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BURNING RATES OF STANDARD ARMY PROPELLANTS IN STRAND BURNER AND CLOSED CHAMBER TESTS

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USA ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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Burning rate data determined over twenty years ago at the Ballistic Research Laboratory (BRL) and disseminated to only a limited audience have been referenced in several recent reports. This report provides a complete compilation of the experiments, the data, and the analyses to provide a usable reference for current investigations. It compares strand burner and closed chamber rates for the same propellant.

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Standard army gun propellants (M1, M2, M5, M6, M8, M10, and M17) were re-extruded into 3mm (1/8 in.) and 6mm (1/4 in.) strands for strand burner tests at pressures of 3.4 to 310 MPa (500 to 45,000 psi) and in closed chamber tests at densities of loading (Δ) of 0.089, 0.174, and 0.258 g/cc. Fifteen additional lots of standard propellants were tested in the closed chamber at densities of loading of 0.084 and 0.140 g/cc.

The report presents the raw data, method of calculation for burning rate, and coefficients for various burning rate equations. The report also proposes an empirical relationship between the propellant flame temperature and the burning rate parameters.

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I. INTRODUCTION

"The chemical system of powder and gas presents a complex in which chemical reactions occur at high speed with remarkable precision. The free energy of powder gas is much less than that of powder, and the reaction between them, when once initiated, goes forward rapidly--in common parlance, the powder burns."[1]

The National Defense Research Committee published in 1946 a summary of their investigation in interior ballistics in "Hypervelocity Guns and the Control of Gun Erosion."[1] The burning rate data for several propellants determined in closed chambers disagreed with test gun results. This was attributed to ignition problems and somewhat different formulations in the test propellants. R. H. Kent[2,3] at Aberdeen proving Ground and BRL had studied the closed chamber data from 1925 on, and when a high pressure strand burner was acquired in 1950, suggested that the same propellants be used in both devices. These experiments were conducted and the results published in the monthly BRL Progress Reports (1953-1956) which had limited distribution. Standard army gun propellants (M1, M2, M5, M6, M8, M10, and M17) were re-extruded into 3mm (1/8 in.) and 6mm (1/4 in.) strands for strand burner tests at pressures of 3.4 to 310 MPa (500 to 45,000 psi) and in a closed chamber at densities of loading (Δ) of 0.089, 0.174, and 0.258 g/cc. Fifteen additional lots of standard propellants were tested in the closed chamber at densities of loading of 0.084 and 0.140 g/cc. Propellant description sheets are available for all the propellants.

This paper describes the experiments, the test data, and the derived burning rates. The results of tests at several other agencies are compared to those of the BRL standard tests.

II. DESCRIPTION OF EQUIPMENT

A. STRAND BURNER

The strand burner, used for the experimental firings, was manufactured by Autoclave Engineers and is capable of firing propellant samples at pressures up to 345 MPa (50,000 psi). The reaction chamber is 5.08 cm (2 in.) in internal diameter and 25.4 cm (10 in.) long. The auxilliary surge tank associated with the system has a capacity of 0.014m^3 (0.5 ft.^{3}).

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[1] *F. C. Kracek, "Hypervelocity Guns and the Control of Gun Erosion," Part II Ballistics, Chapter 2, NDRC, Washington, D. C., 1946, pp. 21-53.*

[2] *R. H. Kent, "Report on Determination of Interior Ballistic Data by Closed Chamber Experiments in Connection with Project RB158," BRLR 32, Jan 1936.*

[3] *R. H. Kent, J. P. Vinti, "Cooling Corrections for Closed Chamber Firings," BRLR 281, Sep 1942.* (AD #491852)

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The propellant samples fired varied in diameter from 0.25 cm (0.10 in.) to 0.64 cm (0.25 in.) and were about 15 cm (6 in.) long. They were inhibited by dipping in a vinyl resin solution. Each grain had four holes laterally drilled through it with a number 75 drill. In the first hole, a nichrome wire was inserted to ignite the grain. The other holes had 0.5 ohm fuse wire inserted through them to activate time interval recorders. The holes were drilled with the aid of a jig and, thus, the distances between holes were quite accurate. For fast burning propellants, 1.6 megacycle Potter counters were used; for slow burning propellants, Standard Electric 0.01 second clocks were used to measure the time intervals.

The nominal distance between two adjacent fuse wires was 5.08 cm (2 in.). Two time intervals were measured per round fired. The first time interval recorded was for the first 5.08 cm (2 in.) of burning and the second time interval was either for the second 5.08 cm (2 in.) or the whole 10.16 cm (4 in.) of burning.

The pressures were read from Bourdon gages. The scale divisions are 20 psi for the low range (0 to 3,000 psi), 500 psi for the middle range (0 to 15,000 psi) and 1,000 psi for the high range (0 to 50,000 psi). Because the system had slow leaks, it was over-pressurized and fired when it reached the desired pressure. While the grain was burning, the pressure increased slightly and was bled off into the surge tank. This surge was noticeable on the Bourdon gage only for very low initial pressures. The overall accuracy is estimated to be within 2%.

B. CLOSED CHAMBER

The closed chamber was manufactured by DuPont. It is capable of firing propellant samples up to pressures of 310 MPa (45,000 psi). The reaction chamber is 3.2 cm (1.25 in.) in diameter and about 6.6 cm (2.6 in.) long with a volume of 59 cc (3.6 $in.^3$).

The propellant samples were fired as received, neither selected for uniformity nor inhibited. A gage plug containing a double piezoelectric gage and a gas release valve was screwed into one end of the chamber. An igniter plug with insulated leads was screwed into the other end. The leads were joined with 0.013 cm (0.005 in.) diameter tungsten wire, and the wire was wrapped with 0.25 g of thread propellant. The propellant charge was wrapped in a silk bag surrounding the igniter. Firing was initiated by applying 24 volts across the external igniter plug leads. Records were taken of the output of the double piezoelectric gage. One set of output leads was attached to a drum camera and a dual beam cathode ray oscilloscope to record pressure and rate of change of pressure versus time. The other set of output leads was attached to a Dumont No. 235 CRO to record pressure versus rate of change of pressure. The rates of change of pressure were obtained by electrically differentiating the pressure gage output.

III. EXPERIMENT MAIN TEST

The re-extruded standard propellants are described in Table I, including basic propellant lot and hexane densities.

For the strand burner test, both size cords were cut into 15 cm (6 in.) lengths and inhibited by dipping in a vinyl resin solution three times. The strands were burned at nine different pressures. The results are shown in Table II. For the smaller diameter grains, both the burning rates determined for the initial segment and the final segment of the seven sample propellants agreed within 2%, except for the M8 propellant at 207 MPa (30,000 psi) and 241 MPa (35,000 psi). The rates determined for the larger grains were somewhat slower than the rates determined for the corresponding smaller propellant grains. This was attributed to an increase in retained volatiles. Also, there were several failures due either to poor retention of coating or physical breakup during pressurization or burning. This series was fired during 1953-1954.

Several years after these tests, the Harwood High Pressure Strand Burner was transferred from the Bureau of Mines to BRL. During the proofing of the apparatus, the few remaining strands from the previous experiment were tested and the limited results are shown in Table III.

For the closed chamber test, the smaller size grains were cut into 5 cm (2 in.) lengths. Five, ten and fifteen gram charges were fired in duplicate for each propellant. The igniter was an 0.25 g thread propellant, having a diameter of 0.013 cm (0.005 in.). For the M1, M6, M10 and M17 samples, the ignitor was re-extruded from an M1 composition; for the M2 and M5 samples, the ignitor was re-extruded from an M2 composition; and for the M8 sample, the ignitor was re-extruded from an M8 composition. The pressure was measured with a stacked quartz piezo-electric gage mounted on a piston. This series of propellant samples was fired July 1954. The burning rates were calculated using the method reported in BRL Report 546, J. Wiegand[4] and are tabulated in Table II. Table IIA contains the combined data and can be used for reference in English or Metric Units.

