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SENSITIVITY CHARACTERIZATION OF LOW VULNERABILITY (LOVA) PROPELLANTS

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Low vulnerability (LOVA) propellants are being developed to improve the combat survivability and effectiveness of our current weapon systems. The basic LOVA formulation contains approximately 75% nitramine filler. This report describes the results of a study that was conducted to determine the sensitivity properties of a number of the candidate LOVA propellants as well as seven conventional nitrate ester propellants (M30, M26, M6+2, NACO, two United Kingdom

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Explosion temperature
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Autoignition temperature

20. ABSTRACT (CONTINUED)

propellants, F527/428, and NQ, and one propellant from the Federal Republic of Germany, JA-2). The laboratory sensitivity and thermal stability tests included impact sensitivity, DTA, TGA, autoignition temperature, explosion temperature, VTS, HFCI, and DDT. The data generated is being used for comparative purposes with the conventional reference propellants, and to develop criteria for evaluation in final selection of a LOVA candidate for scale-up to a Production Improvement Program.

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INTRODUCTION

The problem of ammunition vulnerability has been receiving increasing attention in recent years. Initiation of ammunition stores in armored vehicles is the major factor leading to the loss of weapon and crew (catastrophic kill). The conventional single-base, double-base, and triple-base propellants which contain nitrocellulose (NC), nitroglycerine (NG), and nitroguanidine (NQ) are highly vulnerable to initiation by spall or hypervelocity impact. Therefore, a joint Army and Navy program was undertaken to develop expeditiously low vulnerability (LOVA) propellants which are significantly less sensitive to initiation than the standard nitrate ester propellants.

During the early stages of the development program, only the sensitivity and the ballistic properties of the propellant candidates were evaluated in order to determine whether or not further testing and development were warranted. Then, more detailed studies were conducted only on those formulations which indicated further testing was worthwhile.

The formulations studied in the early stages of the program were a series of cyclotrimethylenetrinitramine (RDX) and cyclotetramethylenetetranitramine (HMX) nitramine compositions with inert binders and plasticizers. Such propellants have higher ignition thresholds and reduced burning rates at low pressures and offer significant reduction in vulnerability to ignition or initiation from the aforementioned stimuli than the conventional propellants in use today. In the latter stages of the program, RDX was the nitramine incorporated into the candidate formulations due to its cost effectiveness, but with the important feature of not compromising vulnerability. The two LOVA candidates chosen for the next phase of the development program, the Engineering Study, were cellulose acetate butyrate/acetyl triethyl citrate/cyclotrimethylenetrinitramine (CAB/ATEC/RDX) and CAB/NC/RDX. The primary criteria that were used to evaluate the formulations were vulnerability, interior ballistics/combustion, processibility, surveillance characteristics, cost, and availability of raw materials. The following report describes the results of a study that was conducted to determine the relative sensitivity of a number of candidate LOVA propellants as well as seven conventional nitrate ester propellants (four U.S., two U.K., and one propellant from the Federal Republic of Germany). Thermochemical properties were included as well to show a comparison between the LOVA candidates and the conventional propellants.

LOVA FORMULATIONS

The basic LOVA formulation contains approximately 75% RDX or HMX filler, an inert or low energy binder, and an inert plasticizer; small quantities of NC were added to some of the compositions. The NC was used primarily to enhance over-all energy, increase burning rates, improve mechanical properties, and improve processibility. The earliest formulations contained RDX or HMX. The compositions are shown in table 1. The formulations tested in the latter stages of the program contained only RDX (table 2). Compositions of the conventional propellants which were used as a basis for comparison are given in table 3. However, the formulation of one of the two U.K. propellants is not shown due to its confidentiality.

The binders studied in the LOVA program can be categorized into four groups: (1) cellulose such as ethyl cellulose (EC), cellulose acetate (CA), CAB, cellulose acetate propionate (CAP), and NC; (2) thermoplastic elastomers like Hycar and Kraton. Hycars are polyethyl or polybutyl acrylate elastomers that are curable with thermoplastic properties. Kraton is a block copolymer incorporating thermoplastic (styrene) end blocks and an elastic (ethylene butylene) mid-block; (3) polybutadienes such as hydroxyterminated-polybutadiene (HTPB), and carboxy-terminated-polybutadiene-acrylonitrile (CTBN); (4) polyurethanes. Acetyl triethyl citrate, triacetin (TA), and dibutylphthalate (DBP) are plasticizers which are incorporated to colloid the cellulosics.

THERMOCHEMICAL PROPERTIES

The first type of performance evaluation performed on any propellant is an analysis of the thermochemical characteristics of the propellant formulation. The heats of formation and the molecular formula of the individual propellant ingredients are inputs to a thermochemical Blake code (ref 1) which calculates the equilibrium distribution of combustion products under conditions found in a gun. From this calculation, covolume (b) and the ratio of specific heats (γ) are determined for the propellant combustion product gases. This information together with the isochoric flame temperature and the gas volume (n) of the propellant (also determined by the thermochemical code) are used to calculate the impetus of the propellant using the Nobel-Abel (nonideal) equation of state as follows:

$$F = I = nRT_v = P(V-b) = \frac{RT_v}{M} \tag{1}$$

where F = force (Joule g^{-1})

I = impetus (Joule g^{-1})

T_v = isochoric flame temperature (K)

M = average molecular weight of the combustion gases (g)

R = universal gas constant (1.987 cal K^{-1} g-mole^{-1})

n = gas volume (g-mole g^{-1})

P = pressure (MPa)

V = chamber volume ($cm^3 g^{-1}$)

b = covolume ($cm^3 g^{-1}$)

The thermochemical properties of the respective propellant compositions involved in this study are shown in table 4. Included are isochoric flame temperature, force, gas volume, covolume, and ratio of specific heats. For the LOVA candidates, flame temperatures range from 2283K for Kraton/RDX to 2725K for CAB/NC/RDX relative to 2402K (NACO) to 3688K (F527/428) for the conventional propellants; force varies from 971 J/g (Kraton/RDX) to 1092 J/g (CAB/NC/RDX) versus 877 J/g (NACO) to 1217 J/g (F527/428); gas volume ranges between 0.0473 and 0.0512 moles/g versus 0.0397 to 0.0446 moles/g; covolume varies from 1.148 to 1.303 cm^3/g relative to 0.996 to 1.082 cm^3/g; ratio of specific heats are between 1.2657 and 1.2769 compared to 1.2221 to 1.2615.

From equation 1, it should be noted that by either raising the flame temperature of the propellant or lowering the molecular weight of its combustion product gases, the impetus (force) will increase. The LOVA propellant compositions have lower flame temperatures and lower molecular weight combustion product gases than many of the conventional propellants. This "trade off" leads to the following impetus results: (1) higher than NACO and M6+2; (2) equivalent to NQ; (3) slightly lower than M30 and M26; and (4) markedly lower than JA-2 and F527/428.

