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COMPARISON OF PERFORMANCE OF A DOUBLE-CORNERED PLUG NOZZLE WITH A CONVENTIONAL CONVERGENT-DIVERGENT ROCKET NOZZLE

Arnold T. Stokes

Army Missile Command
Redstone Arsenal, Alabama

30 June 1972

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Directorate for Research, Development, Engineering
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ABSTRACT

This report presents performance data for double-cornered plug nozzles for comparison with convergent-divergent nozzles. A conventional convergent-divergent (C-D) nozzle was used to develop the propellant charge, ignition and ballistics, and as a baseline for plug nozzle performance evaluation.

CONTENTS

I. INTRODUCTION

The main objective of this program was to demonstrate the feasibility of using a double-cornered plug nozzle to provide combined thrust modulation control and thrust vector control in a solid rocket used in advanced interceptor missiles. The demonstration nozzles were not required to demonstrate Thrust Modulation Control and Thrust Vector Control (TMC/TVC), but were required to operate in a temperature and aluminum particle environment which approximates that of advanced long-range missiles.

The "fixed" nozzles incorporated adjustable means whereby the throat area was fixed at the design value of 1.18 in.^{2} for a first series of test firings; the position of the plug was then adjusted to provide a new throat area of 1.77 in.^{2} and firing tests repeated. Data were taken so that nozzle efficiencies of the double-cornered plug nozzle configuration may be computed for both the design and off-design condition.

The motor design requirements were:

Propellant aluminum content	- 20%
Aluminum oxide particles	- 40%
Flame temperature	- 5700°F
Ratio of specific heats	- 1.18
Nozzle throat areas	- 1.18 in.^{2} and 1.77 in.^{2}
Nozzle expansion ratio	- 6.3
Chamber pressure	- 600 psia
Test duration	- 5 seconds.

Although the nozzle is fixed and does not move for this phase of the program, the program is referred to as Movable Cowl Development (MCD).

II. DISCUSSION

A. Conventional Nozzle

The conventional nozzle body was fabricated from 4130 steel. The nozzle throat was an insert ring of 80% tungsten and 20% copper. The insert was placed in high density graphite. The entrance cone was insulated with RPD asbestos phenolic molded in place. See Figure 1 for the motor assembly drawing with conventional nozzle and Figure 2 for the motor with conventional nozzle before assembly.

Several runs were made with each insert, both at 1.18 $in.^2$ throat area and at 1.77 $in.^2$ throat area. During firings the tungsten-copper insert throat area would decrease. Particle deposition would build up in the throat and some erosion of the insert was experienced. These factors prevented an accurate throat diameter measurement after the first firings. Figure 3 shows a conventional nozzle forward end after firing and Figure 4 shows the conventional nozzle aft end after firing.

B. Case and Head End Plate

The case and head end plate were fabricated from 4130 steel and were common for each type of nozzle. The case provided two threaded holes for pressure gages. The head end plate provided a boss for the thrust gage. See Figures 1, 2, 8, and 10.

C. Liner

The liner between the nozzle and case was fabricated from RPD asbestos phenolic and contains two holes to match with the two threaded holes in the case. The liner length was adjusted as the propellant length changed. Figures 1, 2, 8, and 10 show this.

D. Propellant Charge

The propellant was manufactured at Radford Army Ammunition Plant and was Lot RAD-PE-342. The propellant was a cast double-base designated as DGV (DDP-70). A composite modified double-base 2056D casting powder with 50% NG casting solvent was cast into a phenolic beaker. Forty and fifty percent NG casting solvent was tried and the 50% NG solvent gave the desired flame temperature, burning rate, and burning surface/throat area (K_n) relationships. See Figure 5 for flame temperature versus percent NG in casting solvent. The propellant inside diameter was 3.46 $in.^2$, the outside diameter was 8.40 in., and the beaker thickness was 0.2 in. and remained constant throughout the program. The propellant length was reduced to lower the burning surface/throat area (K_n) thereby reducing the chamber pressure. The propellant length that gave the most desired ballistics was 8 in. This may be seen in Figures 1, 2, 8, and 10. It was necessary to increase the K_n for the motors with the 1.77 $in.^2$ throat area. This was accomplished by machining concentric grooves in the propellant as shown in Figures 6 and 7. The burning rate equation for this propellant is $r = 0.031457 P^{0.4323}$.

E. Double-Cornered Plug Nozzle (Dynetics, Inc.)

The double-cornered plug nozzle was designed and fabricated by Dynetics, Inc., Mountain Lakes, N.J. This nozzle design considers particle dynamics as well as gas dynamics. The plug nozzle was designed for use with metallized propellants whose products of combustion yield two-phase flow. The curve and plug nozzle inserts were fabricated from tungsten-silver material having the potential of eliminating the problem of high velocity particle impact on the isentropic surface. The nozzle was adjusted to provide a throat area of 1.18 in.^{2} for the base-design and 1.77 in.^{2} for the off-design. See Figures 8 through 12.

F. Igniter

The igniter consisted of a Parafilm bag with ignition material, ignition pellets bonded to the motor head end plate, and ignition pellets bonded to the liner as shown in Figures 2 and 10. The bag contained the following charge:

8.0 grams of black powder (Class 3)

4.0 grams of black powder (A-5)

10.0 grams of TCA-22 powder

4.2 grams of TCA-22 pellets

8.0 grams of 2R pellets.

The pellets bonded to the head end plate were one 2L pellet, four TCA-22 pellets, and eight 3D pellets. The pellets bonded to the liner were two 2L pellets, twelve TCA-22 pellets, and sixteen 3D pellets.

III. NOZZLE PERFORMANCE RESULTS

Runs were made with the conventional nozzle to develop the ballistics required for the plug nozzle The propellant charge length was made shorter to reduce the chamber pressure. Ignition pellets were placed around the liner and also on the head end plate to increase the pressure rise rate and to obtain a more uniform propellant burning.

A high pressure problem was experienced early in the program caused by unbonding of the head end RPD propellant inhibitor plate. The partial bonded plate permitted additional propellant surface to burn thus increasing chamber pressure. A "quick fix" was to bond a plug inside the propellant cavity to prevent the burning of propellant under the plate; this "fix" was unsatisfactory. Next the RPD propellant inhibitor plate was omitted and an epoxy inhibitor used; this solved the high pressure problem. See Table I for ballistic data for each run and Figures 13 through 31 for pressure and thrust versus time curves for each run.

Erosion was experienced on the plug during the motor firing and even more during the off-design run. The outer ring, or cowl, eroded only slightly during motor firings as evidenced in Figures 32, 33, and 34.

Another problem was encountered when the nozzle throat area was increased from 1.18 in.^{2} to 1.77 in.^{2}. Erratic propellant burning was experienced because of the low burning surface/throat area (K_n). The first attempt to correct this problem was to machine 11 concentric grooves 1/4 in. deep by 1/4 in. wide inside the propellant cavity as shown in Figure 6. This improved the burning characteristics but was still unsatisfactory. Next six concentric grooves 1/2 in. deep by 1/4 in. wide were machined inside the propellant cavity (Figure 7). Acceptable pressure and thrust versus time records were obtained with this design. Runs 18 through 21 were conducted with this propellant charge design.

IV. CONCLUSIONS

The double-cornered plug nozzle is less efficient at the base design than a convergent-divergent (C-D) nozzle. The efficiency gap is somewhat less at the off-design throat area. The plug was badly eroded during each run and was eroded even more during the off-design run. Improvements for the double-cornered plug nozzle may be made by streamlining the internal struts. Another possibility is to make a convergent-divergent plug. This should straighten the gas flow and reduce erosion of the plug. Some of the loss in efficiency may be attributed to the boundary layer on the nozzle surface. The surface is greater for a plug nozzle than it is for a convergent-divergent nozzle. For this program, the thrust data points were considered when the chamber pressure was 600 psi for the base-design throat area and 300 psi for the off-design throat area. The effective throat area would be less than the designed throat area when the motor pressure was at the designed value. The smaller effective throat area would reduce the thrust value when the motor is operating at the designed pressure level. These data indicate that the plug nozzle is less efficient than a conventional convergent-divergent nozzle.

Table I. Ballistic Data

MCD No.	Date Fired	Nozzle Area, Nominal (in.^{2})	Propellant Weight (lb)	Web (in.)	Max K_n	Avg. K_n	Maximum Pressure (psig)	Average Pressure (psig)	$\int Pdt$ (psig-sec)	Maximum Thrust (lb)	Average Thrust (lb)	$\int Fdt$ (lb-sec)	Action Time (sec)	Delivered Specific Impulse (sec)	Force @ 600 psig (lb)	C_F @ 600 psig
1	1 Dec 71	1.18	25.63	2.471	139	133	718	653	3110	1394	1191	5671	4.760	221.26	1062	1.50
2	2 Dec 71	1.18	24.71	2.478	139	133	737	652	3181	1394	1187	5790	4.877	234.32	1062	1.50
3	17 Dec 71	1.18	23.80	2.491	134	128	756	548	2993	-	-	-	5.457	-	-	-
4	22 Dec 71	1.18	23.84	2.464	134	128	870	587	2999	1559	1035	5287	5.108	221.77	1065	1.50
5	12 Jan 72	1.18	23.64	2.470	134	128	728	553	2897	1314	963	5046	5.240	213.45	1051	1.48
6	12 Jan 72	1.18	23.95	2.472	134	128	820	619	3103	1480	1075	5390	5.013	225.05	1042	1.47
7D	12 Jan 72	1.18	24.10	2.490	134	128	801	599	3070	1292	915	4689	5.124	194.56	920	1.30
8D	13 Jan 72	1.18	23.77	2.480	134	128	1306	730	3506	1826	991	4756	4.798	200.08	832	1.18
9	20 Jan 72	1.18	24.01	2.483	134	128	729	660	3129	1284	1128	5349	4.740	222.78	1013	1.43
10	22 Feb 72	1.18	23.70	2.471	134	128	705	636	3150	1237	1061	5352	4.949	225.82	1021	1.44
11	22 Feb 72	1.18	23.47	2.459	130	116	623	533	2912	1100	897	5069	5.459	215.98	1069	1.51
12	24 Mar 72	1.18	23.14	2.465	130	116	668	598	2938	1176	1037	5093	4.910	220.10	1041	1.47
13	24 Mar 72	1.18	23.32	2.480	130	116	702	601	2885	1227	1068	5124	4.800	219.70	1001	1.41
14D	27 Mar 72	1.18	23.13	2.466	130	116	667	583	2951	1081	928	4698	5.060	203.10	936	1.32
15D	27 Mar 72	1.18	23.16	2.467	130	116	586	526	2803	988	869	4630	5.330	199.91	942	1.33
16	20 Apr 72	1.77	23.12	2.468	87	78	200	-	-	-	-	-	-	-	-	-
17	27 Apr 72	1.77	22.57	2.468	111	-	344	-	-	-	-	-	-	-	-	-
															Force @ 300 psig (lb)	
18	3 May 72	1.77	22.54	2.465	118	-	397	287	1863	899	649	4216	6.500	187.95	676	1.27
19	19 May 72	1.77	22.54	2.467	118	-	418	279	1719	955	643	4388	6.149	194.68	720	1.36
20D	6 Jun 72	1.77	23.18	2.481	118	-	370	260	1519	923	625	3651	5.839	157.50	760	1.43
21D	6 Jun 72	1.77	22.59	2.470	118	-	381	316	1854	902	735	4312	5.865	190.97	722	1.36

Notes: MCD 1 through 6, 9 through 13, and 16 through 19 used C-D nozzles; MCD 7, 8, 14, and 15 used Dynetics, Inc. plug nozzle.
MCD 5 through 8 had 1-1/4 in. long plug bonded to the head end propellant cavity.
MCD 3 through 8 had propellant head end inhibitor unbond.
MCD 3 thrust data not valid.
MCD 16 and 17 operated at low erratic pressure; data not reduced.
MCD 17 propellant had 11 grooves 1/4 in. wide by 1/4 in. deep.
MCD 18 through 21 propellant had 6 grooves 1/4 in. wide by 1/2 in. deep.

5.1

5.2

5.3

Table I. Ballistic Data

MCD No.	Date Fired	Nozzle Area, Nominal (in.^{2})	Propellant Weight (lb)	Web (in.)	Max. K_n	Avg. K_n	Maximum Pressure (psig)	Average Pressure (psig)	$\int$Pdt (psig-sec)	Maximum Thrust (lb)	Aver Thr (lb
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2	2 Dec 71	1.18	24.71	2.478	139	133	737	652	3181	1394	11
3	17 Dec 71	1.18	23.80	2.491	134	128	756	548	2993	-	-
4	22 Dec 71	1.18	23.84	2.464	134	128	870	587	2999	1559	10
5	12 Jan 72	1.18	23.64	2.470	134	128	728	553	2897	1314	9
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7D	12 Jan 72	1.18	24.10	2.490	134	128	801	599	3070	1292	9
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16	20 Apr 72	1.77	23.12	2.468	87	78	200	-	-	-	-
17	27 Apr 72	1.77	22.57	2.468	111	-	344	-	-	-	-
18	3 May 72	1.77	22.54	2.465	118	-	397	287	1863	899	6
19	19 May 72	1.77	22.54	2.467	118	-	418	279	1719	955	6
20D	6 Jun 72	1.77	23.18	2.481	118	-	370	260	1519	923	6
21D	6 Jun 72	1.77	22.58	2.470	118	-	381	316	1854	902	7

Notes: MCD 1 through 6, 9 through 13, and 16 through 19 used C-D nozzles; MCD 7, 8, 14, and 15 used Dyne
MCD 5 through 8 had 1-1/4 in. long plug bonded to the head end propellant cavity.
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MCD 16 and 17 operated at low erratic pressure; data not reduced.
MCD 17 propellant had 11 grooves 1/4 in. wide by 1/4 in. deep.
MCD 18 through 21 propellant had 6 grooves 1/4 in. wide by 1/2 in. deep.

