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RELATIVE EROSIVITY OF NITRAMINE, TRIPLE-BASE, AND DOUBLE-BASE PROPELLANTS

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A series of nitramine, triple-base, and double-base propellants in lots with flame temperatures of 2,700, 3,000 and 3,300K were tested for relative erosivity in vented chambers at BRL, Princeton University and the Large Caliber Weapons Systems Laboratory (LCWSL).

During initial testing, the BRL results suggested that the nitramine propellants were no mc·e erosive then their double- or triple-base counterparts.

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The Princeton experiments concluded the opposite. The LCWSL results suggested the 2,700K nitramine was more erosive than other 2,700K propellants, but the higher-flame temperature nitramines seemed no more erosive.

One weakness in the BRL tests was the small mass losses measured with the 2,700K propellants which could have masked differences among these propellants. To rectify this, the erosivity of the nine propellants was measured with a smaller diameter nozzle to increase mass loss per round. The results with the smaller diameter nozzle confirmed that the nitramines were no more erosive than the other propellants with the same flame temperatures.

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I. INTRODUCTION

Gun propellants with nitramines, RDX or HMX, have higher impetus for a given flame temperature than single-, double-, or triple-base propellants. Nitramine propellants have been advocated because they would cause less barrel wear for the same velocity. Such advocacy stems from the assumption that nitramine propellants are no more erosive then conventional propellants. This was challenged by some workers during World War II,[1-3] although Hobstetter[4] claimed that erroneous thermochemical calculations of the nitramine propellant's flame temperatures clouded their results. The contention that nitramine propellants were more erosive, however, has persisted[5-7] ever since.

Continued interest in nitramines for high-velocity application and new

[1] *N.H. Smith, "Pre-engraved Projectiles," NDRC Armor and Ordnance Report No. A-448, December 1945.*

[2] *N.H. Smith, "The Caliber 0.50 Erosion Testing Gun," NDRC Armor and Ordnance Report No. A-450, January 1946.*

[3] *N.H. Smith, "Comparison of the Erosiveness of Propellant Powders," NDRC Armor and Ordnance Report No. A-451, October 1945.*

[4] *J.N. Hobstetter, "Application of Heat Transfer Theory to Metallographic Evidences of Gun Erosion," NDRC Armor and Ordnance Report No. A-452, December 1945.*

[5] *D.J. Taylor, "Gun Erosion and Methods of Control," Proceedings of Interservice Technical Meeting on Gun Tube Erosion and Control, Watervliet Arsenal, February 1970.*

[6] *E.F. Boggs, B.A. Helman, and R.P. Bauman, "High-Force, Low Flame Temperature, Nitramine-Filled Propellants," Proceedings of the International Symposium on Gun Propellants, Picatinny Arsenal, October 1973.*

[7] *I. Ahmad, "The Problem of Gun Barrel Erosion, An Overview," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, Picatinny Arsenal, March 1977.*

interest in using nitramines as low-vulnerability propellants[8-10] prompted reexamination of the erosivity of nitramine compositions. BRL workers measured erosivity of nitramine propellants prepared by the LCWSL.[11,12] The nitramine propellants were found no more erosive than conventional propellants with equivalent flame temperatures. Princeton University found RDX-propellants to be more erosive.[13]

To try to resolve the continuing controversy over erosivity of nitramine propellants, Geene of BRL used interior ballistic and thermochemical codes to devise a series of nitramine, double-base, and triple-base propellants each with flame temperatures of 2,700, 3,000 and 3,300K. Experiments conducted at BRL concluded that there was no difference in wear among propellants with the same flame temperature.[14] Experiments at LCWSL and

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[8] *J.J. Rocchio, H.J. Reeves, and I.W. May, "Low-Vulnerability Ammunitions Concept Development," Proceedings of the 1976 JANNAF Propulsion Meeting, CPIA Publication 280, February 1977.*

[9] *J.J. Rocchio and R.W. Deas, "Interior Ballistics of Nitramine-Inert Binder Formulations Being Evaluated for Low-Vulnerability Propellants," Proceedings of the 15th JANNAF Combustion Meeting, CPIA Publication No. 297, February 1979.*

[10] *W.H. Vreatt and S.E. Mitchell, "Navy LOVA Propellant Development," Proceedings of the 16th JANNAF Combustion Meeting, CPIA Publication 308, December 1979.*