Furthermore, the low molecular weight gases generated in the burning of the LOVA propellant increases the ratio of specific heats and the covolume of the combustion products. The higher specific heats mean the gases cool more rapidly as they expand, thus decreasing system performance (for equal propellant impetus and maximum gun pressure) by 2 to 4 percent (ref 2). The high covolume, on the other hand, can be used to increase the ballistic efficiency of the system when it is properly coupled with the programmed burning of the propellant (ref 3).

SENSITIVITY TEST PROGRAM AND PROCEDURE

The program consisted of the following sensitivity and thermal stability tests:

a. Impact sensitivity.

b. Differential thermal analysis/thermogravimetric analysis (DTA/TGA).

c. Autoignition temperature.

d. Explosion temperature.

e. Vacuum thermal stability (VTS).

f. Hot fragment conductive ignition (HFCI).

g. Deflagration-to-detonation transition (DDT).

A description of the apparatus and test procedures are listed below. The propellant grains were ground into a powder by means of a Wiley mill only for the impact sensitivity test, DTA/TGA, autoignition temperature measurements, explosion temperature test, and the VTS test.

Impact Sensitivity Test

The impact sensitivity tests were conducted to compare the relative impact initiation sensitivity of LOVA propellants to conventional propellants using a standard technique. The test was performed with the Explosives Research Laboratory (ERL), sometimes called the Naval Ordnance Laboratory (NOL), Type 12 impact tester. The apparatus uses a 2.5 kg steel drop weight with a 30 mg sample resting on sandpaper between two steel anvils. A detailed description of the apparatus is contained in reference 4.

The drop height corresponding to the 50% probability of initiation was used as a measure of impact sensitivity. The 50% initiation point was determined by means of the Bruceton up-and-down method (ref 5). The amount of the test sample burned during a run varied from a low level, as evidenced by a very slight sound or a slight burn mark, to complete burning or detonation. The criterion for initiation in this study was any evidence of burning or detonation observed during impact or in the post-test examination of the sample.

Differential Thermal Analysis/Thermogravimetric Analysis

Simultaneous DTA/TGA (weight change measurements) were conducted as a function of temperature with a Mettler TA-2 thermoanalyzer. The samples, approximately 8 to 10 mg, were heated in platinum containers from ambient temperature through decomposition at a rate of 10°C/min in a static air medium.

Autoignition Temperature

The autoignition temperature was determined by a method using DTA (ref 6). This technique utilizes several heating rates and their respective onset and peak exotherm temperatures to solve the Kissinger's equation (2).

$$k = \frac{E_a \phi}{R T^2} = A e^{-E_a/RT} \qquad (2)$$

where E_a = apparent activation energy (cal g-mole^{-1})

k = rate constant (min^{-1})

A = frequency factor (min^{-1})

R = universal gas constant (1.987 cal K^{-1}-g-mole^{-1})

T = peak exotherm temperature (K)

ϕ = heating rate (K min^{-1})

A computer program was used to calculate the autoignition temperature by extrapolating the DTA data to a near zero heating rate and assuming a rate constant of 0.05 min^{-1}. The DTA data was obtained using a Deltatherm III thermoanalyzer. The samples were heated unconfined in a nitrogen atmosphere at five heating rates, from 1.3 to 20 degrees per minute.

Explosion Temperature Test

The explosion temperature test was used as means of comparing the relative thermal sensitivity of the propellants. The test was conducted by immersing a copper blasting cap containing approximately 40 mg of sample in a nfined state to a fixed depth in a molten metal bath. Time-to-explosion was etermined by measuring the time required for the blasting cap to rupture. Th rocedure was similar to that developed by Henkin and McGill (ref 7) and furtl modified by Zinn and Rogers (ref 8). The relationship between the time-to-ex sion and the temperature is expressed by equation 3.

$$t = Ae^{-E_a/RT} \tag{3}$$

where t = time (sec)

E_a = apparent activation energy (cal/g-$mole^{-1}$)

A = constant (dependent on geometry of experiment and composition of the sample)

T = explosion temperature (K)

R = universal gas constant (1.987 cal K^{-1} $mole^{-1}$)

E_a is only an apparent activation energy since the entire sample is not subjected concurrently to isothermal heating.

The data was utilized in a computer program to determine the apparent activation energy and the temperature values for the 1-second and the 5-second time-to-explosion. Temperature at 5-seconds is the value usually reported in the literature.

Vacuum Thermal Stability

The VTS test was performed on the LOVA RDX nitramine composite propellants in accordance with the Tri-Service Manual (ref 9). In this test, a 5-g sample is subjected to 100°C for 40 hours and the amount of gas evolved is measured. However, for the conventional double-base and triple-base nitrate ester propellants, the test was conducted at 90°C.

Hot Fragment Conductive Ignition Test

An HFCI test was conducted to compare the relative vulnerability characteristics of the propellants to ignition by an imbedded, hot steel fragment. This test was developed at the Ballistic Research Laboratory (BRL), ARRADCOM, (refs 10, 11) as an experimental technique to predict the performance of a new propellant formulation in large-scale field vulnerability tests such as the Controlled Fragment Impact Test (refs 12, 13).

An apparatus similar to the BRL HFCI model was set up at ARRADCOM, Dover site. A schematic of the HFCI test apparatus is shown in figure 1. In the HFCI test, a spherical steel ball is heated in a tube furnace to a preselected temperature. It is then dropped onto a bed of propellant grains housed in a glass beaker maintained at ambient temperature. The response of the propellant to this external stimuli is determined by observing whether or not ignition occurred. The temperature is then raised or lowered based upon the response of the propellant and the test is then subsequently repeated. This up-and-down Bruceton method is continued until the transition between ignition and nonignition is defined. Ignition has been defined as self-sustained decomposition of the propellant sample. The test was carried out with four different weight steel balls, 0.43, 1.03, 2.03, and 3.5 grams.

Deflagration-to-Detonation Transition Test

A DDT test was conducted to determine whether or not a packed bed of porous LOVA propellant grains would undergo a transition from deflagration to detonation when ignited thermally under high confinement conditions. A schematic sketch of the combustion tube used in the test is shown in figure 2. It consisted of a 1 1/4 in. schedule 160 steel pipe having a wall thickness of 0.25 in. Two different lengths of pipe were used, 12 in. and 24 in. Each pipe was filled with a bed of the propellant and closed at both ends with screw-on commercial, forged steel pipe caps having a 3,000 psi rating. The test propellant was thermally ignited at one end of the pipe by means of an ignitor composed of 2 1/2 g of M-9 propellant which, in turn, was ignited by means of a nichrome ignition wire. The internal pressure build-up of the propellant decomposition gases was monitored with a Nicolet Explorer III Oscilloscope through a strain gage mounted on the outside of the vessel at mid-length. The pipes were calibrated at static gas pressure to 1,800 psi. A picture of the assembled pipes in shown in figure 3.

RESULTS AND DISCUSSION

Impact Sensitivity

The 50% impact values are listed in table 5. For the LOVA propellants, the values varied from a low of 27.6 cm for unglazed CAB/NC/RDX to a high of 34.0 cm for Kraton/RDX. The CAB/RDX propellants containing small quantities of NC were slightly more sensitive to impact than their counterpart without NC. The three U.S. conventional propellants, M30, M26, and M6+2, the two U.K. propellants, F527/428 and NQ, and the German JA-2 propellant had impact values of 18.3 cm or lower. It is interesting to note that the NACO conventional propellant had an impact value of 33.7 cm, which is comparable to values obtained by many LOVA propellants.

