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Experiments With Liquid Propellant Jet Ignition in a Ballistic Compressor

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Abstract

This report describes a series of tests that inaugurated the use of a ballistic compressor-based apparatus for the research of liquid propellant (LP) jet combustion. The apparatus consists of an inline ballistic compressor and LP injector. The rebound of the ballistic compressor piston was arrested, trapping 40 to 55 MPa of 750 to 850° C argon for ignition of circular LP jets in a windowed test chamber. The LP jets ignited in less than 2 ms as indicated by a steep rise (ca. 3 MPa/ms) in the chamber pressure. The elevated combustion pressure ruptured a disk above 70 MPa, venting the combustion gas into the compressor's barrel. The rupture of the disk did not always stabilize the combustion pressure; with 3.5-mm jets, we obtained both quasi-steady combustion at about 80 MPa and nonsteady combustion with steep pressure rise-rate (ca. 100 MPa/ms) that culminated in peak combustion pressures over 100 MPa. The nonsteady combustion occurred because LP accumulated excessively in the test chamber and burned rapidly once the combustion pressure exceeded 75 MPa. The accumulation impeded the visualization, obscuring the jet before ignition, and burned in a fireball fashion once ignited. Nevertheless, we could determine from film records that the penetration of 1-mm and 3.5-mm circular XM46 jets with injection velocities over 200 m/s exceed 5 cm when the combustion pressure is below 80 MPa. Large millimeter size drops were observed burning at 80 MPA, indicating that, even at this pressure, XM46 combustion is subcritical. The operation of the piston arrest mechanism was problematic.

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1. Introduction

From strand burner measurements we know that the burn rate of XM46 liquid propellant (LP) has an exponential dependence on pressure [1] and that, around 70 MPa, there is a shift in the exponent from about 0.2 to 1.2. Assuming that LP in regenerative liquid propellant guns (RLPG) burns as a spray, with each droplet having a strand burner-type burn rate, we can explain why combustion pressure oscillations occur in RLPG fixtures once the pressure exceeds 70 MPa. However, the actual combustion of LP jets is a poorly understood process. To understand this process, both pressure and visualization data are needed. Unlike pressure data, visualization data at high pressures are very difficult to obtain. Yet, only visualization data can provide jet penetration and flame standoff distances that can aid in formulating realistic LP jet breakup and combustion algorithms applicable to the high-pressure regime above 70 MPa. Visualization of LP jets burning with pressure oscillations is desired because little is known about the response of jet breakup and flame dynamics to the oscillations. In order to achieve pressure oscillations, it is not sufficient to test at pressures above 70 MPa; it is also required to test LP jets with high-mass flow rates (i.e., thick jets injected with high velocities).

The U.S. Army Research Laboratory (ARL) undertook the challenge of constructing an experimental apparatus [2] that enables the visualization of LP jets burning with pressure oscillations. This report describes a series of tests that inaugurated the use of this apparatus with 1- and 3.5-mm XM46 jets. Although the tests yielded important jet penetration data, they did not exploit the full potential of the apparatus. The experimental phase described herein demonstrated that the experimental methodology and the apparatus are sound, but that the piston arrest mechanism needs modifications in order to achieve high-quality visualization of LP jet combustion above 100 MPa.

2. Experimental

The experimental apparatus is shown in Figure 1, and a full description is given in Birk and Kooker [2]. The apparatus consists of an in-line ballistic compressor and LP injector. The

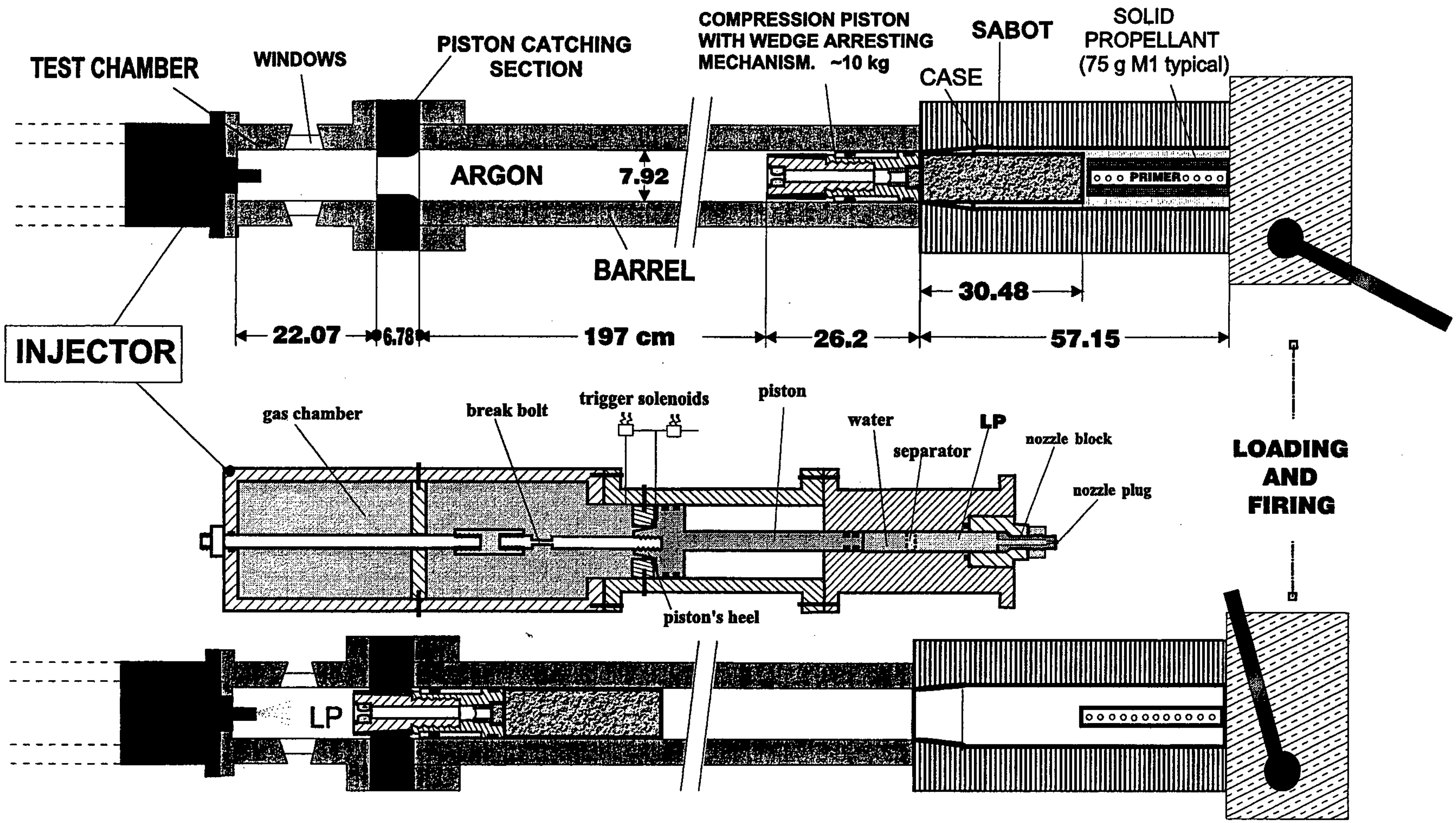


Figure 1. The Experimental Setup.

rebounding ballistic compressor piston is caught, trapping 40 to 55 MPa of 750 to 850° C argon for ignition of circular LP jets in a windowed test chamber. The elevated combustion pressure stabilizes once a disk ruptures above 70 MPa and the test chamber vents through a choked nozzle into the compressor's barrel. The injection is not regenerative; the injection pressure is provided via amplification of gas pressure in a chamber that is separate from the test chamber.

2.1 Operation. In all tests, a 75-g M1 charge was used to propel the compressor piston against 1.048-MPa (152 psi) static argon. The injector's gas chamber was charged with 13.79-MPa (2,000 psi) nitrogen for tests with 2- and 3.5-mm jets, and with 10-MPa (1,450 psi) nitrogen for tests with 1-mm jets. Pressures were measured near the entrance to the barrel to monitor the "breech pressure" at three locaations in the test section (6.99, 12.07, and 17.15 cm from the entrance to the test chamber) and at two locations (P1 and P2) in the injector. The water/LP in the injector was prepressurized with 3.45-MPa (500 psi) nitrogen via a water resevoir connected to the water charge in the injector. (The water flushes the LP.) The LP in the injector was sealed from the test chamber gas with plugs made from hard nylon. The plugs were fit snugly into the injector nozzel to a depth equal to 1.5 nozzle diameters. The plugs held against the 3.5-MPa liquid prepressure but ejected into the test chamber once the full injection pressure was applied. The injecor's nozzle block is removable. It is cylindrical (23-mm outside diameter [OD]), and its injection port protrudes 3.2 cm into the test chamber. The nozzels have a length-to-diameter (L/D) ratio of 4 and ellitical entrance profiles. The vent block in the compression piston (Figure 2), through which the combustion gas vents, was made of titanium and had and orifice initiallly 6.3 mm in diameter.