[11] *R.W. Geene, J.R. Ward, T.L. Brosseau, A. Niiler, R. Berkmire, and J.J. Rocchio, "Erosivity of a Nitramine Propellant," BRL Technical Report No. 02094, August 1978.* (AD #A060590)

[12] *J.R. Ward and R.W. Geene, "Erosivity of a Nitramine Propellant with Flame Temperature of M30 Propellant," BRL Memorandum Report MR-2926, June 1979.* (AD #A074346)

[13] *L.H. Caveny, A. Gany, S.O. Morris, M. Summerfield, and J.W. Johnson, "Effect of Propellant Type on Steel Erosion," Proceedings of the 1978 JANNAF Propulsion Meeting, CPIA Publication 293, February 1978.*

[14] *J.R. Ward, R.W. Geene, A. Niiler, A. Rye, and B.B. Grossman, "Blow-out Gun Erosivity Experiments with Double-Base, Triple-Base, and Nitramine Propellants," Proceedings of the 1980 JANNAF Propulsion Meeting, CPIA Publication 315, March 1980.*

Princeton University reached different conclusions.[15] The Princeton workers found the nitramines more erosive in every instance, while the LCWSL experimenters found only the 2,700K nitramine propellant more erosive than its 2,700K counterparts. In the meantime, Vassallo and coworkers at Calspan reported that a nitramine propellant was more erosive than a triple-base propellant with like flame temperature.[16]

One problem with the BRL results was that small mass losses recorded for the 2,700K propellants may have masked differences among the three propellants. In order to resolve the nitramine propellant controversy, the BRL wear measurements were repeated with a smaller-diameter nozzle to increase the mass loss per shot.

II. EXPERIMENTAL

Propellant ingredients, thermochemical properties, and combustion-gas compositions for a 0.2 g/cm^3 loading density are listed in Tables 1-4.

A description of the blowout gun and the experimental procedure is available in earlier reports.[11,12,14] The only change is that the nozzle diameter is 12.4 mm vs the 17.3 mm in the earlier test.[14] The charge masses were adjusted to give closed-bomb peak-pressures of 303 MPa, well above the rupture pressure of the two 1.6 mm-thick steel shear disks.

III. RESULTS

The mass losses recorded for each shot with each of the nine propelants tested are summarized in Tables 5-7. A sample pressure-time curve for each propellant is provided in the Appendix.

Table 8 summarizes the mean mass loss/shot and the sample standard deviation for each propellant. Table 9 compares the latest results with those recorded in Reference 14 with the larger diameter nozzle.

The smaller diameter nozzle produces larger mass losses per shot as anticipated. In particular, the mass loss/shot for the 2,700K flame temperature propellants exceeds the mass loss/shot for the 3,300K propellants with the large-diameter nozzle. The results confirm earlier findings that nitramine propellants have similar erosivity as the double-base and triple-base propellants with equivalent flame temperatures.

[15] *A.J. Bracuti, L. Bottei, J.A. Lannon, and L.H. Caveny, "Evaluation of Propellant Erosivity with Vented Erosion Apparatus," Proceedings of the 1980 JANNAF Propulsion Meeting, CPIA Publication 315, March 1980.*

[16] *F.A. Vassallo, "Thermal and Erosion Phenomenonolgy in Medium-Caliber Anti-Armor Automatic Cannon (MC-AAAC)," Proceedings of the 1980 JANNAF Propulsion Meeting, CPIA Publication 315, March 1980.*

TABLE 1. COMPOSITION AND GRAIN DIMENSIONS OF THE NITRAMINE PROPELLANTS

Composition	NA-1	NA-2	NA-3
Nitrocellulose (% Nitrogen)	30.0% (12.6)	30.0% (12.6)	30.0% (12.6)
Nitroglycerin	15.6	18.3	21.1
RDX	41.5	41.5	41.5
Ethyl Centralite	1.5	1.5	1.5
Dioctylphthalate	11.2	8.5	5.7
Residual Alcohol	0.2	0.2	0.2
Dimensions			
Length, mm	7.26	9.09	10.9
Outer Diameter, mm	1.78	2.21	2.67
Inner Diameter, mm	0.66	0.84	0.99
Web, mm	0.56	0.69	0.84
Heat of Explosion, J/g	3454	3869	4308