Differential Thermal Analysis/Thermogravimetric Analysis

The DTA/TGA results are summarized in table 6. The table lists the onset and peak temperatures of all endothermic and exothermic reactions, the onset temperature of decomposition and the temperature at which the sample lost 10 percent of its original weight.

The DTA thermograms showed that all the conventional and LOVA propellants had only one exothermic reaction except for two early LOVA candidates, X1A and X2A, which had two exotherms. For the LOVA propellants (except X1A and X2A), the temperature at the onset of the exotherm varied from 192°C to 215°C; the peak temperature ranged from 222°C for CTBN/RDX to 251°C for CA/RDX. The onset temperature of the first exotherm of the X1A and X2A propellants was less than 145°C and the peak temperature was 177°C. It is interesting to note that the first exotherm was not observed during an experiment using a Perkin-Elmer DSC-2 instrument, which heated a confined sample in an inert atmosphere. The TGA temperature measurements at the 10% weight loss varied from 205°C (CTBN/RDX) to 259°C (HTPB/HMX). It can be concluded that the DTA/TGA thermograms of the RDX LOVA propellants were very similar to those of production grade RDX. For the HMX LOVA propellants, the DTA/TGA values were slightly lower than the commercial grade HMX. An important observation should be noted. For the LOVA propellants, these DTA/TGA temperature measurements, which are indicative of decomposition, were significantly higher than those for the conventional propellants. In this latter case, the onset temperature of the exotherm was 170°C or lower, the temperature at the peak ranged from 188°C (M26) to 201°C (F527/428), and the 10% weight loss temperature varied from 162°C (JA-2) to 191°C (NACO).

Autoignition Temperature

The autoignition temperature and the apparent activation energy for the LOVA propellants are shown in table 7. For comparative purposes, the values for RDX, HMX, and NC, as well as for the seven conventional propellants, are also listed in the table. For the composite nitramine RDX propellants, the autoignition temperature varied from 186°C to 197°C except for CTBN/RDX, which had a lower autoignition temperature of 179°C. Higher autoignition temperatures were obtained for the nitramine HMX composites than its RDX counterparts, ranging from 210°C to 228°C. Moreover, the autoignition temperatures of all the LOVA candidates were significantly higher than those for the conventional propellants, which ranged from 154°C for M26 to 169°C for M30 as denoted in table 7. It should likewise be noted that the autoignition temperatures of the LOVA propellants were similar to their nitramine filler.

Explosion Temperature

The explosion temperature for the 1-second and the 5-second time-to-explosion and the apparent activation energy are listed in table 8, together with similar data for the seven conventional propellants. Also shown in the table is the data for the raw propellant ingredients, RDX, HMX, and NC. It should be noted that much higher 5-second explosion temperature values were obtained for the LOVA candidates, ranging from 253°C for the unglazed CAB/NC/RDX to 316°C for CAB/ATEC/RDX, than for any of the conventional propellants, which ranged only from 212°C (M30) to 233°C (NACO). The 5-second explosion temperature value for the two LOVA candidates selected for the Engineering Study were high in comparison to the other LOVA propellants. For the CAB/ATEC/RDX composition, the 5-second value was the highest (310°C), while CAB/NC/RDX showed a slightly lower value of 297°C.

Vacuum Thermal Stability

Data from the VTS test (table 9) showed higher gas evolution by the conventional propellants than the LOVA propellants (except EC/NC/RDX), although the LOVA formulations were tested at a higher temperature than the conventional propellants. Gas liberated on heating the LOVA candidates (except EC/NC/RDX) was less than 0.8 mL. The EC/NC/RDX propellant produced 5.62 mL at 100°C and 3.01 mL at 90°C.

Hot Fragment Conductive Ignition

The HFCI test results are given in table 10. Ignition temperatures were higher with the lighter steel balls than with the heavier balls. The results demonstrated that all the LOVA candidates were less vulnerable to ignition than the conventional propellants. It is noteworthy that CA/RDX, CAB/RDX, and CAB/ATEC/RDX were less susceptible to thermal ignition than the other LOVA candidates and significantly less susceptible than the conventional propellants. Furthermore, Kraton/RDX and EC/NC/RDX were more susceptible to thermal ignition than the other LOVA propellants. It is also noted that two conventional propellants, NACO and NQ, have ignition temperature values which were comparable to the values obtained for Kraton/RDX and EC/NC/RDX. The polybutyl acrylate Hycar 4054/RDX with anti-oxidant stabilizers was observed to be more sensitive than the polyethyl acrylate Hycar 4051/RDX without stabilizers.

It is interesting to note that the EC/NC/RDX composition was considered one of the top LOVA candidates early in the program based on 105 mm, M68 ballistic gun performance. However, large-scale field vulnerability testing eliminated it from further consideration, which has been corroborated by the poor test results obtained with the HFCI test (refs 10, 11).

It has been postulated that the binder acts as a heat sink in the conductive ignition process dissipating heat from the hot fragment and from the exothermic nitramine composition process (ref 14), thereby interrupting the heat feedback required for self-sustained decomposition of the propellant (ref 10).

Deflagration-to-Detonation Transition

At least two identical tests were carried out for each propellant using both the 12-inch and the 24-inch pipes, except for the German JA-2 propellant and the two Hycar compositions. No tests were conducted for the two Hycar propellants, and only two 24-inch pipe tests were performed with the JA-2. All the propellants burned readily; none of the propellants underwent transition to detonation. Each pipe ruptured at approximately 10,000 to 30,000 psi, scattering fragments of unburned propellant throughout the area. A summary of the test results is given in table 11. The propellants are listed in decreasing order according to the number of pipe fragments produced by the pressure build-up in the 24-inch pipe test.

An analysis of the results revealed that there is no correlation between the number of pipe fragments and the time required for the pipe to rupture, and that better comparative results were obtained with the 24-inch pipe than with the 12-inch pipe. The average time required for the 24-inch pipes to rupture ranged from 2.5 milliseconds (ms) for CAB/ATEC/RDX to 12.5 ms for Kraton/RDX. The average number of pipe fragments produced by the LOVA propellants ranged from 6.2 (CAB/ATEC/RDX) to 35.5 (CA/RDX). All the 12-inch pipes fragmented into 8 or less pieces in less than 5 ms. It is noteworthy that five of the seven conventional propellants tested in the 24-inch pipe test produced the least number of fragments (less than 6 fragments); however, 37 and 26 fragments were obtained with M30 and JA-2 propellants, respectively. Further, the M30 propellant produced the most fragments of any of the propellant tested.

Although none of the propellants underwent transitions to detonation, on the basis of the number of fragments obtained in the 24-inch pipe test, the propellants can be grouped into the following three distinct levels of reaction severity.

Level 1 - the pipe fragmented into 9 pieces or less (figs. 4a and 4b).

Level 2 - more than 9 pieces but less than 20 pieces were produced (figs. 5a and 5b).