For photography, a Photec IV 16-mm motion-picture camera equipped with a 110-mm f/2.8 Mamiya Sekor lens and a no. 2 extension ring was used with a 16-mm, 125-ft Kodak 2253 Ektachrome film. Typical framing rates were 5,000 frames/second. The jets were imaged via a specially constructed wide-angle lens attached to the test chamber (see Figure 7 from Birk and Kooker [2]). Mirrors at 45° to the optical axis of the wide-angle lens compensated for recoil movements of the test chamber, keeping the image centered on the film frame. The jets were imaged through a window located 1.72 cm downstream from the injector nozzle exit. A 640-W tungsten halogen lamp provided illumination via a condensing lens through a window opposite the imaging

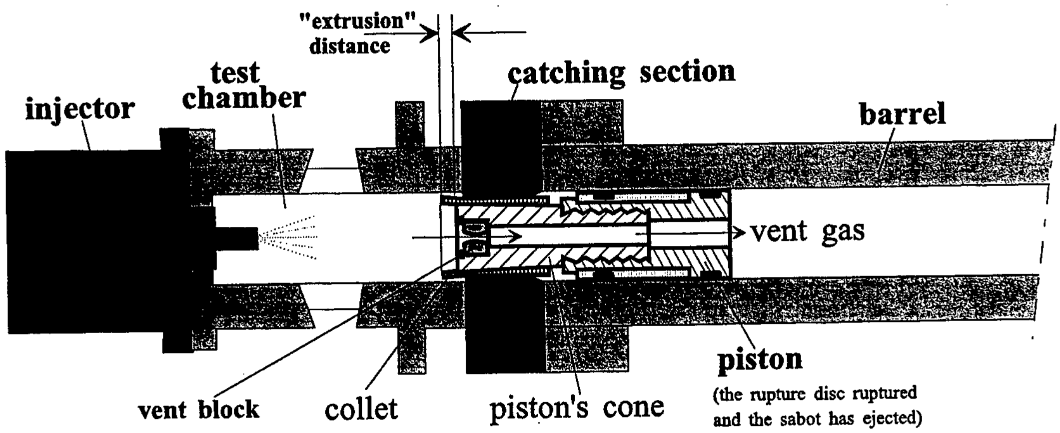


Figure 2. Piston in Caught Position During Combustion.

window. This formed a 10-mm- diameter disk of background light on which the jets were silhouetted. A 3-W copper vapor laser was used for side illumination (i.e., slicing the jet at 90° to the imaging window). This laser, an experimental Russian design, was unstable and could not be synchronized with the Photec camera. The laser illuminated the jet in a random fashion and was of limited value.

2.2 Test Matrix. The test matrix is shown in Table 1. The test program started ominously with an explosion in the injector's LP reservoir. The collet did not engage in the piston catching section, and, as a result, the piston rebounded and the LP injected into less than 10 MPa. The reason for the ignition in the reservoir is not certain. It is possible that hot spots generated via the collapse of cavitation bubbles caused LP ignition in the nozzle. (The cavitation number was highly supercritical.) It is also possible that bubbles formed during the filling of the LP did not fully dissolve under the 0.7-MPa prepressure that was applied on the LP, and, when suddenly compressed under the full injection pressure generated hot spots that ignited the LP. In order to prevent cavitation, we shortened the nozzles (to L/D = 4) and machined elliptical inlet profiles into them. In order to eliminate bubbles in the LP reservoir, we increased the prepressure to 3.5 MPa. After these preventive measures, the LP did not ignite in the injector, even in test no. 5 where the LP was injected inadvertently into 1 MPa.

Table 1. Test Matrix

Test No.	Purpose of Test	LP[a] Charge (cm^3)	Nozzle[b] Diameter (mm)	Peak Breech Pressure (MPa)	Peak[c] Ballistic Pressure (MPa)	Pressure at Injection (MPa)	Maximum Combustion Pressure (MPa)	Results/Comments
1	First test of the new apparatus.	45	2.0	13.5	65.2	—	—	Major failure; the piston did not catch; LP ignited in the injector; damage to test hardware.
2	Water injection; test of the piston arrest mechanism with moderate-fit collet.	—	3.5	13.5	65.8	—	—	Piston successfully caught.
3	Water injection; test of the piston arrest mechanism with loose-fit collet.	—	3.5	13.2	65.7	—	—	Piston successfully caught.
4	Water injection; test of the piston arrest mechanism with tight-fit collet.	—	3.5	13.5	61.1	—	—	Piston successfully caught.
5	LP injection test with the modified nozzle (elliptical inlet).	45	3.5	—	—	—	—	The solid propellant charge did not fire because of pneumatic malfunction; the LP did not ignite.

[a] All LP tests with XM46, except test nos. 18, 19, and 21.
[b] Nominal peak injection pressure is 137.9 MPa, except for the 1-mm nozzle, where it is 95 MPa.
[c] Maximum pressure in the combustion chamber generated by the ballistic compression.

Table 1. Test Matrix (continued)

Test No.	Purpose of Test	LP[a] Charge (cm^3)	Nozzle[b] Diameter (mm)	Peak Breech Pressure (MPa)	Peak[c] Ballistic Pressure (MPa)	Pressure at Injection (MPa)	Maximum Combustion Pressure (MPa)	Results/Comments
6	LP injection test; repeat of test no. 5	47	3.5	13.3	65.6	48.3	100.7	First successful test; significant contamination of test chamber with the collet grease before the LP injection; field of view (FOV) obstructed by combustion of accumulated LP.
7	LP injection test; increased LP charge to achieve steady-state combustion.	64	3.5	13.9	64.4	45.3	82.1	Quasi-steady-state combustion achieved; still significant contamination of the test chamber; FOV obstructed by combustion of accumulated LP.
8	Test of the piston arrest mechanism with the chrome-plated piston's cone (no grease used).	—	—	13.8	63.2	—	—	The piston was not caught, and the collet was severely damaged.
9	Test of piston arrest mechanism (no grease used); loose collet used.	—	—	13.8	61.5	—	—	The piston was not caught, and the collet was severely damaged.

[a] All LP tests with XM46, except test nos. 18, 19, and 21.
[b] Nominal peak injection pressure is 137.9 MPa, except for the 1-mm nozzle, where it is 95 MPa.
[c] Maximum pressure in the combustion chamber generated by the ballistic compression.

Table 1. Test Matrix (continued)

Test No.	Purpose of Test	LP[a] Charge (cm^3)	Nozzle[b] Diameter (mm)	Peak Breech Pressure (MPa)	Peak[c] Ballistic Pressure (MPa)	Pressure at Injection (MPa)	Maximum Combustion Pressure (MPa)	Results/Comments
10	Test of the piston arrest mechanism (grease used).	—	—	13.7	62.1	—	—	The piston was successfully caught.
11	Test of the piston arrest mechanism (reduced grease).	—	—	13.9	60.8	—	—	Quasi-steady-state combustion achieved; still significant contamination of test chamber; FOV obstructed by combustion of accumulated LP.
12	LP injection test; repeat of test no. 7.	64	3.5	13.6	64.1	43.4	80.7	Quasi-steady-state combustion achieved; still significant contamination of test chamber; FOV obstructed by combustion of accumulated LP.
13	LP injection test; increased LP charge to achieve steady-state combustion.	108	3.5	13.9	64.8	46.2	133.8	Steady-state combustion not achieved; LP that accumulated in test section rapidly ignited causing overpressurization of the test fixture and piston disengagement; the catching section seals failed.

[a] All LP tests with XM46, except test nos. 18, 19, and 21.
[b] Nominal peak injection pressure is 137.9 MPa, except for the 1-mm nozzle, where it is 95 MPa.
[c] Maximum pressure in the combustion chamber generated by the ballistic compression.

Table 1. Test Matrix (continued)

Test No.	Purpose of Test	LP[a] Charge (cm^3)	Nozzle[b] Diameter (mm)	Peak Breech Pressure (MPa)	Peak[c] Ballistic Pressure (MPa)	Pressure at Injection (MPa)	Maximum Combustion Pressure (MPa)	Results/Comments
14	Water injection; modified piston's heel to reduce injection pressure gradient.	—	3.5	13.1	40.7	—	—	Successful reduction of rate of liquid pressurization in reservoir.
15	LP injection test; modified piston's heel to reduce injection pressure gradient.	62	3.5	12.4	64.8	44.1	117.2	Reduction of pressurization rate not sufficient to eliminate LP accumulation in the test chamber; the front catching section seal failed.
16	LP injection test; smaller nozzle to reduce LP accumulation.	32	1.0	12.6	51.7	—	—	The LP injection delayed beyond data-recording time.
17	LP injection test; repeat of test no. 16 (improved hardware).	43	1.0	13.3	59.2	42.0	71.0	Visible LP jet in the test chamber; long flame standoff (>5 cm).

