with Kistler 607C piezoelectric gauges. Velocity is measured using a 35 GHz microwave interferometer. High speed cinematography is also available using a Photec high speed motion picture camera. For some tests, flash x-rays were used to observe the condition of the projectile after muzzle exit.

The operation of the fixture is as follows. The booster charge is prepared by bagging 1.5 grams of Class 6 (FFFG) black powder with an M-100 Atlas electric match in a small diameter tube of polyethylene film and installing this igniter in an already prepared polyethylene film tube that has been sealed at one end. This tube is then filled with the 34 grams of booster charge. The leads of the electric match are left protruding from the open end of the tube and the film is sealed around the leads and booster charge. The match leads are then attached to an electric feedthrough device in the breech closure head. The projectile, with the VHBR propellant epoxied into the tailstock, is now positioned in the barrel with a tool that assures reproducible location of the back end of the projectile to insure that each firing had a chamber volume of 100 cm^3. The breech closure head, with the booster charge attached, is installed and sealed.

IV. RESULTS

1. CONVENTIONAL FIRINGS

A series of five conventional test firings was carried out in the 14-mm gun fixture described earlier. The purpose of these tests was to provide ballistic data for calibrating the interior ballistic code (XKTC) that was to be applied to the traveling charge firings. Details of this code have been discussed elsewhere.[10-11]

The booster charge configuration was described in section two and is shown in Figure 6.

A TC projectile is shown in Figure 5. For the conventional firings, an inert nylon tail stock was used in place of the TC holder. The final projectile weight was a nominal 21.5 g, with an overall length of 105 mm. Because of the small interference between the obturator and gun tube, only a small force was required to seat the projectile. Consequently a very small shot start pressure could be used as input data for the code.

The results of the test firings are shown in Table 3. A total of five conventional firings were carried out. Average values and standard deviations are reported in Table 3.

TABLE 3. RESULTS OF TC FIRINGS AND CALCULATIONS

REMARKS	ID	P1	P2	P3	P4	P5	P6	P7	VELOCITY (m/s)	IG DELAY# (ms)
		(pressures in MPa)								
Conventional firings	*	317 ±9	305 ±10	287 ±1	126 ±2	69 ±2	39 ±2	20 ±1	1524 ±25	----
Conventional calculations	C	314	312	250	120	65	42	30	1507	----
TC firings	43	327	322	--	130	78	39	31	1846	+0.03
"	44	323	310	--	141	62	40	25	1867	+0.03
"	50	326	324	375	122	76	30	23	1820	-0.15
"	51	434	408	450	85	79	47	35	1805	-0.25
TC	44	311	--	285	87	52	35	27	1840	+0.16
calculations	51	419	--	404	100	85	51	35	1863	-0.19
TC no ignition	49	306	295	278	133	71	38	23	1440	----
TC no ignit. calculations	49	324	---	---	125	68	45	28	1463	----

#- TC ignition delay with respect to maximum chamber pressure.
*- an average and standard deviation of 5 firings.

The location of the gages is given in Figure 4. Plots of typical pressure and velocity histories are given in Figures 7 and 8. Time zero is arbitrary on these and all subsequent plots. In this series of plots, interferometer data were lost at approximately 1/2 way down the tube (Figure 8, A) due to gas blow-by. This was confirmed by down-bore high speed photography. A bright flame was observed at the same time that the interferometer signal disappeared. The signal was recovered after muzzle exit, however, so that the muzzle velocity is included on the velocity histories.

2. SIMULATION OF CONVENTIONAL FIRINGS

The results of the calculations that were carried out using the XKTC code are given in Table 3, ID C. The resistance profile was varied until both pressure and velocity histories agreed with the experimental data. Once determined, this resistance profile was held fixed throughout all conventional and TC calculations. As was mentioned, the burn rate as a function of pressure for the booster propellant was derived from closed chamber firings and is given by,

$$r(\text{mm/s}) = 2.259 \quad P^{0.863},$$

where P is in units of MPa. This expression was used in all conventional and TC calculations. Plots of the pressure-time and velocity-time calculations are given in Figures 9 and 10. There is a discrepancy between calculation and experiment for P3. However, some electronic problems were experienced with this gage and the results reported for P3 in Table 3 are an average of only two readings. The agreement between experimental results and calculations is considered reasonable. Consequently, when calculations were carried out including the traveling charge routines, no changes were made to the input data for the conventional part of the code. Only the ignition and combustion characteristics of the TC were changed when matching experimental data.

3. TRAVELING CHARGE FIRINGS

Traveling charge firings were carried out using the same booster (34 g) configuration as for the conventional firings discussed above. The projectile used is shown in Figure 5. The TC sample used was TC-49, with a nominal length of 51 mm and mass of 9.6 g. The projectile had an overall length of 104 mm and a total mass, including the TC, of 23.9 g. If the TC burns out in-bore the projectile mass at muzzle exit is 14.3 g.

It was found late in the firing program that the problem of recording in-bore velocities over the total distances from shot start to muzzle exit could be overcome using a lubricant (WD-40) in the gun tube. Apparently the lubricant aided in increasing obturation and reducing gas blow-by. This resulted in acceptable interferometer signals up to muzzle exit. Consequently, some of the firings only have velocity histories to about mid-tube while for later firings, data was recorded out to muzzle exit. However, as was mentioned above, the lost interferometer signal was recovered at projectile exit which permitted accurate recording of muzzle velocities.

It has been found from previous calculations[14] that the best TC performance is achieved when ignition is delayed until after the maximum booster pressure. Consequently, an ignition delay element was added to the end of the TC. As was discussed earlier, a layer of masking tape, with vacuum grease at the edges was used. All TC firings reported here used this delay element.

High speed photographic results and flash x-rays indicate that the projectile is intact and that there is not much if any TC combustion after muzzle exit.

Results for the TC firings described above are given in Table 3, as ID 43, 44, 50 and 51. Included in this table is ID 49. This test is identical to ID 43, 44, 50 and 51 except that the TC did not ignite. The usefulness of test ID 49 is to yield a direct comparison of the effect of TC functioning on the interior ballistic processes. It should be noted that the pressures recorded in Table 3 for the down bore gages are NOT the maximum values, but rather the pressure just as the projectile moves past the gage. It is the projectile base pressure which ultimately determines the projectile velocity. This is not necessarily the maximum pressure recorded at that location. The rapid pressure rise as the base of the projectile passes by the gage often induces substantial pressure oscillations (50 to 100 kHz, see for example, Figure 7, gage 5). Accurate determination of pressure and error estimates are made difficult under these circumstances. Pressure and velocity histories for ID 44 and ID 49 are given in Figures 11, 12, 13 and 14. Ignition of the TC is shown as point D in Figure 15. Prior to this ignition, the pressures and velocities should be the same for these two tests. Examination of the velocity histories (Figure 15) indicates that up until the time of maximum chamber pressure the velocities are the same. After this the TC ignites (point D), and the acceleration is substantially increased for ID 44.

By contrast to the results presented above, the magnitude and character of the pressure and velocity histories are substantially different for TC firing ID 51 shown in Figures 16 and 17. The chamber pressure is larger but the muzzle velocity is lower than for the other TC firings. Additionally, close examination of the velocity history indicates that the largest acceleration for ID 51 occurs prior to maximum breech pressure whereas for 43 and 44 this occurs slightly after maximum breech pressure. This is most likely due to ignition of the TC prior to the maximum chamber pressure. This will be more fully discussed below.

The variability in the traveling charge firings observed can be attributed to the non-reproducibility of the ignition delay element. More will be discussed on this subject in the next section.