Level 3 - the pipe fragmented into 20 or more pieces (figs. 6a and 6b).

It should be noted that the two LOVA candidates chosen for the Engineering Study showed low levels of reaction severity and thus are listed in Level 1. The average number of pipe fragments produced by CAB/ATEC/RDX and CAB/NC/RDX were 6.2 and 8.8, respectively.

CONCLUSIONS

1. Based on all the test data obtained to date, it can be concluded that the overall sensitivity and stability of all the LOVA candidates evaluated in this program are superior to the conventional nitrate ester propellants in use today. Other conclusions reached from the individual tests are noted below.

2. All the LOVA propellants are less sensitive to impact than the conventional nitrate ester propellants except NACO, which has a comparable impact value. Kraton/RDX is the least sensitive to impact. The CAB/RDX propellants containing small quantities of NC are slightly more sensitive to impact than their counterpart without NC.

3. For the LOVA propellants, the DTA/TGA temperature measurements, which are indicative of decomposition, are significantly higher than those for the conventional propellants. The study shows that the DTA/TGA thermograms of the RDX LOVA propellants are very similar to those of production grade RDX. For the HMX LOVA propellants, the DTA/TGA values are slightly lower than the commercial grade HMX.

4. The autoignition temperatures of all the LOVA candidates are significantly higher than those of the conventional propellants. The autoignition temperatures of the LOVA propellants are similar to their nitramine filler.

5. Explosion temperatures for the LOVA propellants are significantly higher than for the reference conventional propellants. The 5-second explosion temperature values of the two LOVA candidates selected for the Engineering Study are high in comparison to the other LOVA propellants.

6. Vacuum thermal stability test results indicate significantly greater chemical stability for the LOVA candidates. One notable exception is the EC/NC/RDX formulation, which only showed comparable thermal stability to a conventional triple-base nitrate ester propellant.

7. Hot fragment conductive ignition test indicates that the majority of the LOVA candidates are significantly less susceptible to thermal ignition than the conventional propellants. Kraton/RDX and EC/NC/RDX, which are the most vulnerable of the LOVA propellants, have equivalent susceptibility to sustained decomposition as NACO and NQ, the least vulnerable of the reference propellants. The CA and the four CAB based propellants are the least vulnerable of all the LOVA candidates.

8. The following conclusions were reached from the DDT test results:

a. Although none of the propellants underwent transition to detonation, the propellants can be grouped into three distinct levels of reaction severity, where Level 1 is the least reactive and Level 3 is the most.

b. The two LOVA candidates chosen for the Engineering Study show low levels of reaction severity and thus are listed in Level 1.

c. There is no correlation between the number of pipe fragments and the time required for the pipe to rupture.

d. Better comparative results are obtained with the 24-inch pipe than with the 12-inch pipe.

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Table 1. Composition of preliminary LOVA candidate propellants

Composition	Propellant (wt %) X1A	X2A	HTPB/HMX	CTBN/HMX	CTBN/RDX
HMX	75.0	80.0	80.0	79.0	-
RDX	-	-	-	-	79.0
HTPB	-	-	20.0	-	-
CTBN	-	-	-	20.0	20.0
KNO_3	-	-	-	1.0	1.0
L-35 polymer	11.7	9.415	-	-	-
TMP	3.14	2.5	-	-	-
IPDI	10.09	8.075	-	-	-
TiO (AA)	0.0125	0.010	-	-	-

Table 2. Composition of second stage LOVA candidate propellants

Composition	CA/RDX	CAB/RDX	EC/NC/RDX	Kraton/RDX	Hycar/RDX	Hycar + Stab RDX
	Propellant (wt %)					
RDX	75.0	75.0	73.5	80.0	80.0	80.0
CA	16.0	—	—	—	—	—
CAB	—	16.0	—	—	—	—
EC	—	—	11.7	—	—	—
NC (%N)	—	—	7.4 (12.6)	—	—	—
Kraton	—	—	—	10.0	—	—
Hycar 4051	—	—	—	—	18.3	—
Hycar 4054	—	—	—	—	—	18.0
ATEC	—	—	—	—	—	—
CAP	—	—	—	—	—	—
DBP	—	—	6.7	—	—	—
Triacetin	8.0	8.0	—	—	—	—
K_2SO_4	1.0	1.0	—	—	—	—
EC	—	—	0.7	—	—	—
Tuflow 6056	—	—	—	10.0	—	—
TP 95	—	—	—	—	1.0	1.0
Graphite	—	—	—	—	0.7	0.7
Staboxol	—	—	—	—	—	0.15
Weston 618	—	—	—	—	—	0.15

	CAB/ATEC/RDX	CAB/NC/RDX	CAB/NC/RDX *	CAP/NC/RDX*
RDX	75.0	76.0	76.0	76.0
CA	-	-	-	-
CAB	16.0	12.0	12.0	-
EC	-	-	-	-
NC (%N)	-	4.0 (12.6)	4.0 (12.6)	4.0 (12.6)
ATEC	8.0	7.6	7.6	7.6
CAP	-	-	-	12.0
K_2SO_4 (Potassium sulfate)	1.0	-	-	-
EC	-	0.4	0.4	0.4

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*Unglazed

Table 3. Composition of reference conventional propellants

Composition	Propellant (wt %)					
	M30	M26	M6+2	NACO	JA-2 (German)	NQ (U.K.)
NC (%N)	27.61 (12.61)	66.10 (13.15)	86.77 (13.15)	93.61 (12.0)	63.5 (13.0)	20.8 (13.2)
NG	22.67	25.80	-	-	14.0	20.6
NQ	47.96	-	-	-	-	55.3
EC	1.49	6.35	-	1.15	-	
Carbamite	-	-	-	-	-	3.6
Cryolite	0.27	-	-	-	-	-
Graphite	0.17[a]	0.36	-	-	0.05	-
Barium nitrate	-	0.71	-	-	-	-
Potasium nitrate	-	0.68	-	-	-	-
Dinitrotoluene	-	-	9.60	-	-	-
Diphenylamine	-	-	1.00[b]	-	-	-
Potasium sulfate	-	-	2.09[b]	1.20	-	-
Lead carbonate	-	-	-	1.14	-	-
Butyl stearate	-	-	-	2.90	-	-
T.V.	0.50	-	-	2.63	-	-
DEGDN	-	-	-	-	21.7	-
Akardit II	-	-	-	-	0.7	-
Magnesium oxide	-	-	-	-	0.05	-
DBP	-	-	3.61	-	-	-

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[a] Added as glaze

[b] Added

Table 4. Thermochemical properties

Propellant	Property				
	Force (J/g)	Flame Temperature K	Gas Volume (mole/g)	Covolume cm^{3}g	Ratio of spec heat
M30	1076	3010	0.0430	1.052	1.2415
M26	1091	3222	0.0407	1.021	1.2349
M6+2	927	2582	0.0432	1.071	1.2598
NACO	877	2402	0.0443	1.067	1.2615
JA-2 (German)	1140	3412	0.0402	0.996	1.2250
F527/428 (U.K.)	1217	3688	0.0397	0.997	1.2221
NQ (U.K)	1052	2835	0.0446	1.082	1.2510
CA/RDX	999	2548	0.0473	1.148	1.2689
CAB/RDX	1018	2499	0.0491	1.182	1.2737
CAB/NC/RDX*	1092	2725	0.0482	1.166	1.2676
CAP/NC/RDX*	1063	2673	0.0478	1.161	1.2684
EC/NC/RDX	1056	2536	0.0501	1.208	1.2761
Kraton/RDX	971	2283	0.0512	1.303	1.2657
Hycar/RDX	1038	2499	0.0500	1.209	1.2769