[a] All LP tests with XM46, except test nos. 18, 19, and 21.
[b] Nominal peak injection pressure is 137.9 MPa, except for the 1-mm nozzle, where it is 95 MPa.
[c] Maximum pressure in the combustion chamber generated by the ballistic compression.

Table 1. Test Matrix (continued)

Test No.	Purpose of Test	LP[a] Charge (cm^3)	Nozzle[b] Diameter (mm)	Peak Breech Pressure (MPa)	Peak[c] Ballistic Pressure (MPa)	Pressure at Injection (MPa)	Maximum Combustion Pressure (MPa)	Results/Comments
18	LP injection test; more energetic propellant (LP1845)[d]	41	1.0	13.4	55.0	36.6	42.8	Broken Collet; very sluggish combustion.
19	LP injection test; repeat of test no. 18.	42	1.0	13.4	52.7	35.	43.9	Some damage to the collet; very sluggish combustion.
20	Test of the piston arrest mechanism.	—	—	13.2	57.8	—	—	The piston was caught.
21	LP injection test; repeat of test no. 19 (unseeded LP.)	42	1.0	12.3	50.3	36.1	46.3	Very sluggish combustion.
22	LP injection test; new LP lot.	42	1.0	12.9	54.5	33.7	38.1	Very sluggish combustion.

[a] All LP tests with XM46, except test nos. 18, 19, and 21.
[b] Nominal peak injection pressure is 137.9 MPa, except for the 1-mm nozzle, where it is 95 MPa.
[c] Maximum pressure in the combustion chamber generated by the ballistic compression.
[d] Propellant seeded with 2% of saturated aqueous $LiNO_3$ to increase flame visibility.

Unfortunately, more than half of the tests was dedicated to solving persistent problems with the collets. In test no. 1, we used silicon-based grease to lubricate the inner surface of the collet. Apparently, the grease was not effective. In test nos. 2–4, we used molybdenum-based grease, and the collets engaged well, despite variations in how they fit into the bore of the catching section. The molybdenum grease contaminated the test chamber gas somewhat, but it was essential for reliable operation. An attempt (test no. 8) to eliminate the need for the grease by using a polished, chrome-plated piston cone (hence reducing friction between the collet and the cone) resulted in a major failure. The collet did not engage in the catching section. It entered the catching section in a manner that produced vibration-induced oscillations in the measured test chamber pressure, something that had not been observed before, and its front end broke into pieces that were thrown into the test chamber. We found out that the grease was necessary not only for friction reduction, but also for prevention of what we suspect was aerodynamic fluttering of the collet.

The inner surface of the collet was extruded by the piston's cone in every test. Typically, the cone recessed to an "extrusion" distance (Figure 2) of about 2 cm, and this resulted in a drop of the compression pressure from its peak value. In test no. 13, the catching mechanism did not withstand the 130-MPa combustion pressure, and the piston broke loose from the collet after severely extruding the inner surface of the collet. The piston rebounded, and the test chamber pressure plummeted. The bore of the catching section deformed; its diameter increased by few tenths of a millimeter, more noticeably toward the test chamber. In subsequent tests, the collets did not fit well in the catching section bore, and the cone recessed more deeply than before, causing larger drops from the peak compression pressures. As a result, in later tests, the LP was injected into reduced pressures, and its combustion became sluggish.

2.3 Pressure Data. Instructive pressure data were obtained in test nos. 6, 7, 12, 13, 15, and 17. The pressure traces from these tests, along with calculated injection velocities and injected LP volumes, are shown in Figures 3–8. The injection velocities and the injected LP volumes are shown until the time that water begins to enter the chamber. Key data from these tests are summarized in Table 2. In Figure 9, the test chamber pressures of the aforementioned tests are overlaid such that the onset of their compression cycles coincide. The compression cycles were very reproducible,

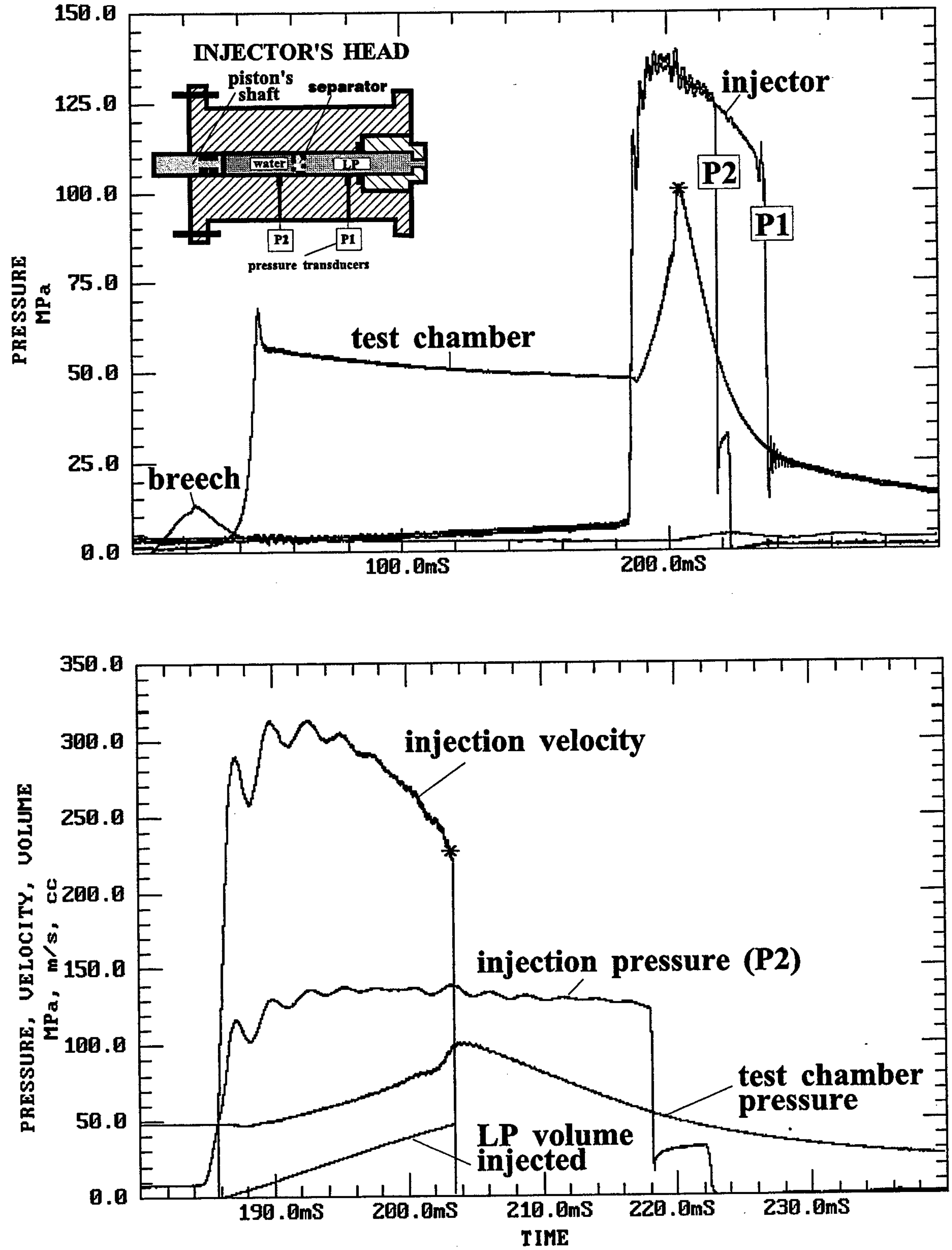


Figure 3. Pressure and Injection Data of Test No. 6.

