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Bipropellant Engine Plume Contamination Program

Volume III
Performance Predictions for the AJ10-181 Bipropellant Rocket Engine Using the CONTAM/TCC Code

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ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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A plume contamination test conducted in the AEDC Aerospace Chamber (10V) with the Aerojet AJ10-181 5-lb-thrust bipropellant engine provided data for comparison with the CONTAM computer program. The Plume Contamination Effects Prediction Program (CONTAM), developed by McDonnell Douglas under Air Force Rocket Propulsion Laboratory (AFRPL) sponsorship, comprises several component codes which describe the gas dynamics and chemistry

20. ABSTRACT (Continued)

in the combustion chamber, nozzle, and free-jet expansion. This report concerns the Transient Combustion Chamber (TCC) program which calculates the combustion products, unburned propellants, and droplets that flow from the combustion chamber. The report further provides results that can be compared with the specific set of conditions of oxidizer-fuel ratio, propellant pressures, and injector configuration which were used in the vacuum chamber test.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), and the Air Force project manager was Dr. H. E. Scott. The results of the research were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Projects No. V32S-R5A and V32K-13. The work was completed December 12, 1978, and the manuscript was submitted for publication on April 30, 1979.

CONTENTS

Page

1.0 INTRODUCTION

2.0 CONTAM/TCC ANALYSIS

ILLUSTRATIONS

Figure

TABLES

1.0 INTRODUCTION

The contamination of spacecraft surfaces by the exhaust products of rockets used for attitude control has become increasingly important with the use of satellites carrying optical instrumentation. The USAF has sponsored the development of comprehensive computer programs that will model the complex of gas dynamic and chemical kinetic processes that characterize rocket engine combustion and exhaust flow, e.g., the Plume Contamination Effects Prediction Program (CONTAM). The experimental data to confirm these computational methods are severely limited by the requirement for a high-altitude (very low ambient pressure) testing facility. A test program with a small 5-lbf bipropellant rocket was completed recently in the Arnold Engineering Development Center (AEDC) Aerospace Chamber (10V) (Chamber 10V), and part of the CONTAM program was run with inputs that corresponded to the test conditions.

1.1 CONTAM

The CONTAM was developed by the McDonnell Douglas Astronautics Company under sponsorship of the Air Force Rocket Propulsion Laboratory (AFRPL) (Ref. 1). In brief, CONTAM models the production, transport, and deposition of rocket engine and plume contaminants upon sensitive spacecraft surfaces such as solar cells, viewing ports, and detectors. CONTAM is composed of several independent computer codes. These include the Transient Combustion Chamber (TCC), the Multiphase Nozzle and Plume Transport (MULTRAN), and the Nonequilibrium Chemical Kinetics and Condensation (KINCON).

The TCC dynamics computer program performs the time-varying analysis of the chemical and physical processes occurring in the feed system, injector, combustion chamber, and nozzle-throat inlet of a bipropellant rocket engine system operating under unsteady conditions. The TCC provides information about the production of contaminants in the combustion chamber and the dynamic and thermodynamic state of combustion gases entering the nozzle throat. Unburned fuel and oxidizer droplet distributions as well as liquid film wall flow are computed for the entire transient pulse.

The MULTRAN computer program performs the subsonic, transonic, and supersonic computations required to define the steady-state multiphase flow field within a rocket nozzle and exhaust plume. The TCC provides the input to MULTRAN in terms of quasi-steady time-averaged gas properties and droplet size distributions. The MULTRAN provides streamlines of the gaseous phase as well as droplet trajectories.

The KINCON computer program performs chemical-kinetic and single species condensation calculations along gas-phase streamlines as computed by MULTRAN.

1.2 THE AJ10-181 ROCKET ENGINE

The 5-lbf-thrust bipropellant AJ10-181 rocket engine was developed for AFRPL by the Aerojet Liquid Rocket Company (Ref. 2). This engine was developed to meet the requirement for a small, high-performance, long-life, fast-response, and reliable engine to be used aboard space satellites for attitude control and station keeping.

The bipropellant engine was designed to operate on green N_2O_4 (MIL-P-26539) and MMH ($CH_3N_2H_3$, MIL-P-27404) at a mixture ratio of 1.6 lb of N_2O_4 per lb of MMH at propellant supply temperatures between 20°F and 120°F.

Three versions of the engine have been subjected to extensive duty cycle testing at Aerojet. Engine No. 1, designated the AJ10-181-2, was optimized for maximum performance with a pressure regulated feed system and a chamber that was free to radiate. This engine, the highest performing and cleanest operating of the three, has successfully demonstrated 300,000 restarts. The AJ10-181-2 incorporates a six-element splash plate injector with 45-deg element orientation and an interchangeable combustion chamber nozzle assembly. One of these had a 2-in.-long chamber with a 100:1 expansion ratio nozzle which was used for the TCC calculations for this engine.

Engine No. 2, designated the AJ10-181-3, was found by Aerojet to have superior pulsing performance over a wide range of chamber pressures, but with limited steady-state operational duration which is chamber pressure dependent. This engine also employs a six-element splash plate injector but with 0-deg orientation (radial injection). A 1.5-in.-long chamber with a 50:1 expansion ratio nozzle was used with this engine.

A third engine, the AJ10-181-1, was optimized for unlimited burn duration in a buried mode. It utilized a fuel-rich zone near the chamber wall for cooling and consequently had decreased performance and increased contamination levels.

1.3 THE AEROSPACE CHAMBER (10V) TEST

There is strong evidence of rocket exhaust plume contamination at large angles relative to the plume axis in the back-flow region of an engine. It is very important to understand the process involved in the transport of exhaust products into the back-flow region under high-vacuum conditions and to develop the analytical capability to predict plume contamination in this region. Such studies require experimental data to characterize the exhaust plume constituents and their distribution.

In order to understand better the mechanisms responsible for the transport of engine-produced contaminants into the back-flow region, a series of engine firings using the AJ10-181-2 and AJ10-181-3 was conducted under high-vacuum conditions in the AEDC/von Kármán Gas Dynamics Facility (VKF) Chamber 10V (Ref. 3). The AJ10-181-1 was not tested. Mass flux measurements were made in the back-flow region at angles up to 147 deg with respect to the plume centerline using temperature-controlled and temperature-compensated quartz crystal microbalances (QCM's). The measurements were conducted under high-vacuum conditions. The addition of new GHe and LHe cryopanels to the cryogenic Chamber 10V provided a blank-off pressure in the 10^6 torr range and maintained the background pressure in the 10^5 torr range while pulse firing the motor (25- to 100-msec pulse width, 1- to 10-percent duty cycle). Chamber recovery time was a few tenths of a second.

Several motor configurations and operating conditions were compared for potential contamination effects. Variations included: injector — zero- and 45-deg splash plate; combustion chamber — 2-in. cylindrical, 1.5-in. cylindrical, and 2-in. conical; nozzle area ratio — 50:1 and 100:1; oxidizer-fuel (O/F) ratio — 1.4, 1.6, and 1.8; and chamber pressure — 75, 100, and 125 psia. The nominal test conditions that were run in the Chamber 10V test cell for the -2 and -3 engines are listed in Table 1.

2.0 CONTAM/TCC ANALYSIS

2.1 INPUT TO TCC PROGRAM

The TCC dynamics computer program requires a large number of input values related to the engine combustion chamber, injector, nozzle, propellant feed system geometries, and bipropellant thermodynamic properties. Table 2 presents a typical set of input conditions reproduced from the computer printout. For the present studies, the characteristics of the monomethylhydrazine-nitrogen tetroxide propellant system were taken to be the same as those of the sample case of Ref. 1. The blocks of input data (Ignition Description, Atomization Parameters, Fuel Properties, Oxidizer Properties, Product Properties, and Adduct Properties) are from such sources as the Battelle "Liquid Propellant Handbook," JANNAF Combustion Meeting papers, and a large number of other reports from the National Aeronautics and Space Administration (NASA), Rocketdyne, McDonnell Douglas, Aerojet, Jet Propulsion Laboratory (JPL), etc. See Ref. 1 reference list.

Operating Conditions

Table 2 subscripts 13 thru 32 were taken to correspond to the test conditions for 100-msec runs that were made during the 5-lb-thrust bipropellant engine contamination test in the AEDC Chamber 10V. Fuel and oxidizer tank pressures were the same as used in the experimental runs; initial temperatures and minimum temperatures of the tanks, injectors, and chamber throat were taken as room temperature, half-rise, and half-fall times for the injector and throat, respectively, as estimated from Figs. 5.3-23, 5.3-31, and 6.4-23 of AFRPL-TR-74-51 (Ref. 2).

Fuel and Oxidizer Feed Systems

The propellant line lengths and diameters correspond to the test installation design. Propellant valve areas, void and dribble volumes, and operating times are from Ref. 2, which summarizes the design and testing of the AJ10-181 engine by Aerojet. The restrictor diameters, (43) and (67), provided a means of adjusting the fuel and oxidizer flows to match the experimentally determined formulas (Ref. 2, AJ10-181 5-lb Bipropellant Engine - Users' Manual):

-2 Engine $\dot{w}_F = \sqrt{\dfrac{\Delta P \times sg}{3.31 \times 10^6}}$ $\dot{w}_O = \sqrt{\dfrac{\Delta P \times sg}{3.77 \times 10^6}}$

and

-3 Engine $\dot{w}_F = \sqrt{\dfrac{\Delta P \times sg}{3.63 \times 10^6}}$ $\dot{w}_O = \sqrt{\dfrac{\Delta P \times sg}{2.23 \times 10^6}}$

where

$\dot{w}$ = Propellant flow, lb/sec

ΔP = Line pressure – chamber pressure, psi

sg = Specific gravity of propellant

In addition, the line pressure is given in Fig. 15b of Ref. 3 as it is related to chamber pressure and O/F ratio determined by Aerojet Co. engine tests. By systematically varying the fuel and oxidant restrictor diameters and the throat diameter, the propellant flow rates and chamber pressure can be made to match the engine test results for the standard performance — 100-psi chamber pressure and O/F ratio of 1.6. The 11 test conditions for the two engine configurations listed in Table 1 were then calculated by the TCC program.

Multiring Injector

The injector configuration specification permits up to three rings of fuel and oxidizer nozzles, although the test engine has only one in this case. The hole diameter, length, number, radial and axial position, and orifice coefficient are required. The orientation of the propellant jet is specified by the radial injection angle and the transverse angle as defined in Fig. 1.

Combustion Chamber Profile

The combustion chambers differed only in length from injector to throat, being 2.0 in. for SN-2 and 1.5 in. for SN-3. The throat diameters of 0.1622 in. for SN-2 and 0.1555 in. for SN-3 were determined as described above to provide propellant flows and chamber pressures corresponding to the standard conditions, C and I.

Table 3 summarizes the important input parameters that were varied for the 11 test conditions which were run in the TCC program. Each of these conditions, designated A through L, was run using a 0.1-sec firing. Computations extended through 0.2 sec to include any cutoff transients.