TABLE 2. COMPOSITION AND GRAIN DIMENSIONS OF THE TRIPLE-BASE PROPELLANTS

Composition	TB-1	TB-2	TB-3
Nitrocellulose (% Nitrogen)	27.4% (12.6)	27.4% (12.6)	27.4% (12.6)
Nitroglycerin	11.0	22.0	33.0
Nitroguanidine	59.6	48.6	37.6
Ethyl Centralite	1.5	1.5	1.5
Sodium Cryolite	0.3	0.3	0.3
Residual Alcohol	0.2	0.2	0.2
Dimensions			
Length, mm	7.06	9.80	11.58
Outer Diameter, mm	1.68	2.11	2.49
Inner Diameter, mm	0.71	0.84	1.02
Web, mm	0.41	0.64	0.74
Heat of Explosion, J/g	3622	3906	4375

TABLE 3. COMPOSITION AND GRAIN DIMENSIONS OF THE DOUBLE-BASE PROPELLANTS

Composition	DB-1	DB-2	DB-3
Nitrocellulose (% Nitrogen)	66.6% (13.25)	69.8% (13.25)	73.2% (13.25)
Nitroglycerin	20.0	20.0	20.0
Barium Nitrate	1.4	1.4	1.4
Potassium Nitrate	0.7	0.7	0.7
Ethyl Centralite	11.1	7.9	4.5
Residual Alcohol	0.2	0.2	0.2
Dimensions			
Length, mm	7.82	9.68	11.91
Outer Diameter, mm	1.98	2.41	2.97
Inner Diameter, mm	0.84	1.04	1.27
Web, mm	0.57	0.69	0.85
Heat of Explosion, J/g	3417	3793	4229

TABLE 4. THERMOCHEMICAL PROPERTIES OF PROPELLANT AND COMBUSTION GASES

Propellant	Flame Temperature T,K	Impetus, J/g	Co Volume, cm^3/g	Molecular Weight, g/mole	Principal Combustion Gases, moles/kg CO	CO_2	H_2O	H_2	N_2	Gas Specific Heat Cp,J/mole	Specific Heat Ratio γ
DB-1	2,705	991	1.084	22.7	21.3	2.6	6.8	8.2	4.9	41.8	1.26
TB-1	2,698	1,007	1.087	22.3	12.1	2.2	9.4	7.6	13.4	42.5	1.25
NA-1	2,709	1,078	1.151	20.9	20.4	1.6	6.1	11.1	8.0	40.6	1.26
DB-2	2,994	1,046	1.043	23.8	19.0	3.5	8.2	6.0	5.0	43.5	1.24
TB-2	3,004	1,075	1.052	23.2	11.7	2.9	10.5	5.6	12.1	44.0	1.24
NA-2	3,002	1,143	1.112	21.8	18.7	2.1	7.6	9.2	8.2	42.0	1.25
DB-3	3,297	1,093	1.003	25.1	16.3	4.8	9.4	4.0	5.0	45.6	1.23
TB-3	3,304	1,133	1.018	24.2	11.1	3.9	11.2	4.0	10.7	45.6	1.23
NA-3	3,307	1,200	1.071	22.9	16.7	2.8	8.9	6.7	8.4	43.5	1.24

TABLE 5. SUMMARY OF MASS LOSSES FOR NA-1, TB-1, AND DB-1 PROPELLANTS

Propellant	ID	Nozzle	Nozzle Shot No.	Charge Mass, g	Rupture Pressure, MPa	Mass Loss, mg
NA-1	5	N	2	70.6	276	2.3
NA-1	8	N	3	70.6	262	2.0
NA-1	11	N	4	70.6	248	3.1
NA-1	14	N	5	70.6	248	3.4
NA-1	17	N	6	70.6	255	6.0
NA-1	20	N	7	70.6	255	5.0
NA-1	23	N	8	70.6	248	4.0
TB-1	3	T	1	74.4	255	7.4
TB-1	6	T	2	74.4	255	4.5
TB-1	9	T	3	74.4	248	4.3
TB-1	12	T	4	74.4	255	7.0
TB-1	15	T	5	74.4	248	4.9
TB-1	18	T	6	74.4	255	6.2
TB-1	21	T	7	74.4	248	4.7
DB-1	4	O	2	75.0	255	4.5
DB-1	7	O	3	75.0	255	3.0
DB-1	10	O	4	75.0	255	5.1
DB-1	13	O	5	75.0	255	3.2
DB-1	16	O	6	75.0	248	3.0
DB-1	19	O	7	75.0	248	3.4
DB-1	22	O	8	75.0	---	4.0
DB-1	24	O	9	75.0	248	4.1