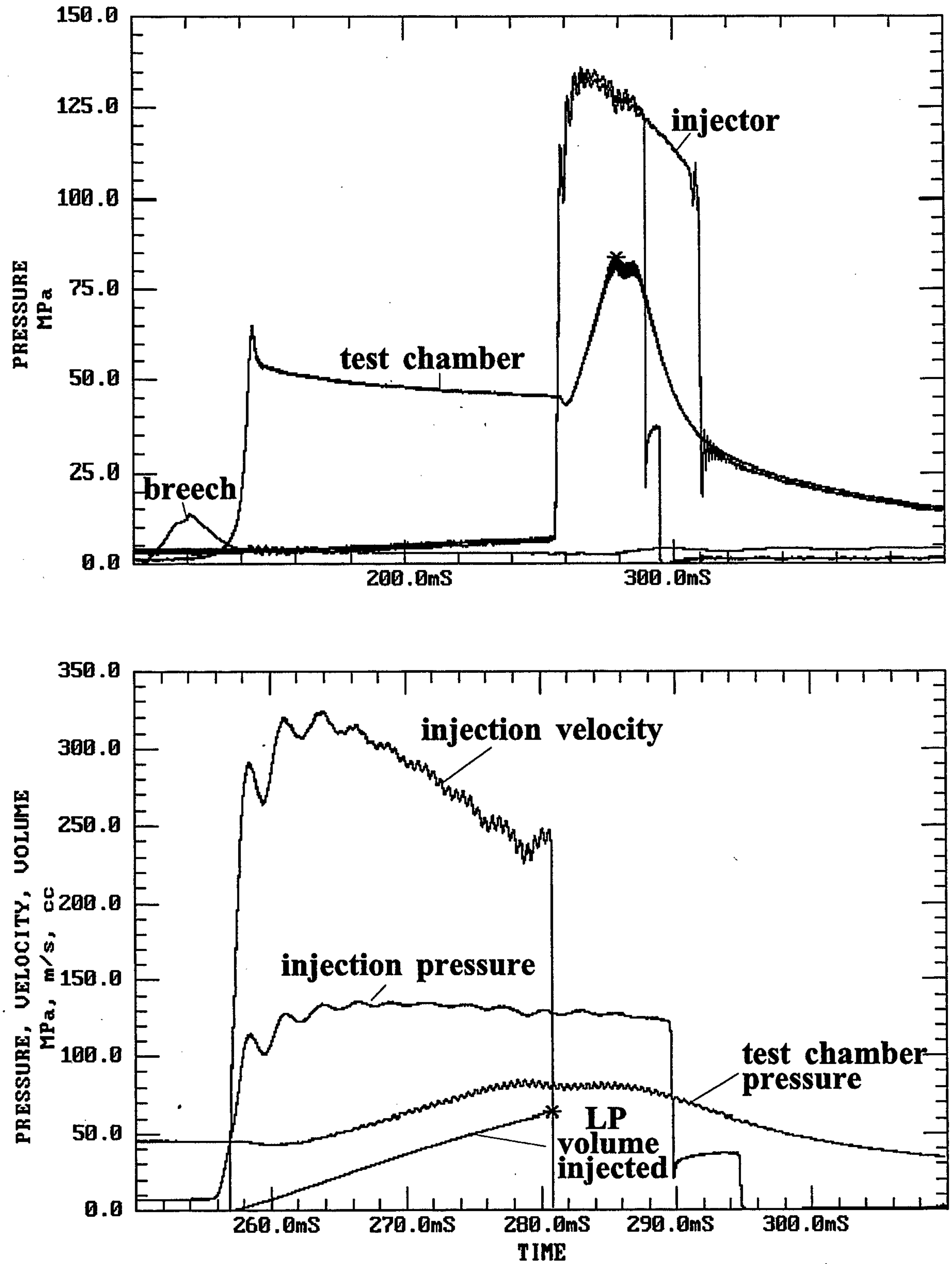


Figure 4. Pressure and Injection Data of Test No. 7.

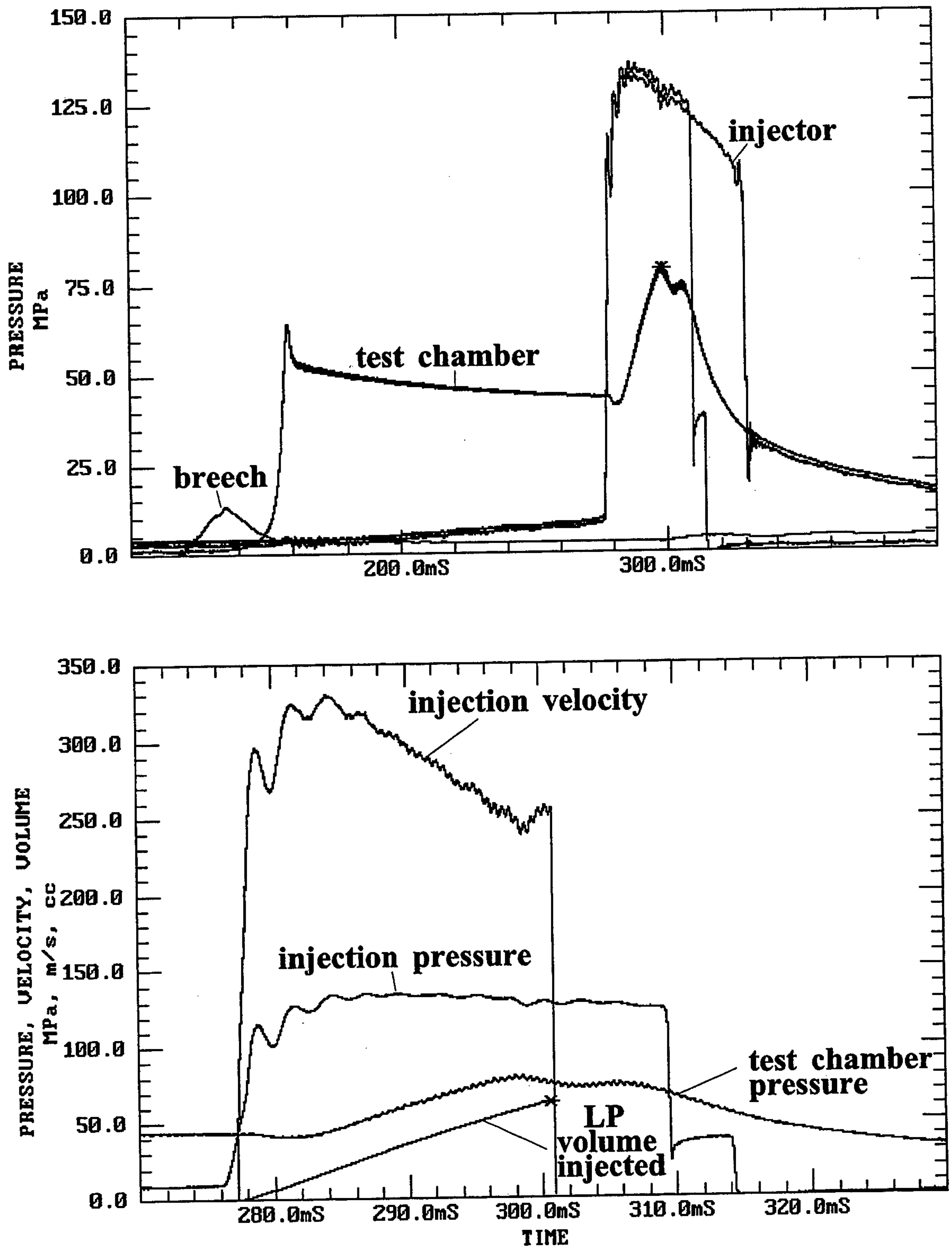


Figure 5. Pressure and Injection Data of Test No. 12.