2.2 RESULTS

Figures 2 through 12 are the time-dependent results for conditions A through L, respectively. Notice that condition F is not shown since it is the same as condition E. It was necessary to use 0.3 msec as the computational time increment in order to obtain convergence.

The first part of each figure gives the calculated chamber pressure. At $t = 0$, the power to open the fuel and oxidizer supply valves is applied. After 0.5 msec, the valves are open and propellants begin to flow. Notice that the chamber pressure increases rapidly after ignition occurs at around 1 or 2 msec, and the pressure decreases a time or two before overshooting the steady-state value. This reversal and overshoot is attributed to the design of the injectors. The propellant flow rates are a function of the difference in pressures between the supply pressures and chamber pressure. When the propellant valves are first opened the chamber pressure is very low; therefore, more than normal fuel and oxidizer are injected into the combustion chamber which reacts to produce a higher than normal chamber pressure. This higher pressure lowers the flow rates which in turn lowers the chamber pressure. After the initial transient, the chamber pressure stabilizes to its steady-state value. Condition G (Fig. 7a) represents the most extreme starting transient (caused by the low fuel and oxidizer tank pressures) of those tested (Table 3).

Parts b, c, and d of Figs. 2 through 12 present the outflow rate of unburned fuel, oxidizer, and total propellant droplets from the combustion chamber. Significant amounts of unburned droplets can be ejected from the engine for up to 80 msec after the propellant valves have closed and propellant flow has ceased.

Parts e, f, and g of Figs. 2 through 12 give the outflow rate of unburned fuel, oxidizer, and total propellant wall film flow from the combustion chamber through the nozzle throat. Notice that the majority of the wall film flow occurs during the startup and shutdown transients. The exception of this is conditions D and J where the film flow occurs during the entire firing. These two conditions are for high O/F ratios.

The last part (h) of Figs. 2 through 12 presents the total propellant present on the wall of the combustion chamber. When the propellant is first injected, some of it is collected on the walls and is later evaporated after ignition occurs. After the propellant valves are closed and the combustion is extinguished, fuel and oxidizer dribbles from the injectors, collects on the walls, evaporates, and reignites causing the pressure pulses that occur after 100 msec. This collection of wall propellant also contributes to the droplet and wall film outflow near the end of the cycle.

Table 4 summarizes the integrated TCC results. Notice that the average chamber pressure, fuel and oxidizer flow, and O/F ratio calculated by TCC is not exactly the same as the nominal values given in Table 1. Probably the most important result given in Table 4 is the disposition of injected fuel and oxidizer in percent of total.

Figure 13 presents the total unburned propellant ejected from the combustion chamber. The droplets ejected from the combustion chamber represent contamination that remains near the centerline or the forward-flow region of the rocket nozzle. However, the contaminant in the form of wall film is at the boundary of the flow, and there is a larger probability that it will be scattered into the back-flow region. The unburned vapor, both fuel and oxidizer, will be dispersed in both the forward- and back-flow region in the same manner as the products of combustion.

3.0 SUMMARY

The CONTAM/TCC computer program was used to evaluate the characteristics of the Aerojet 5-lbf-thrust bipropellant rocket engine (AJ10-181) under the AEDC Chamber 10V test conditions. Calculations were made for two engine configurations operating under a total of 11 different conditions. A 0.1-sec firing was assumed in all cases with computations made for a total of 0.2 sec to include shutdown transients. Nominal chamber pressure varied from 75 to 128 psia and O/F ratio from 1.41 to 1.82.

Results indicate that the major source of contamination is in the form of unburned fuel and oxidizer droplets for all cases except for high O/F ratio (1.8) where the main source can be unburned fuel and oxidizer wall film (Fig. 13). The size of propellant droplets ejected was in the range of 60 to 120 μ. Droplets in that range would remain near the centerline of the nozzle.

4.0 FUTURE WORK

Output of the TCC program will now be used as input into the MULTRAN computer program in order to calculate the nozzle and plume flow fields, droplet trajectories, and streamlines. The next step will be to run the KINCON computer program to obtain chemical-kinetic and single species condensation along gas-phase streamlines. The final result will be a spatial distribution of contaminants in the rocket flow field.

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2. Schoenman, L. and Schindler, R. C. "Five-Pound Bipropellant Engine Final Report." AFRPL-TR-74-51, September 1974.

3. Alt, R. E., et al. "Bipropellant Engine Plume Contamination Program, Vol. I." AEDC-TR-79-28, 1979.

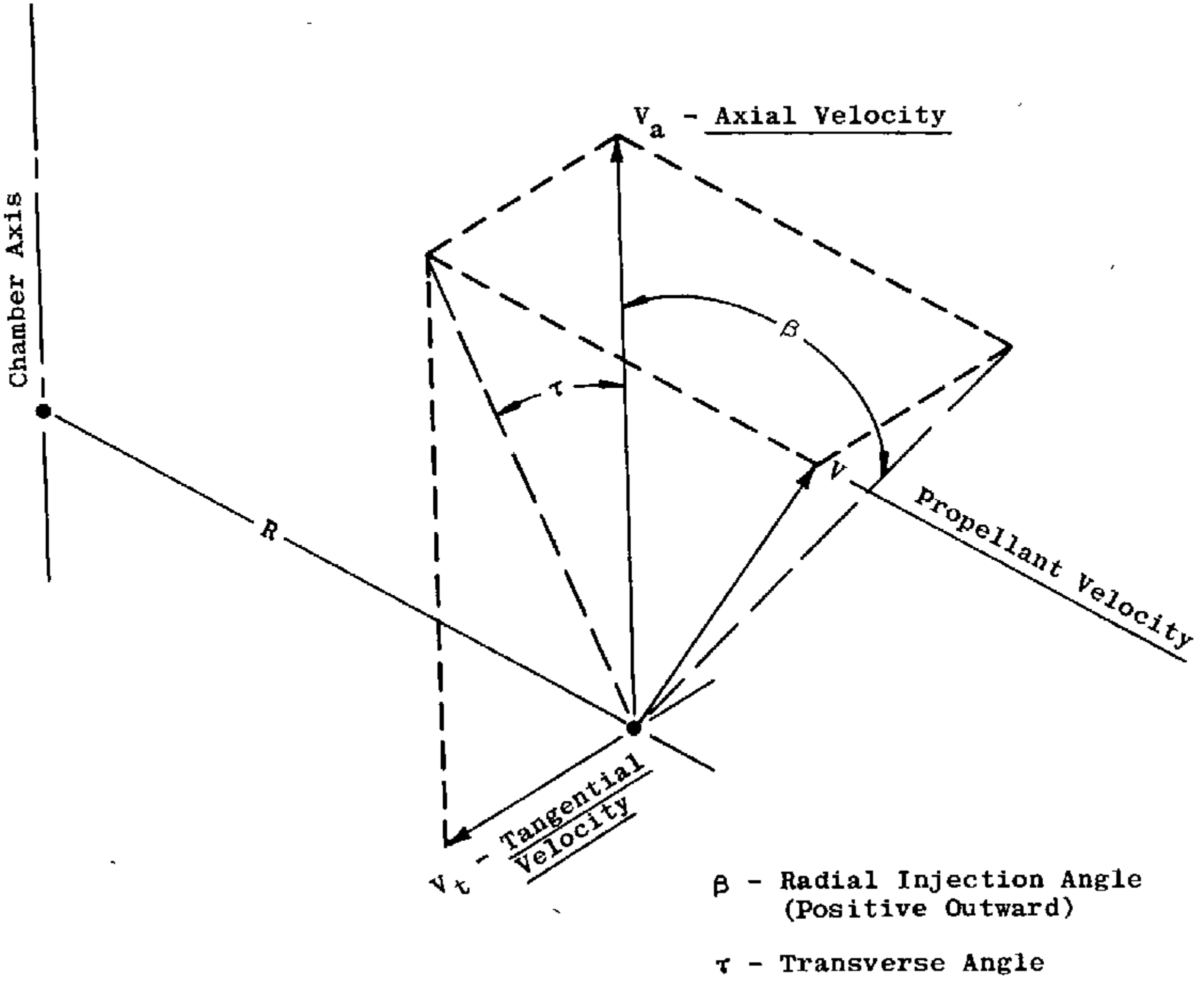
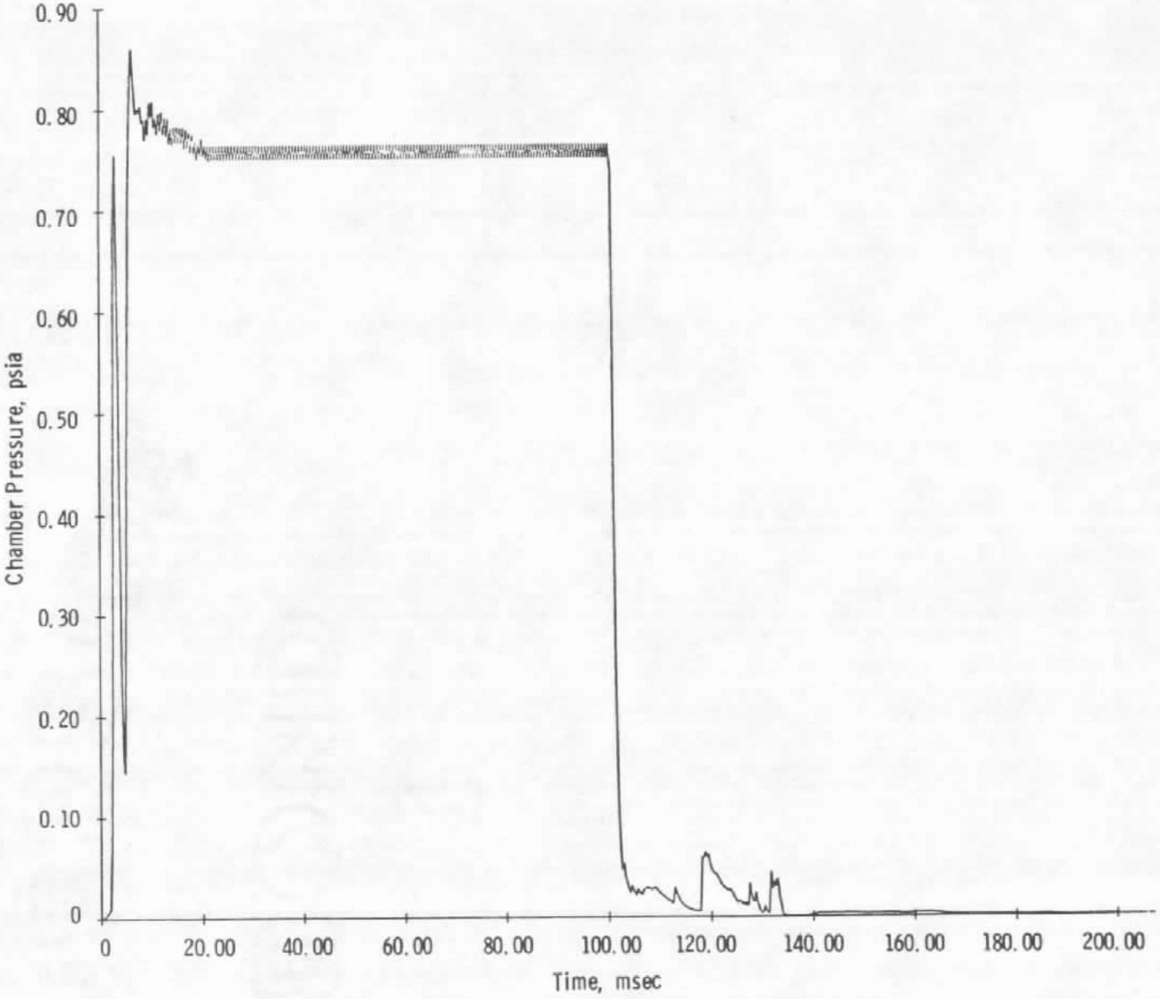
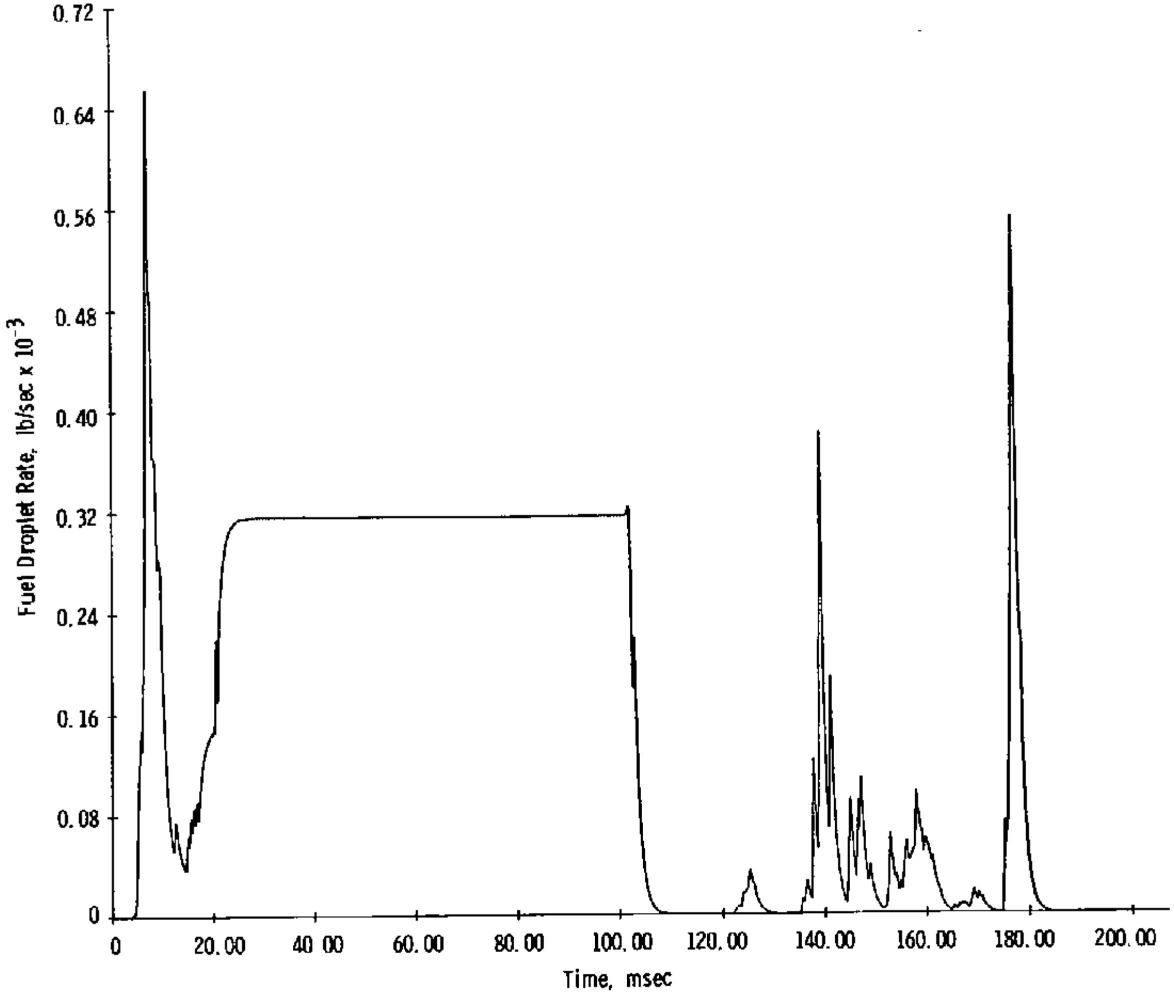