TABLE 6. SUMMARY OF MASS LOSSES FOR NA-2, TB-2, AND DB-2 PROPELLANTS

Propellant	ID	Nozzle	Nozzle Shot No.	Charge Mass, g	Rupture Pressure, MPa	Mass Loss, mg
NA-2	42	N	13	68.4	255	12.7
NA-2	45	N	14	68.4	255	10.8
NA-2	48	N	15	68.4	255	13.4
NA-2	50	N	16	68.4	255	12.9
NA-2	53	N	17	68.4	255	11.2
TB-2	44	T	15	71.9	255	6.9
TB-2*	47	T	16	71.9	248	7.3
DB-2	43	O	16	73.5	255	13.8
DB-2	46	O	17	73.5	255	9.6
DB-2	49	O	18	73.5	255	9.7
DB-2	51	O	19	73.5	255	10.2
DB-2	54	O	20	73.5	255	10.7

* *Sufficient TB-2 available for two shots only.*

TABLE 7. SUMMARY OF MASS LOSSES FOR NA-3, TB-3, AND DB-3 PROPELLANTS

Propellant	ID	Nozzle	Nozzle Shot No.	Charge Mass, g	Rupture Pressure, MPa	Mass Loss, mg
NA-3	85	N	27	65.7	248	30.6
NA-3	89	N	28	65.7	248	18.6
NA-3	92	N	29	65.7	248	18.2
NA-3	95	N	30	65.7	255	24.4
NA-3	98	N	31	65.7	255	11.1
NA-3	101	N	32	65.7	248	22.9
NA-3	102	N	33	65.7	248	25.4
TB-3	84	T	27	69.4	241	34.9
TB-3	88	T	28	69.4	248	23.7
TB-3	91	T	29	69.4	248	28.4
TB-3	94	T	30	69.4	241	20.7
TB-3	97	T	31	69.4	255	27.1
TB-3	100	T	32	69.4	248	23.5
DB-3	83	O	29	71.6	248	15.0
DB-3	87	O	30	71.6	248	22.1
DB-3	90	O	31	71.6	248	28.6
DB-3	93	O	32	71.6	241	20.2
DB-3	96	O	33	71.6	248	20.2
DB-3	99	O	34	71.6	248	18.5

TABLE 8. MEAN MASS LOSS/SHOT FROM 12.4mm DIAMETER NOZZLE*

Propellant Flame Temp, K	Double-Base	Triple-Base	Nitramine
2,700	3.8 ± 0.8**	5.6 ± 1.3	3.7 ± 1.4
3,000	10.8 ± 1.7	7.1 ± 0.3	12.2 ± 1.1
3,300	20.8 ± 4.5	26.4 ± 5.0	21.6 ± 6.3

*Wear given as mg/shot.

**Error given as sample standard deviation.

TABLE 9. COMPARISON OF EARLIER RESULTS WITH MASS LOSSES FROM 12.7mm DIAMETER NOZZLE

Propellant	Wear, mg/shot*	Wear, mg/shot**	Wear, mg/shot***
NA-1	1.9 ± 0.7****	1.3 ± 0.9	3.7 ± 1.4
TB-1	2.8 ± 0.9	2.3 ± 1.0	5.6 ± 1.3
DB-1	1.7 ± 0.7	2.1 ± 0.3	3.8 ± 0.8
NA-2	2.5 ± 0.9	7.1 ± 2.5	12.2 ± 1.1
TB-2	3.0 ± 0.9	4.1 ± 0.9	7.1 ± 0.3
DB-2	2.8 ± 0.7	3.9 ± 0.7	10.8 ± 1.7
NA-3	3.6 ± 1.5	12.6 ± 3.9	21.6 ± 6.3
TB-3	4.1 ± 1.7	11.7 ± 3.0	26.4 ± 5.0
DB-3	3.7 ± 1.4	13.9 ± 2.9	20.8 ± 4.5

* *Wear measured with 17.3mm diameter nozzle, two shear disks, nominal rupture pressure 248 MPa.*

** *Wear measured with 17.3mm diameter nozzle, three shear disks, nominal rupture pressure 324 MPa.*

*** *Wear measured with 12.7mm diameter nozzle, two shear disks, nominal rupture pressure 248 MPa.*

**** *Error expressed as sample standard deviation.*

Since this conclusion contradicts other experiments [13] with the same propellants, it seems worthwhile to speculate about how to convert wear from vented-chamber experiments to large-caliber guns.