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Table 5. Impact sensitivity test results

(ERL-Type 12 Tool, 2 1/2 kg drop weight)

Propellant	50% firing height (cm)
M30	16.2 ± 3.6
M26	< 10
M6+2	16.7 ± 2.1
NACO	33.7 ± 2.3
F527/428 (U.K.)	18.2 ± 3.1
NQ (U.K.)	18.3 ± 4.5
JA-2 (German)	< 10
X2A	38.7 ± 3.8
HTPB/HMX	32.0 ± 3.5
CTBN/HMX	36.0 ± 1.3
CTBN/RDX	38.3 ± 3.3
CA/RDX	32.3 ± 1.6
CAB/RDX	38.5 ± 1.5
EC/NC/RDX	33.9 ± 1.0
Kraton/RDX	43.0 ± 2.5
Hycar/RDX	32.0 ± 1.7
Hycar + Stab/RDX	34.9 ± 2.9
CAB/ATEC/RDX	40.1 ± 2.9
CAB/NC/RDX	36.7 ± 5.0
CAB/NC/RDX*	27.6 ± 3.7
CAP/NC/RDX*	28.9 ± 0.4
RDX	24.0 ± 3
HMX	26.0 ± 2

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*Unglazed

Table 6. Thermal DTA/TGA test results
(Mettler Thermoanalyzer-2 10°C/min in static air medium)

	DTA (°C)				TGA (°C)	
	Endotherm		Exotherm		Weight loss	
Propellant	onset	peak	onset	peak	onset	10%
M30	-	-	157	189	112	171
M26	-	-	156	188	121	169
M6+2	-	-	150	196	136	188
NACO	-	-	163	192	172	191
F527/428 (U.K.)	-	-	167	201	124	171
NQ (U.K.)	-	-	170	195	123	169
JA-2 (German)	-	-	168	195	120	162
X1A	-	195	137	177	166	244
	-	-	203	250	-	-
X2A	-	193	142	177	165	240
	-	-	204	253	-	-
HTBN/HMX	191	197	215	247	212	259
CTBN/HMX	193	203	215	256	223	241
CTBN/RDX	184	191	201	222	186	205
CA/RDX	181	203	203	251	165	222
CAB/RDX	184	190	200	248	144	218
	195	200	-	-	-	-
EC/NC/RDX	182	190	199	230	150	211
Kraton/RDX	189	207	207	228	210	221
Hycar/RDX	178	199	199	232	192	216
Hycar + Stab/RDX	179	199	199	230	189	217
CAB/ATEC/RDX	173	194	194	234	175	213
CAB/NC/RDX	170	192	192	234	168	209
CAB/NC/RDX*	177	197	197	238	153	208
CAP/NC/RDX*	175	195	195	235	147	208
RDX	186	194	215	235	196	219
	190	200	-	-	-	-
HMX	185	190	276	286	258	274

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*Unglazed

Table 7. Autoignition temperature

Propellant	Autoignition temperature (°C)	Apparent activation energy (cal/mole)
M30	169	46,600
M26	154	43,400
M6+2	165	45,000
NACO	160	46,600
F527/428 (U.K.)	163	35,000
NQ (U.K.)	167	41,300
JA-2 (German)	163	45,900
X1A	223	42,300
X2A	210	44,200
HTPB/HMX	228	40,000
CTPB/HMX	219	38,100
CTPB/RDX	179	33,300
CA/RDX	192	39,500
CAB/RDX	192	39,400
EC/NC/RDX	186	38,300
Kraton/RDX	192	35,500
Hycar/RDX	195	55,500
Hycar + Stab/RDX	191	49,000
CAB/ATEC/RDX	197	38,200
CAB/NC/RDX	193	37,400
CAB/NC/RDX*	187	47,700
CAP/NC/RDX*	188	48,000
RDX	187	37,000
HMX	232	55,000
NC (12.6% N)	176	49,000

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*Unglazed

Table 8. Explosion temperature test results

Propellant	Explosion temperature (°C) 1-second	Explosion temperature (°C) 5-second	Apparent activation energy (cal/mole)
M30	254	212	18,300
M26	290	228	14,600
M6+2	282	227	15,900
NACO	286	233	17,000
F527/428 (U.K.)	274	214	14,100
NQ (U.K.)	274	231	20,500
JA-2 (German)	298	223	12,200
X1A	340	301	29,400
X2A	330	294	28,700
HTPB/HMX	346	294	21,700
CTBN/HMX	346	255	11,700
CTBN/RDX	341	277	17,000
CA/RDX	336	273	16,900
CAB/RDX	338	269	15,500
EC/NC/RDX	354	266	12,400
Kraton/RDX	376	306	16,900
Hycar/RDX	391	304	14,100
Hycar + Stab/RDX	391	304	14,100
CAB/ATEC/RDX	373	310	16,600
CAB/NC/RDX	398	297	12,100
CAB/NC/RDX*	326	253	13,900
CAP/NC/RDX*	325	258	15,200
HMX	369	308	19,400
RDX	362	273	12,400
NC (12.6 N)	292	236	16,500

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*Unglazed

Table 9. Vacuum thermal stability test results

Propellant	Vacuum thermal stability (mL/40 hrs/5 g) 90°C	100°C
M30	2.84	-
M26	11+	-
M6+2	1.28	7.81
NACO	2.72	-
F527/428 (U.K.)	3.00	-
NQ (U.K.)	3.57	-
JA-2 (German)	2.48	-
CA/RDX	0.24	0.26
CAB/RDX	0.08	0.77
EC/NC/RDX	3.01	5.62
Kraton/RDX	0.17	0.37
Hycar/RDX	0.34	0.30
Hycar + Stab/RDX	0.11	0.25
CAB/NC/RDX*	0.15	0.45
CAP/NC/RDX*	0.12	0.47
Cellulose	-	0.59
RDX	-	0.21
HMX	-	0.12

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*Unglazed

Table 10. Hot fragment conductive ignition test results

Propellant	Ignition temperature (°C)			
	Fragment (steel ball) weight (g)			
	0.43	1.03	2.03	3.5
M30	363	338	313	288
M26	313	313	313	263
M6+2	363	338	313	288
NACO	413	363	338	313
F527/428 (U.K.)	338	338	313	288
NQ (U.K.)	388	363	363	313
JA-2 (German)	388	338	313	288
CA/RDX	>750	663	513	488
CAB/RDX	>750	>750	688	538
EC/NC/RDX	438	363	338	313
Kraton/RDX	413	388	363	363
Hycar/RDX	613	463	388	338
Hycar + Stab/RDX	563	388	363	363
CAB/ATEC/RDX	>750	738	663	613
CAB/NC/RDX	>750	563	413	388
CAB/NC/RDX*	725	600	475	445
CAP/NC/RDX*	638	538	463	463