Table I. Ballistic Data

Maximum Pressure (psig)	Average Pressure (psig)	$\int Pdt$ (psig-sec)	Maximum Thrust (lb)	Average Thrust (lb)	$\int Fdt$ (lb-sec)	Action Time (sec)	Delivered Specific Impulse (sec)	Force @ 600 psig (lb)	C_F @ 600 psig
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756	548	2993	-	-	-	5.457	-	-	-
870	587	2999	1559	1035	5287	5.108	221.77	1065	1.50
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668	598	2938	1176	1037	5093	4.910	220.10	1041	1.47
702	601	2885	1227	1068	5124	4.800	219.70	1001	1.41
667	583	2951	1081	928	4698	5.060	203.10	936	1.32
586	526	2803	988	869	4630	5.330	199.91	942	1.33
200	-	-	-	-	-	-	-	-	-
344	-	-	-	-	-	-	-	-	-
								Force @ 300 psig (lb)	
397	287	1863	899	649	4216	6.500	187.05	676	1.27
418	279	1719	955	643	4388	6.149	194.68	720	1.36
370	260	1519	923	625	3651	5.839	157.50	760	1.43
381	316	1854	902	735	4312	5.865	190.97	722	1.36

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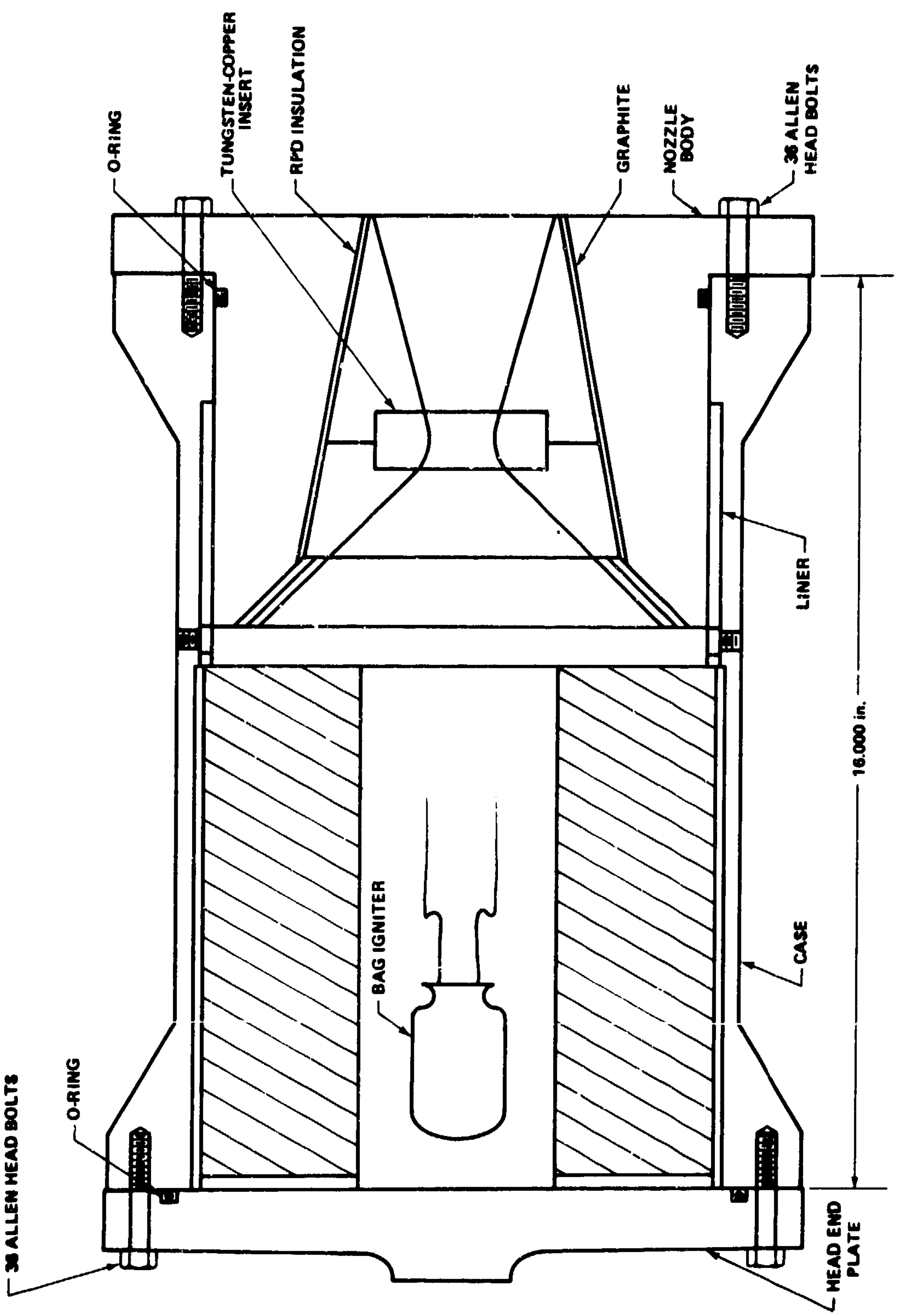

Figure 1. Motor Assembly with Conventional Nozzle

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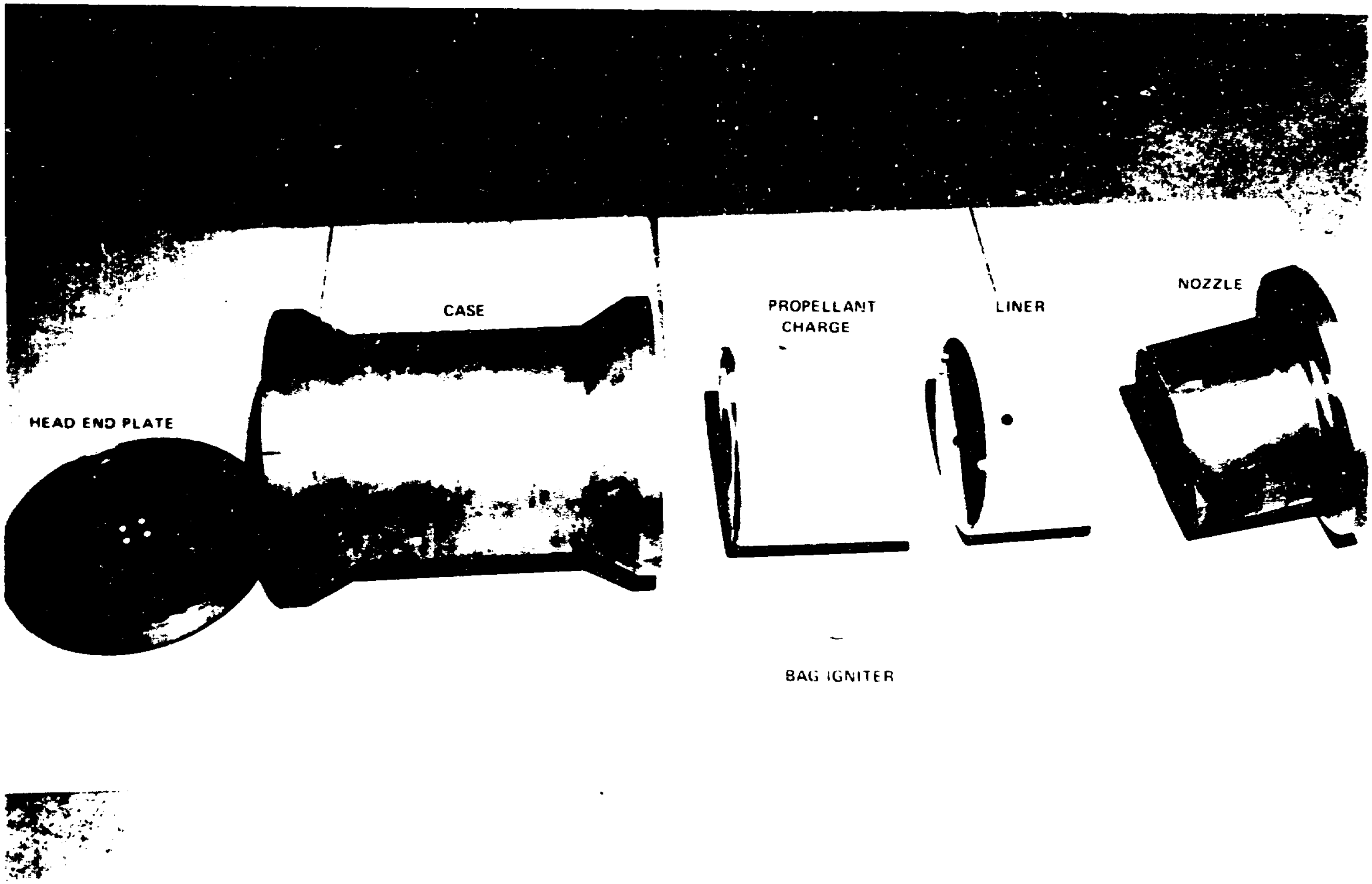