4. SIMULATION OF TRAVELING CHARGE FIRINGS

For these calculations (XKTC code) the same input data was used that was employed in the conventional firings (booster burn rate, as determined from closed chamber firings, and the resistance profile, as determined by matching calculated pressure and velocity histories with experiment).

Only the traveling charge mass and burn rate were adjusted in order to obtain a match between the computed and experimental performance data. The other input data regarding the gun, booster charge, etc. were the same as those used in the simulations of the conventional firings. An estimate of the TC ignition was made from an examination of the experimental velocity histories. The time for the start of deviation of velocity of a TC firing from the case where the TC did not ignite was used as a criterion for TC ignition (Figure 15). This was not difficult to determine since a large acceleration accompanies the ignition of the TC. This ignition time is then referenced to the time for maximum chamber pressure and was then used in the code. The time for maximum chamber pressure was determined from ID 49 where no TC ignition took place.

In the initial set of calculations,[9] a pressure-dependent burn rate law was used to describe the TC combustion. As was found, muzzle velocities were too large compared with experiment. For the present calculations, two changes were then made in the burning characteristics of the TC. Since the calculated velocities were systematically high, it was speculated that not all of the 9.6 g of TC was burning and contributing energy to accelerating the projectile. There is some experimental evidence for this. Closed chamber firings[15] have indicated that the final pressures were not always that predicted from thermochemical calculations. This could be due to incomplete combustion of the formulations. Secondly, a witness plate in front of the muzzle for the experimental firings has indicated that a substantial amount of small particulate matter is being accelerated with the projectile. This could be interpreted as unburned TC. Thus a series of calculations was carried out with TC mass as a variable, starting with 9.6 g.

Secondly, as was discussed in the COMBUSTION DIAGNOSTICS section, closed chamber firings of a number of TC formulations have indicated that cylindrical samples burn with some form of breakup rather than in a laminar fashion. Pressure histories indicate a decreasing mass generation rate as a function of burn time.[9]

As a consequence of these two observations and in order to match experimental velocity histories, the TC combustion data used in the computations were altered in the following way. First, the total amount of TC burned was reduced from 9.6 g to 5.5 g, with the difference of 4.1 g being added to the projectile mass. Second, a dual burn rate law was introduced depending on the amount of TC burned,

$$r(m/s) = 127 \qquad (0 \text{ to } 4.5 \text{ g})$$

$$r(m/s) = 25.4 \qquad (4.5 \text{ to } 5.5 \text{ g}).$$

Thus, the first 4.5 g burned at the rate of 127 m/s and the final 1 g burned at a rate of 25.4 m/s. The velocity data for ID 44 was compared with the velocity calculations simulating ID 49. As was mentioned, the deviation of velocities was used to determine the TC ignition. An ignition delay of +0.162 ms was used.

Results from the calculations are given in Table 3. Pressure and velocity histories are shown in Figures 18 and 19. The agreement with the experimental results (ID 44, Figures 11 and 12) is reasonably good. The pressure waves induced by the TC combustion are clearly evident. The calculations reproduce these waves. From Figure 19 it is seen that the traveling charge ignites at approximately 1.4 ms. In Figure 18 it is seen that the pressure pulse produced by the igniting TC propagates back to gage 3, 1.7 ms, and then to gage 1 at 1.85 ms. Further waves are observed on gages 4, 5 and 6. Examination of Figure 11 shows that all of these general wave characteristics are observed experimentally.

Two points of discrepancy should be mentioned. First, the absolute pressure values for P3 (Figure 11) are suspect because of electronics problems during recording of ID 44. The "best estimated value" of pressure for this gage is plotted here to show the qualitative agreement between calculation and experiment. Second, the calculated pressure at P4 is lower than that measured. The most likely reason for this is that the precise location of burn-out of the TC has a dramatic effect on the pressure at a particular time and location. To demonstrate this, a calculation was carried out in which the amount of TC was increased to 8 g with a constant burn rate of 102 m/s. These changes would be expected to affect the point of burnout of the TC. The pressure histories are given in Figure 20. Whereas the general character of P1 and P3 has not changed there is a substantial increase in maximum value of P4 indicating the large sensitivity to the location of burn-out of the TC. As a matter of fact, examination of the velocity histories of the TC firings clearly shows the dramatic increase in acceleration when the TC turns on and the lowered acceleration when it turns off.

Although a better fit to the data could probably be achieved by a systematic variation of the ignition delay and burning characteristics of the TC, no further effort was made to do this at this time. The code results were used mainly as an aid in explaining the physics and chemistry of the problem.

An attempt was made to simulate the experimental results from ID 51. In this case the ignition of the TC is taking place prior to the maximum booster pressure. The value chosen was -0.190 ms with respect to the maximum chamber pressure. The results are shown in Table 3 and Figures 21 and 22. Comparing these with experiment, Figure 16, shows the predicted large pressure waves observed experimentally. The velocity history (Figure 22) shows some interesting characteristics. The first element of the TC ignites at time C and burns out at time E. The second element ignites at E and burns out at F. These characteristics are also observed in the experimental data, Figure 17. After the burnout, a decrease in acceleration is observed until point G. Both the calculated and experimental velocity histories show an unusual inflection at point G. (Although the experimental inflection occurs at a slightly later time.)

A study was made of the pressure vs. distance and gas velocity vs. distance produced by the code. These results indicate that the ignition and burn-out of the TC induces large pressure pulses at the base of the projectile. At a later time in the interior ballistic cycle, this pulse dissipates after stagnating against the breech face. Slightly later, the normal pressure gradient from breech to projectile decreases. The pressure at the breech goes down but the projectile base pressure increases. This occurs at G producing an increase in velocity through the remainder of the projectile travel. The code is showing the inflection in the velocity history. This phenomenon is somehow related to the pressure pulses generated by the traveling charge, but the exact details of the hydrodynamics are not clear at this time. The implications of these observations and its impact on the overall TC process will be a subject for future investigation.

Finally, it was of interest to determine potential optimal performance, as predicted by the code, for the experimental traveling charge firings. Starting with the data base used to match ID's 43 and 44, the ignition time of the traveling charge element was varied to obtained improved velocity. By delaying the ignition of the traveling charge by an additional 1.0 ms a velocity of 2074 m/s was obtained without increasing maximum gun pressures. The ignition delay could not be increased beyond this time since velocities reached the point where the Mach 1 limitation was imposed. Thus, for this system, the velocity can be further increased by over 200 m/s. It is important to note that to achieve this optimal performance the TC ignition must be tailored to provide burnout of the traveling charge at muzzle exit.

V. CONCLUSIONS

* Experimental data indicate a distinct difference between the character and magnitude of pressure and velocity histories of TC and conventional firings.

* The two phase hydrodynamic interior ballistic code (XNOVAKTC) gives a good representation of the pressure and velocity histories for both conventional and TC firings. It can confidently be used to study the wave dynamics of the problem and help determine the important criteria that must be met for a successful application of the traveling charge concept.

* The results indicate that not all of the potential energy from the traveling charge was realized in our 14-mm gun finings. The reasons for this are not clear at this time.

* Results indicate that the VHBR formulations show regressive burning characteristics under TC conditions. This confirms what was observed in combustion diagnostic studies.

* Successful application of the traveling charge concept will require precise control over ignition and burnout times of the TC propellant.