IV. RELATIONSHIPS OF THE COMBINED RESULTS

The burning rates determined in the strand burner and closed chamber were combined as shown in Table II and were used to fit the following expressions:

[4] *J. H. Wiegand, "A Method for the Calculation of the Burning Rate of Powders from dp/dt Records for Closed Chambers," BRLR 546, May 1945.*

Table I. Description of Standard Lots

Propellant	M1		M2		M5		M6		M8		M10		M17	
Specification	JAN-P-309		JAN-P-323		JAN-P-323		JAN-P-309		JAN-P-381		PA-PD-123		MIL-PD-688A	
Army Lot No.		15529		302		4005		32412		9698		31831		6911
Nitrocellulose	85.00	83.54	77.45	75.08	81.95	80.93	87.00	85.74	52.15	52.35	98.00	97.93	22.00	22.30
% Nitrogen	13.15	13.13	13.25	13.23	13.25	13.23	13.15	13.14	13.25	13.22	13.15	13.16	13.15	13.20
Nitroglycerin			19.50	20.67	15.00	15.96			43.00	42.66			21.50	20.78
Barium Nitrate			1.40	1.36	1.40	1.45								
Potassium Nitrate			0.75	0.98	0.75	0.93			1.25	0.92				
Nitroguanidine													54.70	54.97
Dinitrotoluene	10.00	(15.49)		0.96			10.00	(13.24)						
Dibutylphthalate	5.00						3.00							
Diphenylamine	1.00	0.97		0.68		0.73	1.00	1.02		0.70	1.00	1.09		
Ethyl Centralite			0.60		0.60				0.60				1.50	1.68
Graphite			0.30	0.27	0.30	0.25							0.10	
Cryolite											0.10		0.30	0.27
Ethyl Alcohol	0.75	0.35	2.30	0.57	2.30	2.10	0.90	0.47	0.40		1.50	1.26	0.30	0.09
Water	0.50	0.31	0.70	0.36	0.70	0.43	0.50	0.52		0.18	0.50	0.91	0.10	0.00
Diethylphthalate									3.00	3.08				
Potassium Sulphate											1.00	0.98		
Isochoric Flame Temp, °K, Tv.	2433		3372		3294		2583		3757		3034		2474	
A Re-extruded Dia inches ±.002		.121		.117		.119		.118		.118		.134		.121
Dimensional Density g/cc ±.01		1.51		1.62		1.59		1.51		1.61		1.51		1.69
A Hexane Density		1.505		1.613		1.608		1.527		1.608		1.535		1.665
B		1.531		1.642		1.632		1.552		1.612		1.555		1.689
A BRL Lot No.		T466		T468		T470		T472		T474		T476		T478
B		T465		T467		T469		T471		T473		T475		T477

B Re-extruded Larger Diameter grains about .240 inches

A .150 Die
B .250 Die

The first column for each propellant lists the specification values for the composition while the second is from the lot propellant description sheet

Table II. Burning Rate Results for BRL Extruded Standard Propellants (Rates in./s)

Propellant		Test Run	5000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000 psi
T465	M1	SB		1.13	1.74	2.21		3.30			
467	M2	SB	1.65	3.14	4.48	5.48	6.67	7.96			
469	M5	SB	1.71	2.76	4.00	4.99	6.30	7.55	8.44	8.99	10.21
471	M6	SB	.65	1.28	1.85	2.47	3.04	3.64	4.03	4.73	5.13
473	M8	SB	2.10	3.75	5.57	6.76	7.56	9.30	10.52	11.28	
475	M10	SB	.90	1.61	2.33	3.27	4.00	4.50	5.20	5.82	6.57
477	M17	SB		3.20*	7.00*	16.00*	20.00*				
T466	M1	SB	.59	1.17	1.68	2.26	2.89	3.36	4.10	4.59	5.12
		cc-1	.65	1.19							
		cc-2	.65	1.19	1.82						
		cc-3	.69	1.19	1.72	2.29	2.89				
		SB-cc	.65	1.18	1.74	2.27	2.89	3.36	4.09	4.59	5.12
T468	M2	SB	1.53	2.94	4.12	5.47	6.63	7.77	9.46	10.37	11.91
		cc-1	1.34								
		cc-2	1.53	2.74	4.12	5.62					
		cc-3	1.72	2.82	4.12	5.33	6.51	7.73			
		SB-cc	1.53	2.83	4.12	5.48	6.54	7.75	9.46	10.37	11.91
T470	M5	SB	1.41	2.78	3.99	5.47	6.67	7.92	8.43	9.95	11.86
		cc-1	1.30								
		cc-2	1.46	2.55	3.73						
		cc-3	1.57	2.60	3.71	4.72	5.74	6.78			
		SB-cc	1.43	2.64	3.85	5.08	6.36	7.54	8.43	9.95	11.86
T472	M6	SB	.68	1.31	1.91	2.53	3.13	3.97	4.50	5.05	5.51
		cc-1	.72								
		cc-2	.66	1.24	1.97						
		cc-3	.85	1.54	2.13	2.81	3.52				
		SB-cc	.72	1.36	1.98	2.62	3.26	3.97	4.50	5.05	5.61
T474	M8	SB	2.00	3.75	5.50	6.78	8.25			12.44	14.12
		cc-1	1.86								
		cc-2	2.20	3.83	5.60						
		cc-3	2.15	3.59	5.31	6.84	8.39	9.90			
		SB-cc	2.04	3.73	5.47	6.80	8.31	9.90	11.30	12.44	14.12
T476	M10	SB	.91	1.68	2.50	3.29	3.90	4.80	5.28	6.03	6.63
		cc-1	.89								
		cc-2	.89	1.47	2.14						
		cc-3	1.02	1.59	2.19	2.87	3.54				
		SB-cc	.92	1.60	2.33	3.15	3.78	4.80	5.28	6.03	6.63
T478	M17	SB	1.26	2.14	2.89	3.70	4.48	4.88	6.14	6.46	7.58
		cc-1	1.16								
		cc-2	1.22	2.03	2.96						
		cc-3	1.07	1.93	2.63	3.32	4.01	5.30			
		SB-cc	1.20	2.06	2.82	3.70	4.48	5.09	6.14	6.46	7.58

SB-cc - Average of all results
SB Strand Burner
* erratic results

Closed Chamber cc-1 = .089 g/cc
Closed Chamber cc-2 = .174 g/cc
Closed Chamber cc-3 = .258 g/cc

Table IIA. Propellant Burning Rate

MPa	psi	M1		M2		M5		M6		M8		M10		M17	
		mm/s	in./s	mm/s	in./s	mm/s	in./s	mm/s	in./s	mm/s	in./s	mm/s	in./s	mm/s	in./s
3.45	500	3.6	.14	7.4	.29	7.1	.28	3.0	.12	9.1	.36	5.1	.20	4.6	.18
10.34	1500	7.9	.31	14.7	.58	15.7	.62	8.1	.32	21.3	.84	10.9	.43	13.2	.52
20.69	3000	11.9	.47	23.9	.94	24.1	.95	12.7	.50	41.7	1.64	17.5	.69	20.8	.82
27.59	4000	13.7	.54	29.2	1.15	29.2	1.15	15.7	.62	45.7	1.80	19.8	.78	24.1	.95
34.48	5000	16.5	.65	38.9	1.53	36.3	1.43	18.3	.72	51.8	2.04	23.4	.92	30.5	1.20
68.97	10000	30.0	1.18	71.9	2.83	67.1	2.64	39.6	1.56	94.7	3.73	40.6	1.60	52.3	2.06
103.45	15000	44.2	1.74	104.6	4.12	97.8	3.85	50.3	1.98	138.9	5.47	59.2	2.33	71.6	2.82
137.93	20000	57.6	2.27	139.2	5.48	128.3	5.08	66.5	2.62	172.7	6.80	80.0	3.15	94.0	3.70
172.41	25000	73.4	2.89	167.4	6.59	161.5	6.36	82.8	3.26	211.1	8.31	96.0	3.78	113.8	4.48
209.60	30000	85.3	3.36	196.9	7.75	141.5	7.54	100.8	3.97	251.5	9.90	121.9	4.80	129.3	5.09
241.38	35000	103.9	4.09	240.5	9.47	214.1	8.43	114.3	4.50	287.0	11.30	134.1	5.28	156.0	6.14
275.86	40000	116.6	4.59	263.4	10.37	252.7	9.95	128.3	5.05	316.0	12.44	153.7	6.05	164.0	6.46
310.34	45000	130.0	5.12	302.5	11.91	301.2	11.86	142.5	5.61	358.6	14.12	168.4	6.63	192.5	7.58

Table III. High Pressure Strand Burner Data

Propellant	Pressure		Burning Rate Measured		Burning Rate Calculated	
	MPa	Ksi	mm/s	in./s	mm/s	in./s
T465 (M1)	379	55	149	5.88	155	6.12
	448	65	177	6.97	182	7.17
	544	79	212	8.33	219	8.63
	621	90	271	10.67	248	9.77
T466 (M1)	193	28	84	3.30	82	3.22
	276	40	121	4.76	115	4.52
	283	41	126	4.98	117	4.62
	379	55	165	6.50	155	6.12
	469	68	218	8.57	190	7.49
	586	85	282	11.11	235	9.26
T467 (M2)	172	25	145	5.70	171	6.74
	303	44	284	11.19	290	11.42
	434	63	381	15.00	406	15.97
	517	75	435	17.14	426	16.79
	579	84	476	18.75	531	20.89
T468 (M2)	138	20	132	5.21	139	5.48
	283	41	264	10.39	272	10.70
	414	60	368	14.50	386	15.21
	483	70	417	16.40	448	17.62
T470 (M5)	138	20	134	5.27	130	5.13
	283	41	257	10.12	257	10.13
	414	60	343	13.50	369	14.54
	414	60	353	13.90	369	14.54

*The burning rates were calculated using the bp^n equations in Table IV.