Figure 2. Motor with Conventional Nozzle Before Assembly

Figure 3. Conventional Nozzle Forward End After Firing

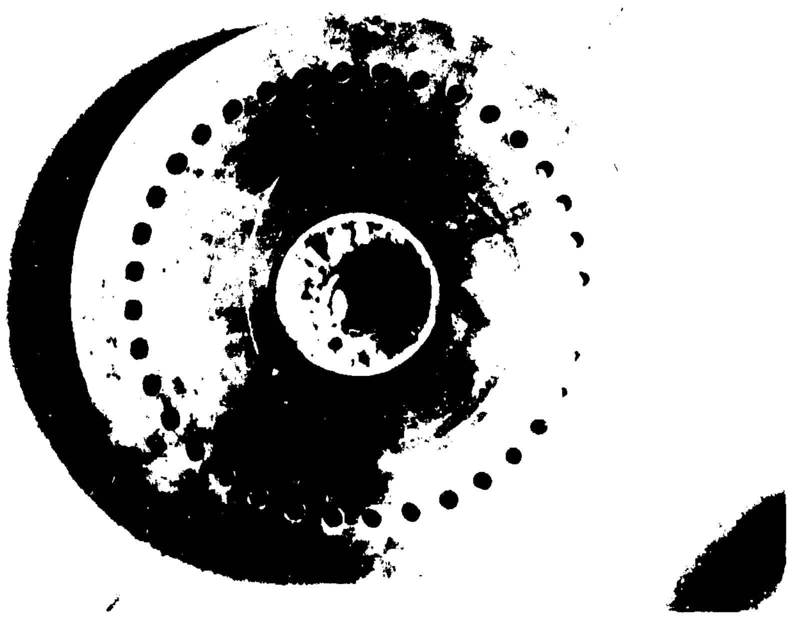

Figure 4. Conventional Nozzle Aft End After Firing

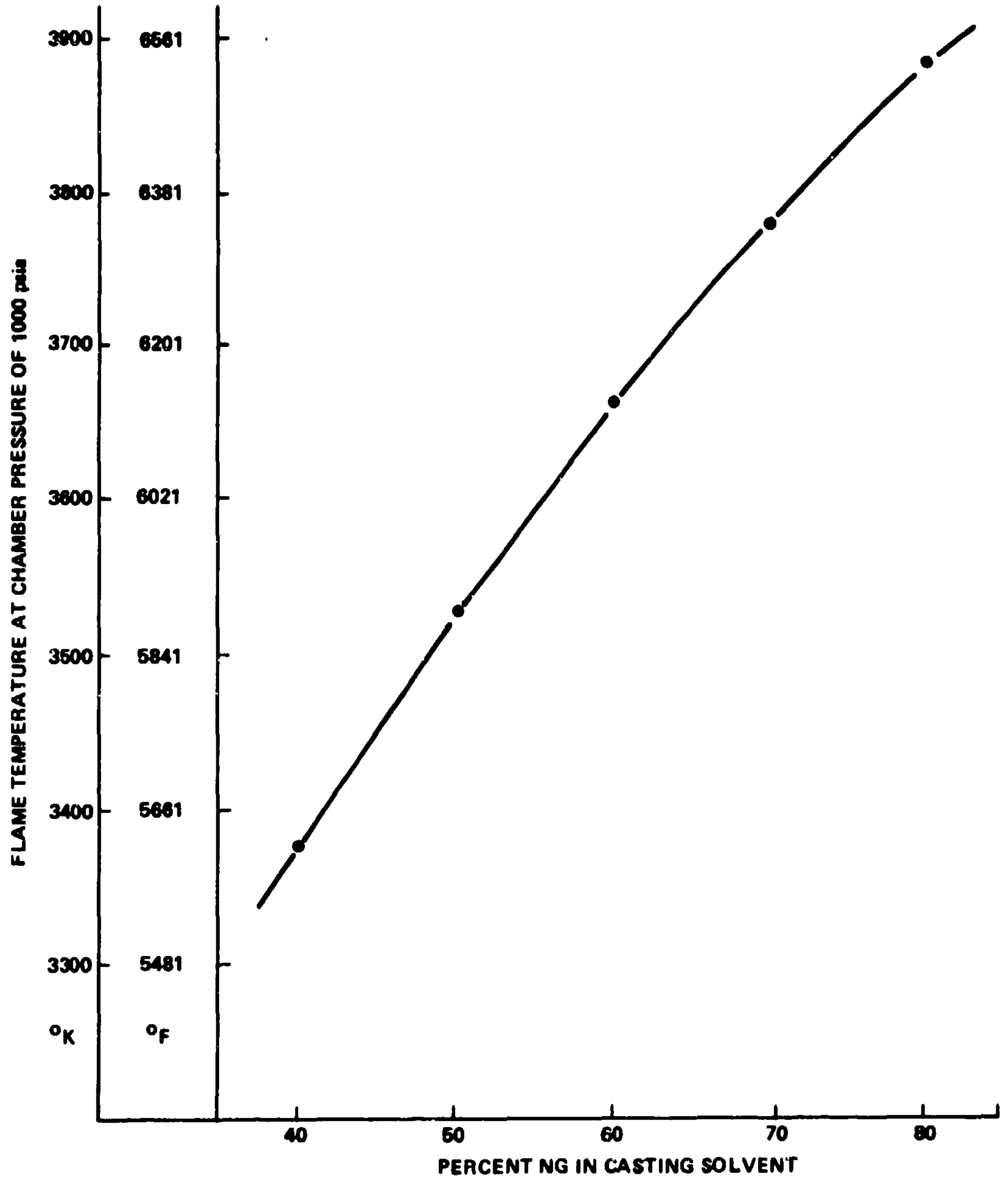

Figure 5. Flame Temperature Versus Percent Nitroglycerin (NG) in Casting Solvent

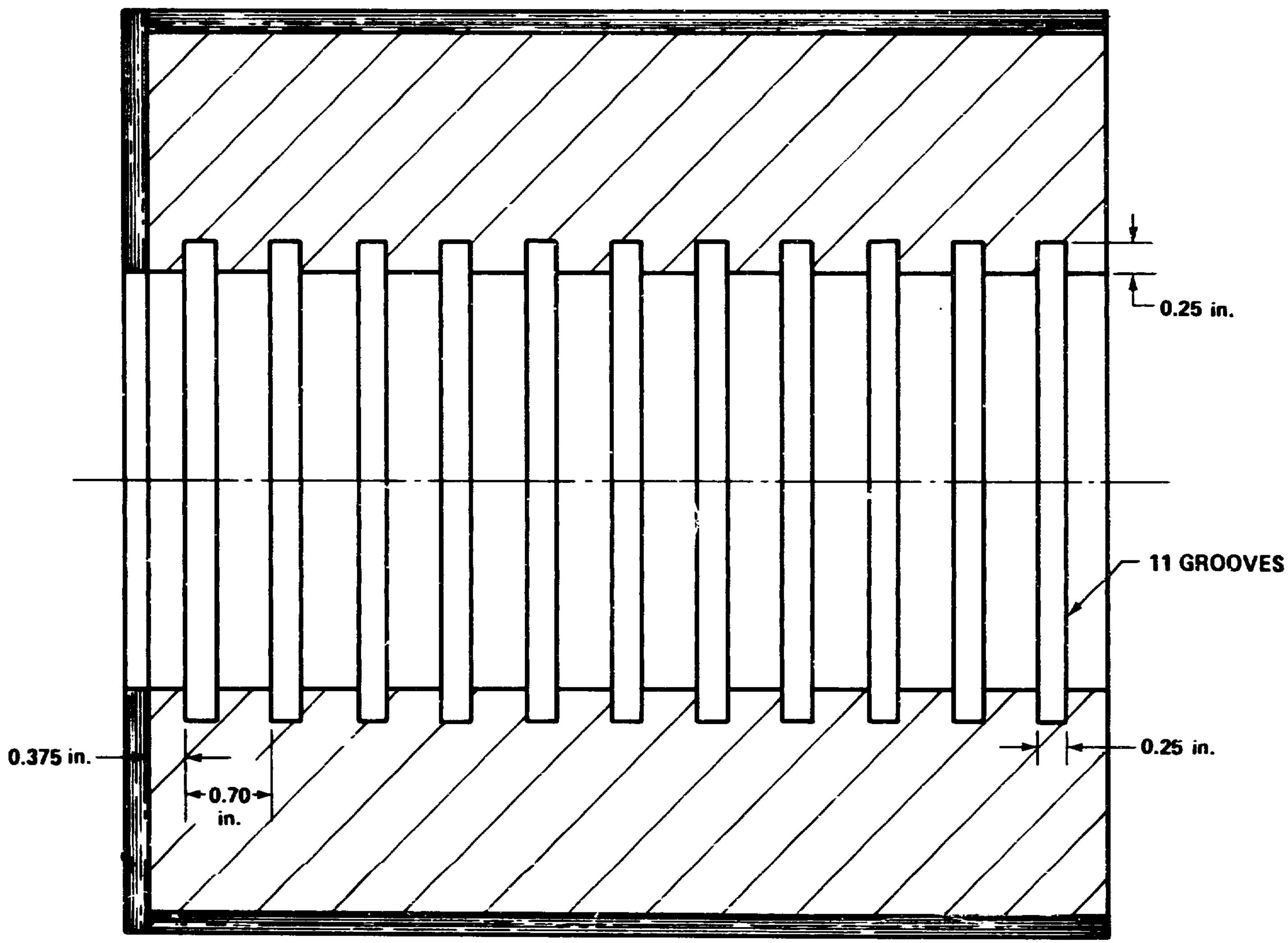

Figure 6. Propellant Charge with Eleven Grooves

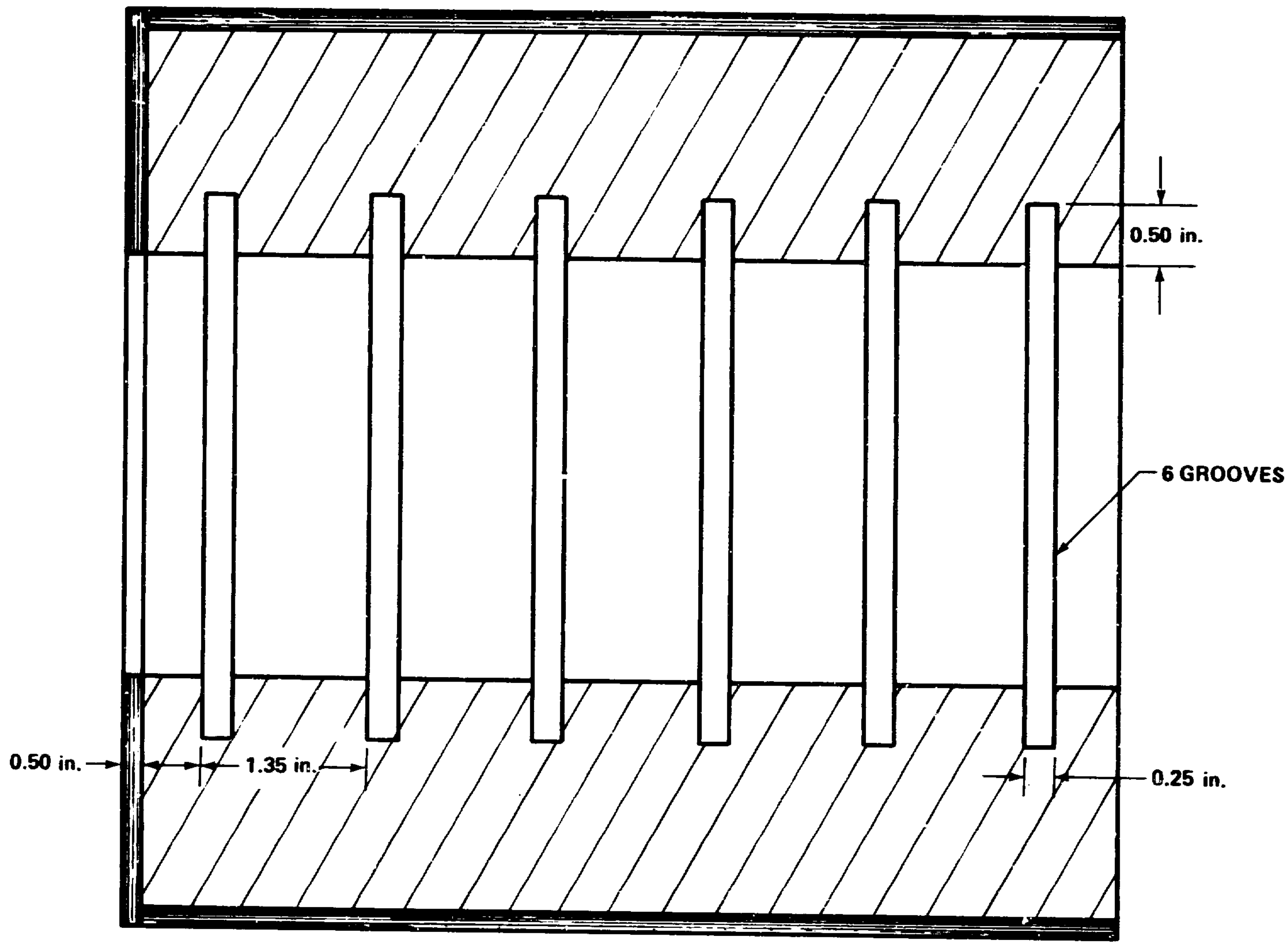

Figure 7. Propellant Charge with Six Grooves