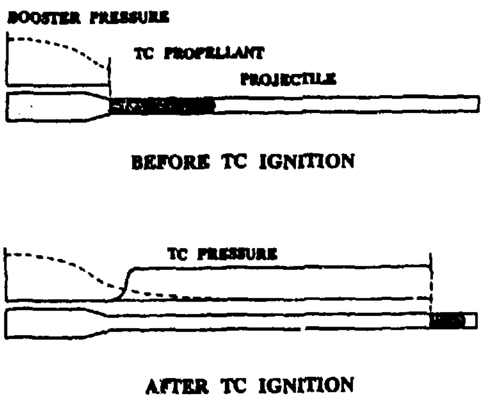


Figure 1. Traveling Charge Schematic

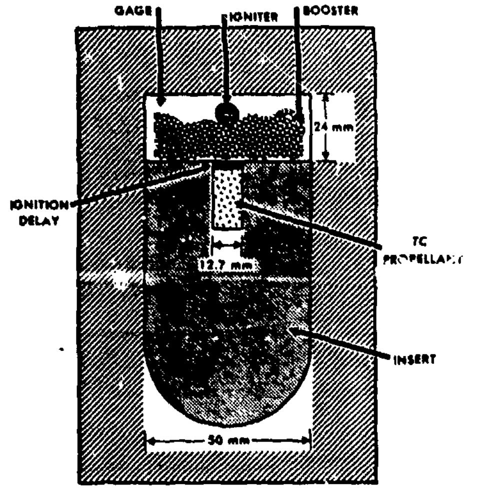


Figure 2. Closed Chamber Schematic

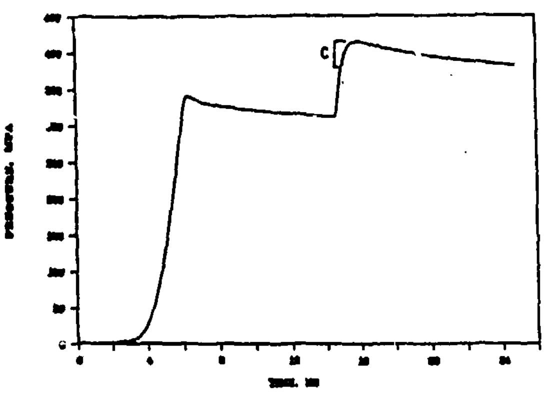


Figure 3. Closed Chamber: Booster and TC

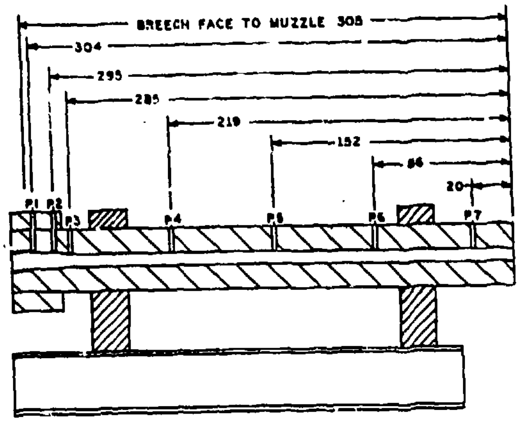


Figure 4. 14-mm Test Fixture; Units in CM

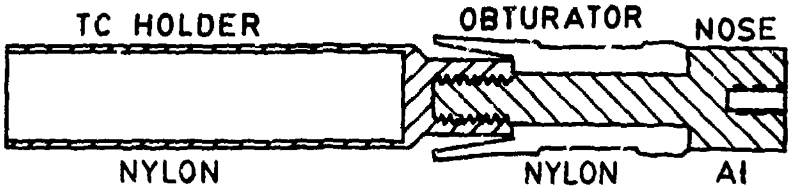


Figure 5. Traveling Charge Projectile Schematic

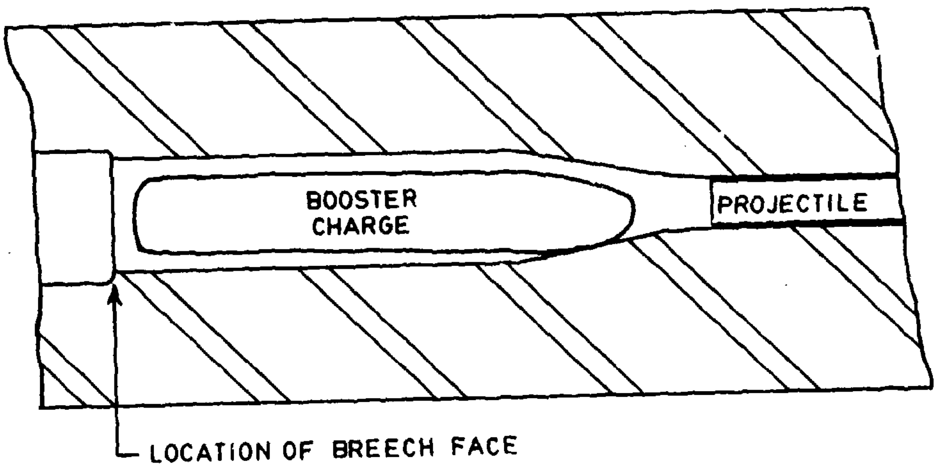


Figure 6. Booster Charge, Chamber and Projectile Schematic

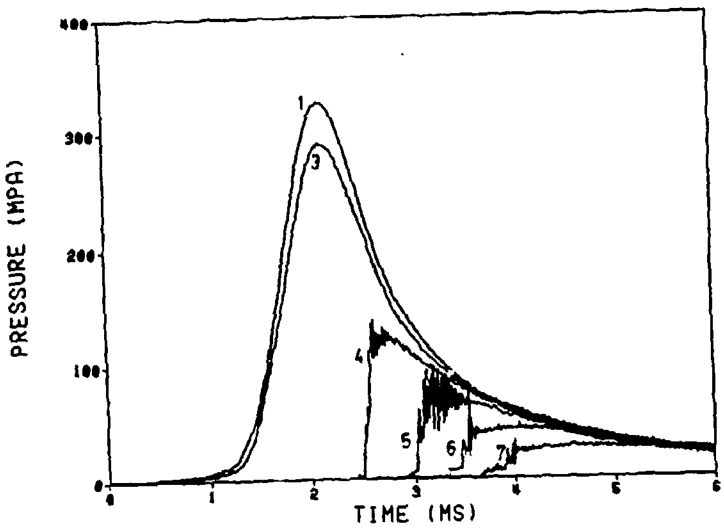


Figure 7. Conventional Firing: Experimental Pressures

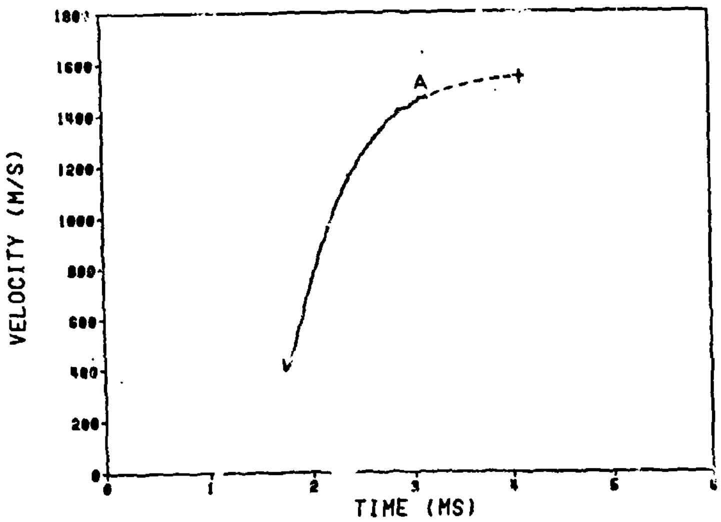
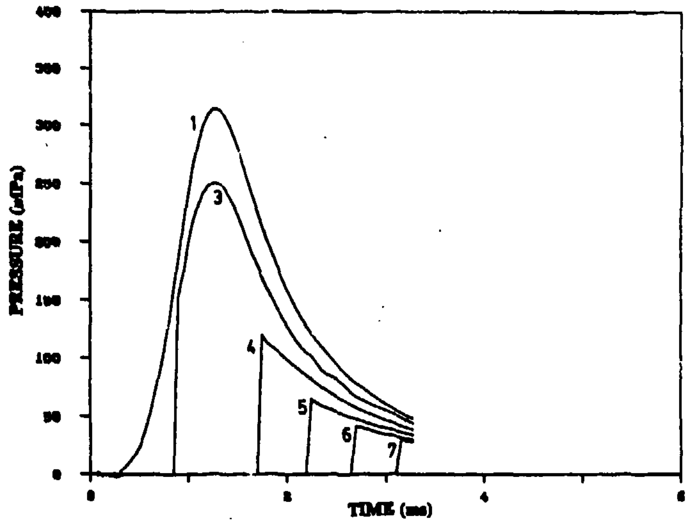


Figure 8. Conventional Firing: Experimental In-Bore Velocity



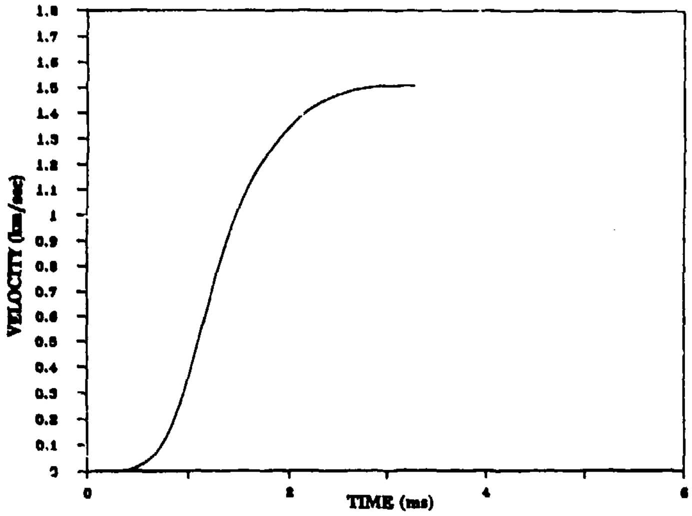
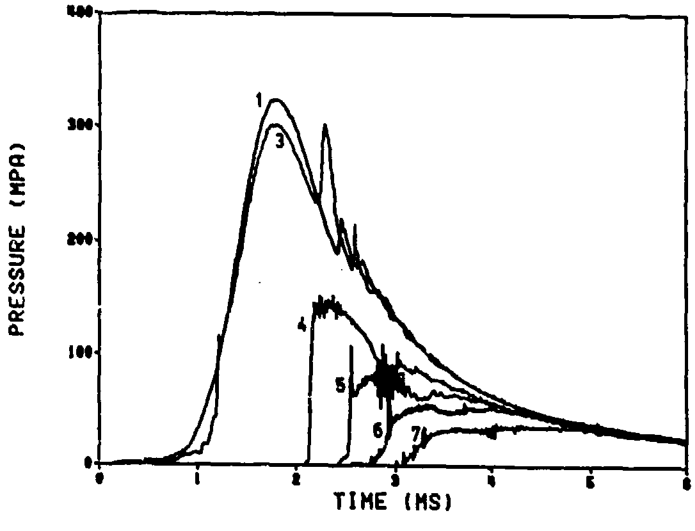