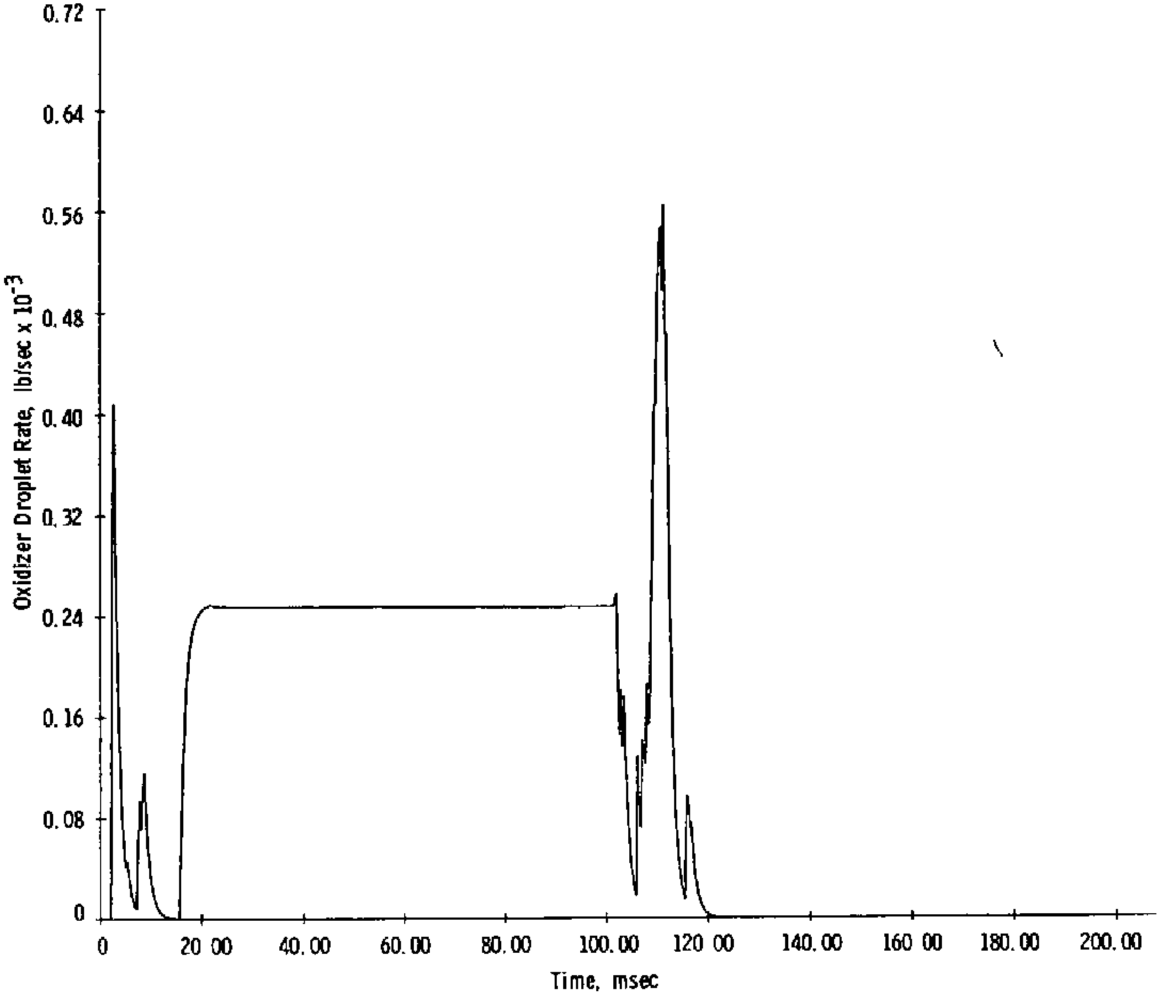
Figure 1. Injector nozzle geometry.



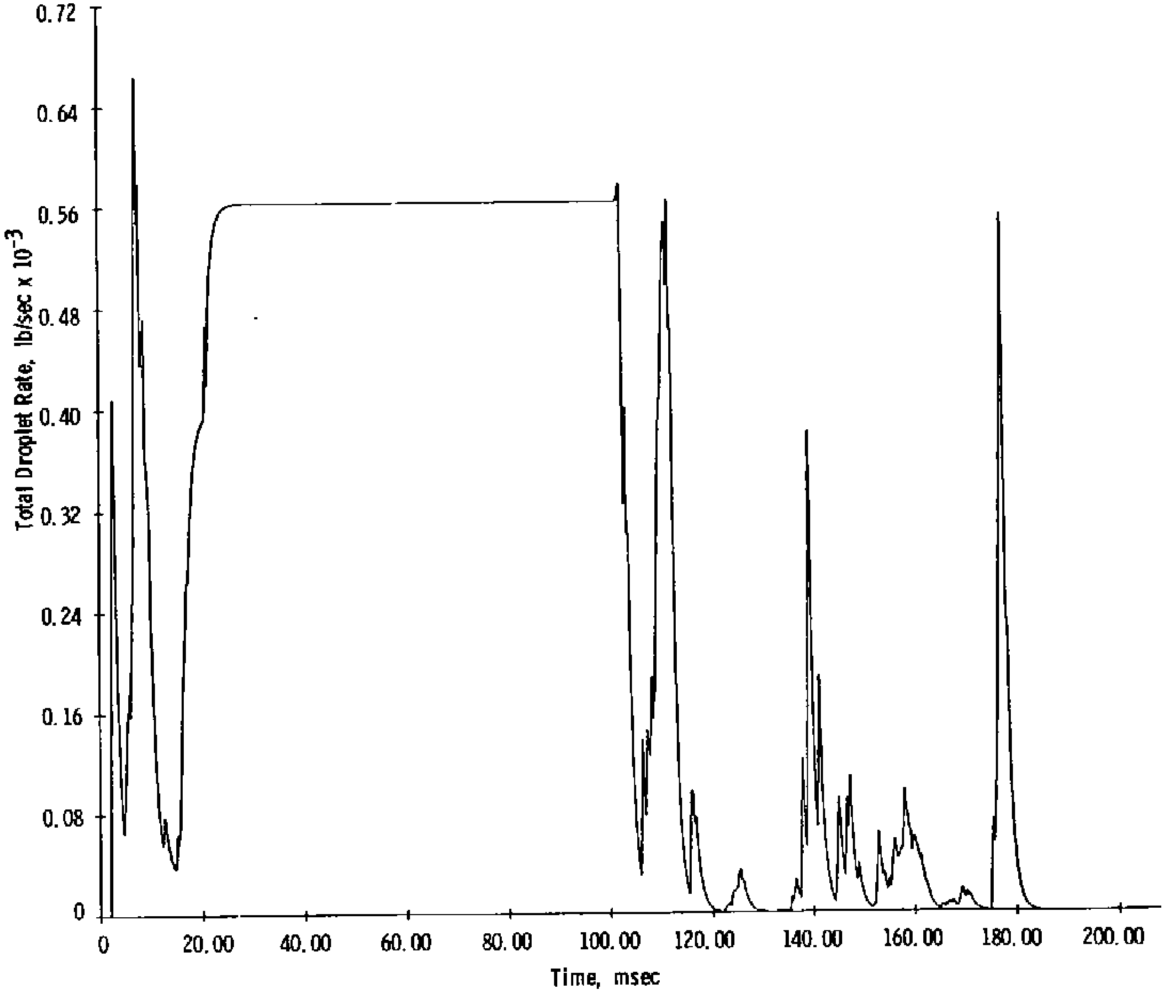
a. Chamber pressure
Figure 2. Case A results for AJ10-181-2.