$r = a + bp^n$	or	$r = bp^n$
$a + bp$		bp
$a + bp^{.95}$		$bp^{.95}$
$a + bp^{.90}$		$bp^{.90}$
$a + bp^{.85}$		$bp^{.85}$
$a + bp^{.80}$		$bp^{.80}$

Some form of the equations cited above is often used in simplified interior ballistic calculation schemes. The least square fits of the above data to the various specific equations were computed. The results are tabulated in Tables IVA and IVB.

When the coefficients for the various experiments are plotted against the adiabatic flame temperature of the propellant (T) as shown in Figures 1A and 1B, it is seen that the lines cross the temperature axis at 1800K. This suggests an analytical expression for the coefficient b as a function of flame temperature and exponent as shown below:

$$b = (T - 1800)\ (1.65 \times 10^{-7})\ (n^{-9.4});\ r = \text{in./s},\ p = \text{psi}$$

$$b = (T - 1800)\ (4.19 \times 10^{-7})\ (145^{n})\ (n^{-9.4});\ r = \text{mm/s},\ p = \text{MPa}$$

V. PREVIOUS TEST IN CLOSED CHAMBER AT BRL

A series of 15 lots of Army propellants were fired in a 181 cc Dupont Closed Chamber in 1951 at BRL. The chamber was 12 cm (4.72 in.) long and was 4.45 cm (1.75 in.) in diameter. The propellants were single perforated grains, 7-perforated grains and sheets of M1, M2, M6, M15 and M8 composition. These propellants are described in Table V.

Figures 2 through 8 compare these burning rates with the previously described re-extruded standards. The slight disagreement is attributed to small differences in composition. The data plotted on these figures include each of the standard propellants shown in Table II. The line shown is the least square fit of only the closed chamber data. The points within the square symbols are the best fit to the equation $r = bp^n$ for the combined data shown in Table IV. Since only the standard propellant data are available, the figures for the M5 and M10 propellants are presented for information only.

VI. BURNING RATE DATA FROM OTHER AGENCIES

I. During the first quarter of the 20th century, many European agencies conducted burning rate experiments which are summarized in Section 18 of

Table IVA. Least Square Parameters for Various Burning Rate Equations Using Combined Strand Burner and Closed Chamber Results

Standard Army Propellant Type		M1	M2	M5	M6	M8	M10	M17
$r = a+bp^n$	a	.122	.288	.475	-.048	.015	.082	.272
	$b \times 10^4$	.834	2.29	.838	2.87	11.5	2.38	3.38
	n	1.027	1.011	1.100	.924	.878	.955	.930
	ε	.0158	.143	.373	.0167	.0815	.0721	.129
$a+bp$	a	.050	.242	.060	.129	.800	.19	.483
	$b \times 10^4$	1.131	2.572	2.515	1.247	2.968	1.458	1.563
	ε	.0173	.145	.470	.056	.227	.080	.141
$a+bp^{.95}$	a	-.062	-.013	-.189	.019	.499	.046	.278
	$b \times 10^4$	1.964	4.47	4.369	2.182	5.170	2.533	2.715
	ε	.0250	.419	.548	.051	.134	.0702	.153
$a+bp^{.90}$	a	-.187	-.298	-.467	-.116	.169	-.115	.155
	$b \times 10^4$	3.420	7.78	7.609	3.800	9.003	4.420	4.729
	ε	.0429	.243	.706	.053	.089	.0738	.132
$a+bp^{.85}$	a	-.447	-.89	-1.046	-.400	-.515	-.450	-.205
	$b \times 10^4$	6.153	14.00	13.69	6.836	16.199	7.94	8.51
	ε	.0883	.471	1.020	.092	.249	.127	.198
$a+bp^{.80}$	a	-.513	-1.042	-1.195	-.473	-.691	-.537	-.297
	$b \times 10^4$	10.54	23.97	23.44	11.70	27.736	13.59	14.57
	ε	.0979	.505	1.103	.294	.161	.119	.185
bp^n	$b \times 10^4$	1.90	5.316	4.293	2.20	12.00	3.46	9.41
	n	.951	.933	.948	.949	.874	.921	.836
	ε	.0361	.152	.661	.027	.085	.076	.173
bp	$b \times 10^4$	1.146	2.68	2.648	1.280	3.226	1.518	1.715
	ε	.212	.260	1.42	.068	1.447	.512	.608
$bp^{.95}$	$b \times 10^4$	1.931	4.46	4.266	2.16	5.44	2.557	2.890
	ε	.0448	.181	.617	.0185	.579	.0746	.334
$bp^{.90}$	$b \times 10^4$	3.249	7.508	7.179	3.630	9.157	4.305	4.868
	ε	.2305	.386	.982	.037	1.139	.094	.179
$bp^{.85}$	$b \times 10^4$	5.461	12.62	12.06	6.102	15.402	7.238	8.189
	ε	.4677	.904	1.73	.1311	.152	.220	.148
$bp^{.80}$	$b \times 10^4$	9.347	21.27	20.32	10.282	25.961	12.195	13.805
	ε	1.857	1.778	2.72	.309	.679	.467	.259

Units r in./s

a in./s

b in./s/(psi)^n

$\varepsilon = \Sigma (r_c - r_e)^2$

r_c = calculated

r_e = experimental

Table IVB. Least Square Parameters for Various Burning Rate Equations Using Combined Strand Burner and Closed Chamber Results

Propellant Type		M1	M2	M5	M6	M8	M10	M17
$\dot{r} = a+bp^n$	a	3.099	7.315	12.065	-1.219	.381	2.083	6.909
	b	.351	.891	.508	.724	2.308	.701	.879
	n	1.027	1.011	1.100	.924	.878	.955	.930
$a+bp$	a	1.270	6.147	1.524	3.276	20.320	4.826	12.268
	b	.417	.947	.926	.459	1.093	.537	.576
$a+bp^{.95}$	a	-1.574	-3.302	-4.801	.482	12.675	1.168	7.061
	b	.564	1.284	1.255	.627	1.485	.727	.780
$a+bp^{.90}$	a	-4.750	-7.569	-11.862	-2.946	4.292	-2.921	3.937
	b	.766	1.742	1.704	.851	2.016	.990	1.059
$a+bp^{.85}$	a	-11.353	-22.606	-26.568	-10.160	-13.001	-11.430	-5.207
	b	1.074	2.444	2.390	1.193	2.828	1.386	1.486
$a+bp^{.80}$	a	-13.030	-26.466	-30.353	-12.014	-17.551	-13.640	-7.544
	b	1.435	3.263	3.191	1.593	3.781	1.850	1.983
bp^n	b	.548	1.403	1.221	.629	2.361	.860	1.532
	n	.951	.933	.948	.949	.874	.921	.836
bp	b	.422	.987	.975	.471	1.188	.559	.632
$bp^{.95}$	b	.554	1.281	1.225	.620	1.562	.734	.830
$bp^{.9}$	b	.727	1.681	1.607	.812	2.050	.964	1.090
$bp^{.85}$	b	.953	2.203	2.105	1.065	2.689	1.264	1.430
$bp^{.80}$	b	1.272	2.895	2.766	1.400	3.534	1.660	1.879