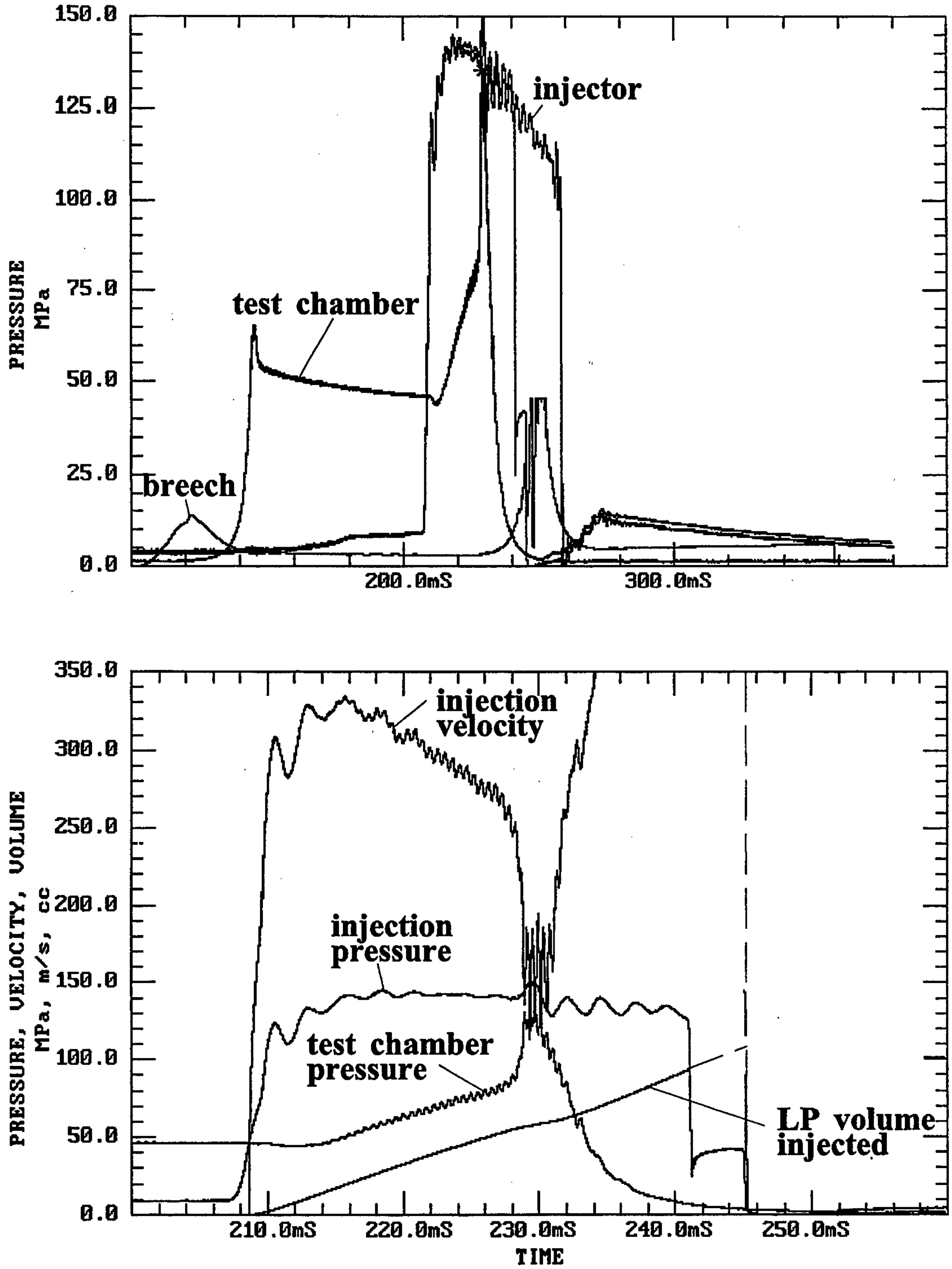


Figure 6. Pressure and Injection Data of Test No. 13.

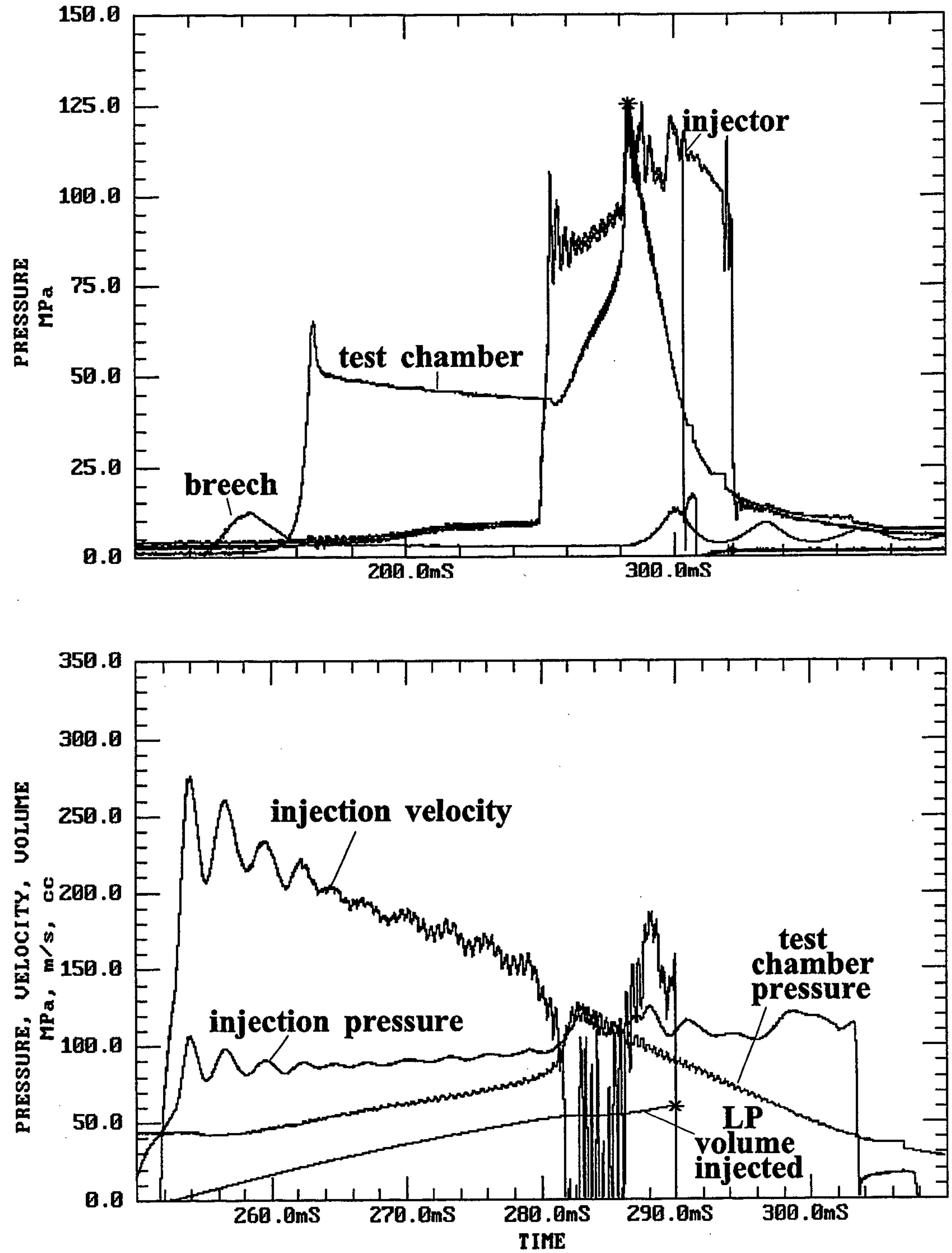
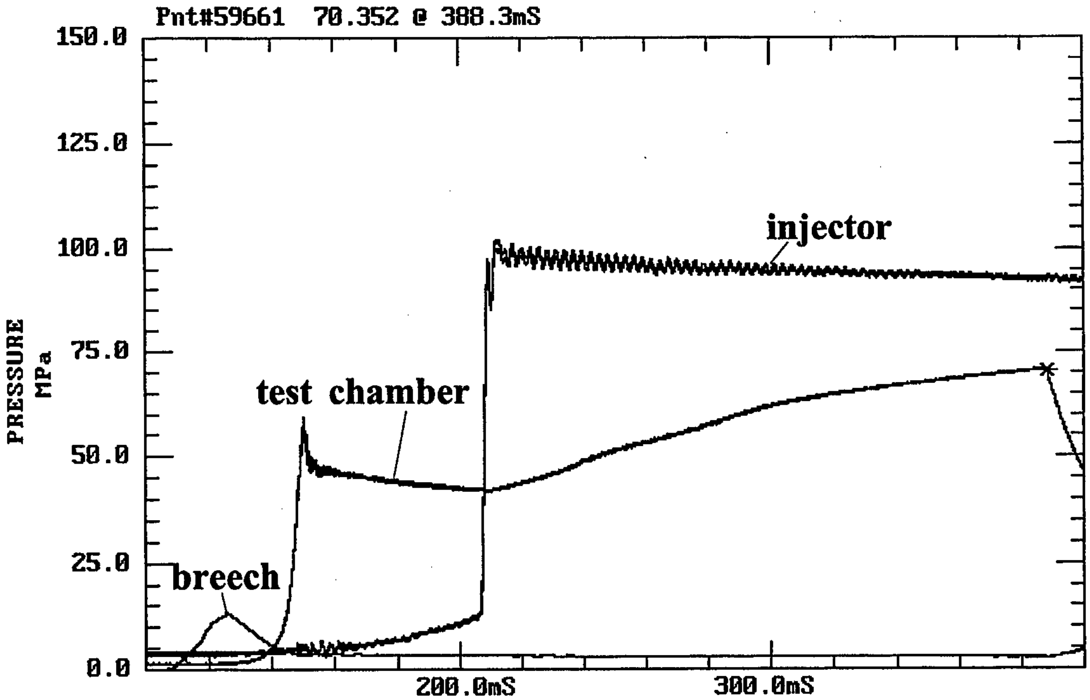


Figure 7. Pressure and Injection Data of Test No. 15.