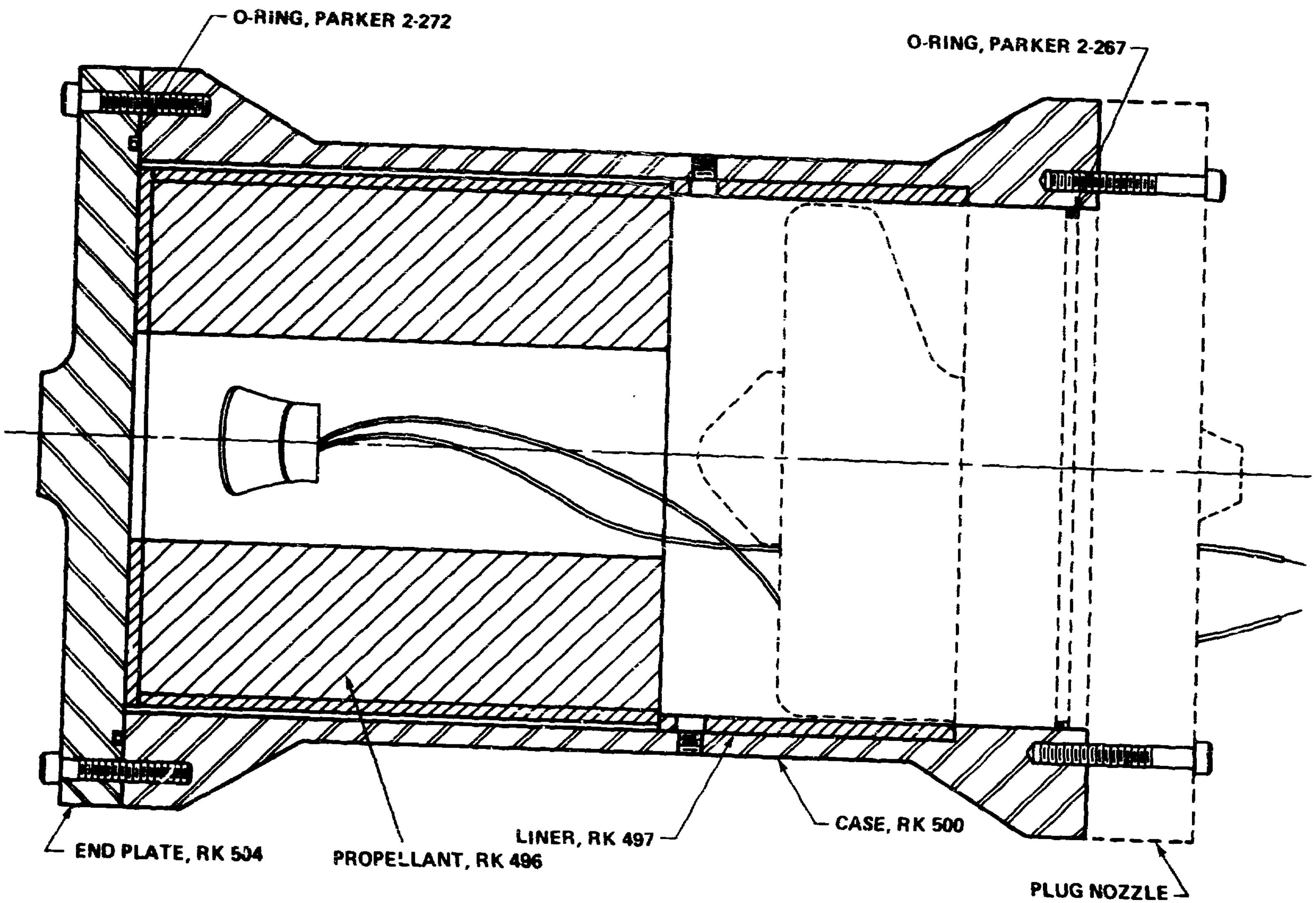

Figure 8. Motor Assembly with Plug Nozzle

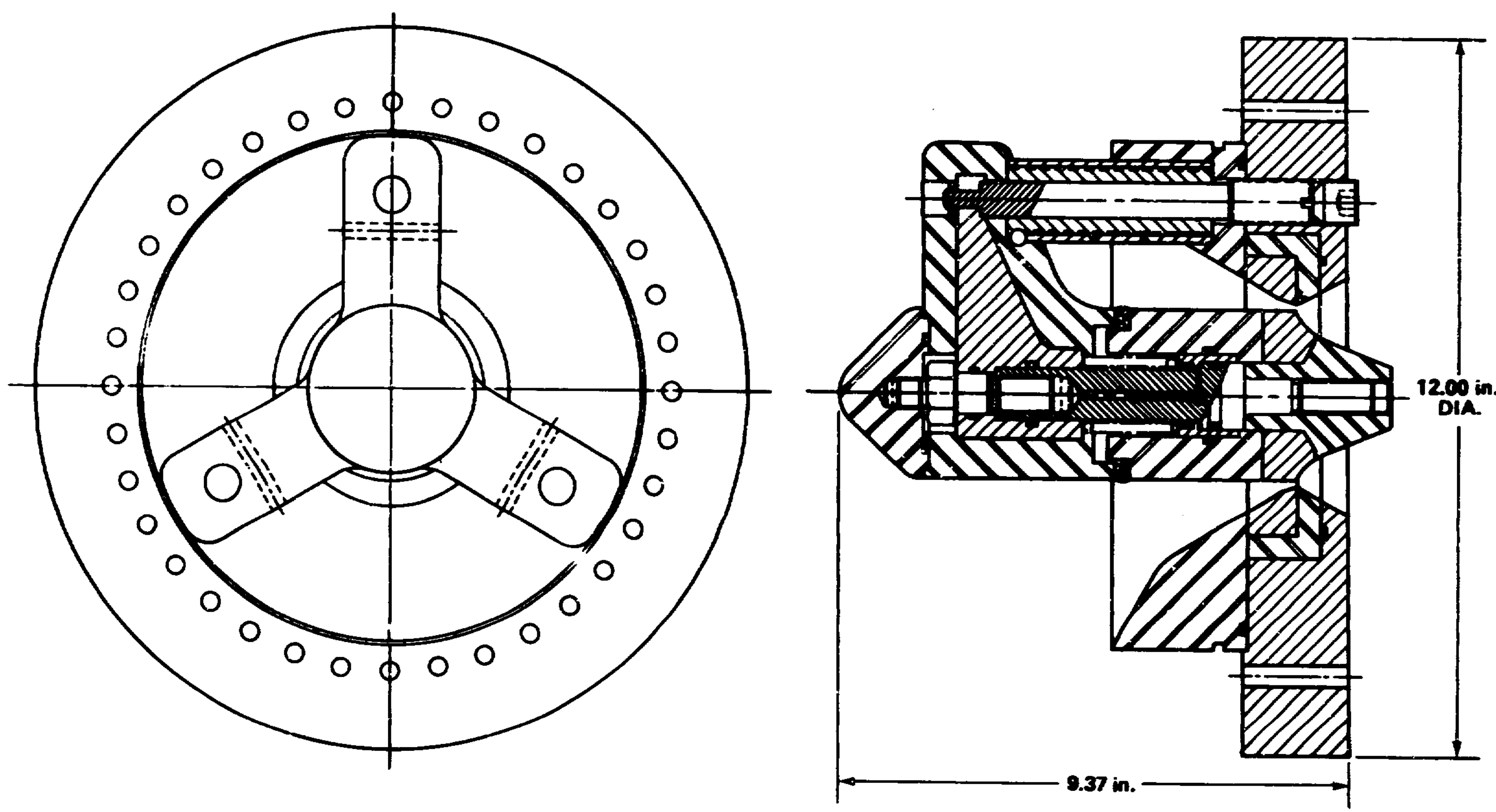

Figure 9. Plug Nozzle Assembly

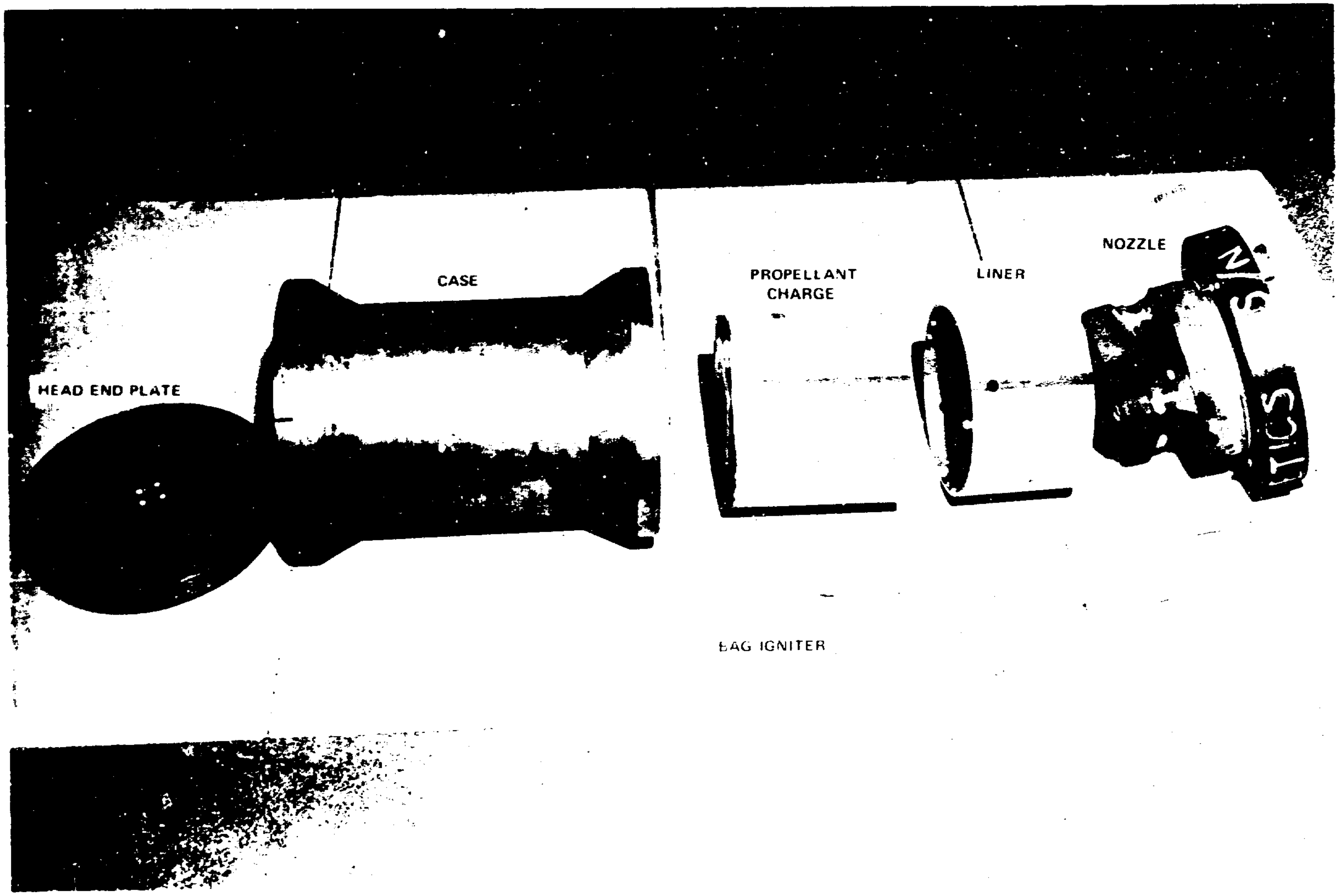

Figure 10. Motor with Plug Nozzle Before Assembly

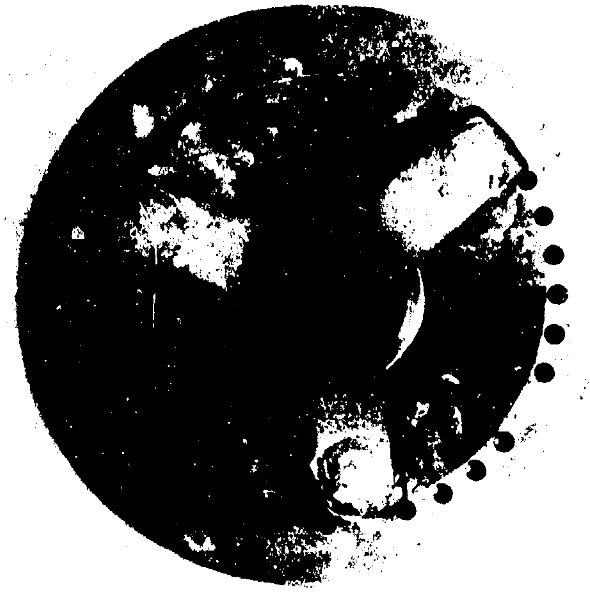

Figure 11. Plug Nozzle Forward End Before Firing

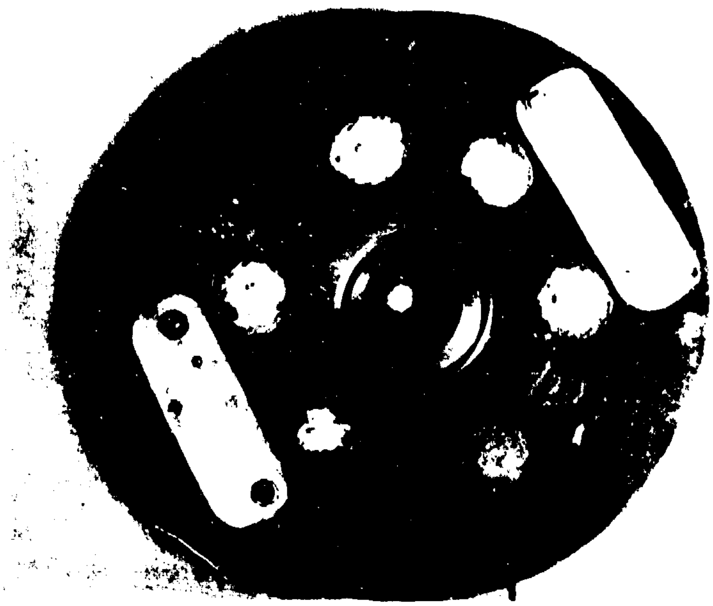

Figure 12. Plug Nozzle Aft End Before Firing

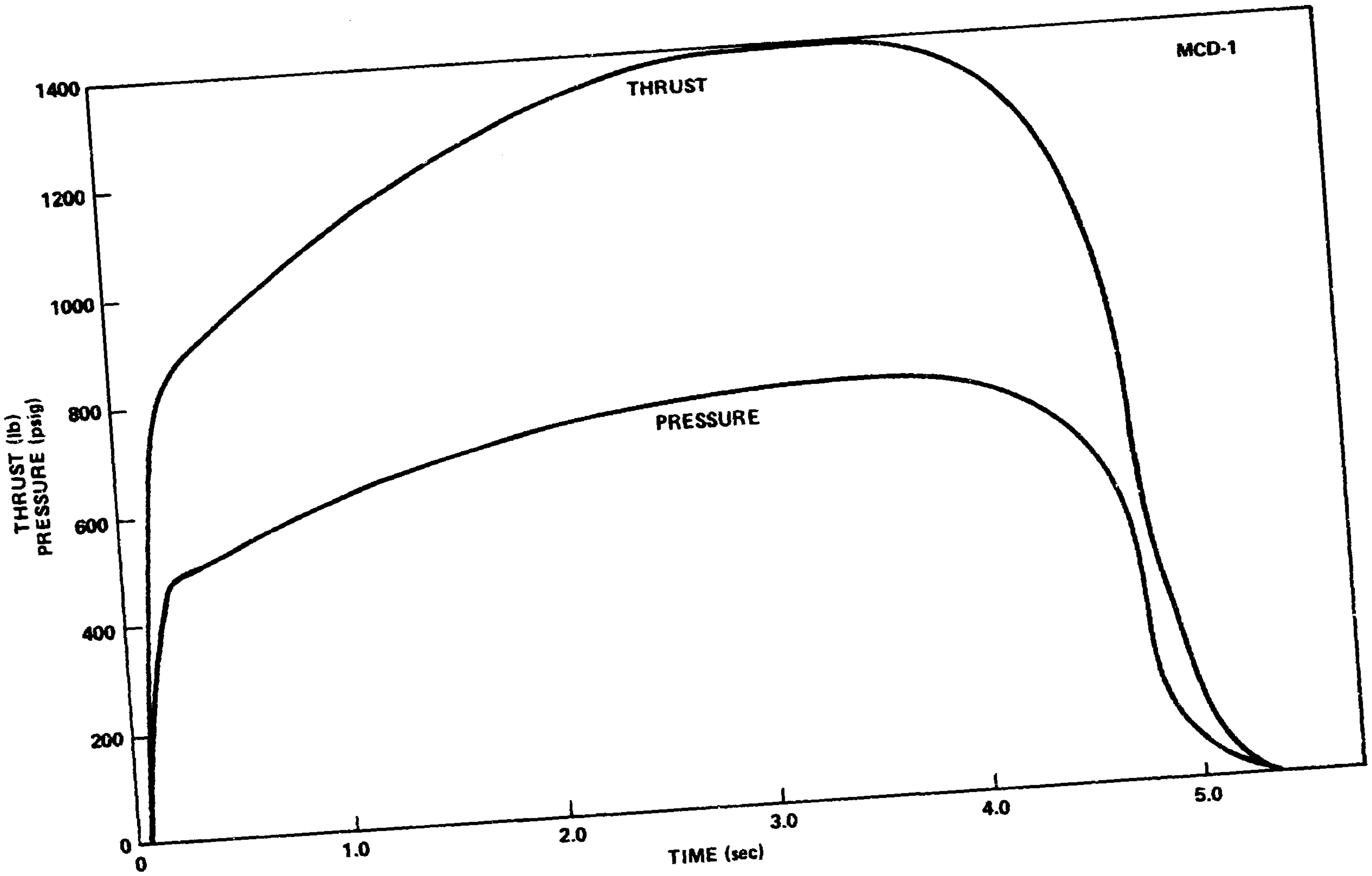