Units
r mm/s
a mm/s
b $mm/s/(MPa)^n$

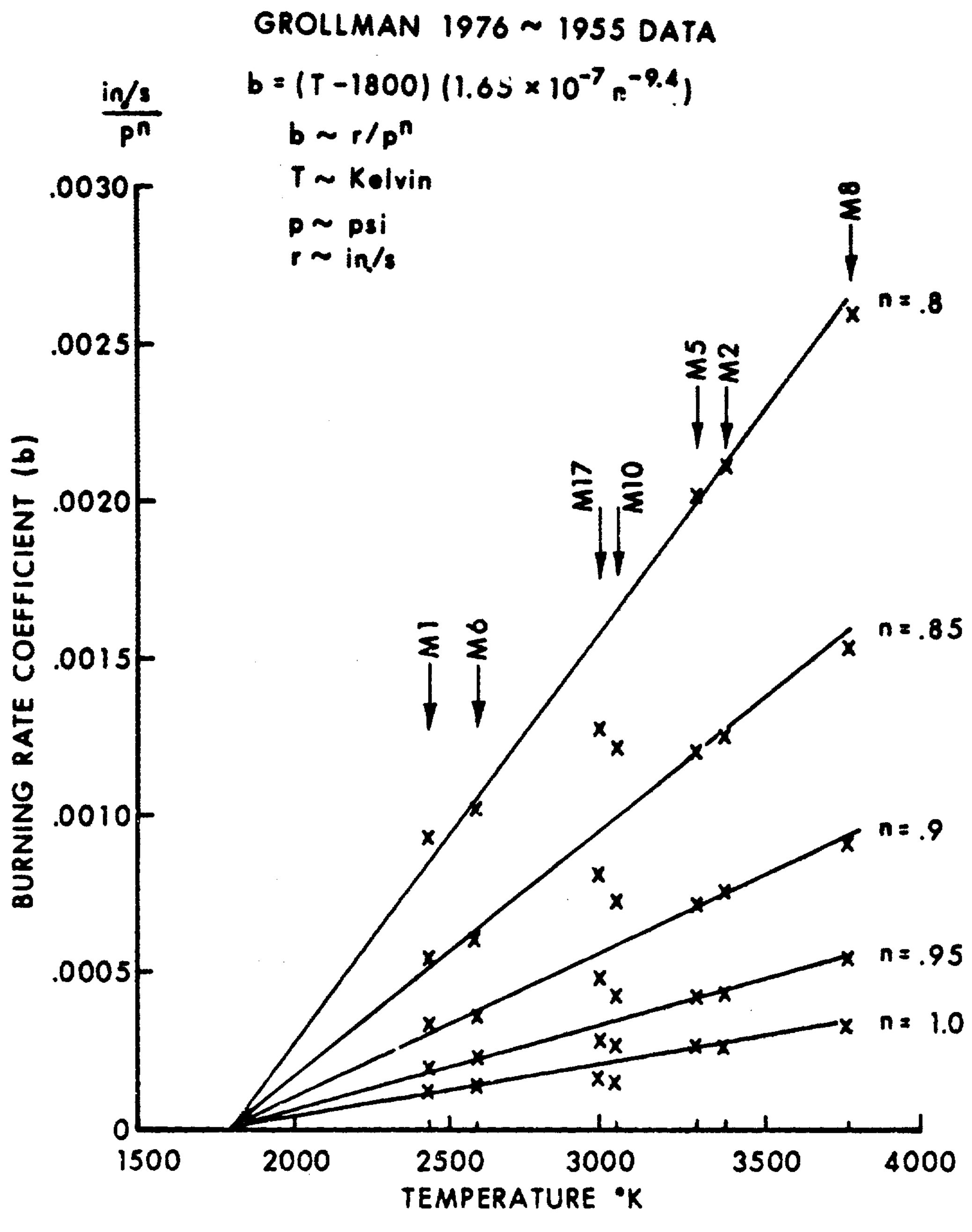

Figure 1A. Correlation of Burning Rate Coefficient with Flame Temperature

$$b = (T - 1800)(4.13 \times 10^{-6})(145^n)\,n^{-9.4}$$

$r = bp^n \qquad r = mm/s$

$p = MPa$

$$b = \frac{mm/s}{(MPa)^n}$$

$T = Kelvin$

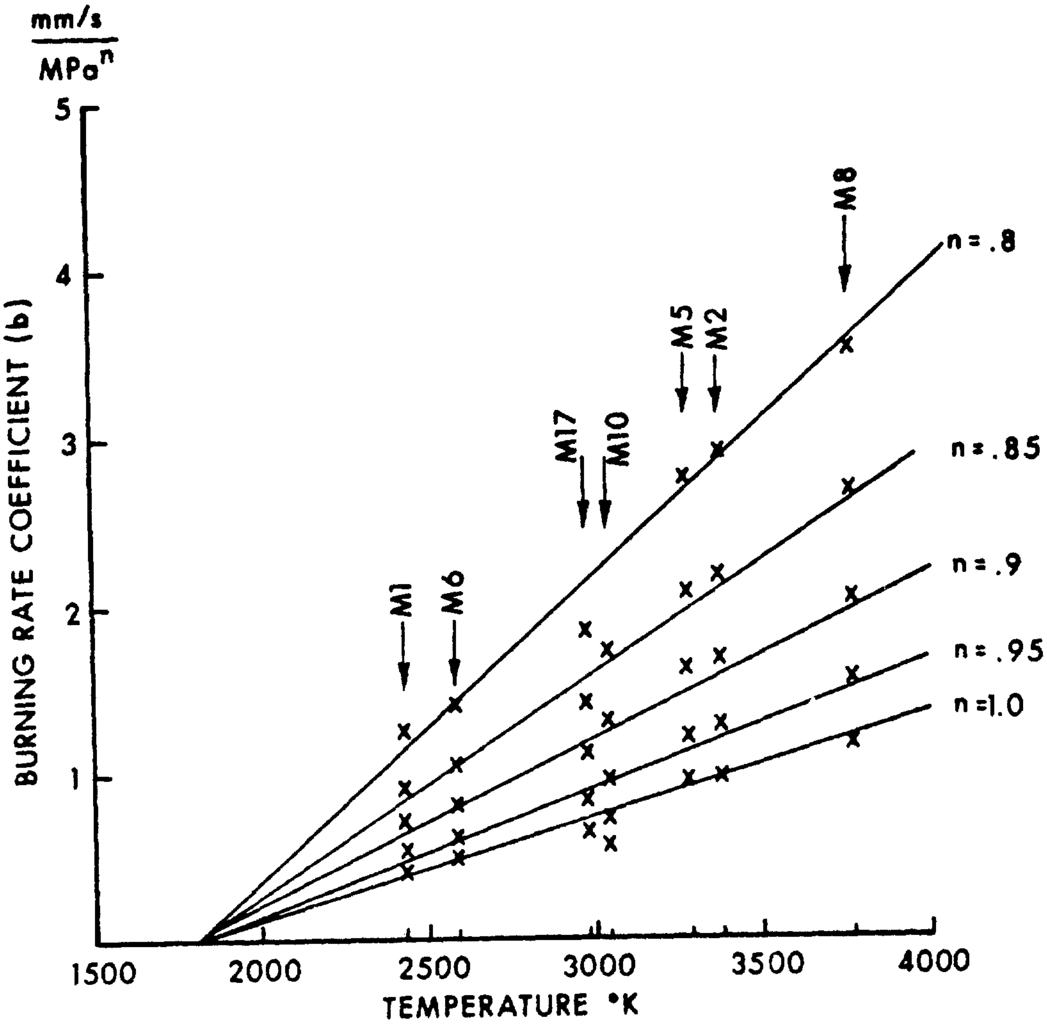

Figure 1B. Correlation of Burning Rate Coefficient with Flame Temperature

Table V. Description of Additional Closed Chamber Lots

Army Lot No.	X6658	10793	X5677	4258	302	5316	5280	19582	3727	EX6526	14085	9607	16395	208	EXA6298
Propellant Type	M1	M1	M1	M2	M2	M2	M2	M2	M6	M6	M6	M8	M8	M8	M15 (T7)
Nitrocellulose	84.17	83.15	84.36	75.09	75.08	76.04	75.98	75.44	85.44	85.02	85.91	52.28	5226	51.83	20.10
% Nitrogen	13.14	13.14	13.16	13.23	13.23	13.23	13.22	13.23	13.14	13.13	13.15	13.23	1324	13.21	13.15
Nitroglycerin				19.34	20.67	20.76	20.70	20.26				42.86	42.62	43.19	17.14
Barium Nitrate				1.37	1.36	1.47	1.44	1.40							
Potassium Nitrate				0.94	0.98	0.92	0.99	0.98				1.25	1.13	1.31	
Nitroguanidine															56.80
Dinitrotoluene	(14.84)	(14.92)	(14.61)	1.06	0.96	(in NC)	(in NG)	.99	(12.97)	(13.83)	(13.04)				
Dibutylphthalate															
Diphenylamine	0.99	0.99	1.02	0.58	0.68	0.53	0.63	0.68	0.98	1.00	1.05	0.71	0.73	0.69	
Ethyl Centralite															5.75
Graphite				0.46	0.27	0.28	0.26	0.25							
Cryolite															.21
Ethyl Alcohol	0.07	0.30	- 0.26	0.30	0.57	1.12	1.85	2.65	0.13	0.21	0.45				
Water	0.46	0.49	0.51	0.86	0.36	0.27	0.29	0.33	0.60	0.60	0.42	0.17	0.23	0.16	
Diethylphthalate												2.92	3.26	2.96	
Potassium Sulphate		0.94													
Manufacturer	IOW	IOW	IOW	HK	HR	HR	HR	HR	DuPont	DuPont	OOW	HR	HR	HR	DuPont
Date	1942	1943	1941	1941	1944	1942	1942	1940	1933	1948	1943	1944	1944	1944	1946
Length in.	.2828	.2790	.3617	.0472	.1290	.2500	.4320	1.1780	.0048	.3401	.5204	2.817	2.624	9.910	
Diameter in.	.0476	.0660	.1422	.0363	.0547	.0691	.2032	.5322	.0336	.1429	.2155	2.706	2.695	0.509	
Perforation Diameter in.	.0184	.0192	.0157	.0067	.0119	.0089	.0142	.0638	.0084	.0141	.0217	1.342	1.340		
Inner Web in.	.0146	.0234	0230	.0148	.0214	.0301	.0403	.0838	.0126	.0244	.0368	.0202	.0255	.0463	.014
Outer Web in.			0246				.0400	.0866		.0258	.0384				
Average Web In.			0238				.0402	.0852		.0251	.0376				
Granulation	SP	SP	MP	SP	SP	SP	MP	MP	SP	MP	MP	Square	Square	Slab	Cord Reextruded