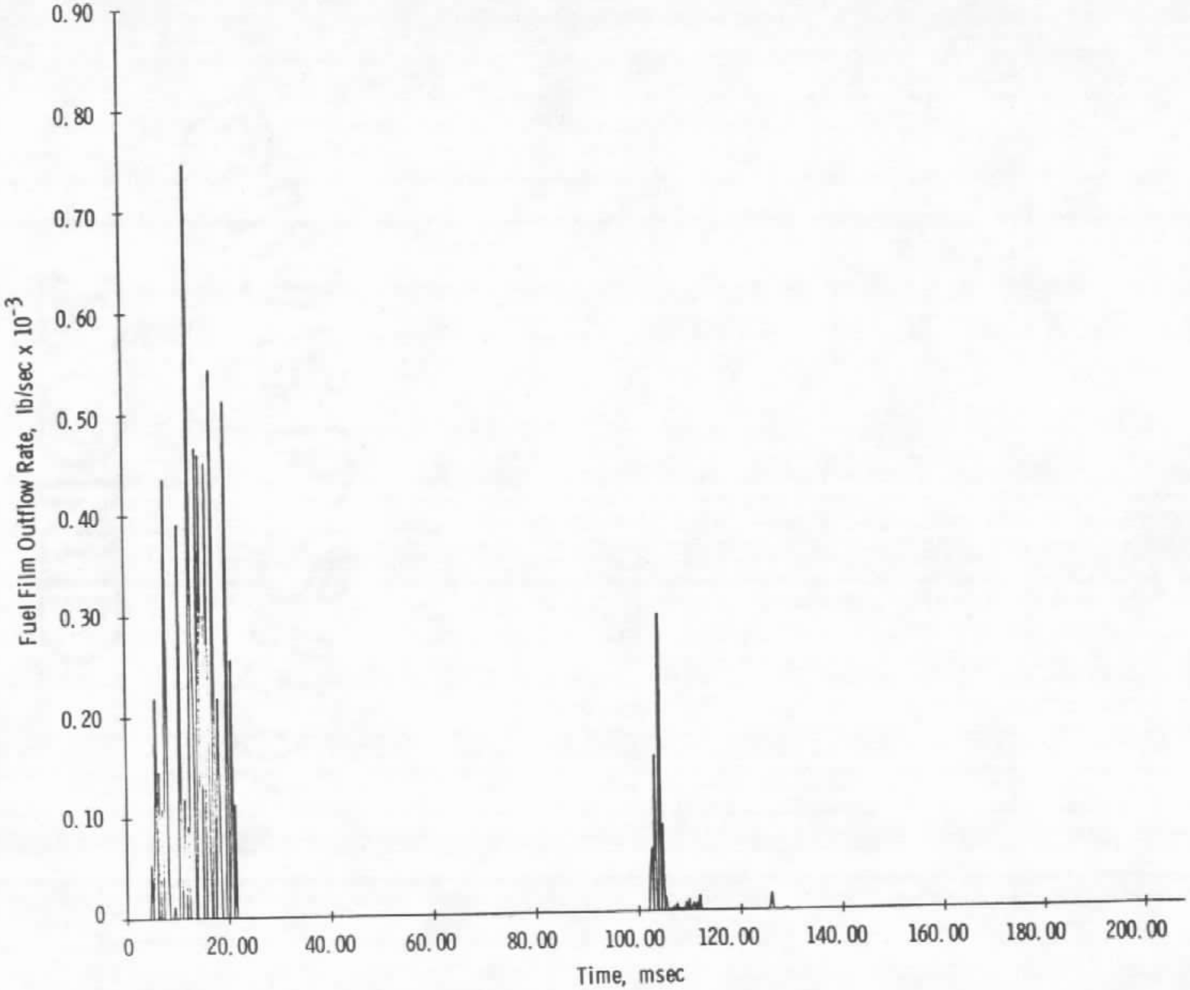
b. Fuel droplet rate
Figure 2. Continued.



c. Oxidizer droplet rate
Figure 2. Continued.

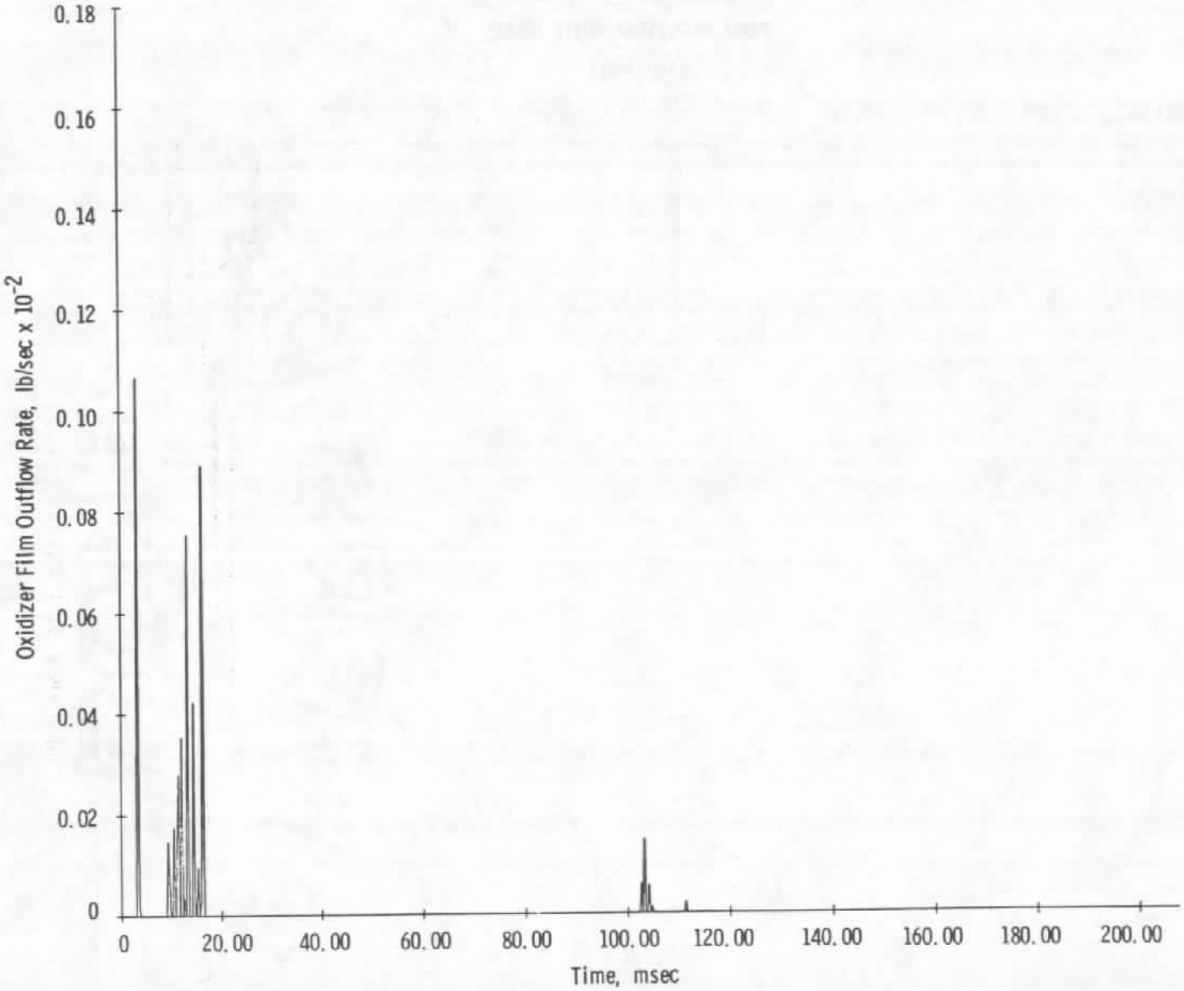


d. Total droplet rate
Figure 3. Continued.



e. Fuel film outflow rate

Figure 2. Continued.