Figure 9. Conventional Firing: Simulation of Pressure

Figure 10. Conventional Firing: Simulation of In-Bore Velocity



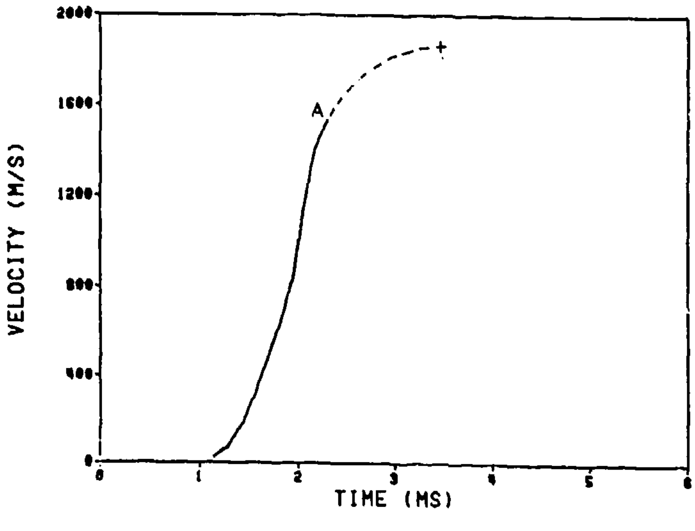


Figure 11. Late TC Ignition: Experimental P, ID 44

Figure 12. Late TC Ignition: Experimental V, ID 44

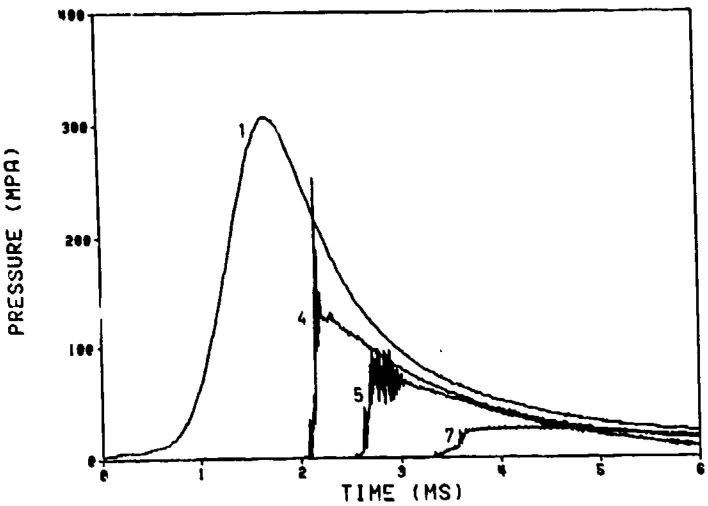


Figure 13. No TC Ignition: Experimental P, ID 49

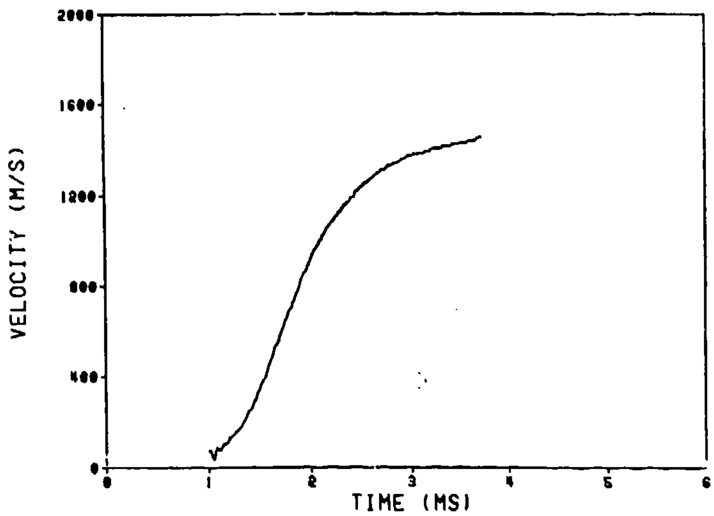


Figure 14. No TC Ignition: Experimental V, ID 49

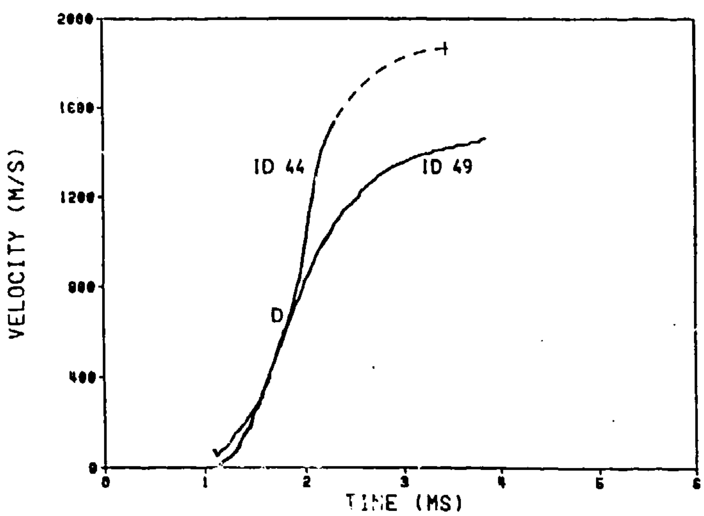


Figure 15. Experimental In-Bore Velocities: No TC Ignition (ID 49), Late TC Ignition (ID 44)