IOW Indiana Ord Works
HR Hercules Radford
OOW Oklahoma Ord Works
HK Hercules Kenvil

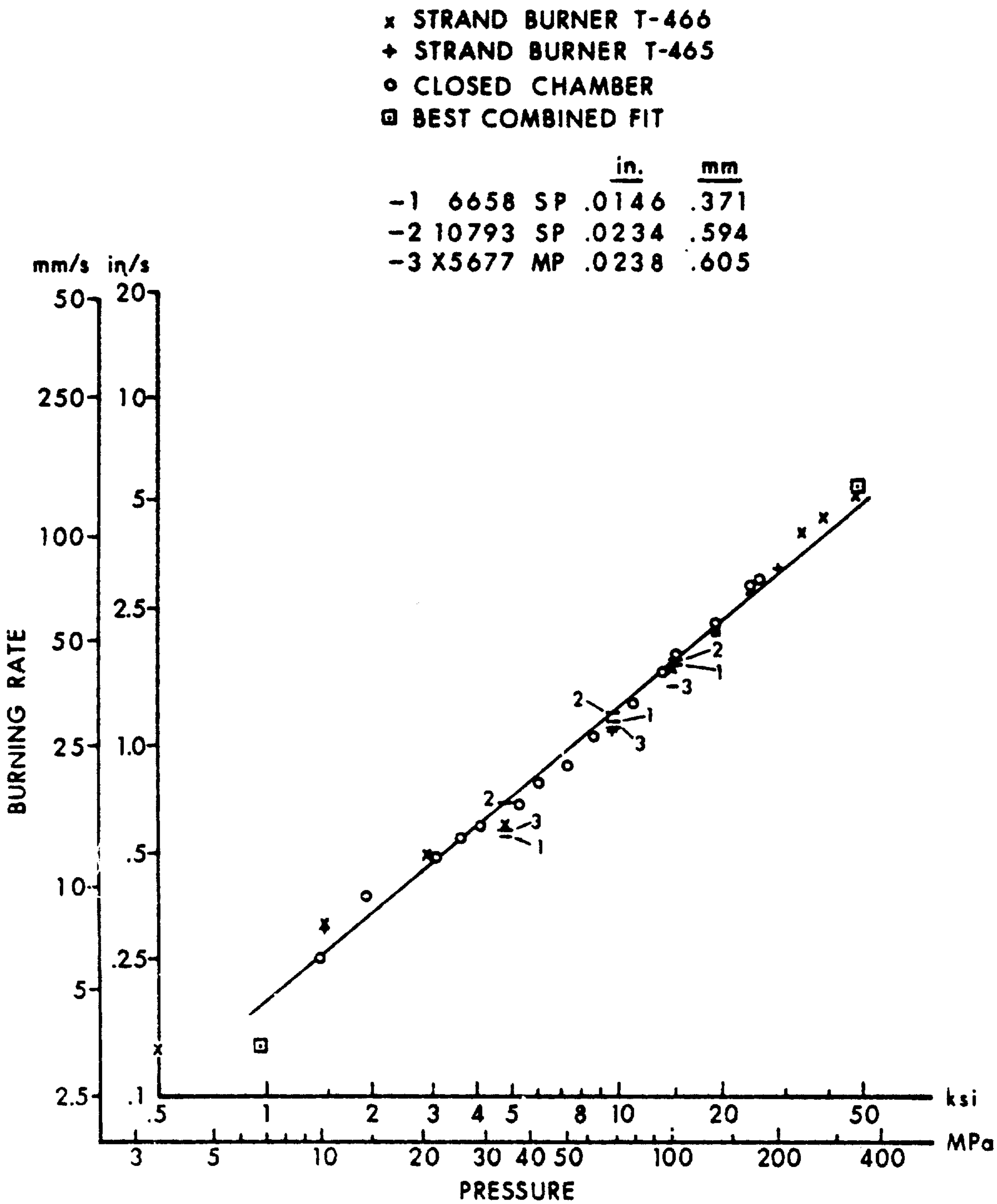

Figure 2. Burning Rate Comparison for M1

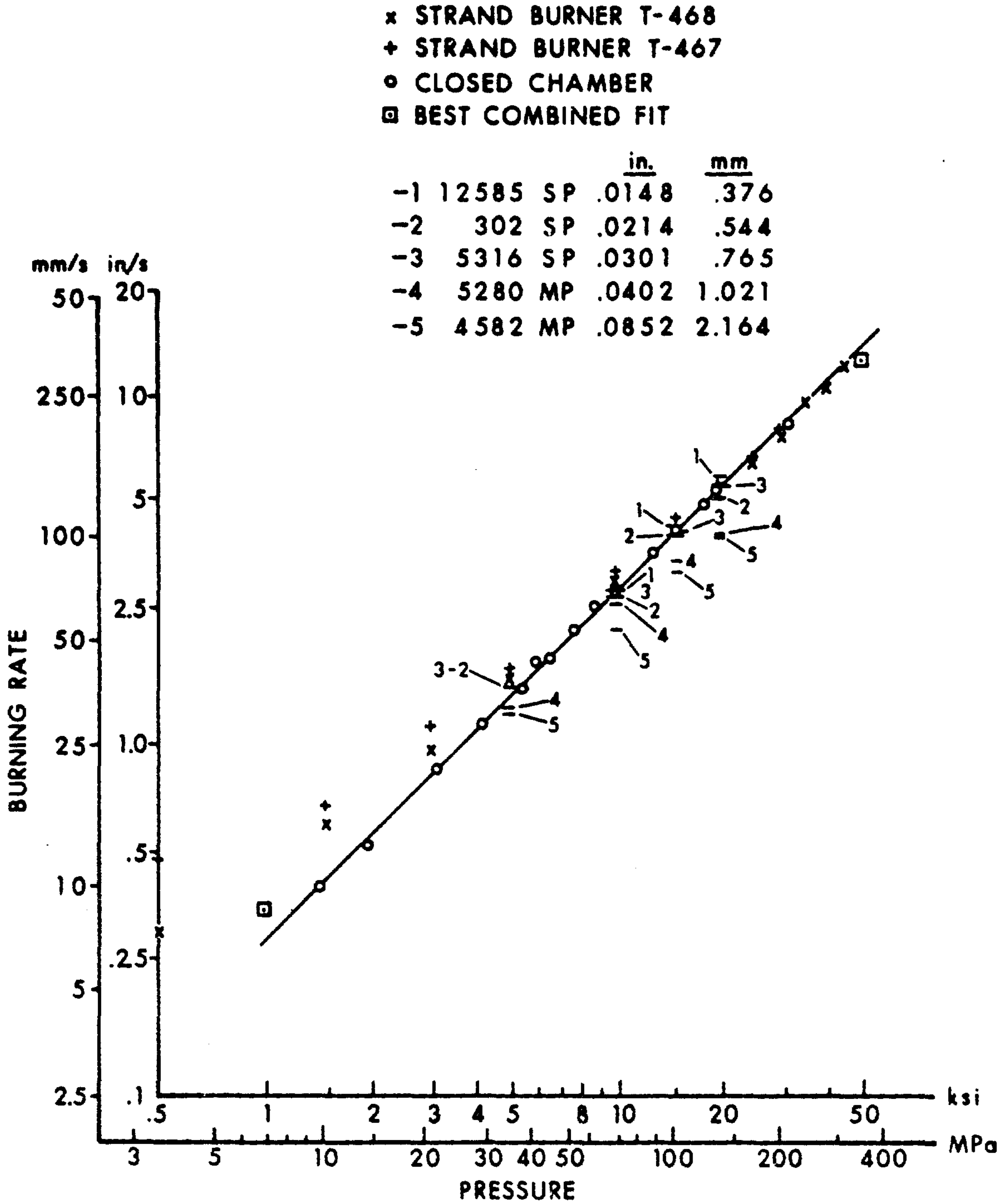

Figure 3. Burning Rate Comparison for M2

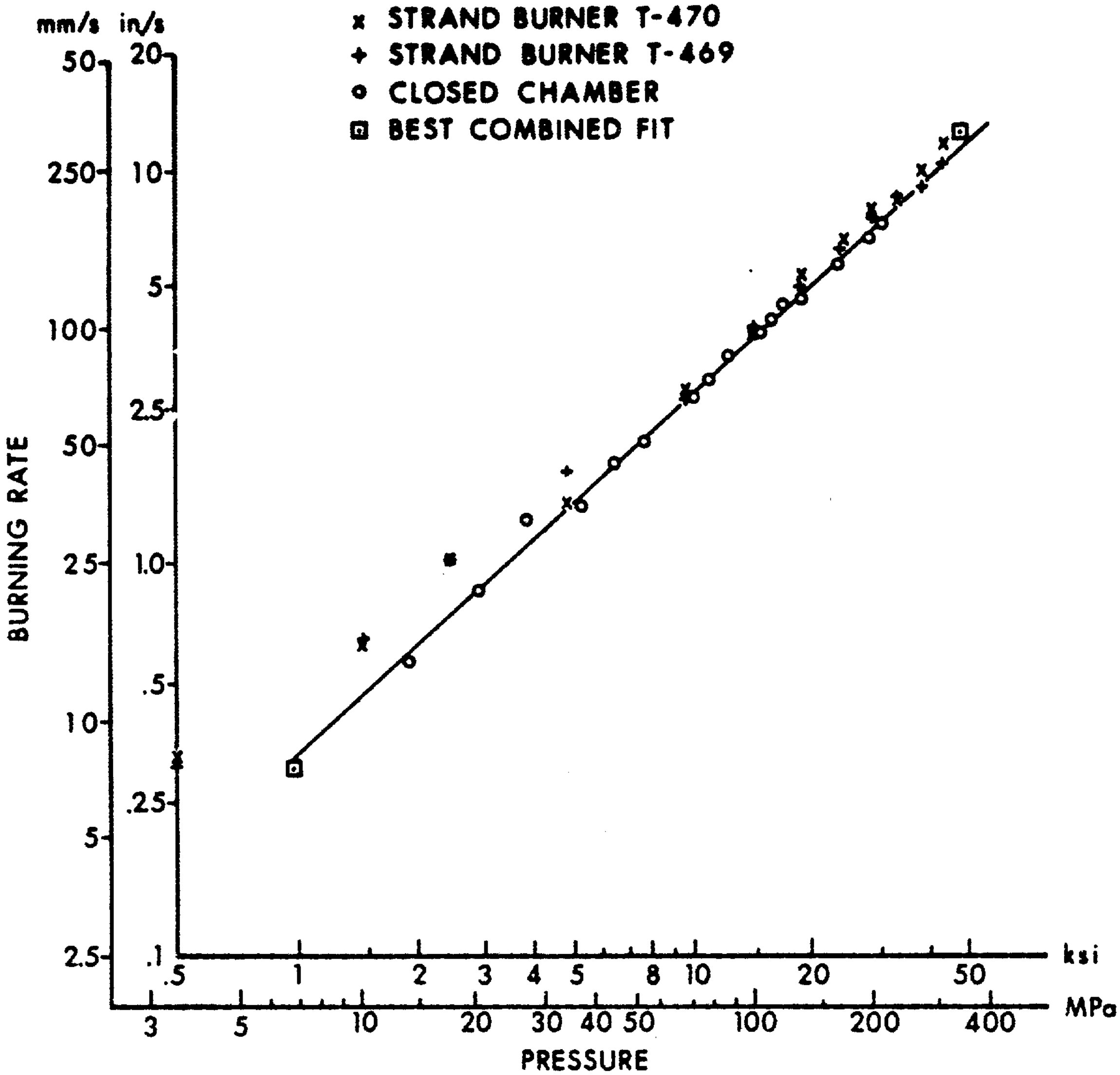

Figure 4. Burning Rate Comparison for M5

Figure 4. Burning Rate Comparison for M5

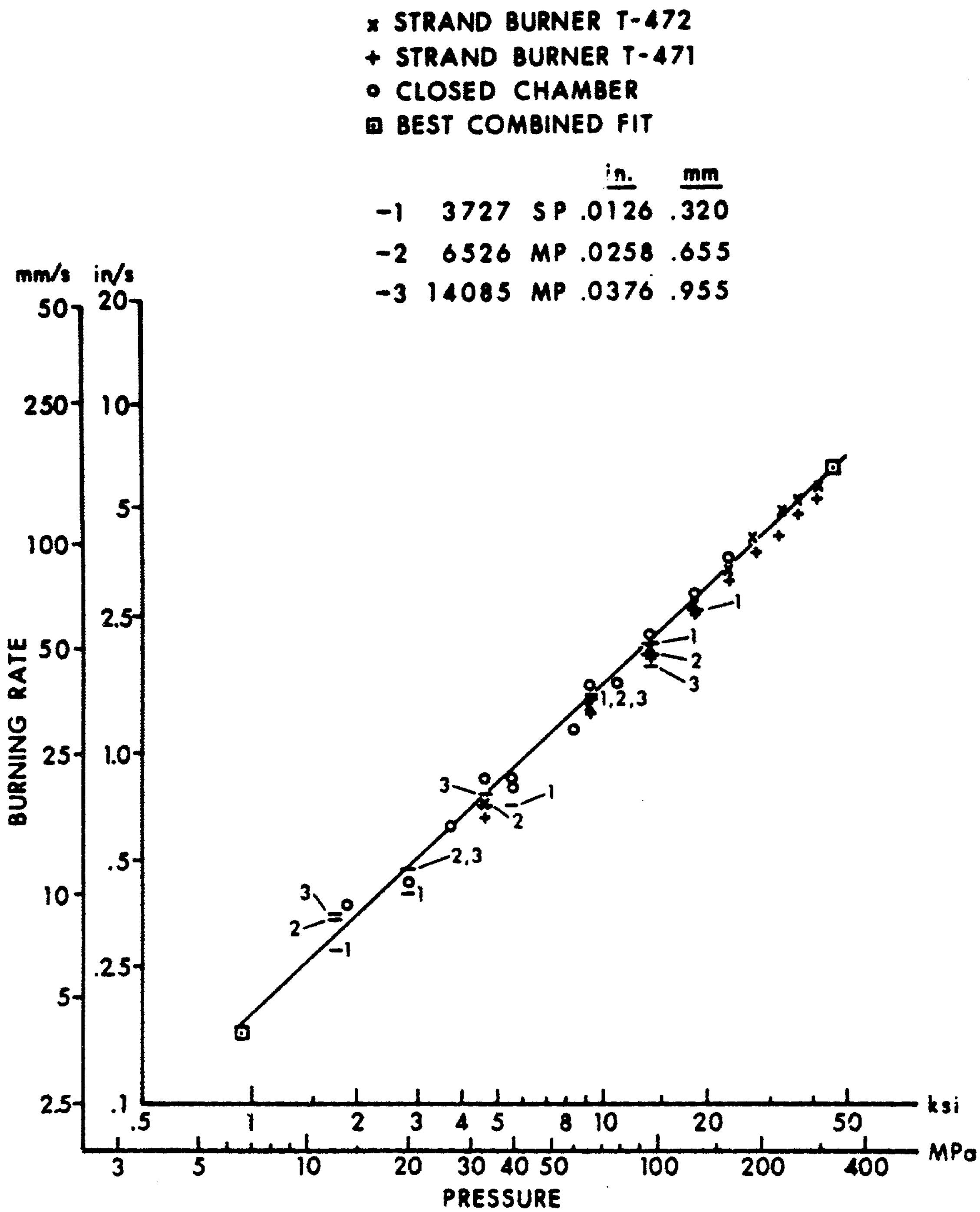

Figure 5. Burning Rate Comparison for M6

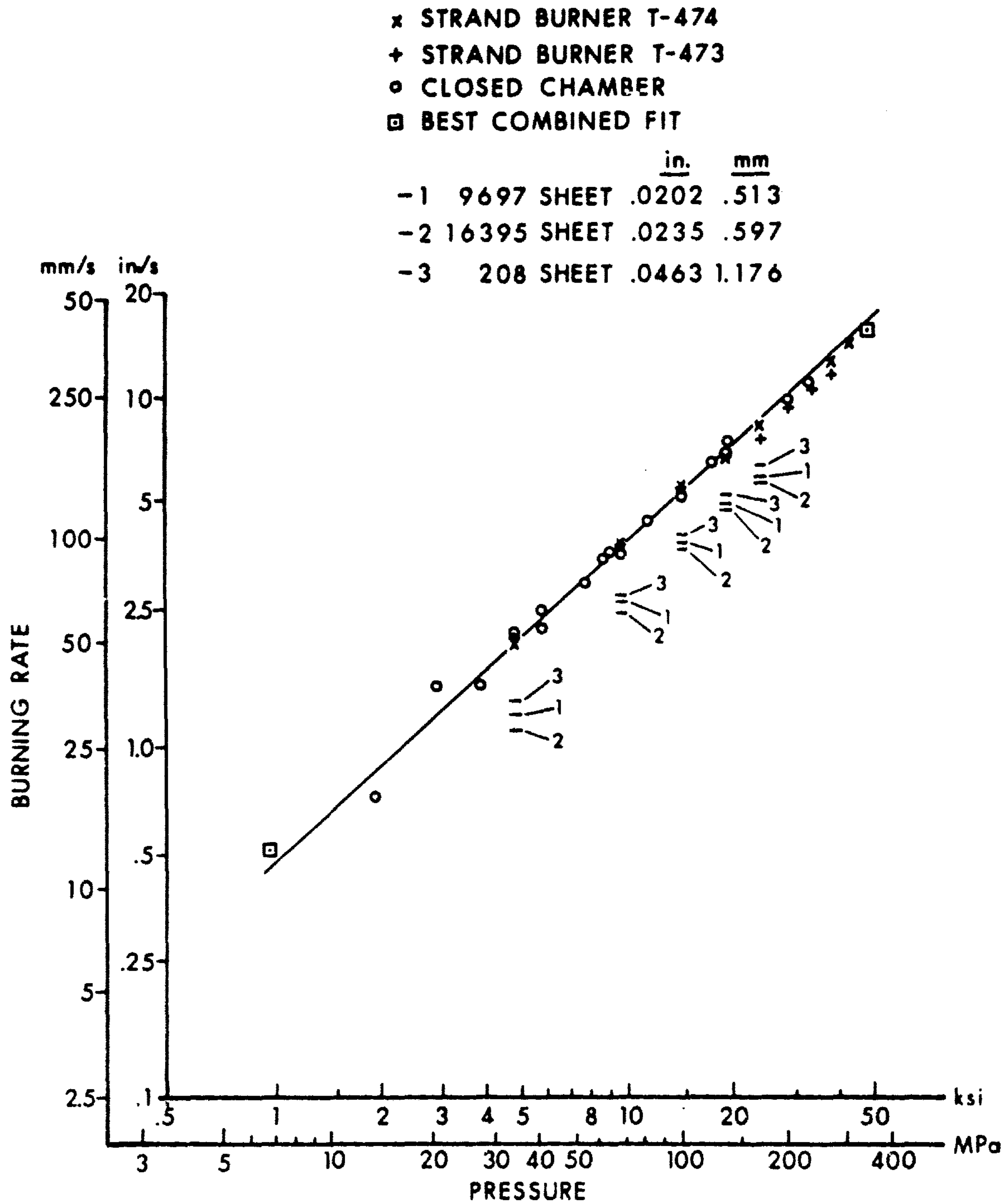

Figure 6. Burning Rate Comparison for M8

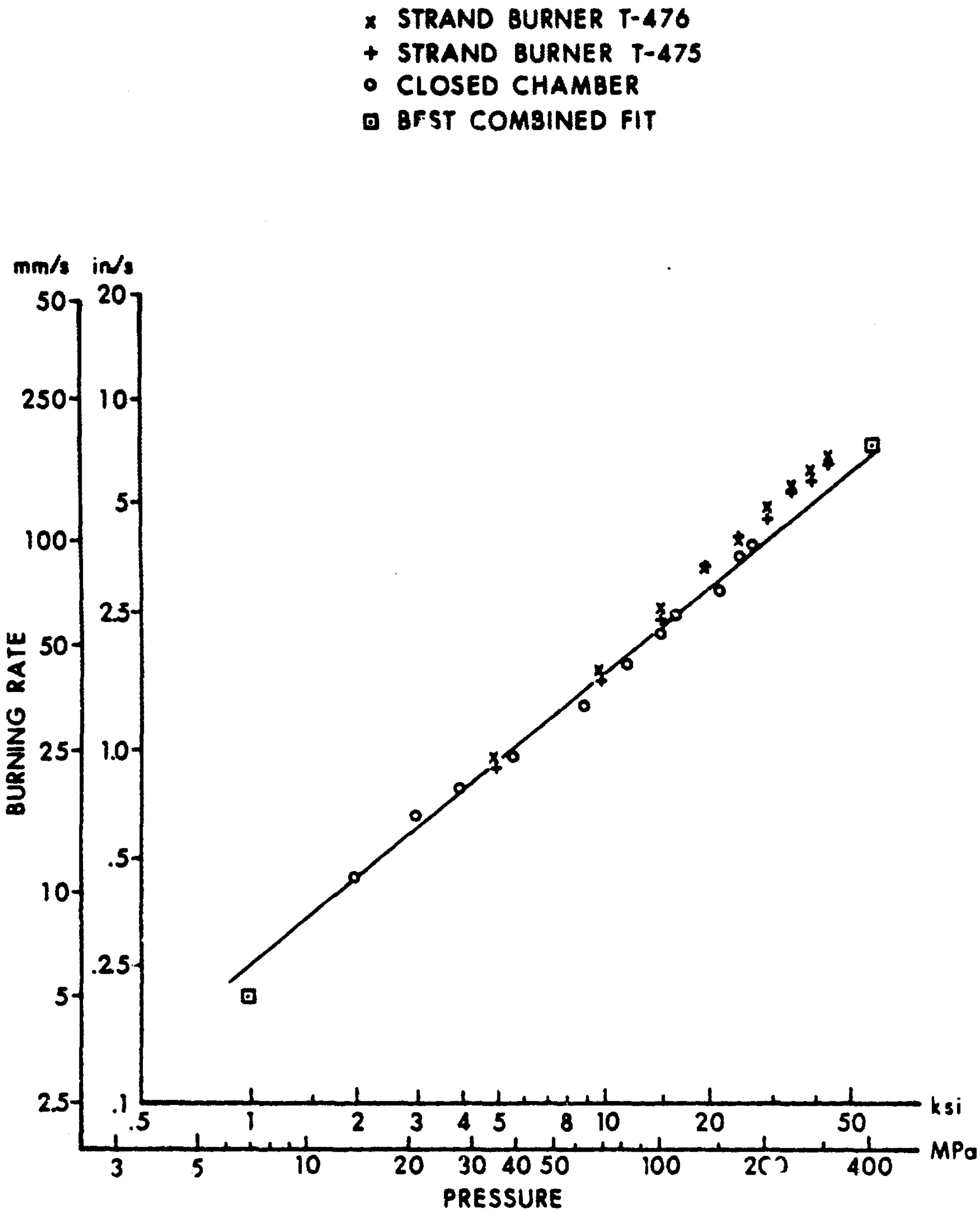

Figure 7. Burning Rate Comparison for M10

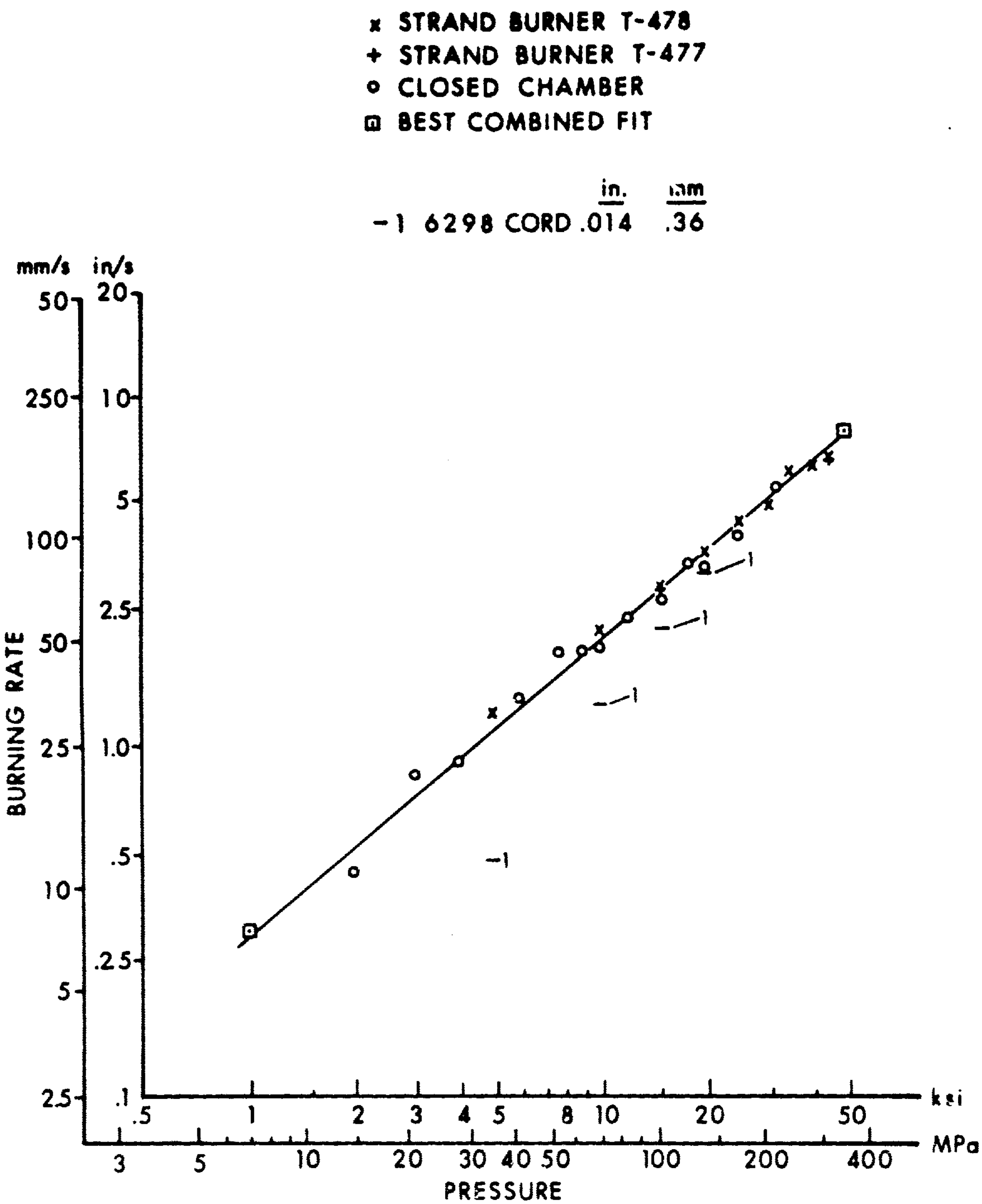

Figure 8. Burning Rate Comparison for M17

Cranz[5], 1925. These rates for the NC propellant, which is similar to M1 propellant, were close to our measured values. In 1917, Col. Tschappat[6] of the USA published the following:

The specific rate of combustion (k') is the regression normal to the surface of the propellant burning in its own gas at a pressure of one pound per square inch. It is proportional to the energy per pound of propellant (n') and is inversely proportional to the sum of the following:

(1) The energy required to heat a pound of propellant to the ignition temperature.

(2) The energy required to evaporate the water and alcohol from the propellant.

His equation (6) is

$$k' = \frac{.00000677n'}{87.5\ (356^{\circ}F - \text{Temp of Prop}) + 8400\ (\%\ H_2O) + 2980\ (\%\ \text{alcohol})}$$

The value of k' agrees with our presented coefficient for M1.