One needs, first of all, to define "inherent" erosivity. The interpretation adopted here is how will gun barrel wear vary when a conventional propellant is replaced with a nitramine propellant such that the interior ballistics are unchanged through adjustment of charge mass, web, or burning rate. Experience dictates that wear is reduced whenever the flame temperature is reduced. Thus, the assertion that nitramine propellants are "inherently" more erosive than conventional propellants implies an important gap exists in our understanding of gun barrel wear.

In BRL experiments the charge masses are adjusted to the same closed chamber peak pressure which is twenty percent larger than the shear disks' rupture pressure. The resulting flow through the nozzle is independent of propellant web and burning rate. The experiment deviates from a gun in that there is no projectile accelerated. The only potential contribution from the projectile is friction which should be inconsequential compared to the wear from convective heat transfer. This latter conclusion is buttressed by experiments in which plastic rotating bands replaced metal bands without changing wear.[17,18]

Some further justification for matching chamber pressure to test propellant erosivity comes from Nordheim's[19] analysis of flow through vents.

Nordheim devised the following expression relating chamber pressure vs time where the subscript, o, represents conditions at propellant burnout with no heat loss to the walls,

$$P = P_o \; [1+\tfrac{1}{2}(\gamma-1)B(1+b\eta\sigma_o)t]^{-2\gamma/(\gamma-1)} \quad , \qquad (1)$$

[17] *M.C. Shamblen, "Overview of Erosion in U.S. Naval Guns," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, Picatinny Arsenal, March 1977.*

[18] *R. Berkmire and A. Niiler, "Radioactive Tracers in Erosion Wear Measurements," Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, Picatiny Arsenal, March 1977.*

[19] *L.W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns," NDRC Armor and Ordnance Report No. A-262, March 1944.*

where P = chamber pressure at time, t,

γ = ratio of specific heats,

η = co-volume, and

σ,B,b = expressions defined in Eqs. (2) - (5).

The quantity, σ is defined as

$$\sigma = \rho/(1-\eta\rho) \quad , \tag{2}$$

where ρ = density of gas.

B is defined as

$$B = \frac{A}{M_o}\left[\sigma_o P_o \gamma \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma+1}\right)}\right]^{\frac{1}{2}} \quad , \tag{3}$$

where A = cross-sectional area at nozzle throat, and

M = propellant mass.

The expression for b is

$$b = -1 + \frac{(\gamma-1)}{(3-\gamma)}\left[2+\tfrac{1}{2}(\gamma+1)\varepsilon\right]^{*}\left[\frac{1-\left(1+\tfrac{1}{2}(\gamma-1)Bt\right)^{-\left(\frac{3+\gamma}{\gamma-1}\right)}}{\tfrac{1}{2}(\gamma-1)Bt}\right] \quad , \tag{4}$$

where the only undefined quantity, ε, is given by

$$\varepsilon = \frac{1}{\gamma}\left[1 - 2\left(\frac{2}{\gamma+1}\right)^{\left(\frac{1}{\gamma-1}\right)}\right] \quad . \tag{5}$$

The pressure in the vent is related to the chamber pressure as follows:

$$p^{*} = \left[\left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma}{\gamma-1}\right)}\right] \cdot P \cdot (1 + \varepsilon\gamma\eta\sigma) \quad , \tag{6}$$

where p^{*} = pressure at nozzle throat.

The propellant's burning time to peak pressure should be matched as closely as possible to avoid different heat losses to the wall. For the nine propellants tested here, the heat loss was the same, as evidenced by the closed bomb results in Reference 13 where the ratio of the experimental peak pressure to the theoretical peak pressure was the same for all the propellants.