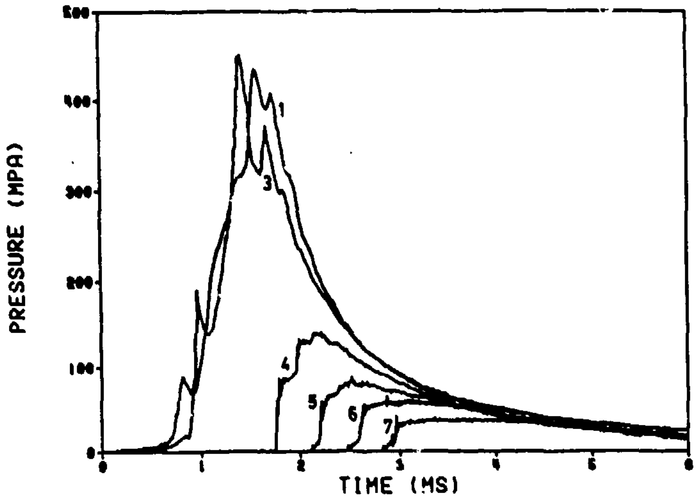


Figure 16. Early TC Ignition: Experimental V, ID 51

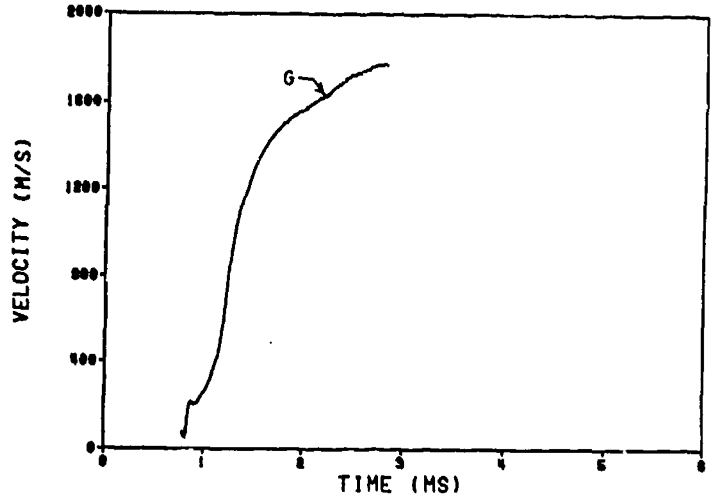


Figure 17. Early TC Ignition: Experimental, P

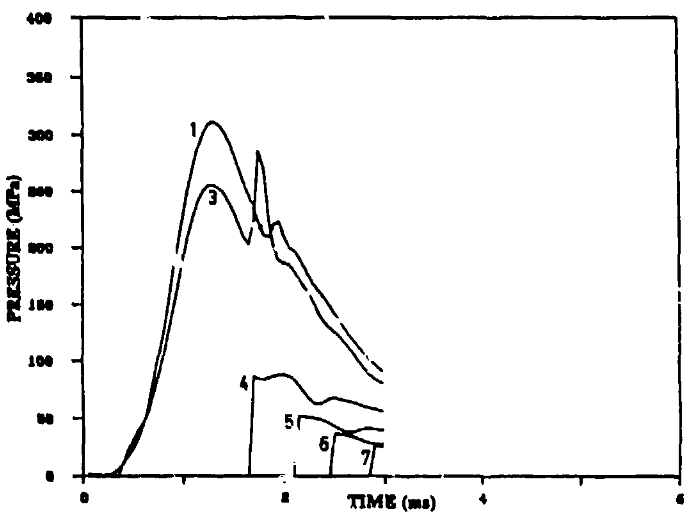


Figure 18. Late TC Ignition: Simulation of P, ID 44

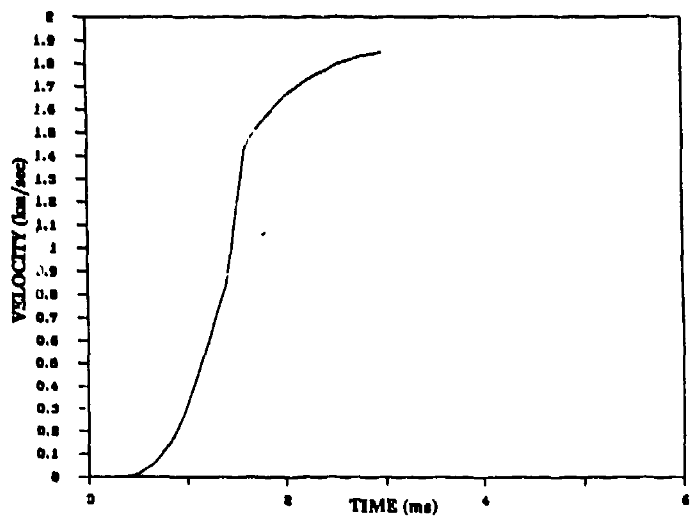


Figure 19. Late TC Ignition: Simulation of V, ID 44

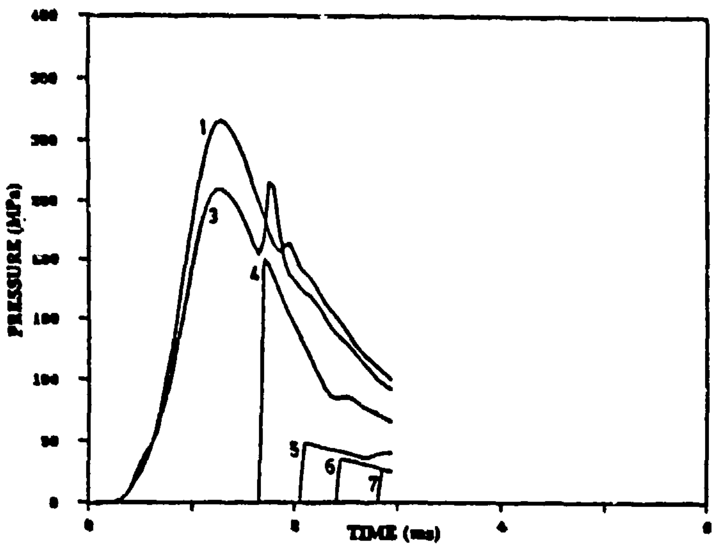


Figure 20. Late TC Ignition: Simulation of P, ID 44, Altered TC Burn Rate

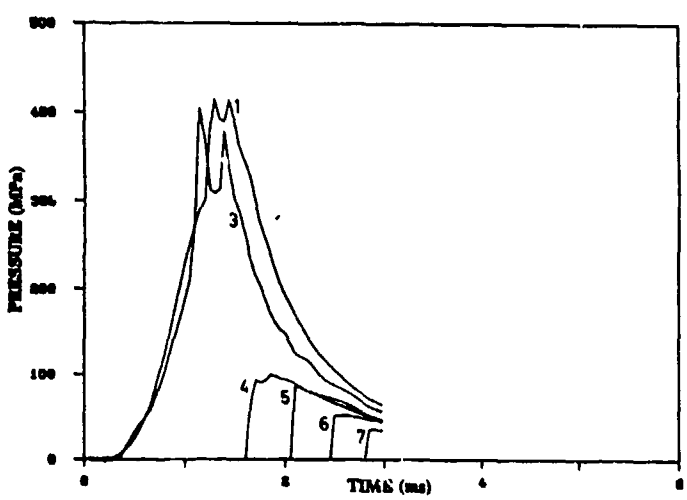


Figure 21. Early TC Ignition: Simulation of P, ID 51

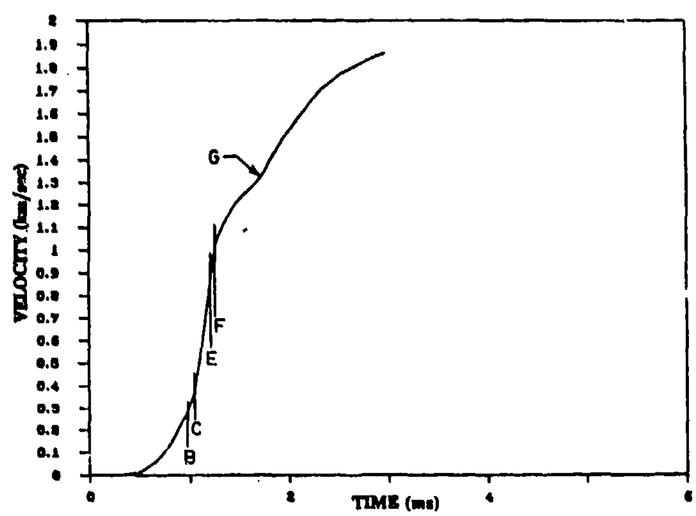


Figure 22. Early TC Ignition: Simulation of V, ID 51

REFERENCES

1. Langweiler, H., "A Proposal For Increasing the Performance of Weapons by the Correct Burning of Propellant," British Intelligance Objective Sub-Committee, Group 2, Ft. Halstead Exploiting Center, 1247.

2. Braind, R., Dervaux, M., and Nicolas, M., "Etude Theorique De La Balistique Interieure De Canons Avec Charge Embarquee," AGARD Conference Proceedings No. 392, Interior Ballistics of Guns, AGARD-CP-392, January 1986.

3. May, I.W., Baron, A.F., Gough, P.S., and Baer, P.G., "The Traveling Charge Effect," BRL Memorandum Report ARBRL-MR-03034, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, July 1980.

4. Lee, L. and Laidler, K.J., "The Interior Ballistics of the Impulse Propulsion Gun," Nord 10260 Contract Report CU/F/51.2, August 1951.

5. Smith, H.C., "An Investigation of the Use of Porous Propellants in a Traveling Charge Gun," BRL Memorandum Report No. 1554, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, January 1964. (AD#441254)

6. Vinti, J.P., "Theory of the Rapid Burning of Propellants," BRL Report No. 841, Ballistic Research Laboratories, Aberdeen Proving Ground, MD, December 1952. (AD#PB137128)

7. Barbarek, L.A.C. and Jeslis, J., "Feasibility Study of Traveling-Charge-Type 20-mm Caseless Ammunition," IIT Research Institute, Final Report K6091, Contract DA-36-038-AMC-2907(A), February 1967.

8. Baer, P.G. and May, I.W., "Traveling Charge Effect," Published in "Gun Propulsion Technology," Progress in Astronautics and Aeronautics Series, Volume 109, AIAA Wash., D.C., June 1988.

9. Tompkins, R.E, White, K.J., Oberle, W.F. and Juhasz, A.A., "Traveling Charge Concept-Combustion and Interior Ballistic Studies," 23rd JANNAF Combustion Meeting, CPIA Publication 457, pp 135-151, The Johns Hopkins Applied Physics Laboratory, Laurel, MD, October 1986.