Figure 13. Pressure and Thrust Versus Time for MCD-1

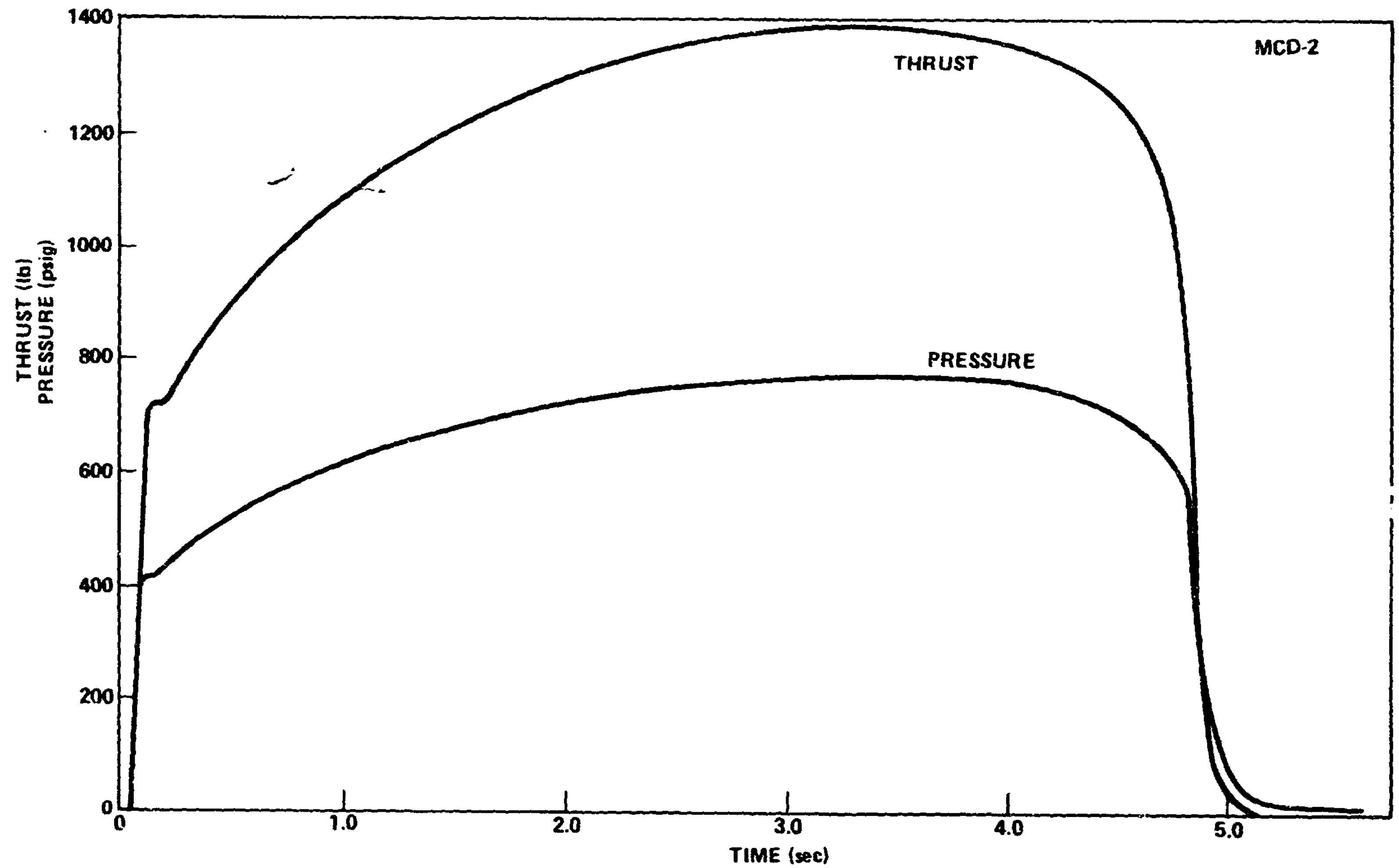

Figure 14. Pressure and Thrust Versus Time for MCD-2

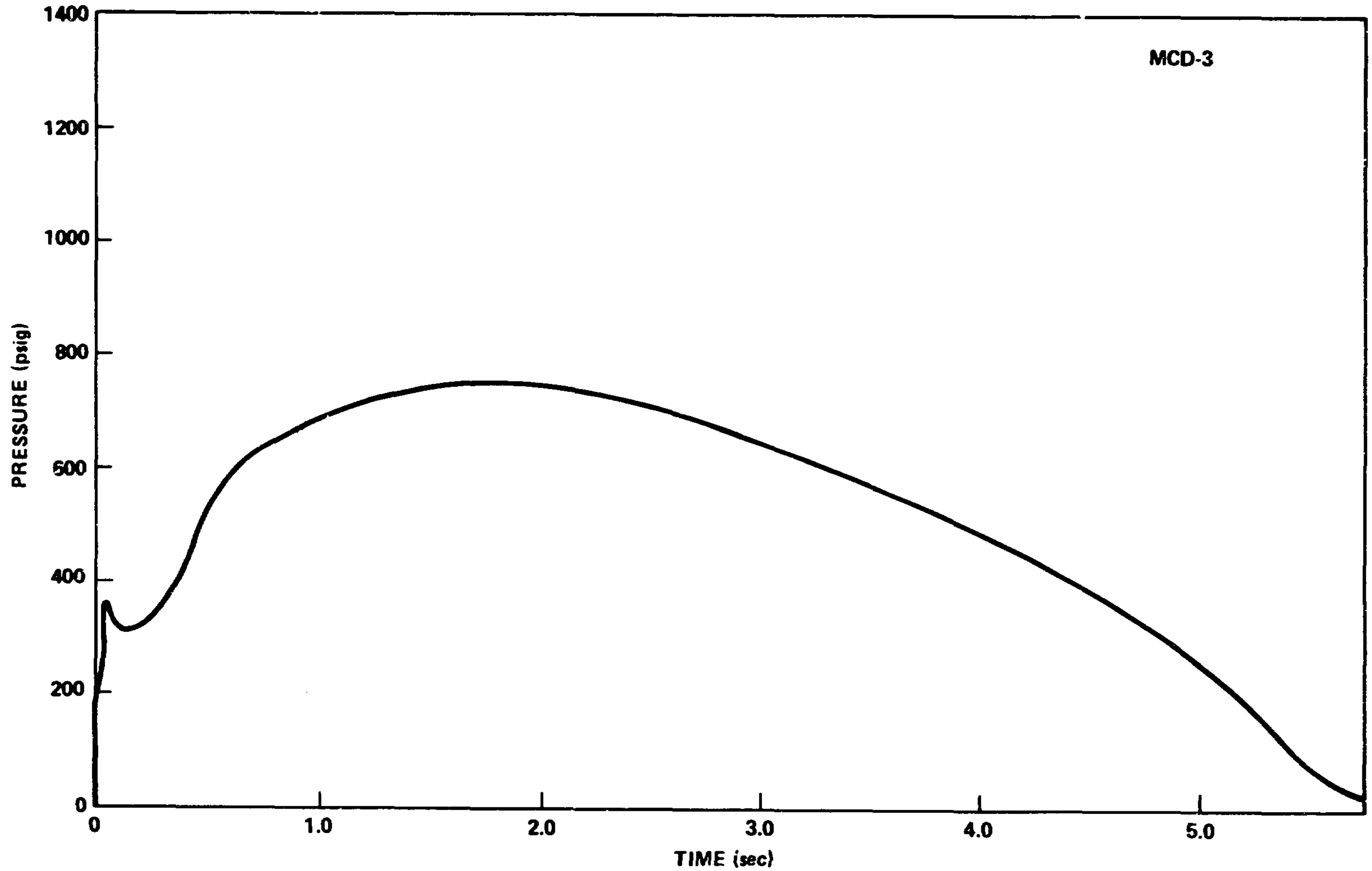

Figure 15. Pressure Versus Time for MCD-3

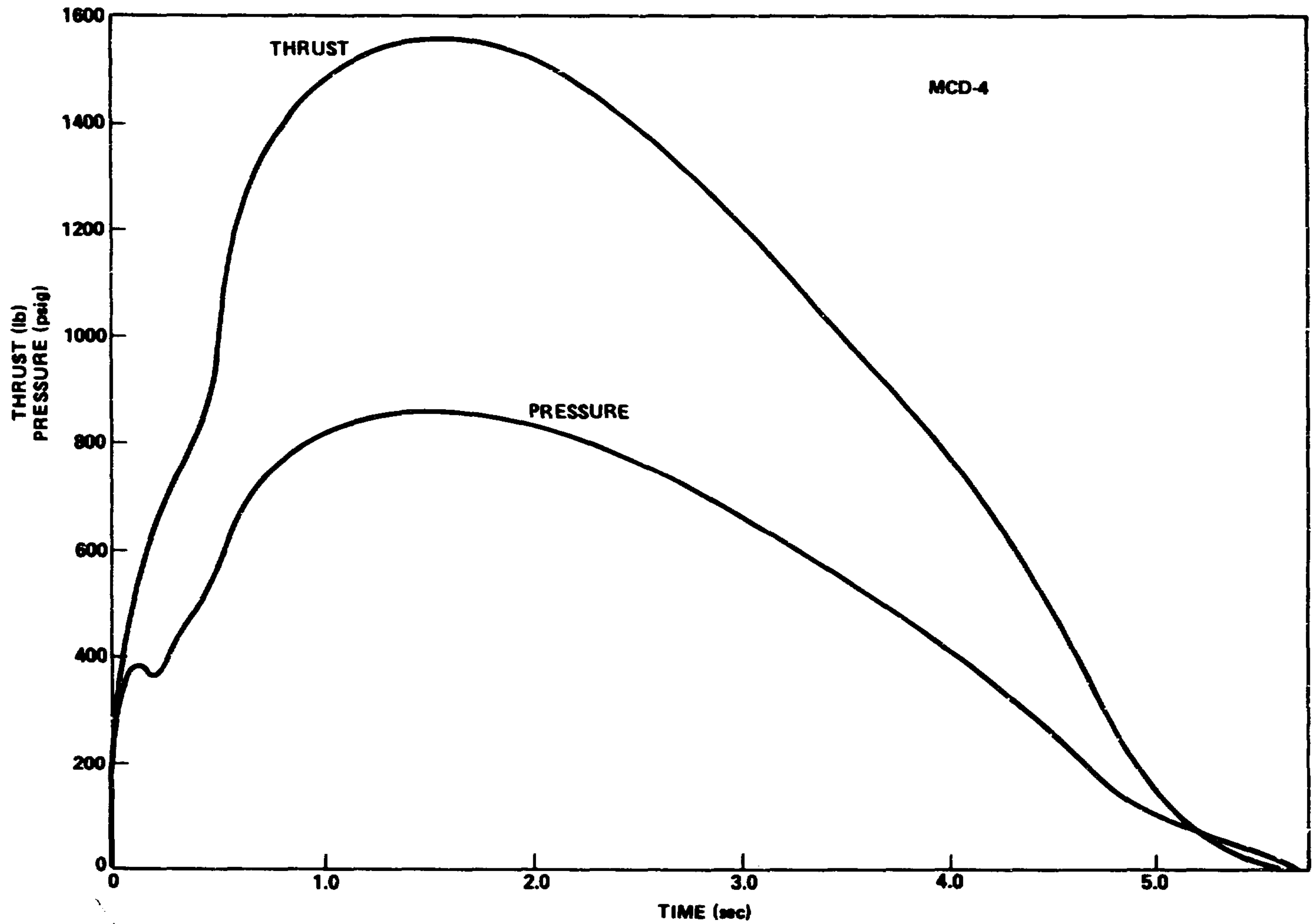

Figure 16. Pressure and Thrust Versus Time for MCD-4

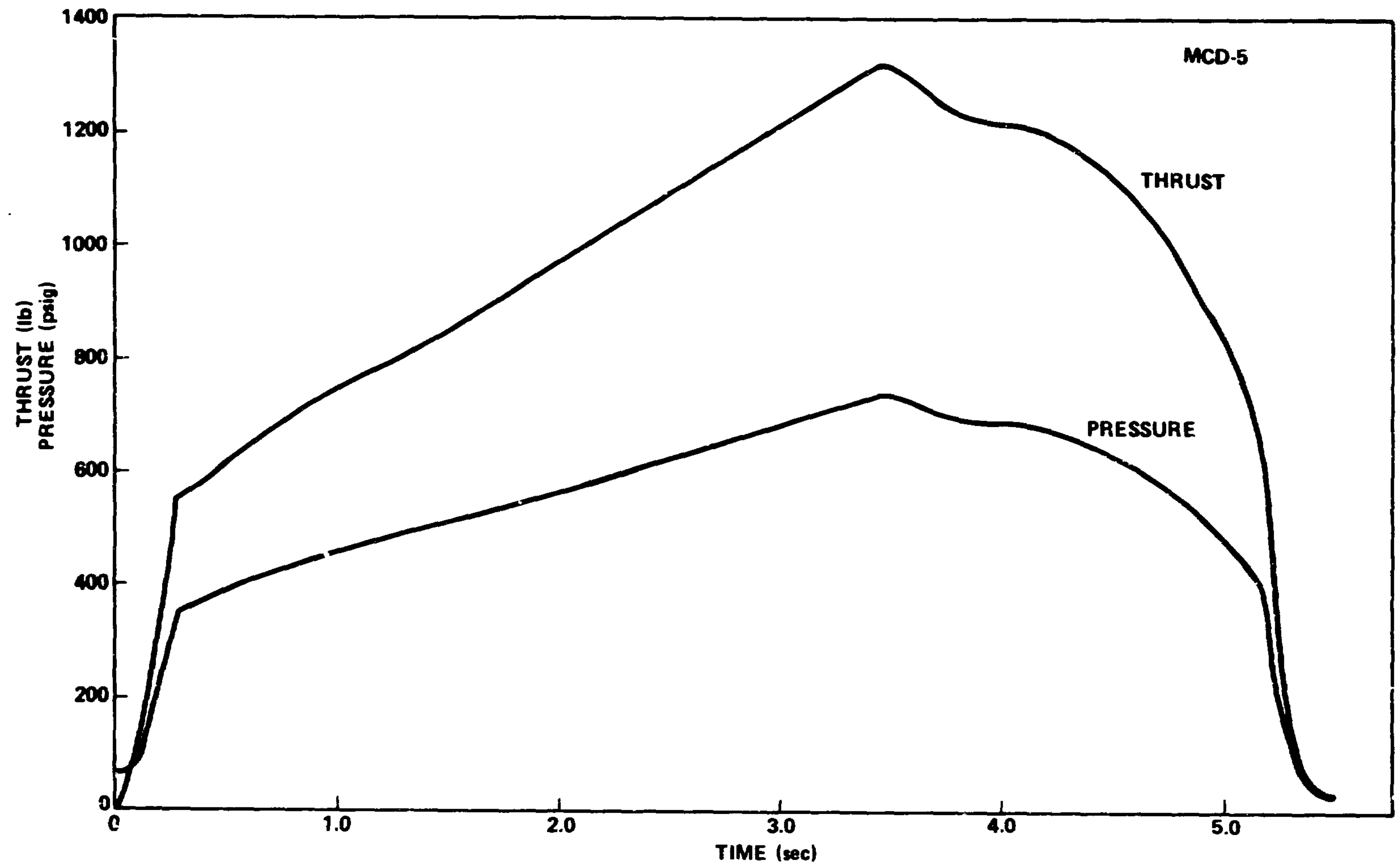

Figure 17. Pressure and Thrust Versus Time for MCD-5

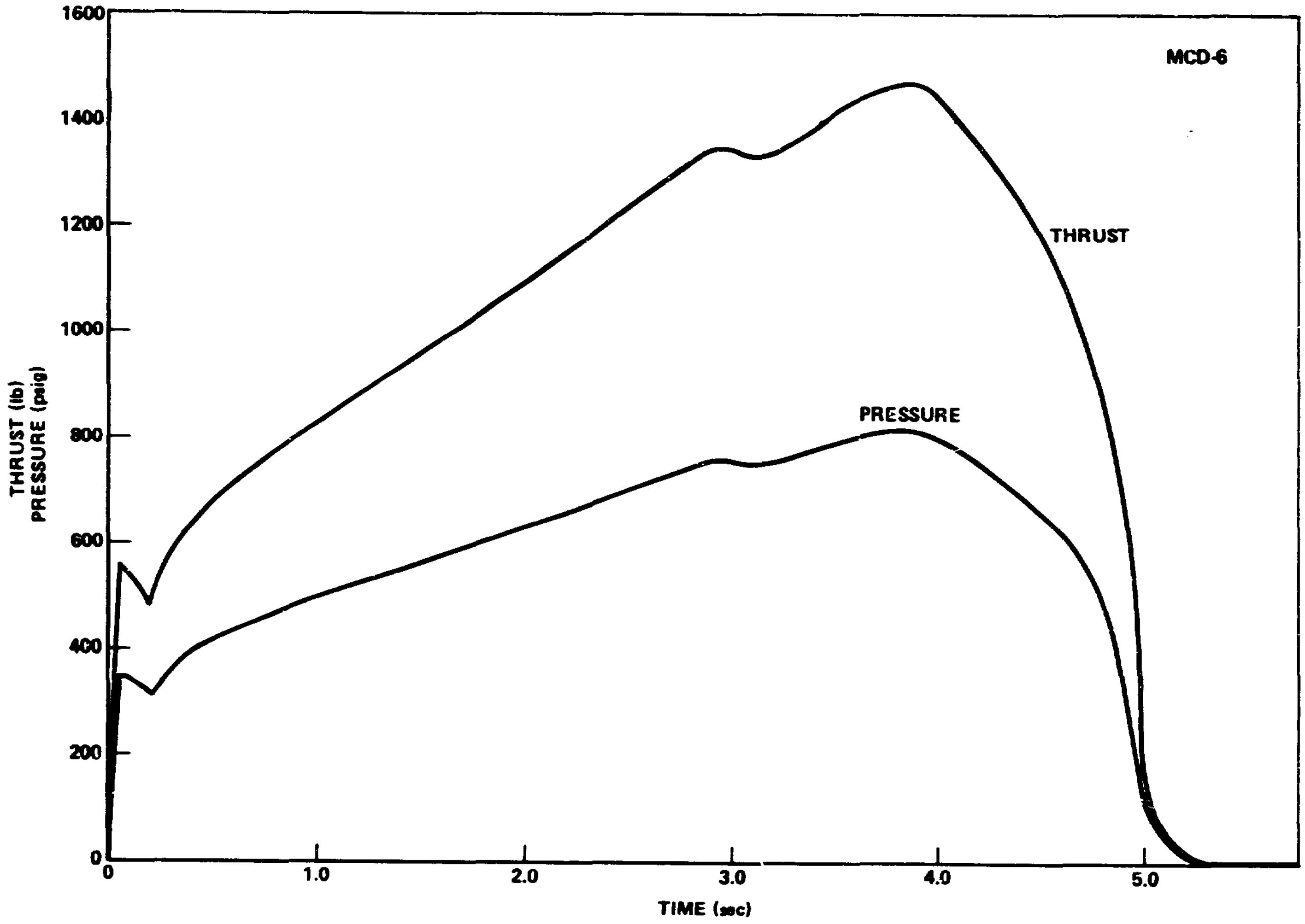

Figure 18. Pressure and Thrust Versus Time for MCD-6