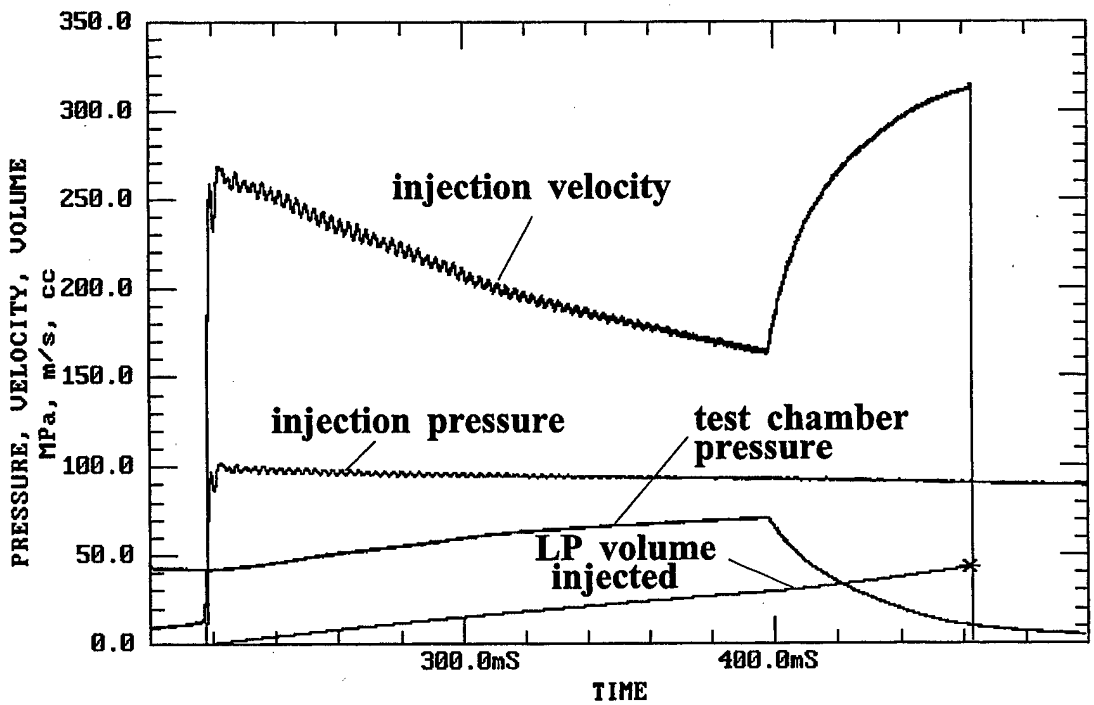


Figure 8. Pressure and Injection Data of Test No. 17.

Table 2. Chamber Pressures and Injected LP Volume

Test No.	Rupture Disk Pressure (MPa)	LP Injected Until Rupture (cm^3)	Combustion Pressure[a] if All LP Combusted (MPa)	Peak Combustion Pressure (MPa)	LP Injected Until Peak Pressure (cm^3)	Combustion Pressure[a] if All LP Combusted (MPa)
6	81	42.4	106.9	100.7	47	113
7	79	52.4	117.8	82.1	58.5	126.2
12	77	54.4	118.6	80.7	57.2	122.5
13	79.2	50.7	116.3	133.8	58.4	128
15	83	52.7	117	117.2	53.9	119.6
17	71	29	82	71	29	82

[a] BLAKE code calculation, assuming no venting of gas from the chamber.

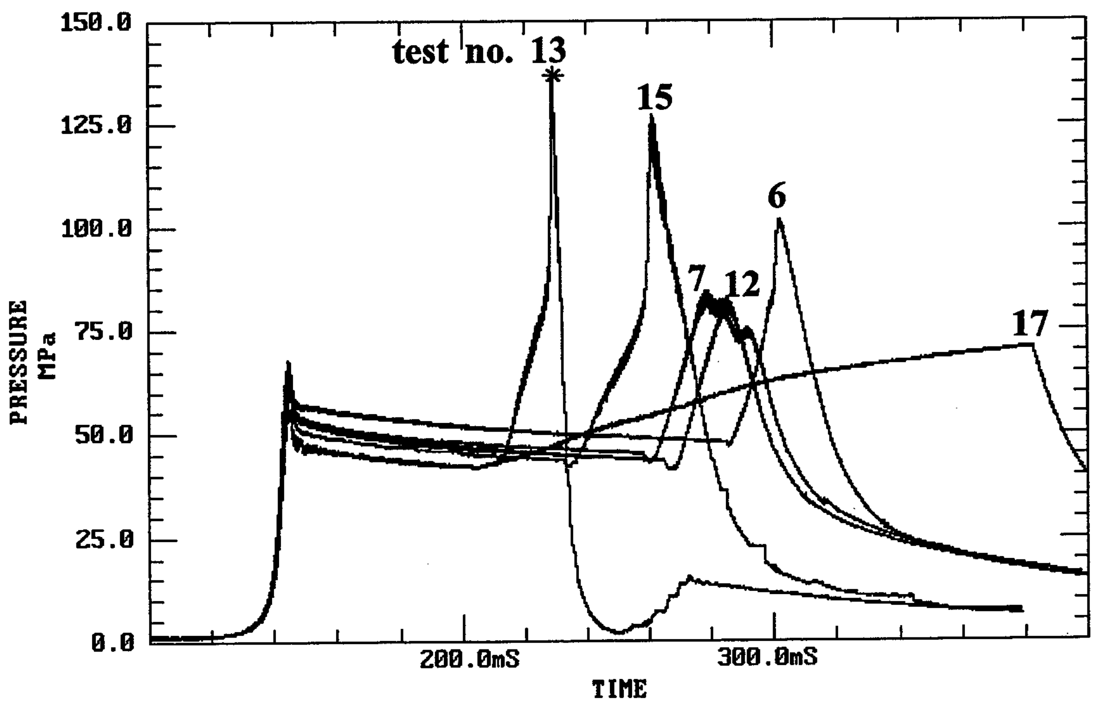


Figure 9. Overlay of Test Chamber Data From Test Nos. 6, 7, 12, 13, 15, and 17.

owing to the reproducibility of the breech pressure profiles. The increasingly larger drop from the peak compression pressure due to the progressive deterioration of the catching section is evident in Figure 9.

The time of disk rupture could be estimated only in test no. 17 (1-mm jet) because there is little LP accumulation in the 1-mm jet; hence, the disk rupture causes an immediate drop in the chamber pressure. The sabot ejects following the disk rupture, generating a pressure wave that reaches the breech pressure transducer after a certain delay. In test no. 17, this delay was about 2 ms. Therefore, in all other tests, we assumed that the rupture disks ruptured 2 ms before the responses of the breech pressures.

The LP jets ignited in less than 2 ms as indicated by a steep rise (ca. 3 MPa/ms) in the chamber pressure. However, the disk rupture did not always stabilize the combustion pressure. With 3.5-mm jets, we achieved both quasi-steady combustion at about 80 MPa (tests 7 and 12) and nonsteady combustion with a steep pressure rise-rate (ca. 100 MPa/ms) culminating in peak combustion pressures over 100 MPa (test nos. 6, 13, and 15). The nonsteady combustion occurred because LP accumulated in the test chamber, and the accumulation burned rapidly once the pressure exceeded 75 MPa.

Based on the geometry of the injector, the drop in pressure P2 (Figure 3) marks the point at which 97 cm^3 of liquid (combined volume of LP and water that flushes the LP) have been injected. The injection velocities (and in turn the volumes of LP injected by any time) are calculated from the differential injection pressure using the Bernoulli equation. (The liquid injection velocity varies as square root of the differential injection pressure.) We use a discharge coefficient of 0.95 (calculated based on a preliminary experiment with pure water) for the calculations of the injection velocities. The maximum injection velocities for the 3.5-mm jets were about 325 m/s and decreased to about 287 m/s once the combustion pressure reached 75 MPa. In test no. 15, the injection pressure was applied gradually (using a modified heel on the back of injector's piston) and this resulted in hazardous flashback condition—at the peak combustion pressure in test no. 15, the injection velocity dropped to 0 m/s. The BLAKE Code [3] was used to calculate theoretical combustion pressures in the test chamber (i.e., assuming no heat losses and no venting into the barrel). The calculated pressures are given shown in Table 2. For example, for the 1-mm jet in test no. 17, by the time of disk rupture, 29 cm^3 of the LP had injected. The 29-cm^3 LP corresponds to a loading density of 0.044 g/cm^3 in the test chamber. Taking into account that the chamber was pressurized to 42 MPa at the time of injection, we calculate that complete adiabatic combustion of the LP would have raised the chamber pressure to about 82 MPa. The actual pressure was 71 MPa, the difference most likely because of heat losses over the extended injection period in this test. In test no. 6, the LP loading density is about 0.071 g/cm^3 and the peak combustion pressure of 100.7 MPa is close to the adiabatic value 113 MPa, despite the fact that the rupture disk ruptured at 81 MPa. The rapid combustion overwhelmed the pressure loss through the ruptured disk. In all tests except test no. 17, there is significant LP accumulation just before the disk ruptured. The rapid combustion occurred after rupture. It is possible that pressure waves generated by the rupture event triggered rapid combustion because the disks ruptured at pressures where the burn-rate exponent of the LP is greater than 1. Although, by test no. 15, erosion had increased the vent orifice in the piston to about 10-mm diameter, the peak pressure in this test was 117.2 MPa, almost the calculated value. In test no. 13, the peak pressure exceeded the calculated value. We must assume that test nos. 13 and 15 started to exhibit pressure waves. The peak pressures in test nos. 7 and 12 do not correspond to complete combustion of the LP. It is likely that significant amount of LP vented into the barrel.