10. Gough, P.S., "The NOVA Code: A User's Manual. Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, December 1980.

11. Gough, P.S., "Extensions of BRLTC. A Code for the Digital Simulation of the Traveling Charge," Contract Report.

12. Oberle, W.F., Wren, G.P., White, K.J., Tompkins, R.E., and Juhasz, A.A., "Optimization of Traveling Charge Gun Systems," 24th JANNAF Combustion Meeting, Naval Postgraduate School, Monterey, CA, October 1987.

13. White, K.J., McCoy, D.G., Doali, J.O., Aungst, W.P., Bowman, R.E., and Juhasz, A.A., "Closed Chamber Burning Characteristics of New VHBR Formulations," BRL-MR-3471, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, October 1985.

14. Oberle, W.F., White, K.W., Tompkins, R.E., and Juhasz, A.A., "Traveling Charge Concepts Interior Ballistic Computations," 23rd JANNAF Combustion Meeting, CPIA Publication 457, pp 193-213, The Johns Hopkins Applied Physics Laboratory, Laurel, MD, October 1986.

15. Juhasz, A.A., May, I.W., Aungst, W.P., and Lynn, F.R., "Combustion Diagnostics of Very High Burning Rate Propellants," 17th JANNAF Combustion Meeting, CPIA Publication 329, November 1980.

DISTRIBUTION LIST

No. of Copies	Organization
12	Commander Defense Tochnical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Director Defense Advanced Research Projects Agency ATTN: J. Richardson 1400 Wilson Boulevard Arlington, VA 2209
1	Commander USA Concepts Analysis Agency ATTN: D. Hardison 8120 Woodmont Avenue Bethesda, MD 20014
1	HQDA/DAMA-ZA Washington, DC 20310
1	HQDA, DAMA-CSM, E. Lippi Washington, DC 20310
1	HQDA, DAMA-ART-M Washington, DC 20310
1	HQDA (SARDA-TR) Washington, DC 20310
1	Commander US Army War College ATTN: Library-FF229 Carlisle Barracks, PA 17013
1	Director US Army BMD Advanced Technology Center PO Box 1500 Huntsville, AL 35807

No. of Copies	Organization
1	Chairman DOD Explosives Safety Board Room 856-C Hoffman Bldg 1 2461 Eisenhower Avenue Alexandria, VA 22331
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
5	Project Manager Cannon Artillery Weapons System, ARDEC, AMCCOM ATTN: AMCPM-CW, F. Menke AMCPM-CWW AMCPM-CWS, M. Fisette AMCPM-CWA, R. DeKleine H. Hassmann Picatinny Arsenal, NJ 07806-5000
1	Project Manager Munitions Production Base Modernization and Expansion ATTN: AMCPM-PBM-E, L. Laibson Picatinny Arsenal, NJ 07806-5000