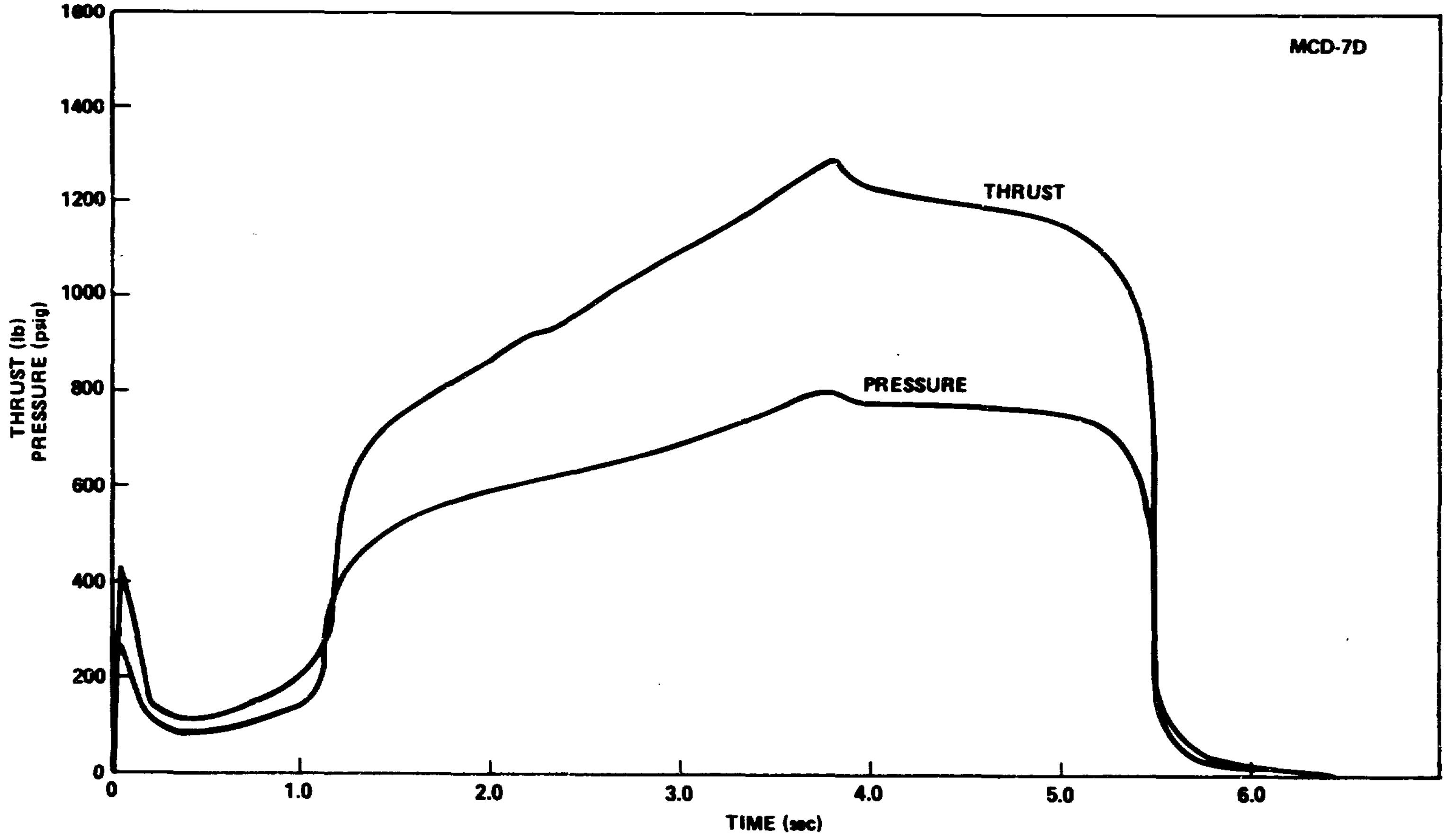

Figure 19. Pressure and Thrust Versus Time for MCD-7D

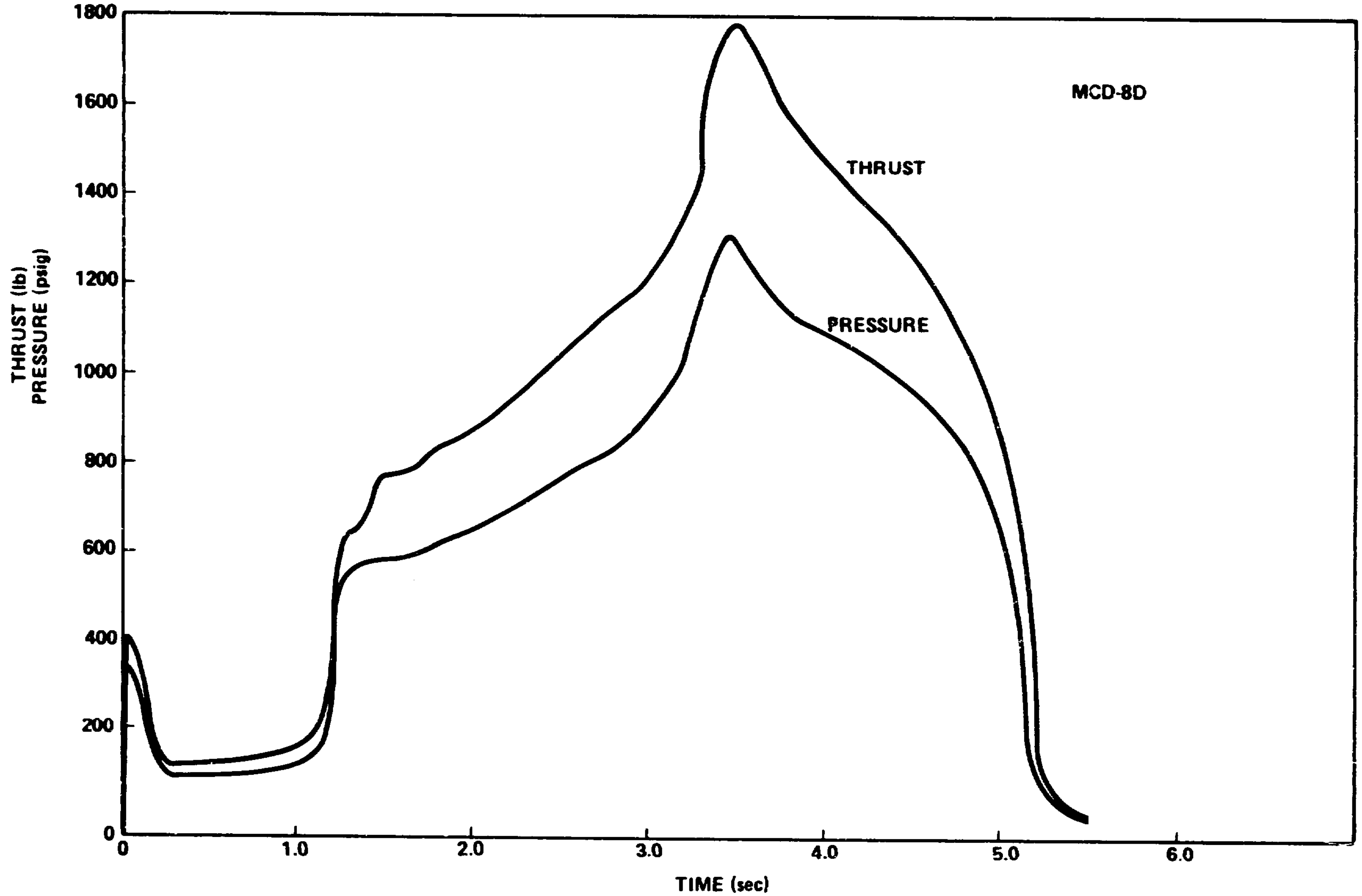

Figure 20. Pressure and Thrust Versus Time for MCD-8D

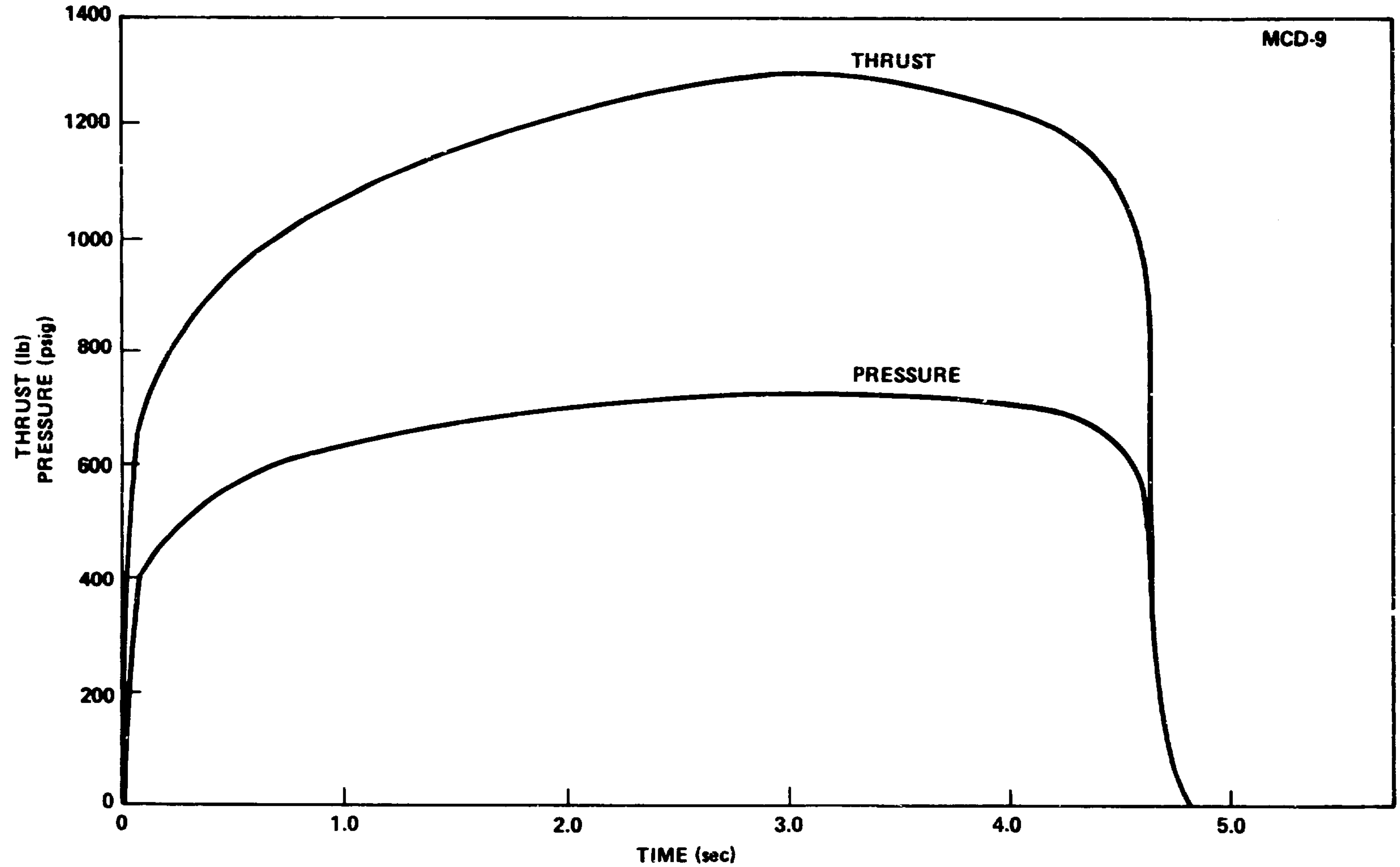

Figure 21. Pressure and Thrust Versus Time for MCD-9

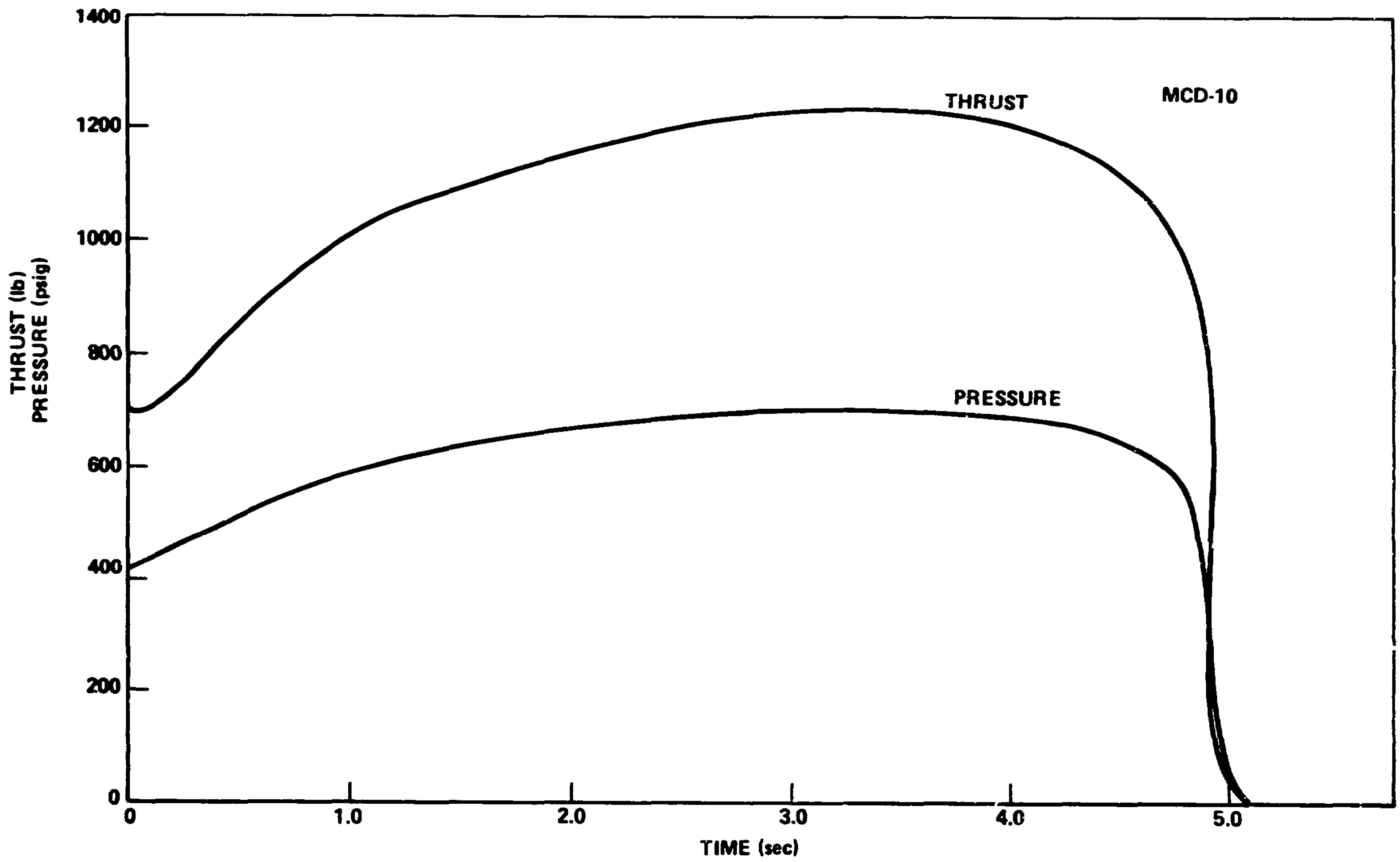

Figure 22. Pressure and Thrust Versus Time for MCD-10

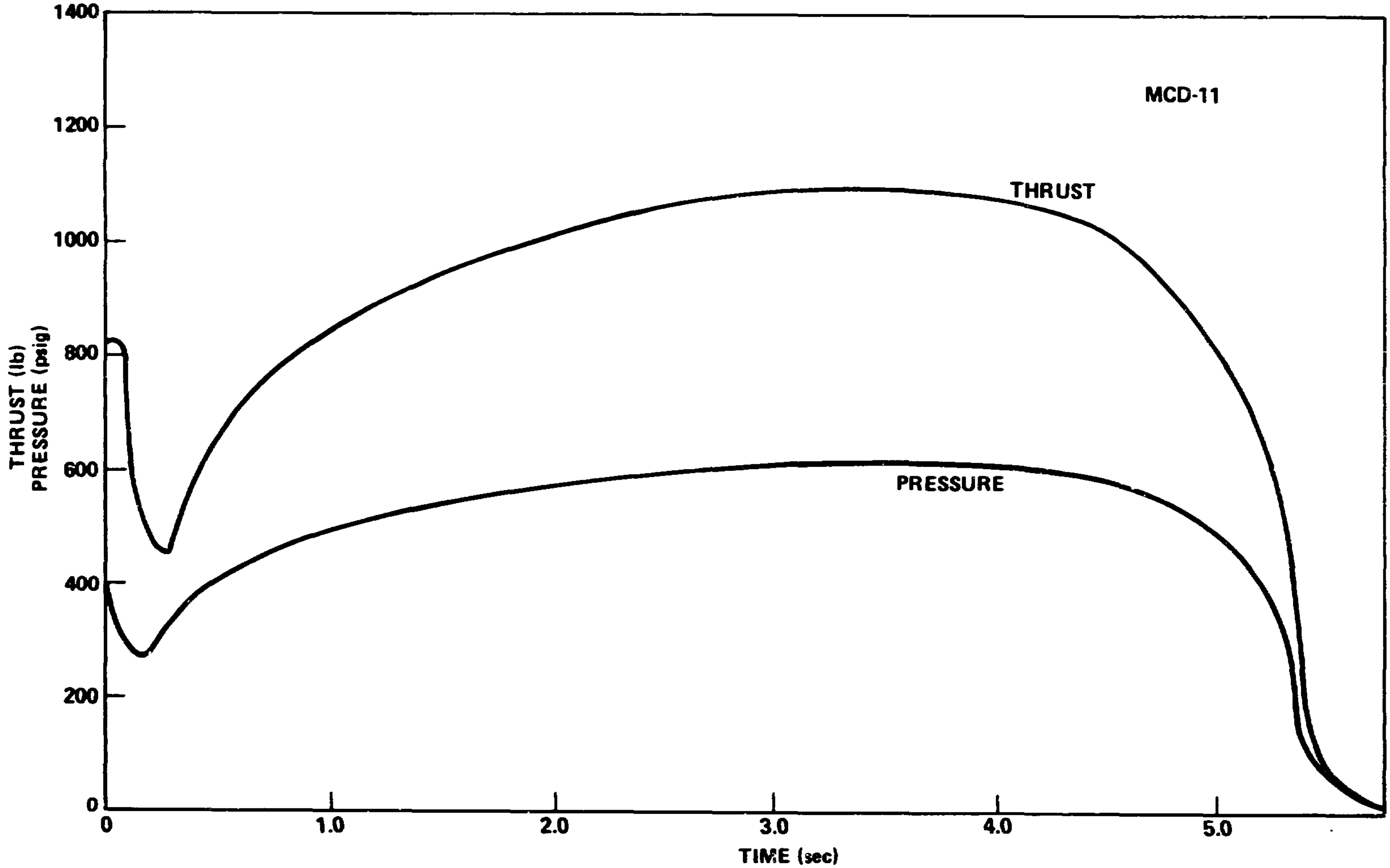

Figure 23. Pressure and Thrust Versus Time for MCD-11