f. Oxidizer film outflow rate
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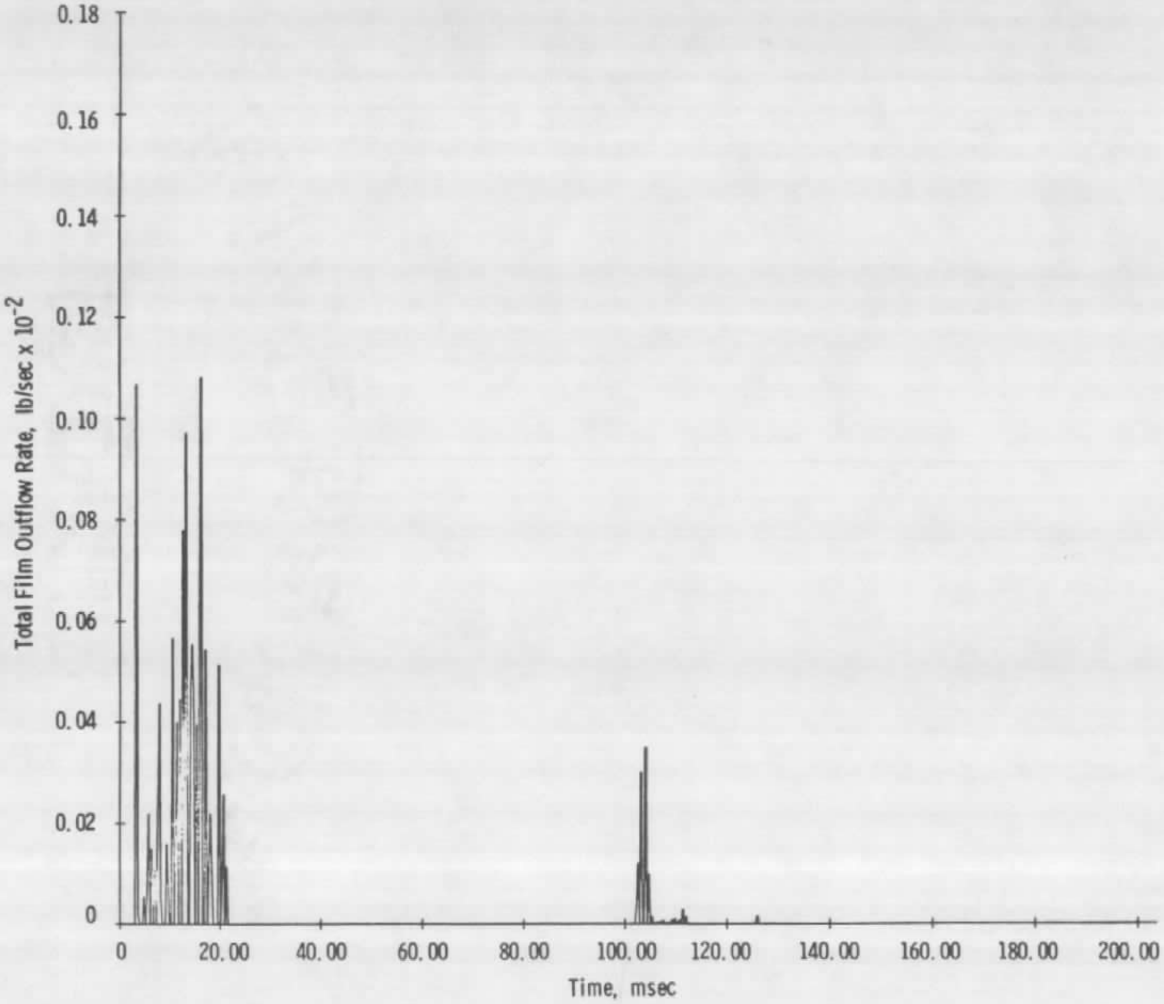
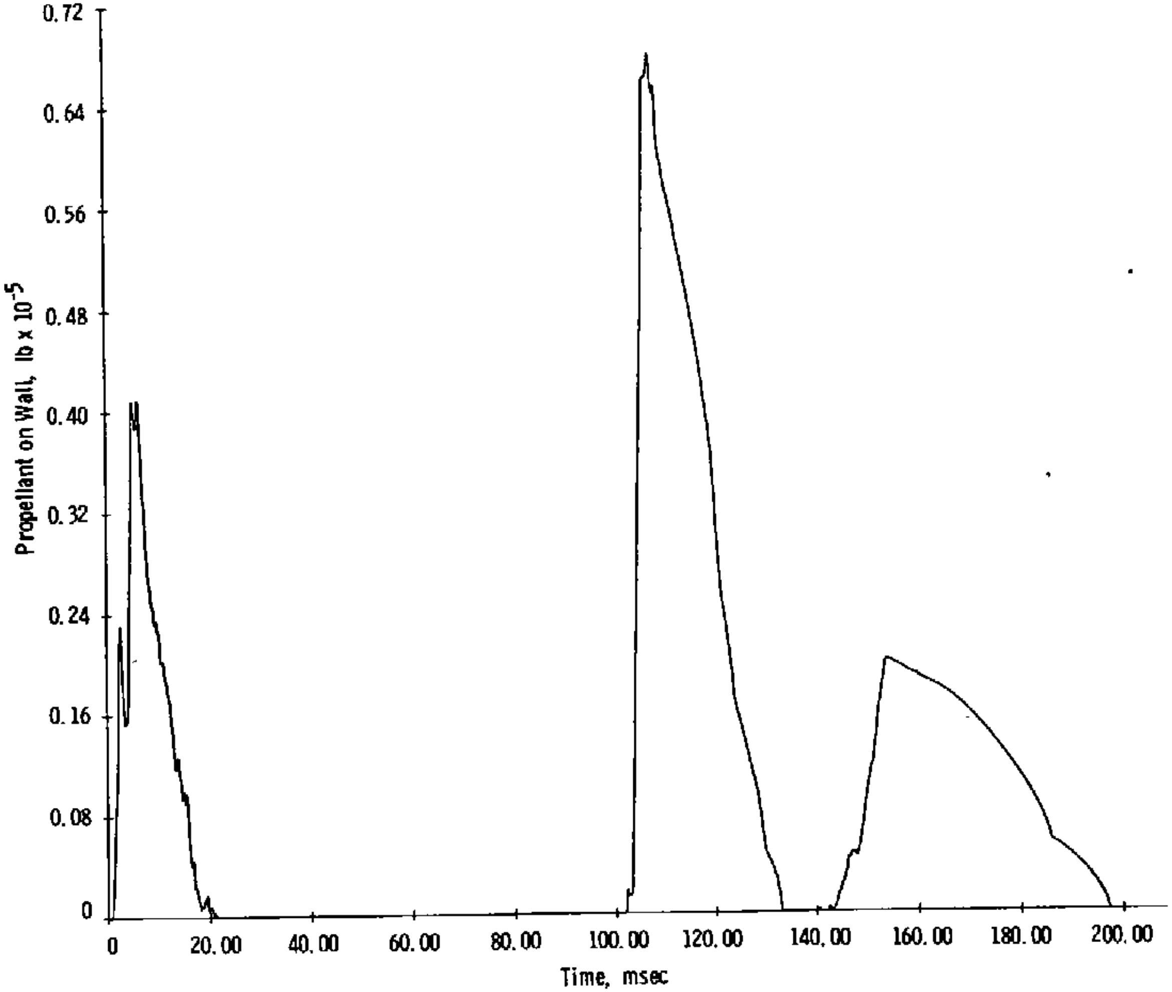
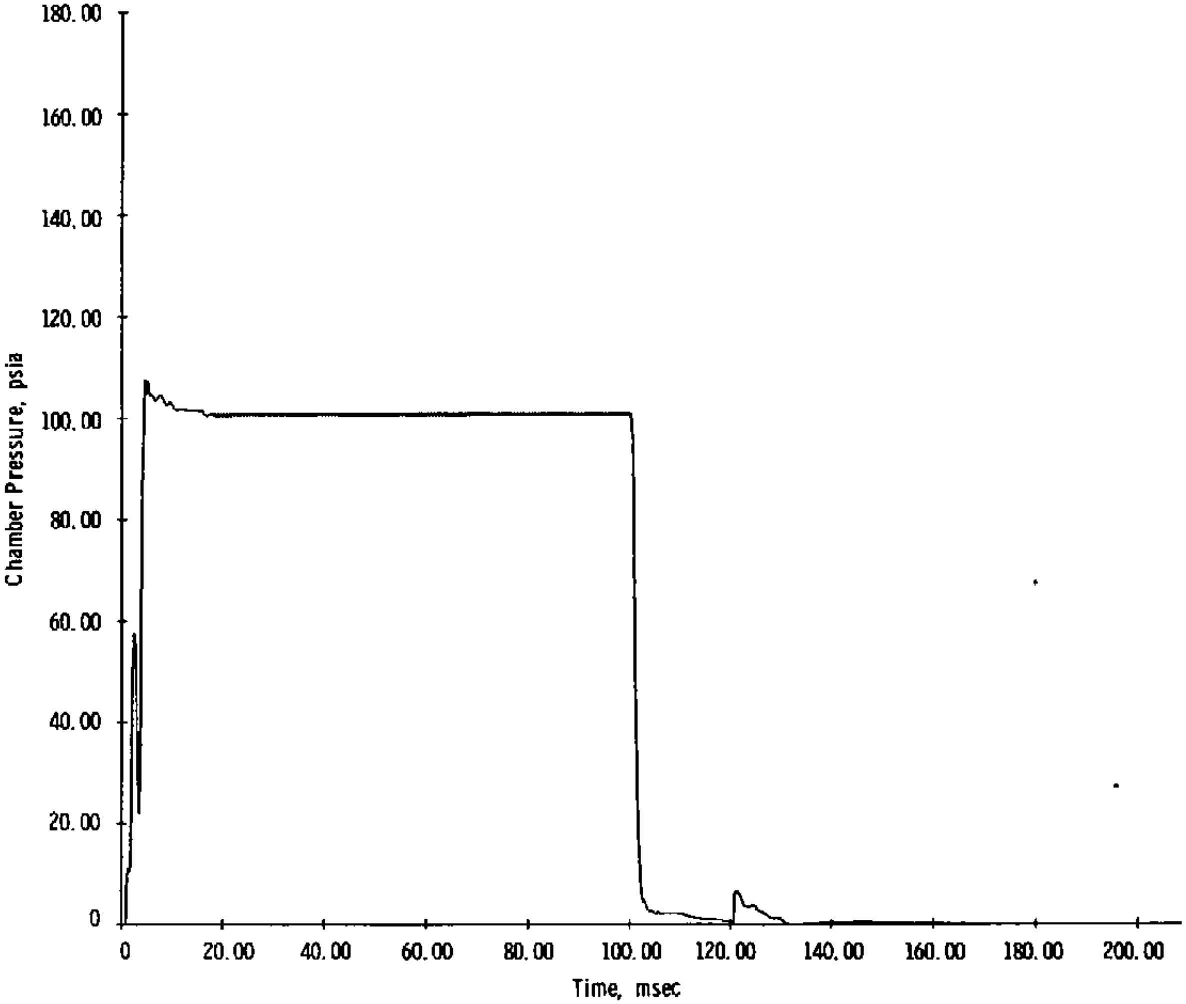


g. Total film outflow rate
Figure 2. Continued.