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*Unglazed

Table 11. Deflagration-to-detonation transition test results

Propellant	Average loading density (g/cm^3)		Average time to rupture (ms)		Average no. of fragments	
	12 in. pipe	24 in. pipe	12 in. pipe	24 in. pipe	12 in. pipe	24 in. pipe
M30	0.798	0.761	3.54	-	6.5	37.3
CA/RDX	0.903	0.945	2.20	3.02	6.0	35.5
CAB/RDX	0.922	0.935	2.90	3.50	8.0	33.0
EC/NC/RDX	0.811	0.870	3.70	5.38	6.5	27.0
JA-2 (German)	-	0.812	-	3.03	-	26.0
HTPB/HMX	0.878	0.844	4.15	9.60	2.0	24.5
Kraton/RDX	0.765	0.776	4.13	12.46	5.0	12.5
CTBN/RDX	0.841	0.797	4.50	12.33	3.5	10.0
CAB/NC/RDX	0.940	0.772	1.89	-	3.0	8.8
CTBN/HMX	0.825	0.784	3.98	11.94	2.0	8.5
CAB/ATEC/RDX	0.965	0.773	1.51	2.50	5.5	6.2
M6+2	0.637	0.599	4.53	4.30	3.7	5.5
NQ (U.K.)	0.777	0.678	2.57	3.51	2.5	5.5
F527/428 (U.K.)	0.703	0.596	2.98	6.72	2.5	5.0
NACO	0.765	0.754	3.13	-	2.5	3.0
M26	0.687	0.526	4.36	6.04	2.5	2.0