Nordheim also developed a scheme to compute convective heat transfer from propellant gases using Reynold's analogy between momentum transfer and heat transfer. The heat transfer coefficient

$$h = \tfrac{1}{2} \lambda C_p \rho U \quad , \tag{7}$$

where h = heat transfer coefficient,

λ = friction factor,

C_p = specific heat at constant pressures,

ρ = gas density, and

U = gas velocity.

The heat transfer to the wall is then

$$q = h(T_g - T_s) \quad , \tag{8}$$

where q = heat transfer,

T_g = gas temperature, and

T_s = surface temperature of wall.

Eqs. (7) and (8) suggest one can predict what the relative erosivity should be comparing the internal energy of the combustion gases. Table 10 computes the internal energy per milliliter for the nine propellants with thermochemical data from Table 4. Table 10 shows the internal energy is the same within a few percent for each set of propellants with a given flame temperature implying that the wear should be the same within the experimental error of the vented chamber experiments.

Further justification for taking care to match pressure-time curves to infer erosivity is given in another calculation by Nordheim in which he computed heat transfer and peak bore surface temperature for a 37mm gun with constant propellant mass and peak pressure but with various projectile masses. Table 11 summarizes the calculations showing that the lightest

TABLE 10. INTERNAL ENERGY OF PROPELLANT GASES IN VENTED CHAMBER EXPERIMENTS

Propellant	C_p, J/g-K	Charge Mass, g	Density, g/cm^3	Internal Energy, J/cm^3,x10^{-3}
DB-1	1.84	75.0	0.227	1.13
TB-1	1.89	74.4	.225	1.15
NA-1	1.96	70.6	.214	1.14
DB-2	1.83	73.5	.223	1.22
TB-2	1.90	71.9	.218	1.24
NA-2	1.93	68.4	.207	1.20
DB-3	1.81	71.6	.217	1.30
TB-3	1.88	69.4	.210	1.30
NA-3	1.99	65.7	.199	1.25

TABLE 11. HEAT INPUT AND BORE SURFACE TEMPERATURE FOR DIFFERENT PRESSURE-TIME CURVES WITH EQUIVALENT CHARGE MASS

Projectile Mass, g	Propellant Mass, g	Muzzle Velocity, m/s	Bore Temperature, K	Heat Input, J/mm^2
670	182	792	953	0.494
335	182	1,067	1,023	.469
168	182	1,417	1,093	.448

projectile produces the highest peak temperature and, presumably, the highest wear, since the action time decreases. One set of workers compensates for differences in propellant burning rates by comparing wear of propellants with equivalent pressure-time integrals.[13] Nordheim's calculations suggest that pressure-time curves with equal integrals will produce higher fluxes and higher bore surface temperatures as the action time decreases (peak pressure increases).

IV. CONCLUSIONS

1. Mass losses measured with the smaller diameter nozzle confirm earlier BRL results that nitramine propellants are no more erosive than double-base or triple-base propellants with comparable flame temperatures.

2. Contradictions among BRL, Princeton University, and the LCWSL about the relative erosivity of nitramine propellants seem to reflect differences in analysing wear in the vented chambers. The BRL procedure is based on the presumption that pressure-time curves must be matched in order to assess relative erosivity.

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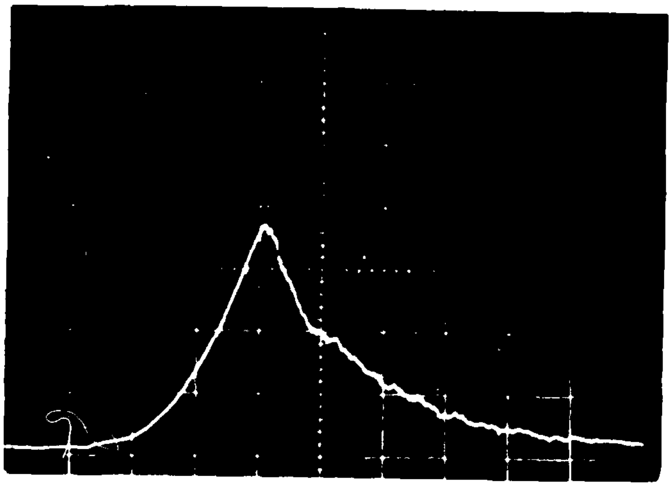
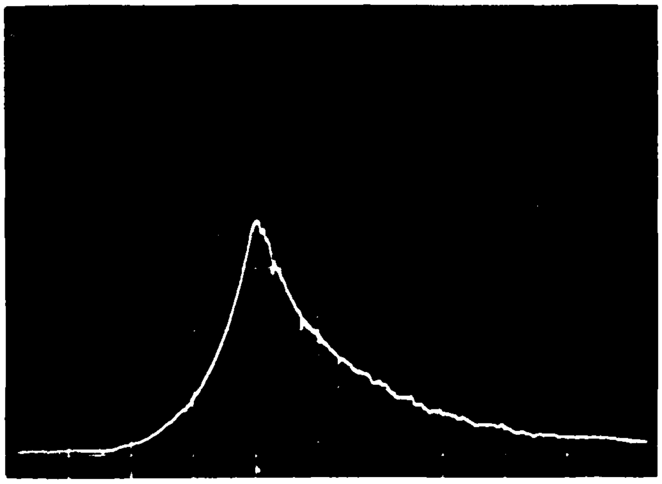
APPENDIX