He experimentally determined k' by placing several large grains in gun charges and measured the regressed distance in the recovered grains. His equation (9) was used to calculate the value of k' and it agreed for the several weapons tested. Then he determined the coefficients in the previous equation (6).

II. Geckler has a thorough treatment of combustion[7]. He tabulated the data of several investigators, and the results of Muraour are of particular interest. Both strand burner and closed chamber results are shown but unfortunately are not for identical propellants. The equations in section 2.4 relating the burning rate coefficients to the flame temperature of the propellants provide a very good fit to the data presented in Table II.

These equations are

$$r = 0.2 + 0.0000212e^{.709(T/1000)}p;\ r = \text{in./s},\ p = \text{psi}$$

$$r = 5.0 + 0.078e^{.709(T/1000)}p;\ r = \text{mm/s},\ p = \text{MPa}$$

---

[5] *C. Cranz, "Lehrbuch der Ballistik," Bd II, Innere Ballistik, Springer, Berlin, 1926, translated NDRC, 1945.*

[6] *W. H. Tschappat, "Text Book of Ordnance and Gunnery," Wiley, New York, 1917.*

[7] *R. D. Geckler, "Selected Combustion Problems," AGARD, "The Mechanisms of Combustion of Solid Propellants," Butterworths, London 1954, pp. 289-299.*

III. **The composition of small arms propellants varies during burning as a result of the change in concentration of nitroglycerin (NG), nitrocellulose (NC) and the deterrent coating dibutylphthalate (DBP). As a consequence, BRL had a contract with Olin Corporation in 1974 to conduct closed chamber firings to