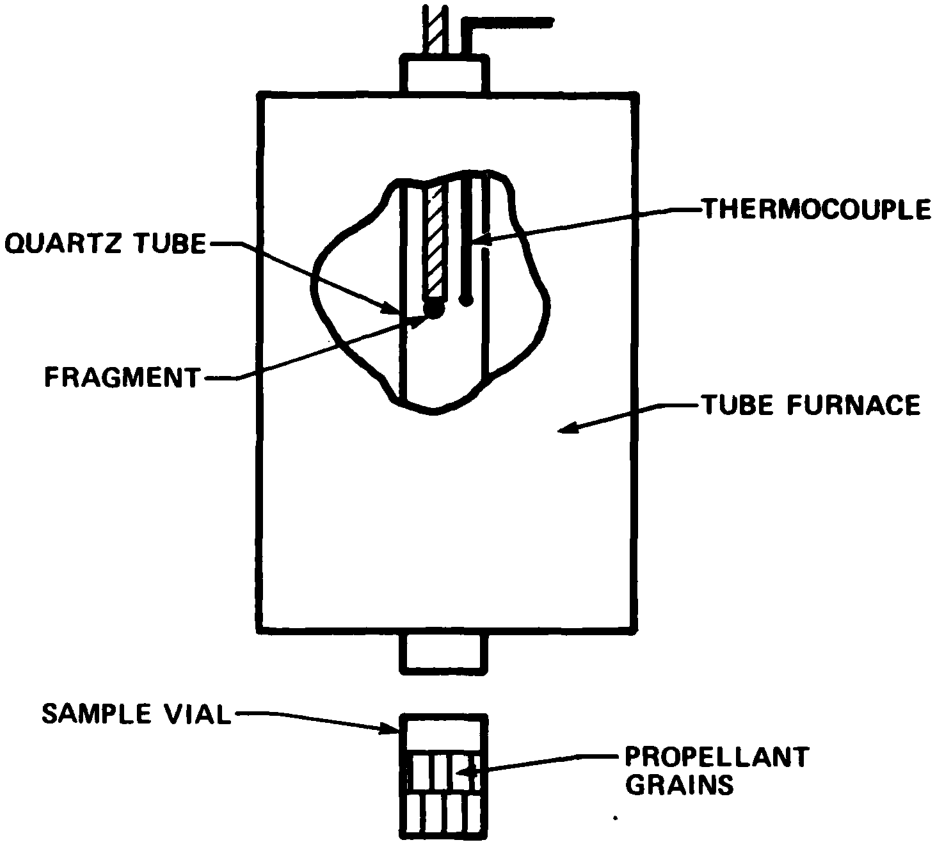

Figure 1. Schematic of the hot fragment conductive ignition test apparatus

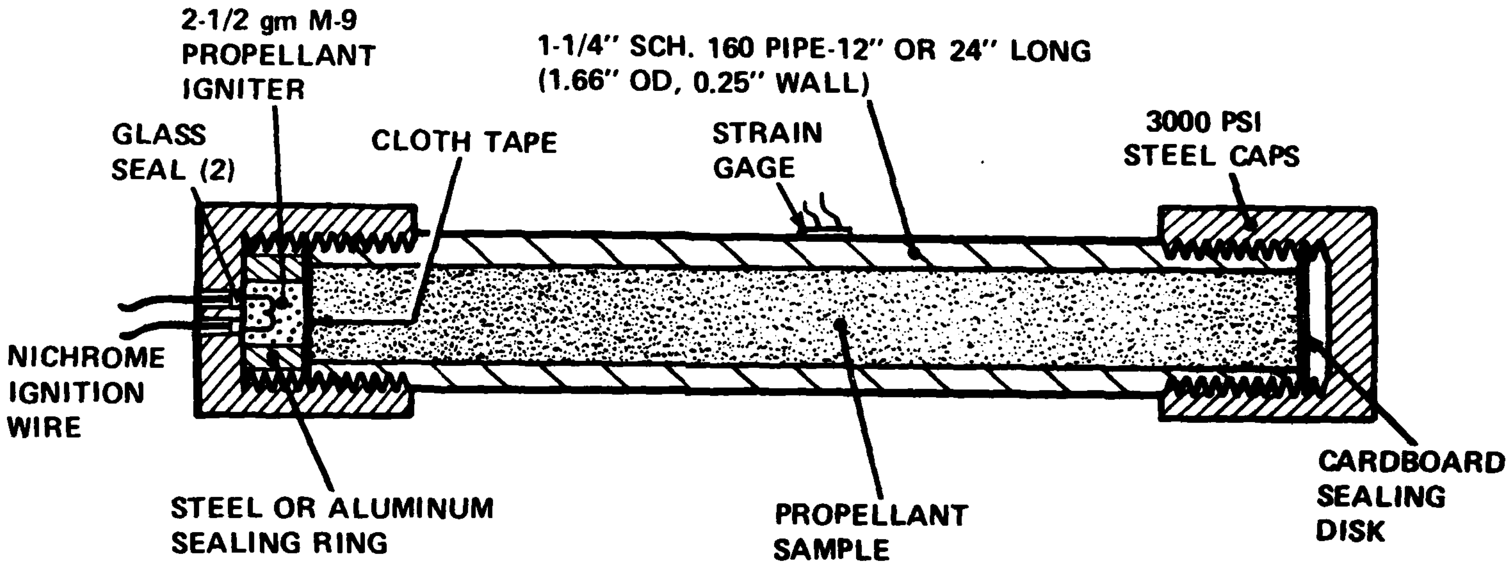

Figure 2. Schematic of the deflagration-to-detonation transition test apparatus

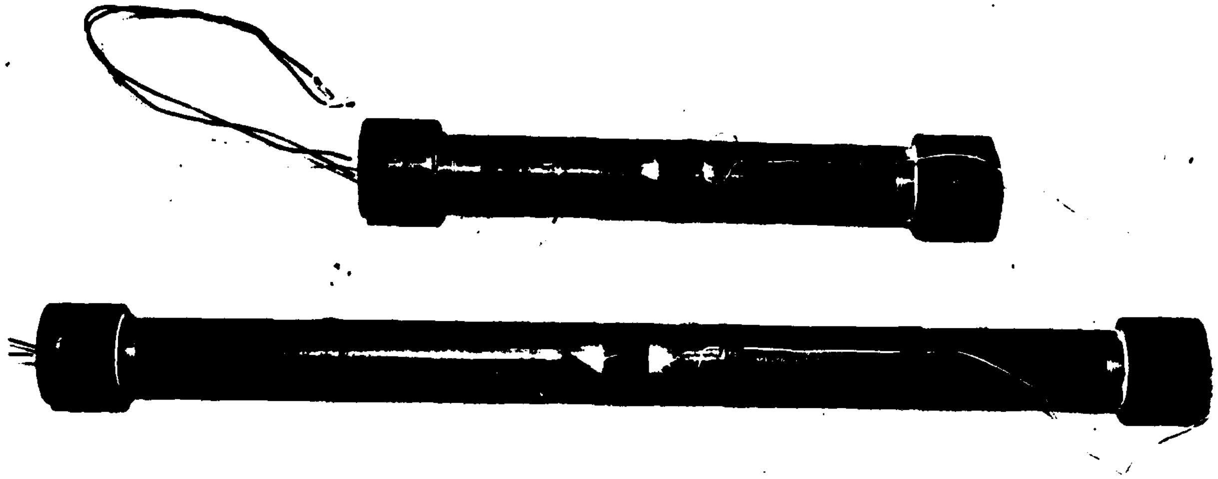

Figure 3. Picture of the assembled deflagration-to-detonation transition pipes

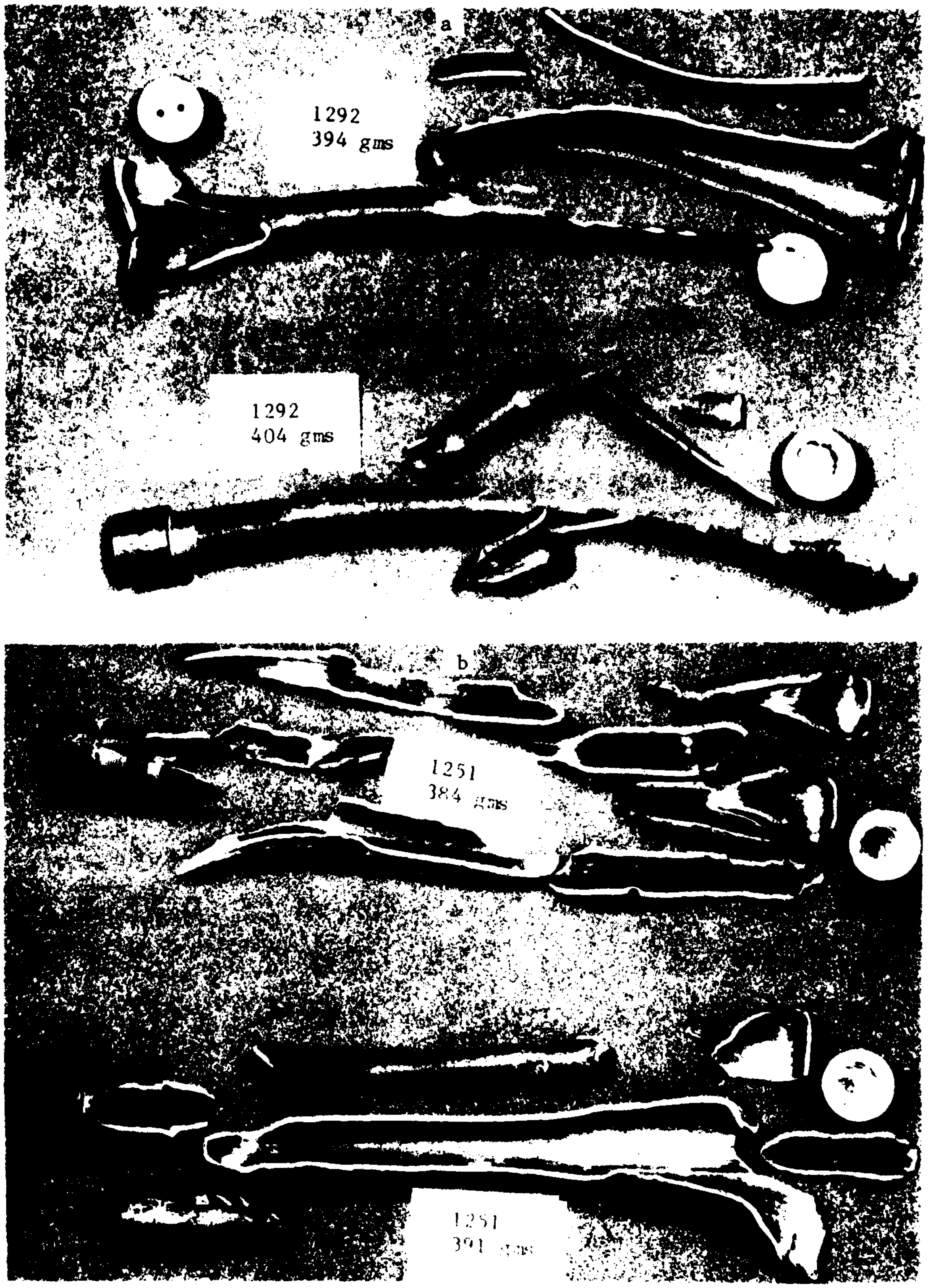

Figure 4. Deflagration-to-detonation transition test results
Level 1, 9 fragments or less