2.4 Visualization Data. The excessive accumulation of the LP in the tests with the 3.5-mm nozzles impeded the visualization, obscuring the jet before ignition and burning in a fireball that engulfed the jet and filled the entire combustion chamber. Nevertheless, we could determine from visualization that the penetration of 1- and 3.5-mm-circular XM46 jets with injection velocities over 200 m/s exceed 5 cm when the combustion pressure is below 80 MPa. The photographic records are of poor quality as represented by Figure 10. Only the jet penetration could be determined but not the flame standoff. It is possible that the flame standoff of the 1-mm jet in Figure 10 is less than 5 cm. The flame standoff of the 3.5-mm jet was clearly beyond the FOV. Large millimeter-size drops were observed burning at 80 MPa, indicating that XM46 combustion is subcritical at this pressure. We attempted to measure the LP droplet burn rate. The fireball flame exhibited distinct, small, very bright particles moving through the FOV of the optical system (Figure 11). These

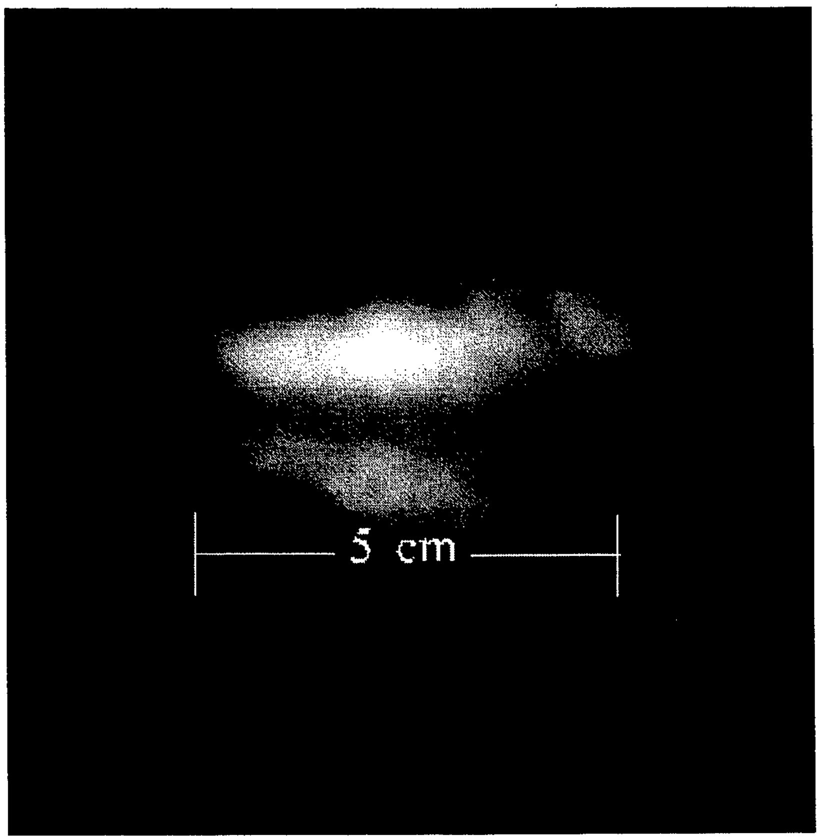


Figure 10. Silhouette of 1-mm XM46 Jet at 70 MPa From Test No. 17 Showing Penetration Deeper Than 5 cm.

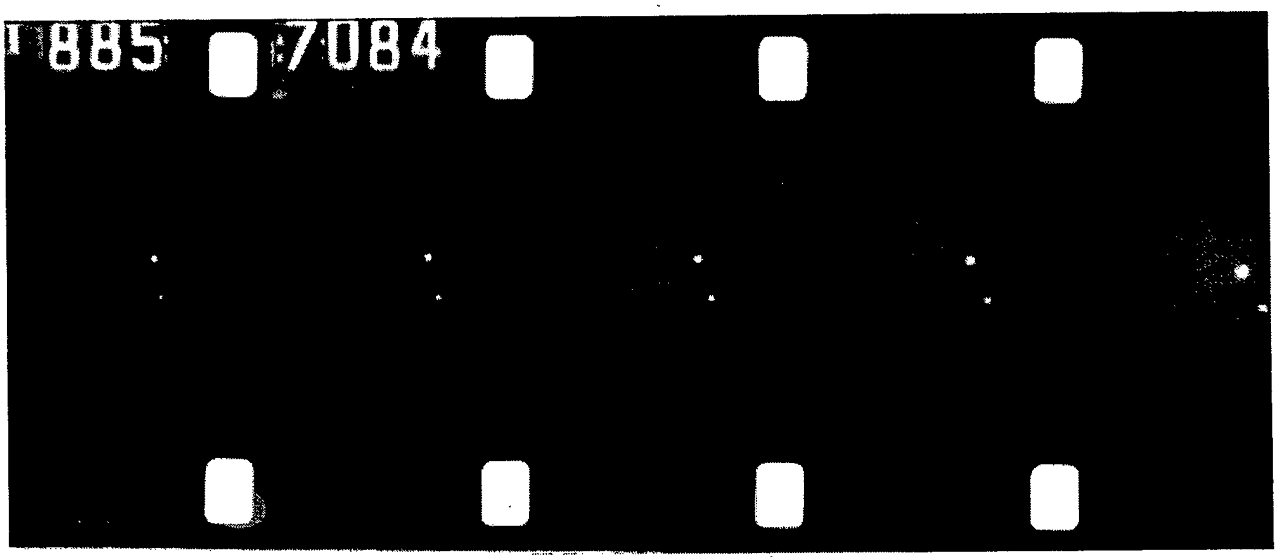


Figure 11. High-Speed Movie Frames Clearly Showing Bright Particles and Their Decrease in Size With Time.

particles are thought to be burning droplets of LP. Therefore, an attempt was made to determine the burn rate of LP from the rate that the size of these particles decreased. One has to realize that, for this approach to give accurate results, several conditions must be met. First, the particles (droplets) must stay in the vicinity of the window. Any motion of the particle perpendicular to the window would result in inaccurate reading of the droplet size. Second, variation in light intensity would result in falsification of measurement of droplet size. Third, the flame zone must be very thin in comparison to droplet size (this pertains also to the luminous zone of hot combustion products). Fourth, the flame zone must be very close to the liquid surface.

We selected the brightest droplet shown in Figure 11. The droplet was believed to satisfy the aforementioned conditions—for long periods of time (several frames) the droplet seemed not to move away from the window, and its brightness, especially toward the end of recording time, remained constant. We believe that, at these (high pressure) conditions, the flame zone is thin and very close to the liquid surface [4]. Furthermore, we assume that the burn rate of fast-burning, large, liquid monopropellant droplets (as in Figure 11) satisfy the relation dr/dt = constant, where "r" is the droplet radius. This burn-rate assumption is based on the experimental results of Lee, Tseng, and Faeth [4] and on the theoretical analysis of Williams [5]. Nevertheless, it must be said that this method of measurement of LP burn rate is very crude and may be inaccurate. The measured average droplet radius regression for a selected droplet (test no. 12) is presented in Figure 12. The average burn rate measured over a period of almost 3 ms is about 12 cm/s. This is much higher than expected at this pressure. (A measured burn rate of XM46 at 75 MPa is reported [1] to be about 3 cm/s.) Rapid increase or decrease of the droplet radius can be attributed to droplet motion toward and away from the window. However, one can also observe periods of steady reduction of the droplet radius (e.g., between 0.6 and 1.2 ms and between 2.2 and 2.7 ms). During those periods, the rate of droplet regression rate is also about 12 cm/s. It is possible that the difference between the literature data and burn rate obtained from this experiment is due to the bulk liquid temperature. In the strand burner experiments of McBratney and Vanderhoff [1], the bulk liquid temperature was room temperature. Possibly, the bulk liquid temperature of the large droplet in Figure 10 is much higher than room temperature because the droplet was likely formed from the coalescence of much smaller droplets that were rapidly heated up by the hot ambient gas.