PRESSURE-TIME CURVES FOR EACH PROPELLANT TESTED



Propellant	TB-1
Nozzle	T
ID	3
Ordinate	69 MPA/div (10ksi/div)
Abscissa	2 ms/div



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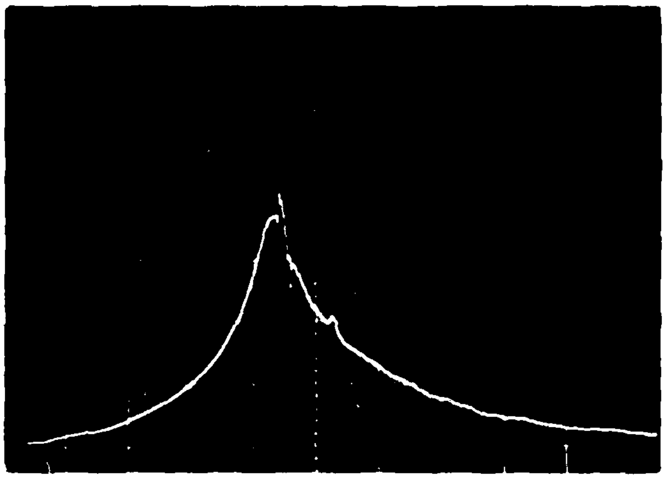
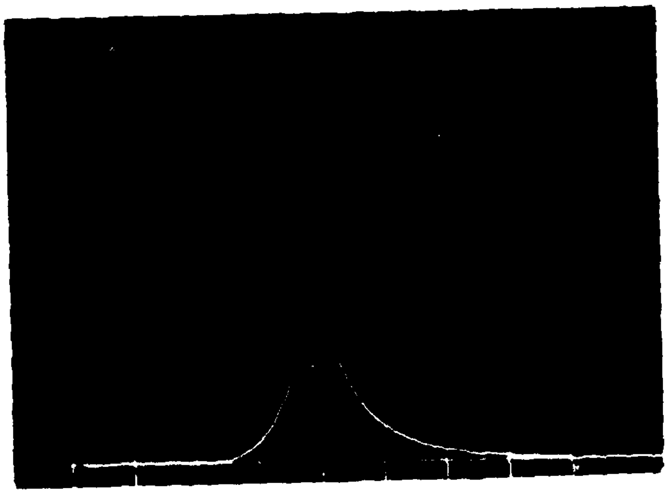
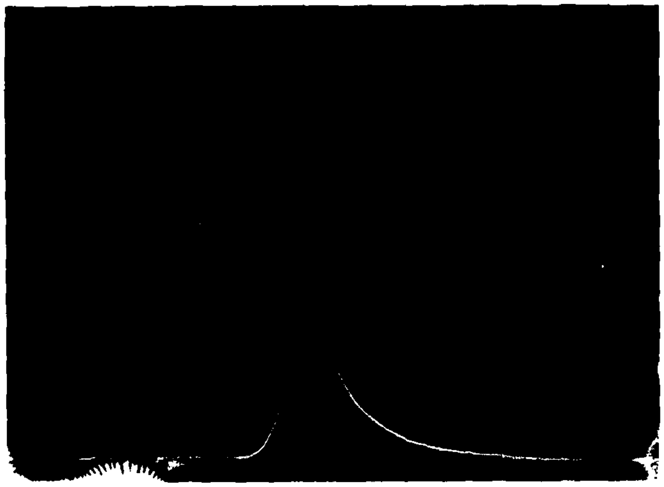
Nozzle	0
ID	1
Ordinate	69 MPa/div (10ksi/div)
Abscissa	2 ms/div