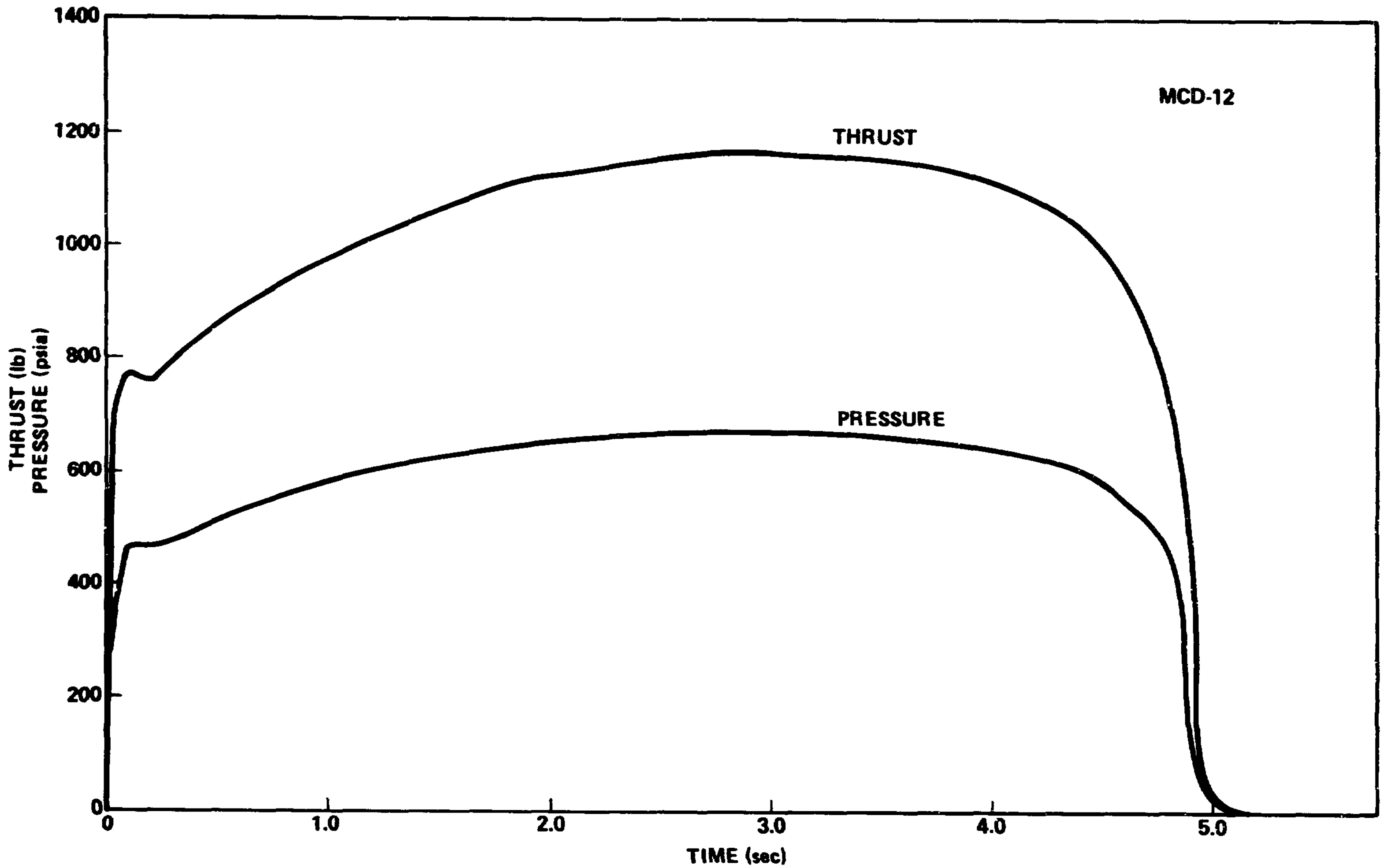

Figure 24. Pressure and Thrust Versus Time for MCD-12

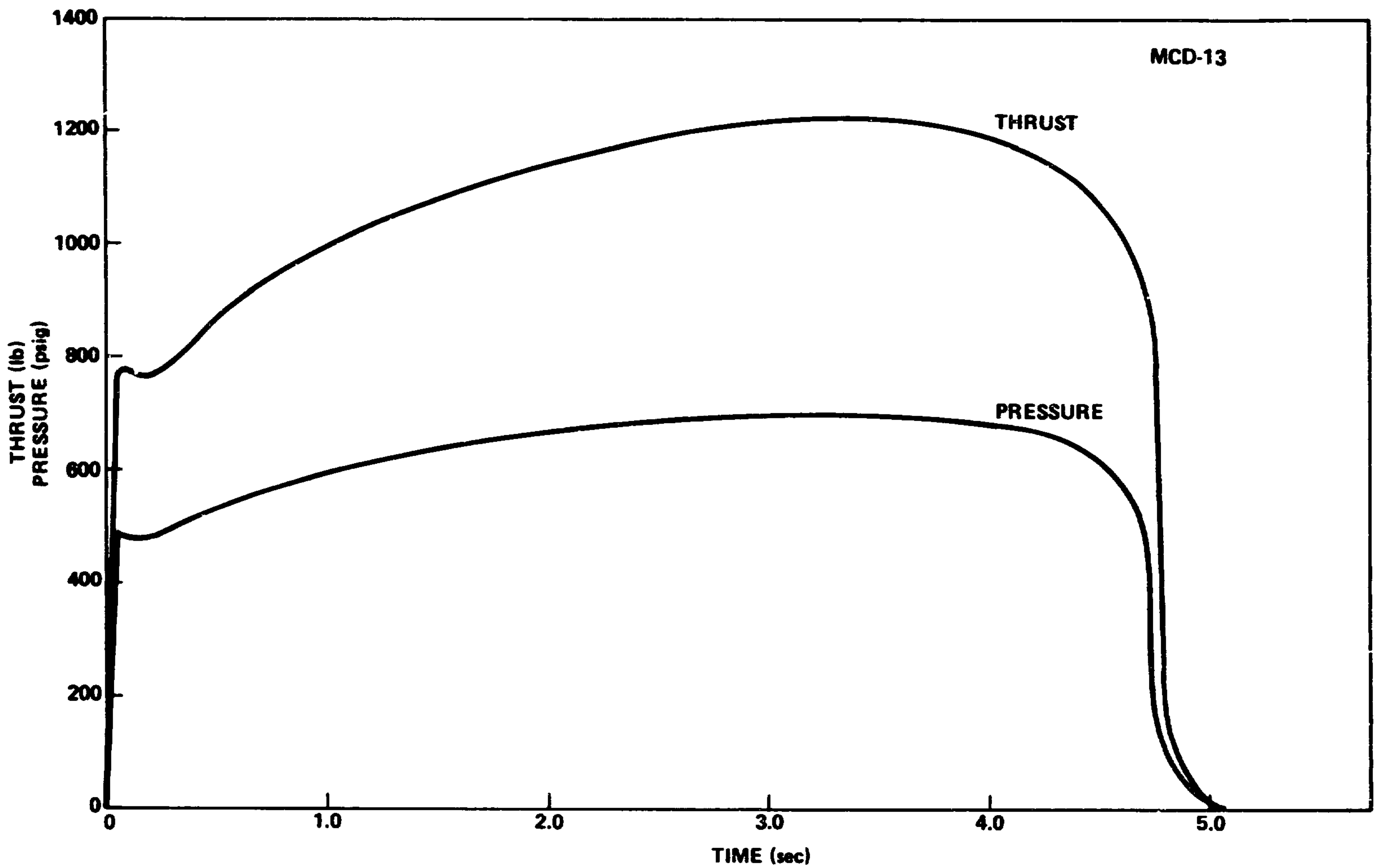

Figure 25. Pressure and Thrust Versus Time for MCD-13

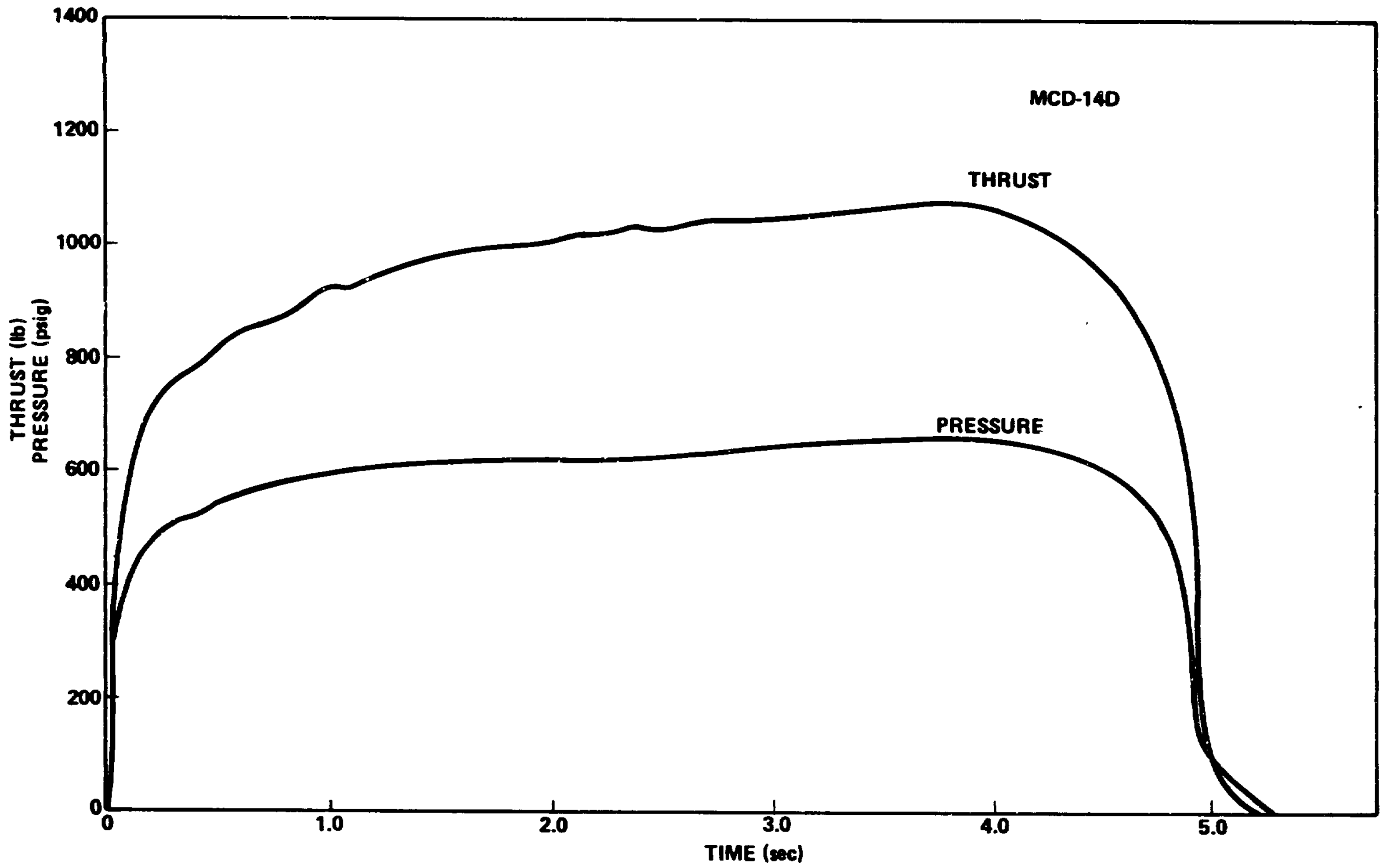

Figure 26. Pressure and Thrust Versus Time for MCD-14D

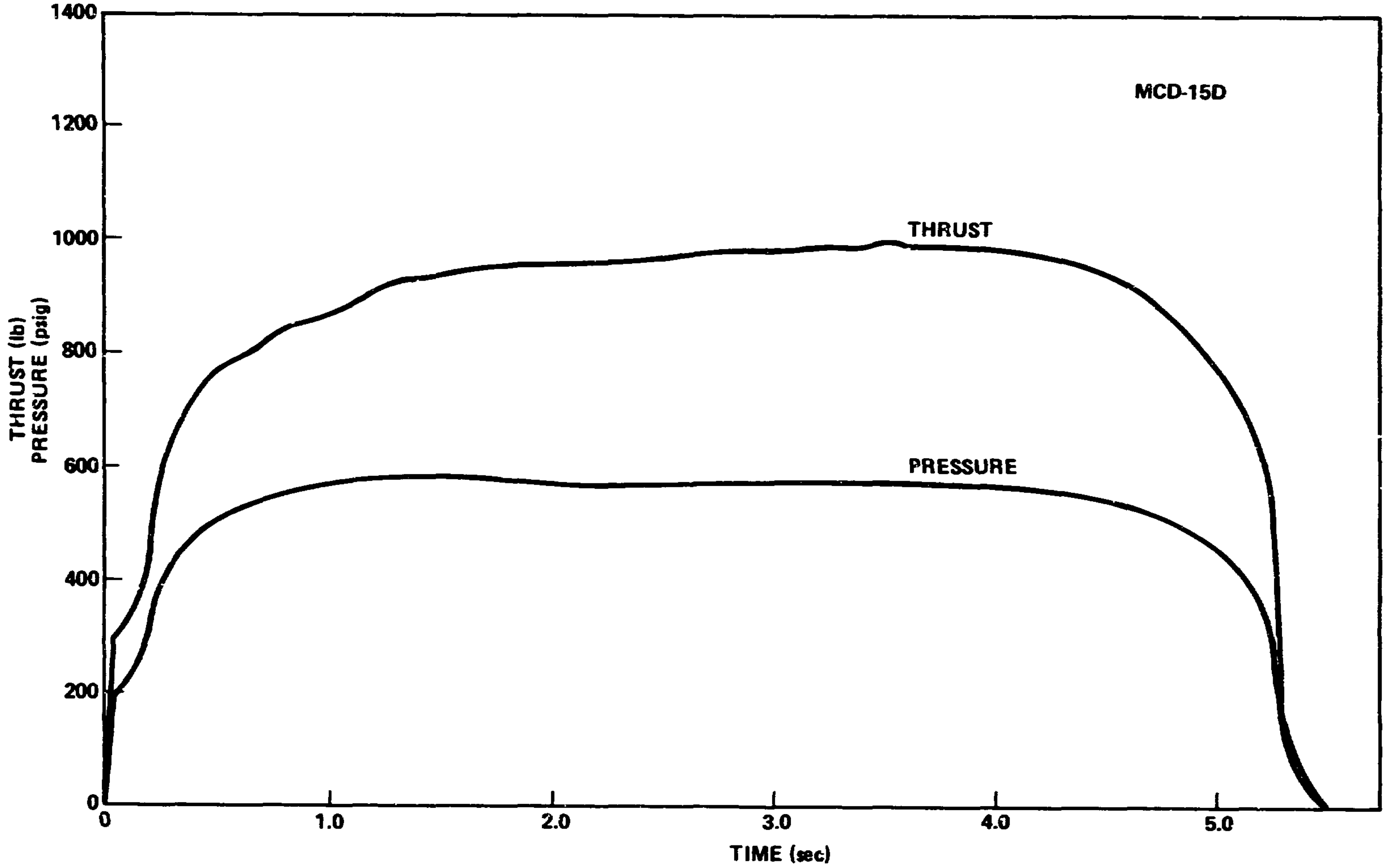

Figure 27. Pressure and Thrust Versus Time for MCD-15D

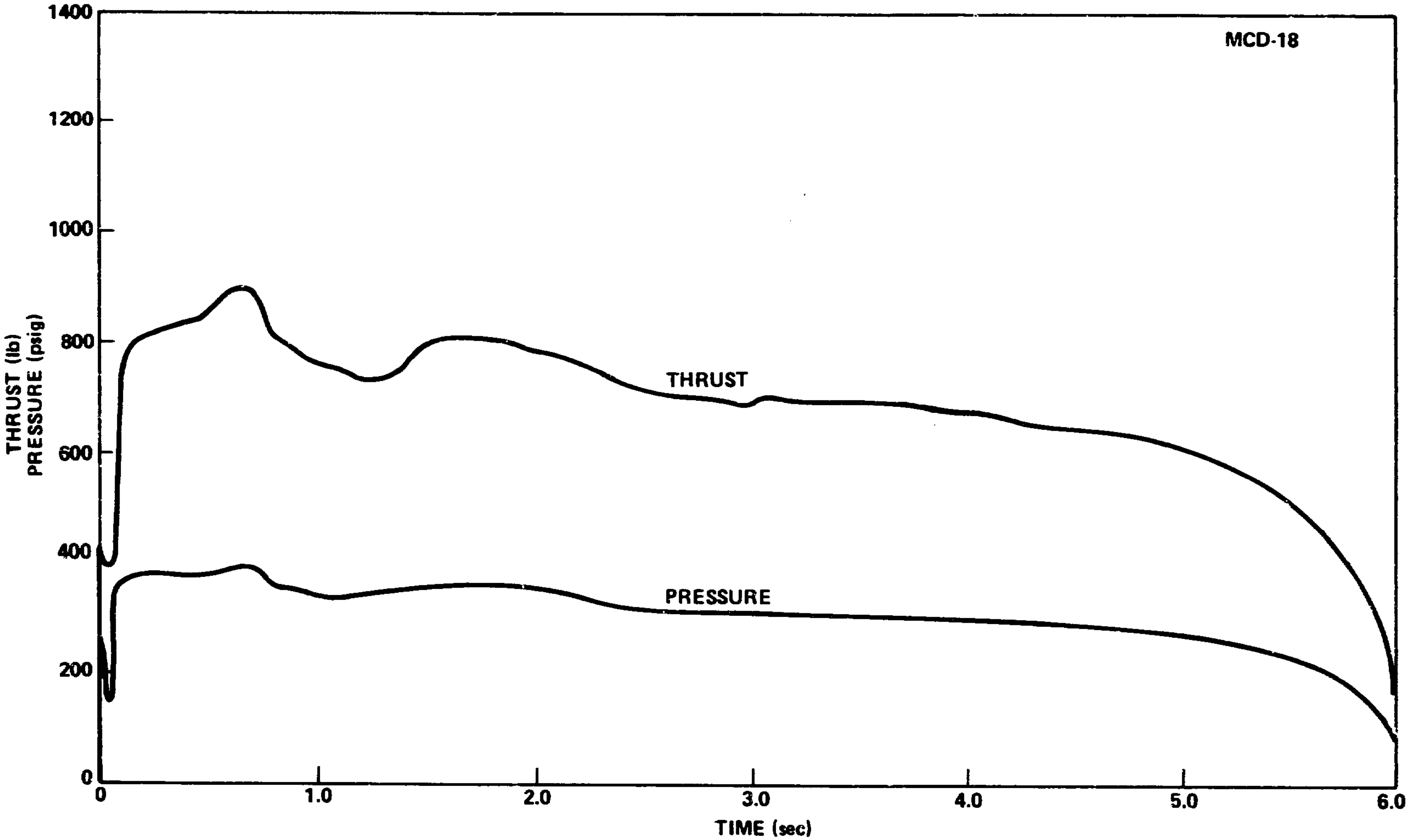

Figure 28. Pressure and Thrust Versus Time for MCD-18