DISTRIBUTION LIST

No. of Copies	Organization
3	Project Manager Tank Main Armament System ATTN: AMCPM-TMA, K. Russell AMCPM-TMA-105 AMCPM-TMA-120 Picatinny Arsenal, NJ 07806-5000
1	Commander US Army Watervliet Arsenal ATTN: SARWV-RD, R. Thierry Watervliet, NY 12189
21	Commander Armament RD&E Center US Army AMCCOM ATTN: SMCAR-MSI SMCAR-TDC SMCAR-AE SMCAR-TD (V. Lindner) SMCAR-AEE-B, A. Beardell D. Downs S. Einstein S. Westley S. Bernstein N. Baron A. Bracuti J. Rutkowski L. Stiefel B. Brodman SMCAR-CCD, D. Spring SMCAR-AEE, J. Lannon SMCAR-AES, S. Kaplowitz SMCAR-CCS SMCAR-CCH-T, L. Rosendorf SMCAR-CCH-V, E. Fennell SMCAR-FSA-T, M. Salsbury Picatinny Arsenal, NJ 07806-5000

No. of Copies	Organization
1	Commander US Army Laboratory Command ATTN: AMSLC-TD Adelphi, MD 20783-1145
1	Commander US Army Laboratory Command ATTN: AMSLC-TD (R. Vitali) 2800 Powder Mill Road Adelphi, MD 20783
1	Deputy Commander US Army Strategic Defense Cmd ATTN: CSSD-H-QL MAJ Nobel Johnson PO Box 1500 Huntsville, Ala 35807-3801
4	Commander US AMCCOM ATTN: SMCAR-ESP-L AMSMC-IRC, G. Cowan SMCAR-ESM(I), W. Fortune R. Zastrow Rock Island, IL 61299-7300
1	Director Benet Weapons Laboratory Armament R&D Center US Army AMCCOM ATTN: SMCAR-LCB-TL Watervliet, NY 12189
1	Commander US Army Aviation Systems Cmd ATTN: AMSAV-DACL 4300 Goodfellow Blvd St. Louis, MO 63120
1	Commander US Army TSARCOM 4300 Goodfellow Blvd St. Louis, MO 63120

DISTRIBUTION LIST

No. of Copies	Organization
1	Director US Army Aviation Research and Technology Activity Ames Research Center Moffett Field, CA 94035-1099
1	Commander US Army Communications Electronics Command ATTN: AMSEL-ED Fort Monmouth, NJ 07703
1	Commander ERADCOM Technical Library ATTN: STET-L Fort Monmouth, NJ 07703-5301
1	Commander US Army Harry Diamond Lab ATTN: DELHD-TA-L 2800 Powder Mill Road Adelphi, MD 20783
1	Commander US Army Missile Command ATTN: AMSMI-RD Redstone Arsenal, AL 35898-5000
1	Director US Army Missile Command ATTN: AMSMI-AS Redstone Arsenal, AL 35898-5000
1	Commandant US Army Aviation School ATTN: Aviation Agency Fort Rucker, AL 36360
1	Commander US Army Tank Automotive Cmd ATTN: AMSTA-DI Warren, MI 48090

No. of Copies	Organization
1	Commander US Army Tank Automotive Cmd ATTN: AMSTA-CG Warren, MI 48090
1	Project Manager Improved TOW Vehicle US Army Tank Automotive Cmd ATTN: AMCPM-ITV Warren, MI 48090
1	Program Manager M1 Abrams Tank System ATTN: AMCPM-GMC-SA, T. Dean Warren, MI 48090
1	Project Manager Fighting Vehicle Systems ATTN: AMCPM-FVS Warren, MI 48090
1	President USA Armor & Engineer Board ATTN: ATZK-AD-S Ft. Knox, KY 40121
1	Project Manager M-60 Tank Development ATTN: AMCPM-M60TD Warren, MI 48090
1	Director TRADOC Analysis Command ATTN: ATAA-SL White Sands Missile Range, NM 88002-5502
1	Director Requirements & Programs Directorate HQ, TRADOC Analysis Command ATTN: ATCD-MA/MAJ Williams Ft. Monroe, VA 23651-5143

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander USA Materials Technology Lab Dyna East Corporation ATTN: Christine P. Brandt, Document Control 3132 Market Street Philadelphia, PA 19104-2855
1	Commander US Army Research Office ATTN: Tech Library PO Box 12211 Research Triangle Park, NC 27709-2211
1	Commander US Army Belvoir R&D Ctr ATTN: STRBE-WC Tech Library (Vault) Bldg 315 Ft. Belvoir, VA 22060-5606
1	Commander US Army Logistics Ctr Defense Logistics Studies Ft. Lee, VA 23801
1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Ft. Benning, GA 31905
1	President US Army Artillery Board Ft. Sill, OK 73503
1	Commandant US Army Command and General Staff College Ft. Leavenworth, KS 66027-5200
1	Commandant USA Special Warfare School ATTN: Rev & Tng Lit Div Ft. Bragg, NC 28307

No. of Copies	Organization
1	Commander Radford Army Ammo Plant ATTN: SMCRA-QA/HI LIB Radford, VA 24141
1	Commander US Army Foreign Science & Technology Center ATTN: AMXST-MC-3 220 Seventh Street, NE Charlottesville, VA 22901
1	Commandant US Army Field Artillery Center & School ATTN: ATSF-CO-MW, B. Willis Ft. Sill, OK 73503
1	Office of Naval Research ATTN: Code 473, R.S. Miller 800 N. Quincy Street Arlington, VA 22217
2	Commander Naval Sea Systems Command ATTN: SEA 62R SEA 64 Washington, DC 20362-5101
1	Commander Naval Air Systems Command ATTN: AIR-954-Tech Lib Washington, DC 20360
1	Assistant Secretary of the Navy (R, E, and S) ATTN: R. Reichenbach Room 5E787 Pentagon Bldg Washington, DC 20350
1	Naval Research Lab Tech Library Washington, DC 20375

DISTRIBUTION LIST

No. of Copies	Organization
2	Commander US Naval Surface Weapons Ctr ATTN: J.P. Consaga C. Gotzmer Silver Spring, MD 20902-5000
3	Naval Surface Weapons Center ATTN: S. Jacobs/R10 Code 730 K. Kim/Code R-13 R. Bernecker/Code R-13 Silver Spring, MD 20902-5000
5	Commander Naval Surface Weapons Center ATTN: Code G33, J.L. East W. Burrell J. Johndrow Code G23, D. McClure Code DX-21 Tech Lib Dahlgren, VA 22448-5000
2	Commander Naval Underwater Systems Ctr Energy Conversion Dept ATTN: Code 5B331, R.S. Lazar Tech Library Newport, RI 02840
1	Commander Naval Weapons Center ATTN: Code 388, C.F. Price Info Science Div China Lake, CA 93555-6001
1	Superintendent Naval Postgraduate School Dept of Mechanical Engr Code 1424 Library Monterey, CA 93943
1	Program Manager AFOSR Directorate of Aerospace Sciences ATTN: L.H. Caveny Bolling AFB, DC 20332
3	Commander Naval Ordnance Station ATTN: D. Brooks W. Vienne Tech Library Indian Head, MD 20640
1	HQ AFSC/SDOA Andrews AFB, MD 20334
1	AFRPL/DY, Stop 24 ATTN: J.N. Levine/DYCR Edwards AFB, CA 93523-5000
1	AFRPL/TSTL (Tech Library) Stop 24 Edwards AFB, CA 93523-5000
1	AFRPL/MKPB, Stop 24 ATTN: B. Goshgarian Edwards AFB, CA 93523-5000
1	AFFTC ATTN: SSD-Tech Lib Edwards AFB, CA 93523
1	AFATL/DLYV ATTN: George C. Crews Eglin AFB, FL 32542-5000
1	AFATL/DLJE Eglin AFB, FL 32542-5000
1	Air Force Armament Lab ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000