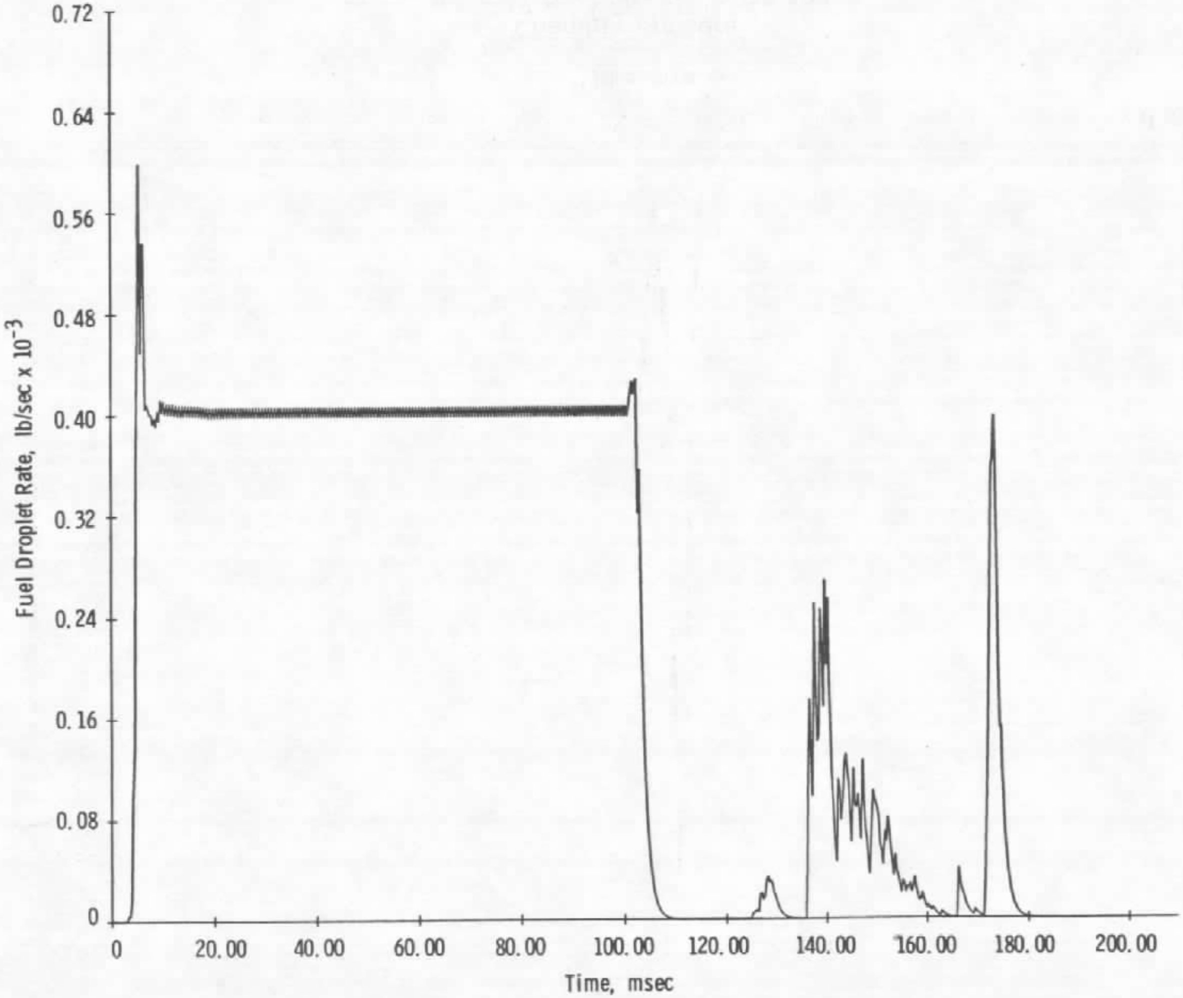


h. Propellant on wall
Figure 2. Concluded.



a. Chamber pressure

Figure 3. Case B results for AJ10-181-2.



b. Fuel droplet rate

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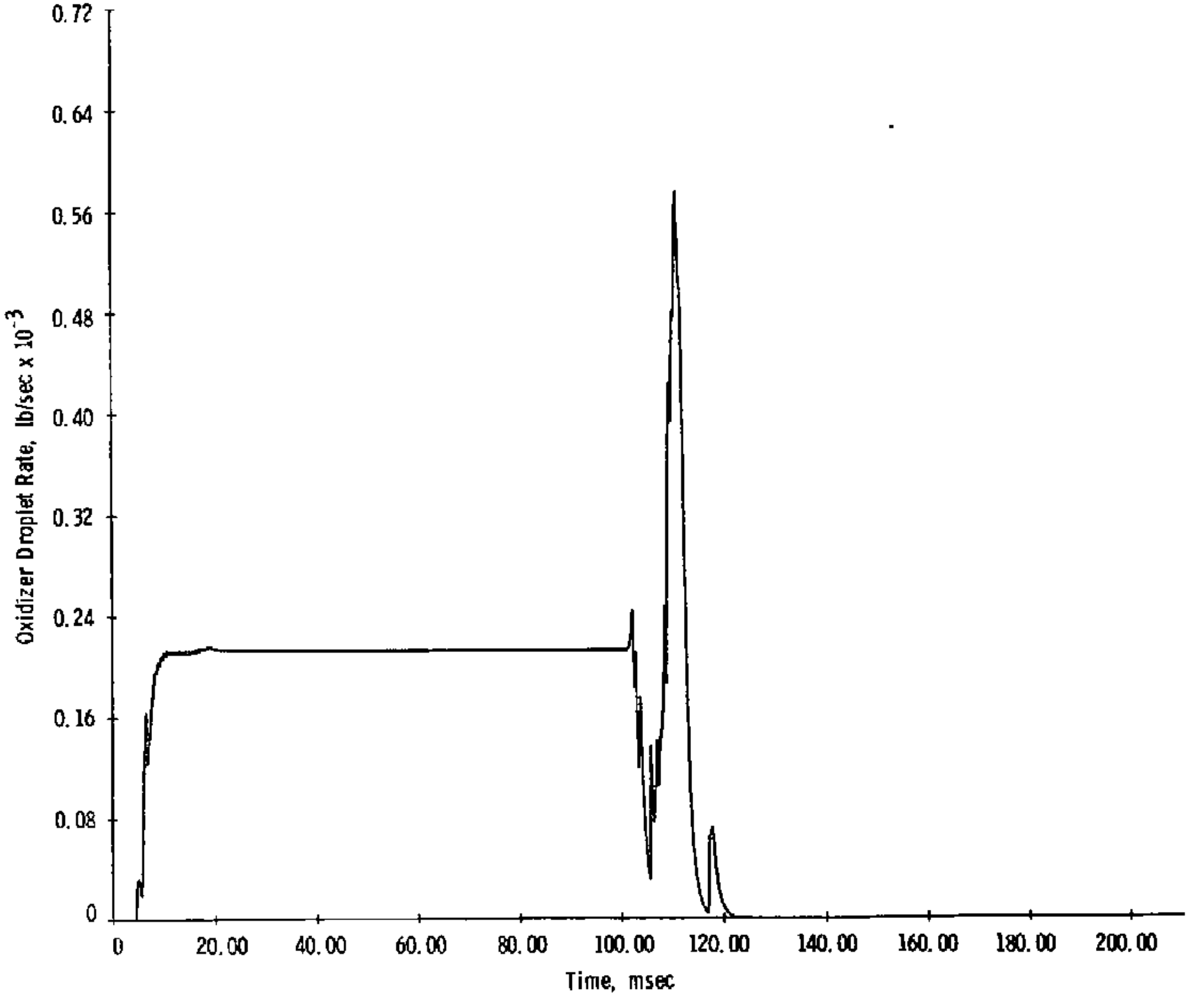

c. Oxidizer droplet rate

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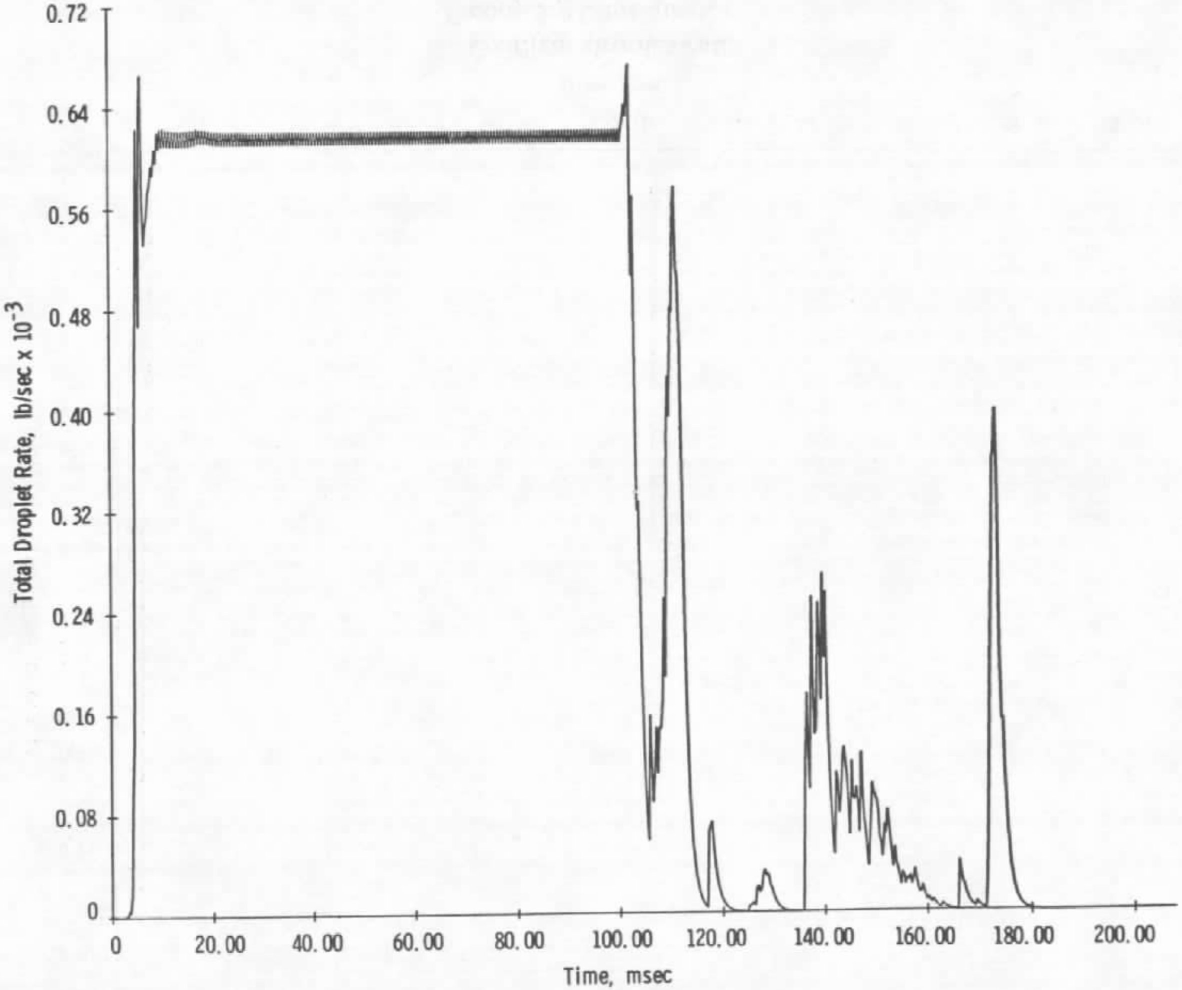