provide burning rates for the interior ballistic prediction codes for small arms[8]. The work included manufacturing 16 lots of propellant in two web sizes with 0 or 10% NG and with 0, 5, 10 and 15% DBP. Five samples of each propellant composition were burned in a closed chamber at a density of loading calculated to achieve a no heat loss maximum pressure of 180 MPa (26,000 psi). The smaller web for each propellant was also burned at 60% and 80% of the full charge. The raw data are reported as well as the calculated burning rates. Chemical analyses and thermochemical properties of all the propellants are tabulated in the Olin Corporation report.**

The data for all the full charge firings were combined to obtain the linear burning rate constants as functions of propellant composition.

$$r = bp^n$$

$$\log_e r = \log_e b + n \log_e p$$

$$\log_e b = A_o + A_1 (\%\ DBP) + A_2 (\%\ NG) + A_4 (web)^2$$

$$n = n_o = n_1 (\%\ DBP) + n_2 (\%\ NG) + n_3 (web) + n_4 (web)^2$$

The web effect was very small and the following coefficients and exponents best fit the data:

	r (in./s), p (psi)	r (mm/s), p (MPa)
Constant Coefficient	$b = 9.833 \times 10^{-4}$	$b = 0.0250(145)^n$
	$n_o = 0.83881$	0.83881
	$n_1 = 0.00581$	0.00581
	$n_2 = 0.00175$	0.00175
Constant Exponent	$A_o = 6.61822$	0.62429
	$A_1 = -0.052882$	-0.052882
	$A_2 = 0.015907$	0.015907
	$n = 0.80530$	0.80530

[8] *D. W. Riefler, "Linear Burn Rates of Ball Propellants Based on Closed Bomb Firings," BRL CR 172, Olin Corporation, Aug 1974.* (AD #921704L)