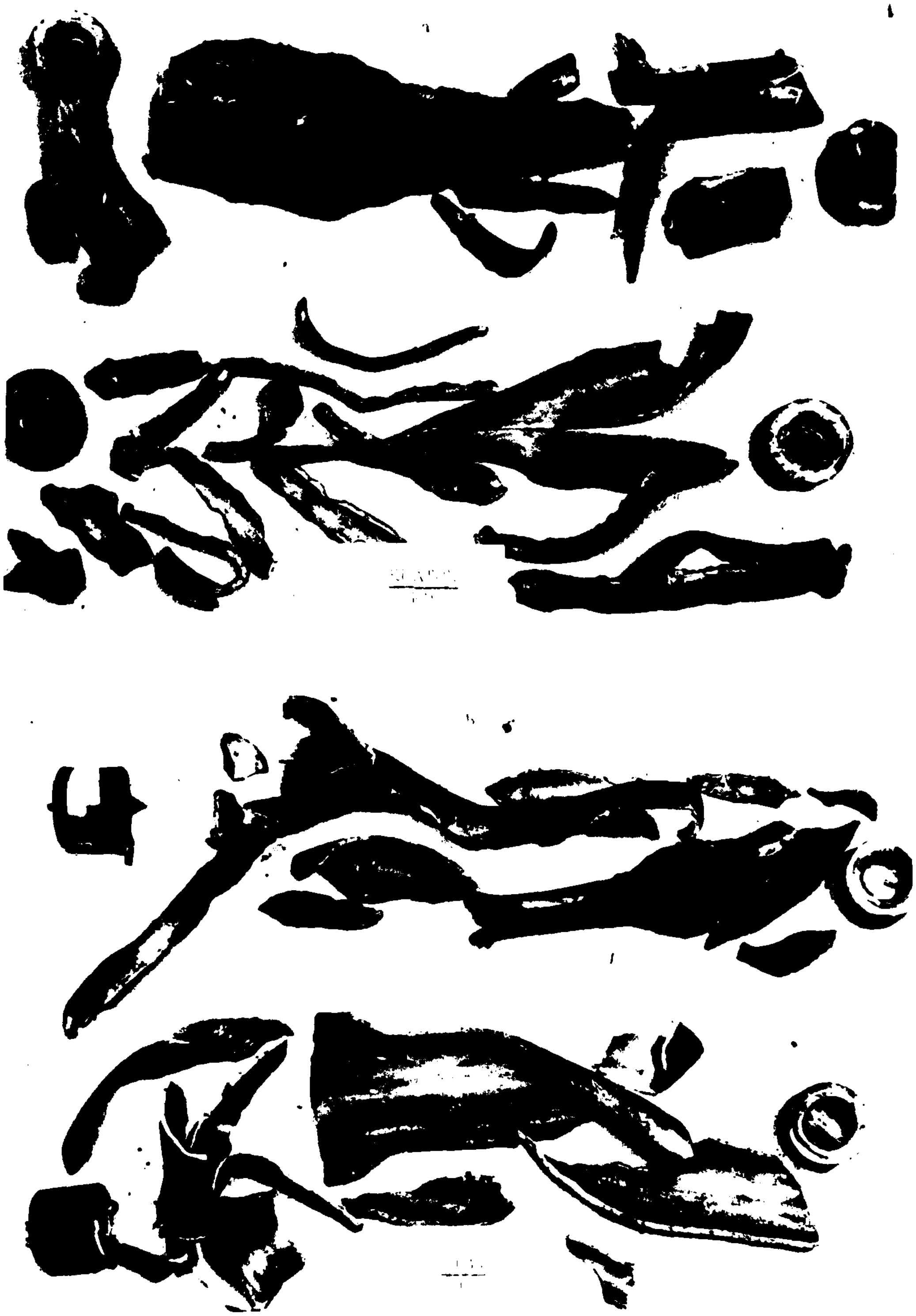

Figure 5. Deflagration-to-detonation transition test results
Level 2, more than 9 fragments but less than 20 fragments

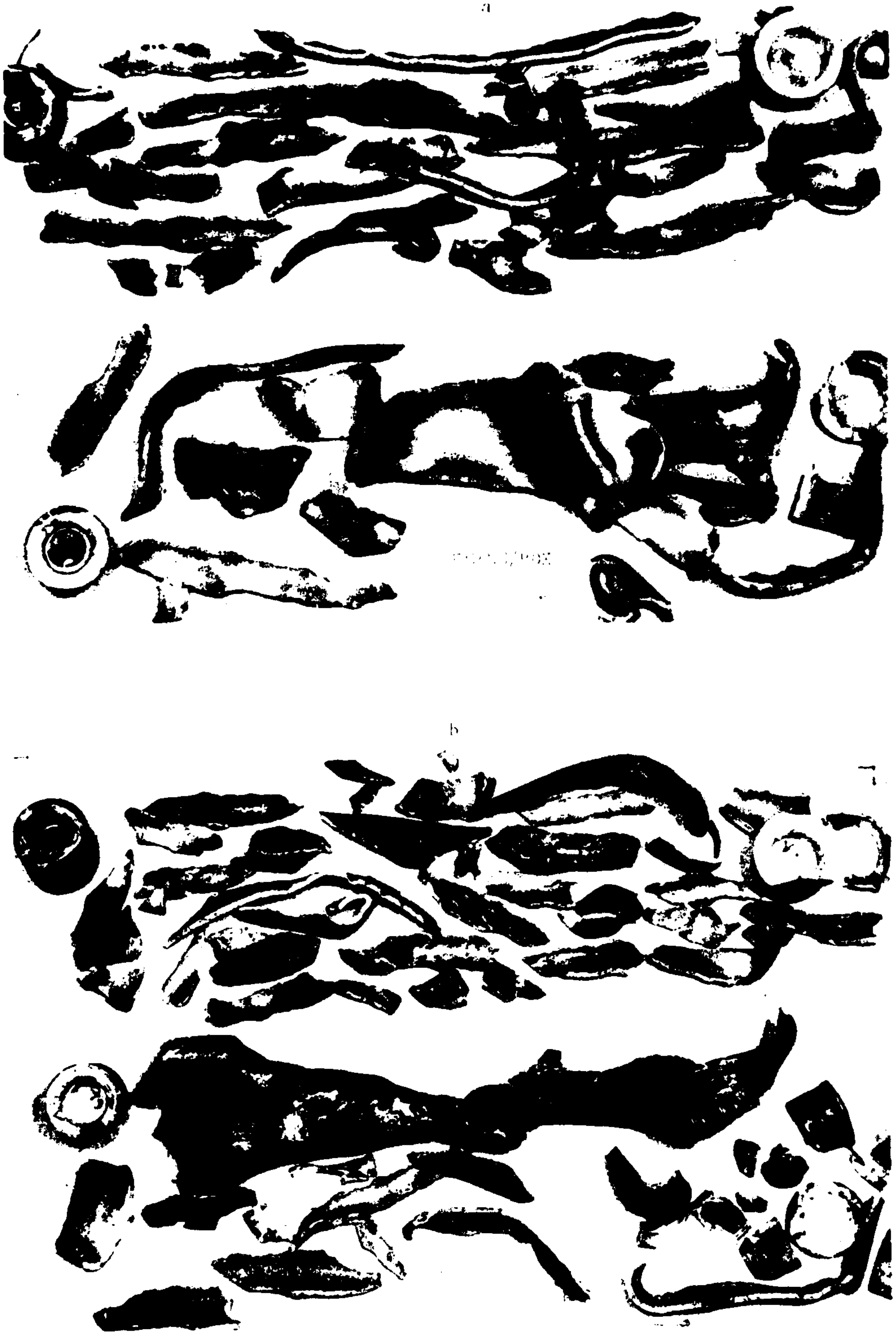

Figure 6. Deflagration-to-detonation transition test results
Level 3, 20 fragments or more

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