d. Total droplet rate
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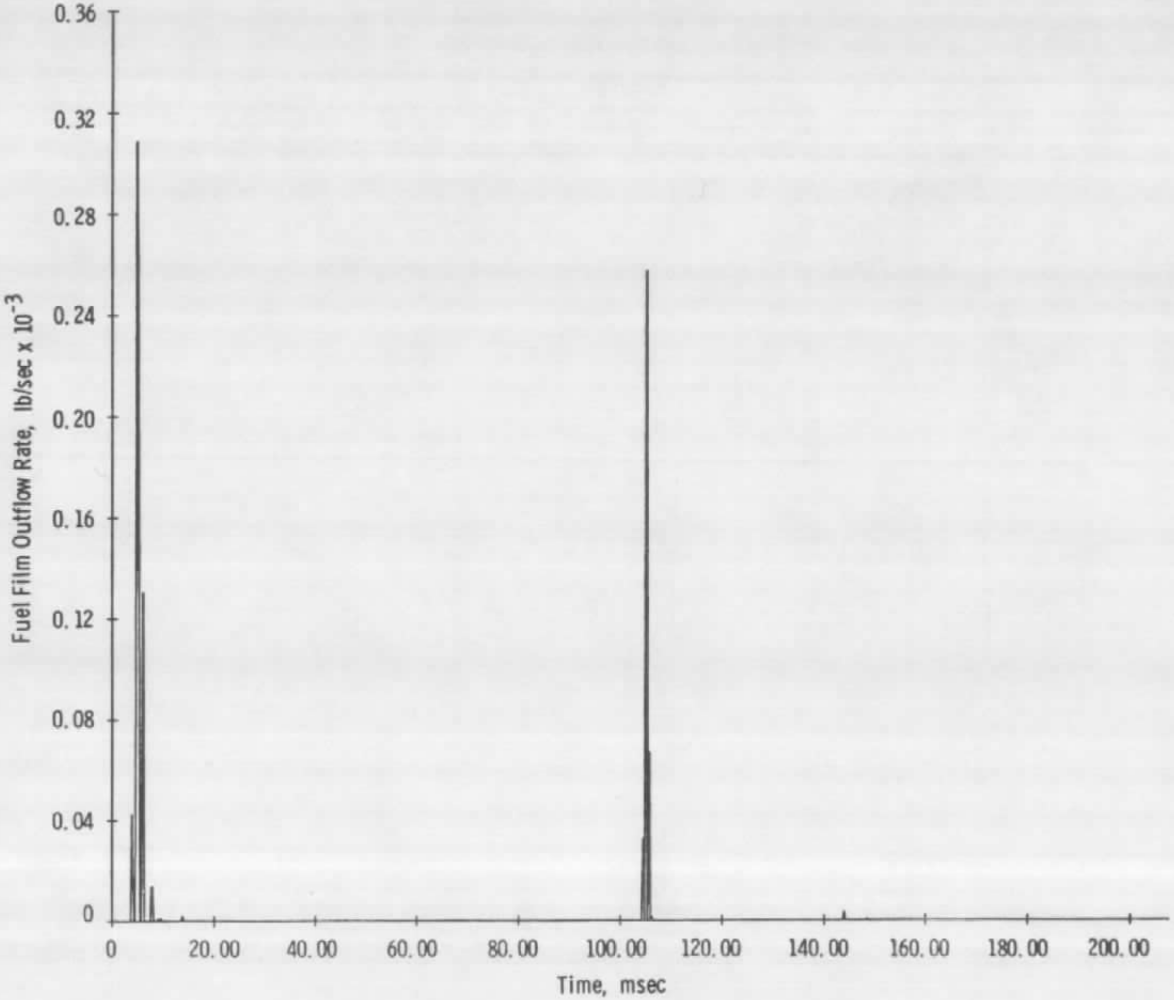

e. Fuel film outflow
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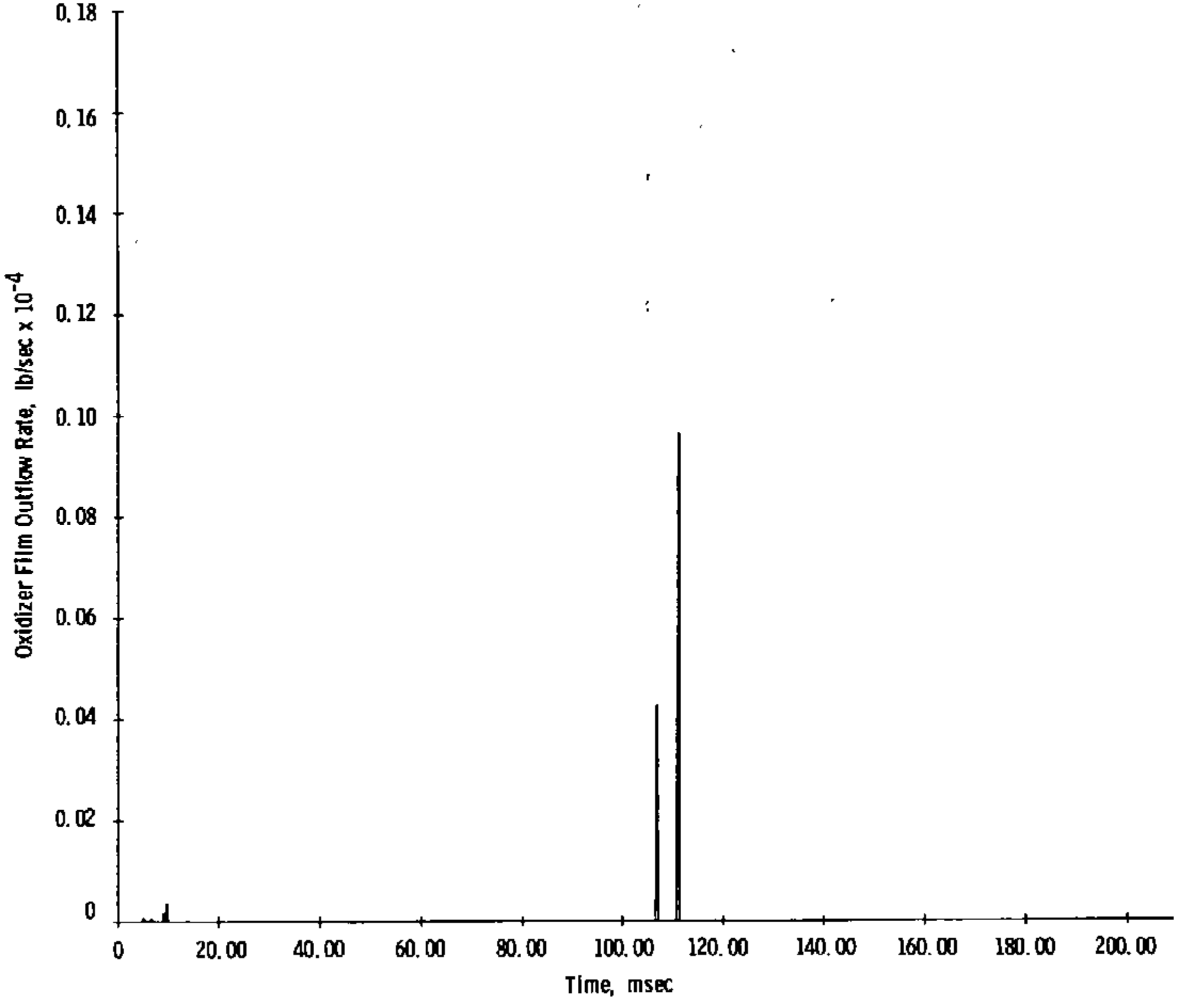

f. Oxidizer film outflow rate
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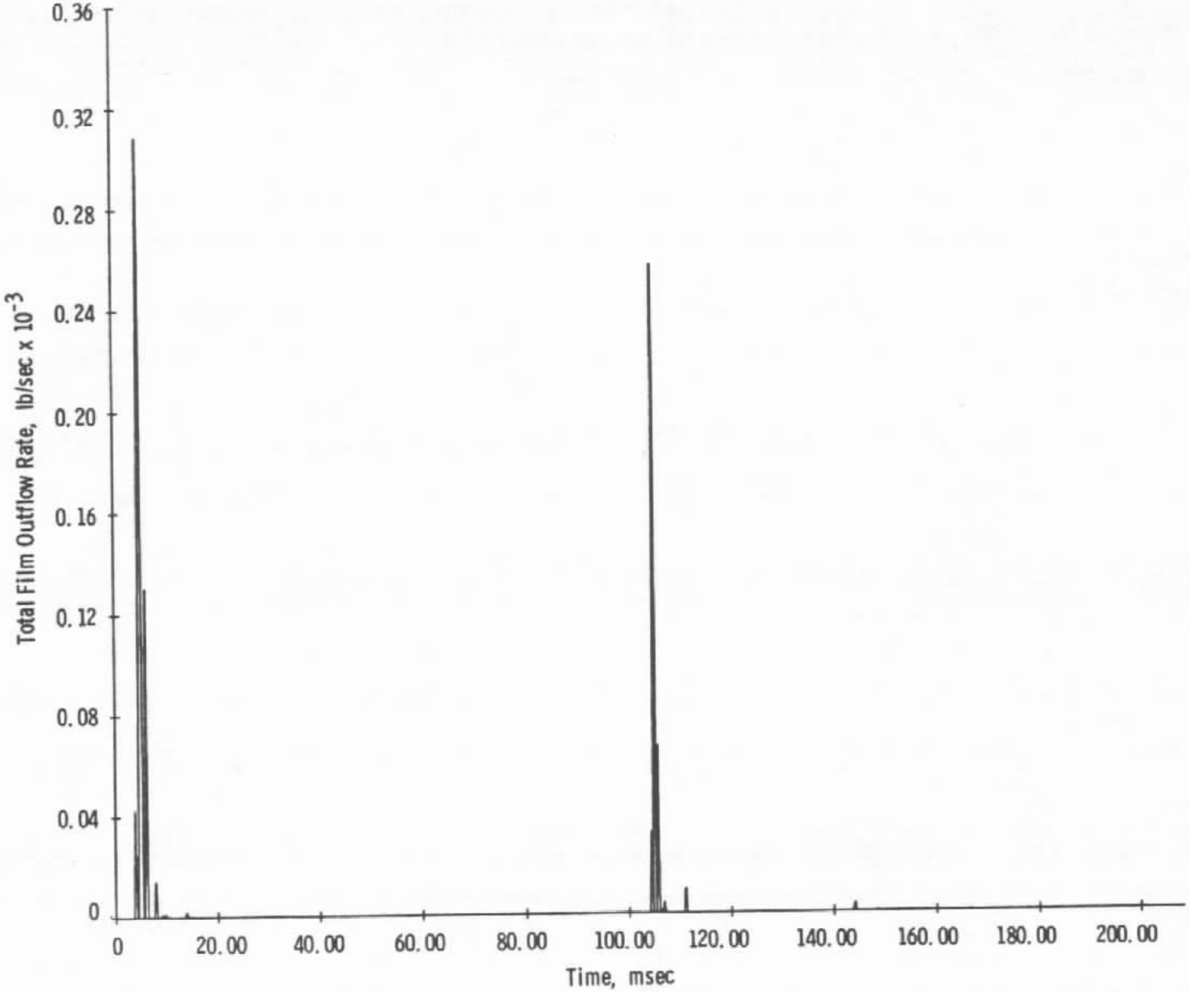