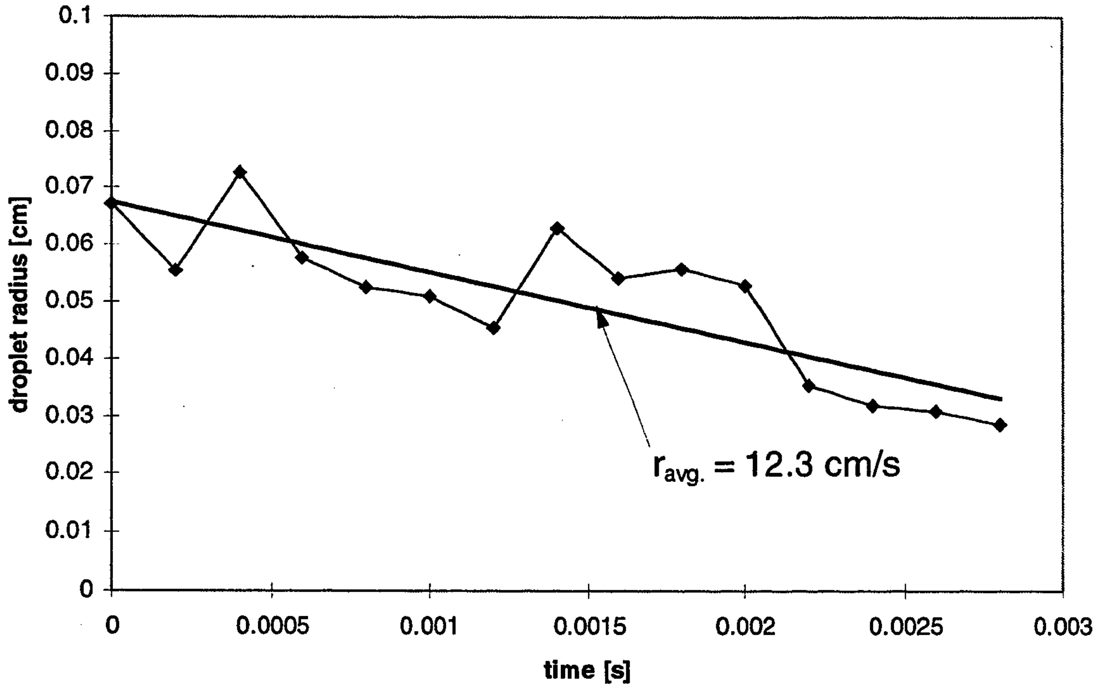


Figure 12. Regression of Droplet Radius as a Function of Time (Arbitrary "Zero").

3. Discussion

Ignition data aside, the main goal of the experiment was to obtain high-quality visualization of flame standoff along LP jet (a goal not yet accomplished). We chose to visualize through the window closest to the injector because we expected the jet penetration (especially of the 1-mm jet) to be within 5 cm of the injector (within the imaging FOV). Clearly, the jet penetration was, beyond the FOV. This is perplexing in view of earlier work [6] at lower pressure and temperature (33 MPa, 500° C) where excellent visualization of 1-mm LGP1845 (seeded with about 2% saturated solution of lithium nitrate) was obtained, and the jet penetration was below 5 cm. Although the present tests were with XM46 that is less energetic than LGP1845, the results of test nos. 19 and 21 with LGP1845 and 22 with XM46 lead us to believe that an XM46 jet should behave quite similar to an LGP1845 jet. We therefore assume that the reason for the extended penetration is the higher injection velocity in the present tests compared to the earlier work [6]. Here, the average injection velocity of the 1-mm jet exceeds 200 m/s, while, in Birk, McQuaid, and Bliesener [6] it is 150 m/s.

Perhaps higher injection velocity "blows" the flame further downstream. Here, we did not risk testing the 1-mm jet at 150 m/s because it requires low injection pressure. The present injector is not regenerative and, therefore, the differential injection pressure may drop dangerously low when combustion elevates the test chamber pressure, risking flashback into the injector. The injector in Birk, McQuaid, and Bliesener [6] is regenerative, and its operation is therefore inherently safe (the higher the test chamber pressure, the higher the injection velocity).

The lack of an efficient copper vapor laser and contamination from the collet grease detracted from the visualization. An important difference between the tests of Birk, McQuaid, and Bliesener [6] and the present tests is the optics for visualization. In Birk, McQuaid, and Bliesener [6], large rectangular windows were used with narrow-angle optics. The small-aperture conical window used here and the wide-angle optics mean that any obstruction near the inner surface of the window (within a 25-mm-diameter circle) will hinder details from the jet (from within a 75-mm-diameter circle). Therefore, in the present tests, if the LP jet does not ignite promptly and the flame is not close to it, jet details will be obscured by dispersed, burning or nonburning, LP particles near the inner surface of the window. This was certainly the case with the 3.5-mm jets that had excessive LP accumulation.

Although, the 3.5-mm jets ignited promptly (within 2 ms of injection), excessive LP accumulation in the test chamber took place until the combustion pressure exceeded 75 MPa. We suspect that the same physics or chemistry responsible for the transition of the burn-rate exponent to value larger than 1 around 75 MPa also causes accelerated burning of accumulated LP around 75 MPa. By inference, we suppose that had we injected the LP into pressures higher than 75 MPa, accumulation would have been much smaller, and visualization would have been better. We conclude that, in order to achieve good visualization, we need to ignite the LP jet at higher pressures than 75 MPa, preferably above 100 MPa. The grease contamination has to be eliminated, and a 10-W, camera-synchronized, copper vapor laser has to be used for side illumination.

The tests revealed shortcomings of the present piston catching method. It does not create as clear an ambient gas as was achieved with a particle bed heater, and its reliability at pressures above

100 MPa is poor. We devised the collet-based catching method because the collet does not contact the chrome-plated barrel of the ballistic compressor. A peeling of the chrome would have doomed the experimental program. However, the chrome plating proved robust and durable. In test no. 13, the piston became stuck in the barrel upon rebound and had to be rammed out against very high friction, and the chrome was not damaged. Therefore, we now consider that a wedge-based catching method where the piston is caught in the barrel itself (and not in a catching section) a viable alternative. In this method, used by Pinakov [7] and Meshcheryahov, Pinakov, and Topchiyan [8], the grease is sealed from the test chamber, and, thus, does not create a contamination problem. Furthermore, because the barrel is long, the piston catching length in the barrel can be made long enough to reliably hold against 150 MPa test chamber pressure.

Aside from the collet, the test hardware performed well. The test chamber windows were virtually maintenance free. The injector was reliable, although, its triggering solenoids could not be controlled to an accuracy better than 20 ms. The elastomeric o-rings that seal the test chamber to the barrel failed at about 100 MPa. They will have to be replaced with metallic o-rings.

4. Summary

A series of tests that employed a ballistic compressor-based apparatus for the research of LP jet combustion was conducted. Even though visualization of a 5-mm jet burning at 140 MPa with pressure oscillations was not achieved, the experiments yielded valuable information on LP combustion at pressures of 80–120 MPa. Excessive LP accumulation impeded the visualization, obscuring the jet before ignition and burning in a fireball fashion once ignited. Nevertheless, it was possible to estimate, from the high-speed-film records, that the penetration of 1- and 3.5-mm-circular XM46 jets with injection velocities over 200 m/s exceed 5 cm when the combustion pressure is below 80 MPa. Also, large millimeter-size drops were observed burning at 80 MPa, indicating that XM46 combustion is subcritical, even at this pressure.

The operation of the piston arrest mechanism was problematic. Grease from the mechanism degraded visualization of the jets, and the mechanism failed when the test chamber pressure reached

133 MPa. A new design will have to be incorporated to achieve the original goal of the test program. The results of the tests lead us to believe that, in order to avoid LP accumulation, a 5-mm jet will have to be ignited in argon at a pressure and temperature that are higher than 100 MPa and 850° C.

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13. ABSTRACT ***(Maximum 200 words)***

This report describes a series of tests that inaugurated the use of a ballistic compressor-based apparatus for the research of liquid propellant (LP) jet combustion. The apparatus consists of an inline ballistic compressor and LP injector. The rebound of the ballistic compressor piston was arrested, trapping 40 to 55 MPa of 750 to 850° C argon for ignition of circular LP jets in a windowed test chamber. The LP jets ignited in less than 2 ms as indicated by a steep rise (ca. 3 MPa/ms) in the chamber pressure. The elevated combustion pressure ruptured a disk above 70 MPa, venting the combustion gas into the compressor's barrel. The rupture of the disk did not always stabilize the combustion pressure; with 3.5-mm jets, we obtained both quasi-steady combustion at about 80 MPa and nonsteady combustion with steep pressure rise-rate (ca. 100 MPa/ms) that culminated in peak combustion pressures over 100 MPa. The nonsteady combustion occurred because LP accumulated excessively in the test chamber and burned rapidly once the combustion pressure exceeded 75 MPa. The accumulation impeded the visualization, obscuring the jet before ignition, and burned in a fireball fashion once ignited. Nevertheless, we could determine from film records that the penetration of 1-mm and 3.5-mm circular XM46 jets with injection velocities over 200 m/s exceed 5 cm when the combustion pressure is below 80 MPa. Large millimeter size drops were observed burning at 80 MPA, indicating that, even at this pressure, XM46 combustion is subcritical. The operation of the piston arrest mechanism was problematic.

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