The Olin constant exponent equation fits the BRL data very well; even though the BRL M8 composition has four times the NG content of that tested by Olin and the pressure levels were approximately twice that obtained by Olin.

VII. CONCLUSIONS

1. The burning rates calculated from strand burner and closed chamber data agree for identical propellants; however, the burning rates can be altered due to lot-to-lot variations in propellant ingredients.

2. The burning rate coefficient and exponent can be correlated to the calculated adiabatic flame temperature for the various types of propellant.

3. The burning rate coefficient and exponent are not independent.

REFERENCES

1. F. C. Kracek, "Hypervelocity Guns and the Control of Gun Erosion," Part II Ballistics, Chapter 2, NDRC, Washington, D. C., 1946, pp. 21-53.

2. R. H. Kent, "Report on Determination of Interior Ballistic Data by Closed Chamber Experiments in Connection with Project RB158," BRLR 32, Jan 1936.

3. R. H. Kent, J. P. Vinti, "Cooling Corrections for Closed Chamber Firings," BRLR 281, Sep 1942. (AD #491852)

4. J. H. Wiegand, "A Method for the Calculation of the Burning Rate of Powders from dp/dt Records for Closed Chambers," BRLR 546, May 1945.

5. C. Cranz, "Lehrbuch der Ballistik," Bd II, Innere Ballistik, Springer, Berlin, 1926, translated NDRC, 1945.

6. W. H. Tschappat, "Text Book of Ordnance and Gunnery," Wiley, New York, 1917.

7. R. D. Geckler, "Selected Combustion Problems," AGARD, "The Mechanisms of Combustion of Solid Propellants," Butterworths, London, 1954, pp. 289-299.

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