DISTRIBUTION LIST

No. of Copies	Organization
1	AFWL/SUL Kirtland AFB, NM 87117
1	Commandant USAFAS ATTN: STSF-TSM-CN Ft. Sill, OK 73503-5600
10	Central Intelligence Agency Office of Central Reference Dissemination Branch Room GE-47 HQS Washington, DC 20502
1	Central Intelligence Agency ATTN: Joseph E. Backofen HQ Room 5F22 Washington, DC 20505
2	Aeroject Solid Propulsion Co ATTN: P. Micheli P. Krshner Sacramento, CA 95813
1	ARMTEC ATTN: D. Simpson 85-901 Avenue 53 Coachella, CA 92236
1	Atlantic Research Corporation ATTN: M.K. King 5390 Cheorokee Avenue Alexandria, VA 22314
1	AVCO Everett Rsch Lab ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149
1	Calspan Corporation ATTN: Tech Library PO Box 400 Buffalo, NY 14225

No. of Copies	Organization
1	FMC Corporation ATTN: Dr. G. Chryssomallis 1300 South Second Street PO Box 59043 Minneapolis, MN 55459-0043
1	GT Devices ATTN: Dr. S. Goldstein 5705A General Washington Dr Alexandria, BA 22312
1	General Electric Company Armament Systems Dept ATTN: M.J. Bulman, R-1311 Lakeside Avenue Burlington, VT 05401
1	IITRI ATTN: M.J. Klein 10W. 35th Street Chicago, Il 60616
1	Hercules, Inc Bacchus Works ATTN: K.P. McCarty PO Box 98 Magna, UT 84044
2	Director Lawrence Livermore National Laboratory ATTN: M.S. L-355, A. Buckingham PO Box 808 Livermore, CA 94550
1	Lawrence Livermore National Laboratory ATTN: M.S. L-355 M. Finger PO Box 808 Livermore, CA 94550

DISTRIBUTION LIST

No. of Copies	Organization
1	Olin Corporation Badger Army Ammunition Plant ATTN: R.J. Thiede Baraboo, WI 53913
2	Olin Corp/Smokeless Powder Operations R&D Library ATTN: V. McDonald Don Mann PO Box 222 St. Marks, FL 32355
1	Paul Gough Associates, Inc. ATTN: P.S. Gough PO Box 1614 1048 South St. Portsmouth, NH 03801
1	Physics International Company ATTN: Library H. Wayne Wampler 2700 Merced Street San Leandro, CA 94577
1	Systems Planning Corp ATTN: David C. Hardison 1500 Wilson Blvd Arlington, VA 22209-2454
2	Rockwell International Rocketdyne Division ATTN: BA08 J.E. Flanagan J. Gray 6633 Canoga Avenue Canoga Park, CA 91304
1	Princeton Combustion Rsch Lab ATTN: M. Summerfield 4275 US Highway One Monmouth Junction, NJ 08852

No. of Copies	Organization
1	Science Applications, Inc. ATTN: R.B. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364
3	Thiokol Corporation Huntsville Division ATTN: D. Flanigan R. Glick Tech Library Huntsville, AL 35807
1	Scientific Rsch Assoc, Inc ATTN: H. McDonald PO Box 498 Glastonbury, CT 06033
1	Thiokol Corporation Wasatch Division ATTN: Tech Library PO Box 524 Brigham City, UT 84302
2	Thiokol Corporation Elkton Division ATTN: R. Biddle Tech Library PO Box 241 Elkton, MD 21921
1	Universal Propulsion Company ATTN: H.J. McSpadden Black Canyon Stage 1 Box 1140 Phoenix, AZ 85029
1	Veritay Technology, Inc. 4845 Millersport Hwy PO Box 305 East Amherst, NY 14051-0305
1	Battelle Memorial Institute ATTN: Tech Library 505 King Avenue Columbus, OH 43201

DISTRIBUTION LIST

No. of Copies	Organization
1	Brigham Young University Dept of Chemical Engr ATTN: M. Beckstead Provo, UT 84601
1	California Institute of Tech 204 Karman Lab Main Stop 301-46 ATTN: F.E.C. Culick 1201 E. California Street Pasadena, CA 91109
1	California Institute of Tech Jet Propulsion Laboratory ATTN: L.D. Strand 4800 Oak Grove Drive Pasadena, CA 91103
1	Professor Herman Krier Dept of Mech/Indust Engr University of Illinois 144 MEB; 1206 N. Green St Urbana, IL 61801
1	University of Minnesota Dept of Mechanical Engr ATTN: E. Fletcher Minneapolis, MN 55455
1	Washington State University Dept of Mechanical Engr ATTN: C.T. Crowe Pullman, WA 99163
1	Case Western Reserve U. Division of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135
3	Georgia Institute of Tech School of Aerospace Engr ATTN: B.T. Zinn E. Price W.C. Strahle Atlanta, GA 30332

No. of Copies	Organization
1	Institute of Gas Technology ATTN: D. Gidaspow 3424 S. State Street Chicago, IL 60616
1	Johns Hopkins University Applied Physics Laboratory Chemical Propulsion Information Agency ATTN: T. Christian Johns Hopkins Road Laurel, MD 20707
1	Massachusetts Institute of Technology Dept of Mechanical Engr ATTN: T. Toong 77 Massachusetts Avenue Cambridge, MA 02139
1	Pennsylvania State Univ. Dept of Mechanical Engr ATTN: K. Kuo University Park, PA 16802
1	University of Michigan Gas Dynamics Lab Aerospace Engr Bldg ATTN: Dr. G.M. Faeth Ann Harbor, MI 48109-2140
1	Purdue University School of Mechanical Engr ATTN: J.R. Osborn TSPC Chaffee Hall West Lafayette, IN 47906
1	SRI International Propulsion Sciences Division ATTN: Tech Library 333 Ravenswood Avenue Menlo Park, CA 94025

DISTRIBUTION LIST

No. of Copies	Organization
1	Rensselaer Polytechnic Inst. Department of Mathematics Troy, NY 12181
1	Director Los Alamos National Lab ATTN: M. Division, B. Craig T-3 MS B216 Los Alamos, NM 87545
1	Stevens Inst. of Tech Davidson Laboratory ATTN: R. McAlevy, III Castle Point Station Hoboken, NJ 07030
1	Rutgers University Dept of Mechanical and Aerospace Engr ATTN: S. Temkin University Heights Campus New Brunswick, NJ 08903
1	U. of Southern California Mechanical Engr Dept ATTN: OHE200, M. Gerstein Los Angeles, CA 90007
2	University of Utah Dept of Chemical Engineering ATTN: A. Baer G. Flandro Salt Lake City, UT 84112

No. of Copies	Organization
	Aberdeen Proving Ground
	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
	Cdr, USATECOM ATTN: AMSTE-TO-F
	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-SPS-IL
	Cdr, USACSTA ATTN: S. Walton G. Rice D. Lacey C. Herud
	Dir, HEL ATTN: J. Weisz

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T(NEI)
Aberdeen Proving Ground, MD 21005-5066

- PASTE LABEL HERE -