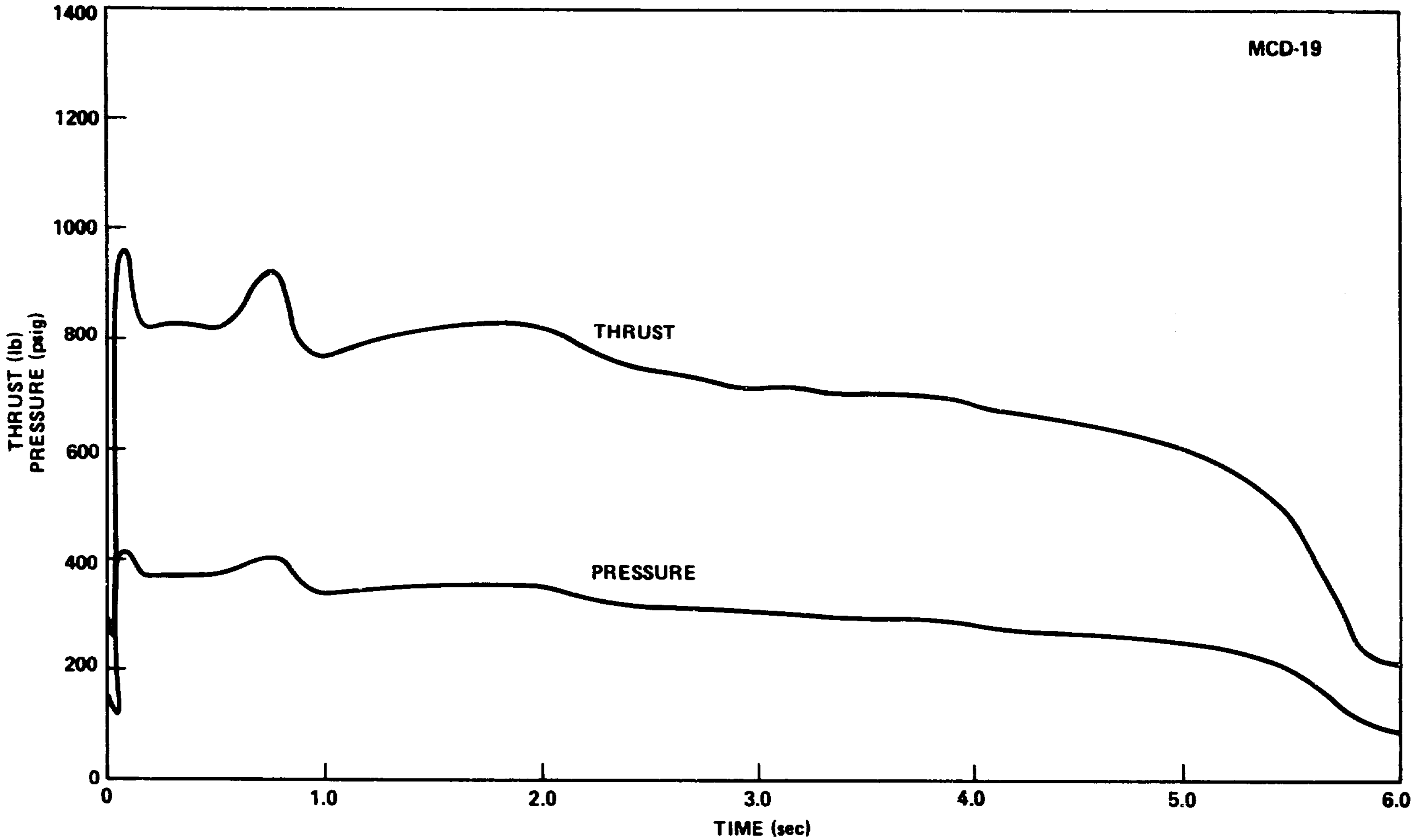

Figure 29. Pressure and Thrust Versus Time for MCD-19

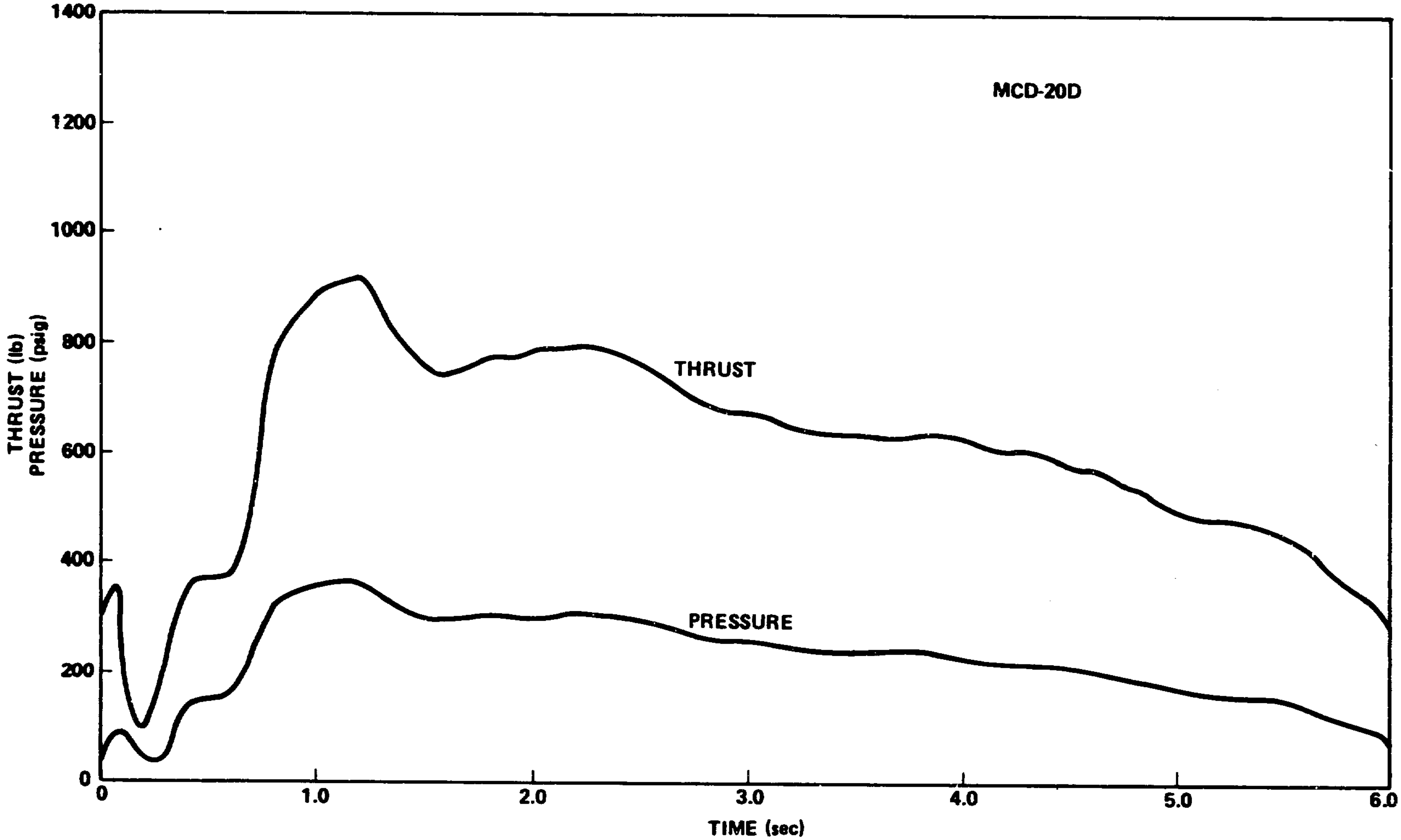

Figure 30. Pressure and Thrust Versus Time for MCD-20D

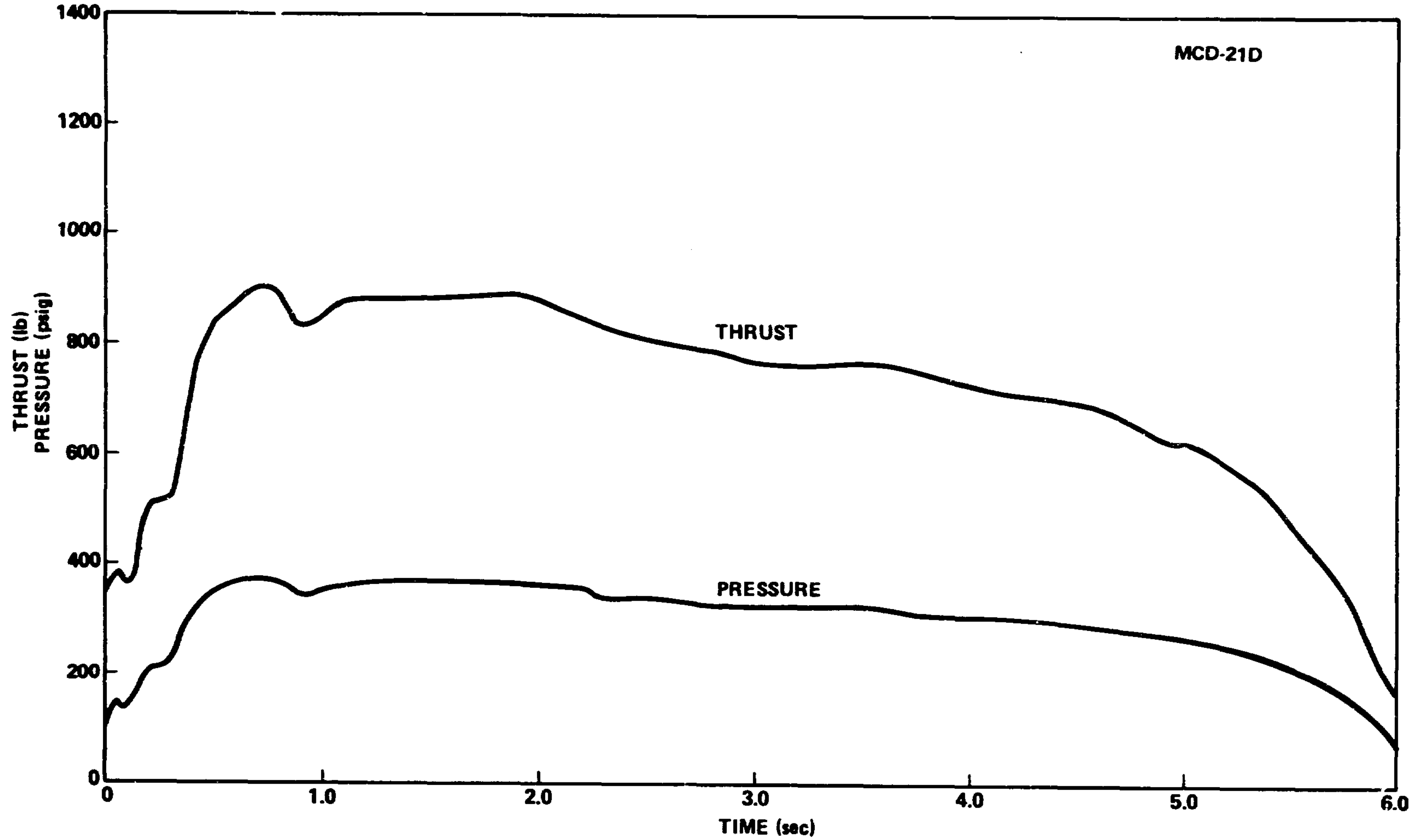

Figure 31. Pressure and Thrust Versus Time for MCD-21D

Figure 32. Plug Nozzle Forward End After Firing

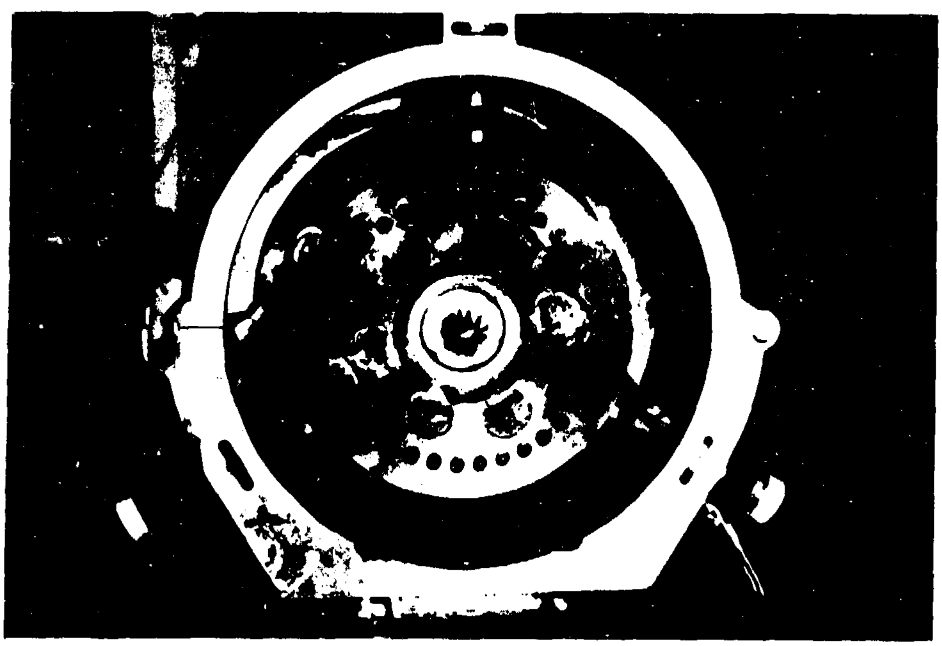

Figure 33. Motor in Stand After Firing

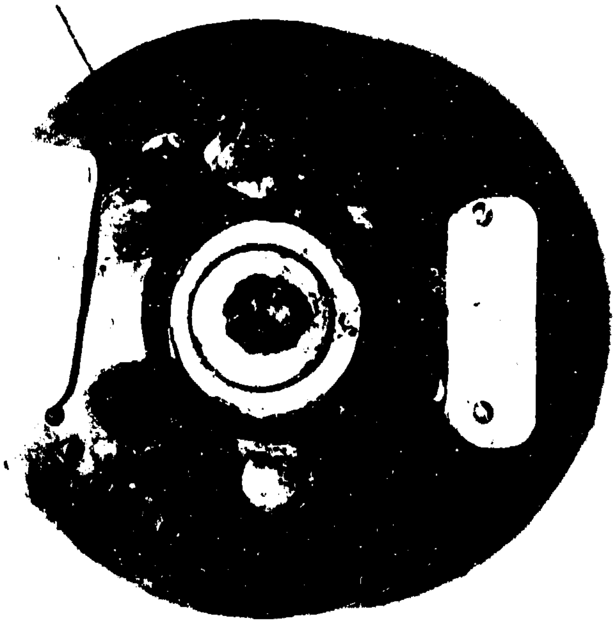

Figure 34. Plug Nozzle Aft End After Firing