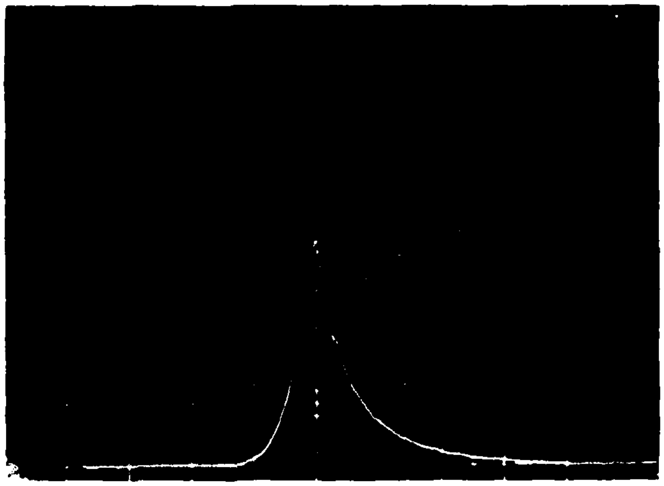
Propellant	M-1
Nozzle	N
ID	5
Ordinate	69 MPa/div (10ksi/div)
Abscissa	2 ms/div



Propellant	XA-2
Nozzle	X
ID	45
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div

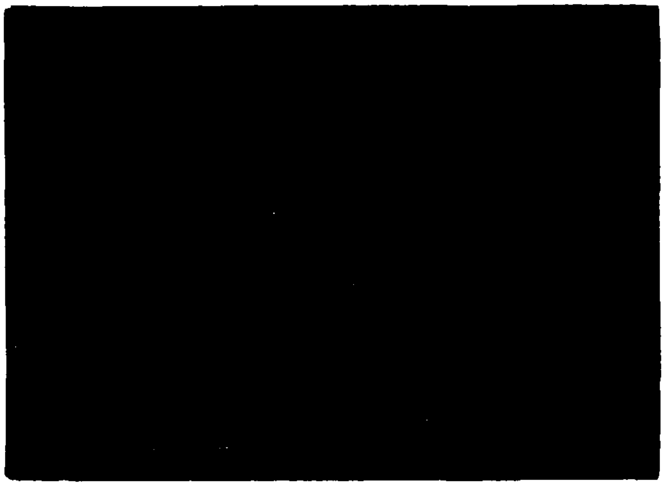


Propellant	DB-2
Nozzle	0
ID	46
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div

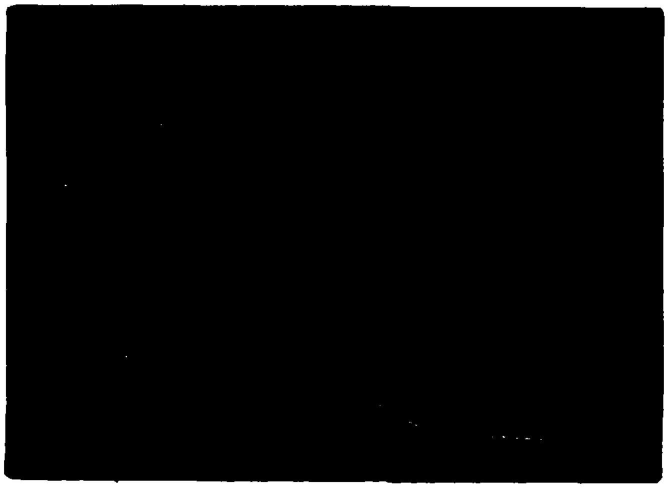


Propellant	TB-2
Nozzle	T
ID	47
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div

Propellant	NA-3
Nozzle	N
ID	92
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div



Propellant	DB-3
Nozzle	0
ID	93
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div



Propellant	TB-3
Nozzle	T
ID	94
Ordinate	69 MPa/div (10ksi/div)
Abscissa	5 ms/div

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