g. Total film outflow rate
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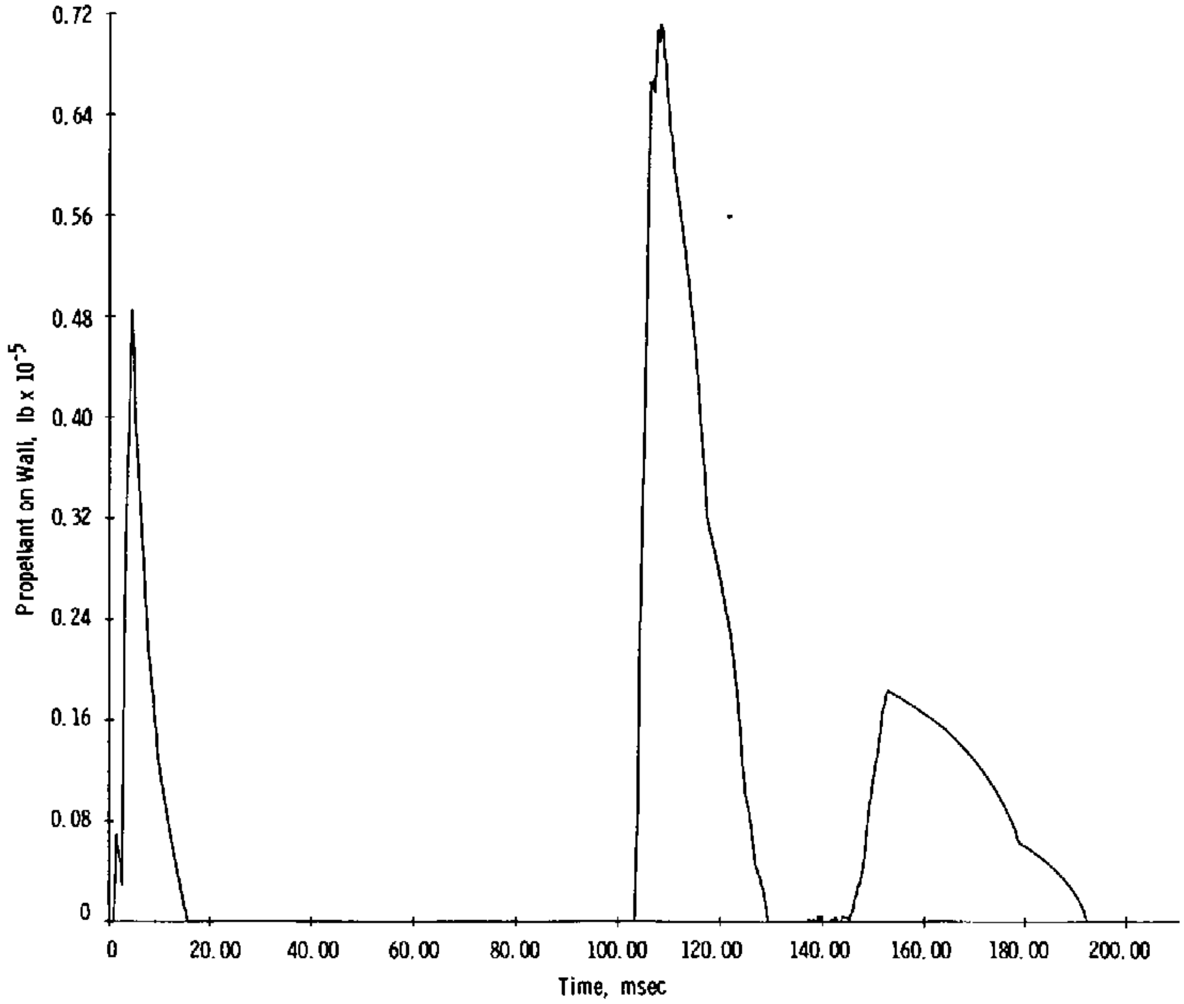

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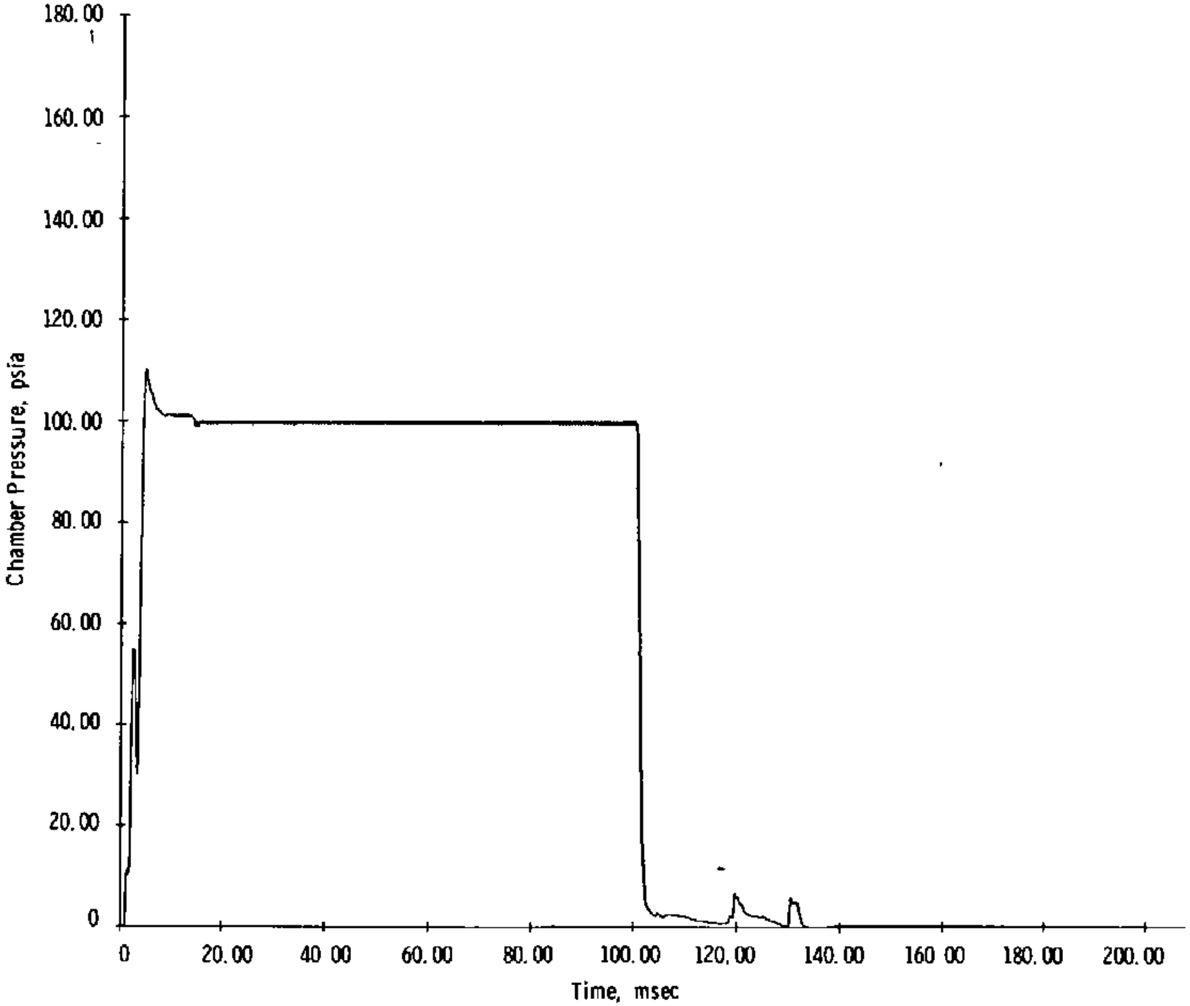
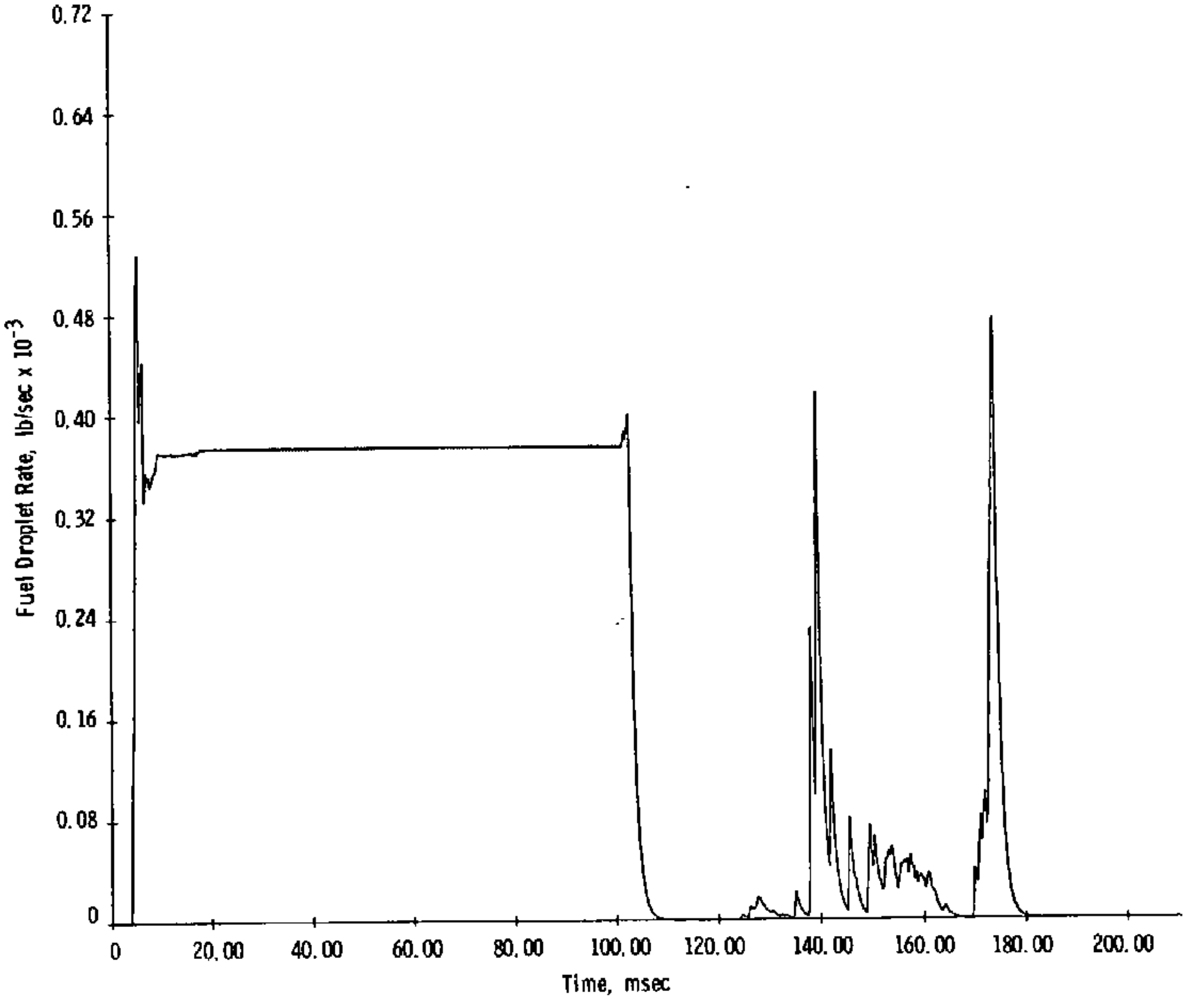


a. Chamber pressure
Figure 4. Case C results for AJ10-181-2.



b. Fuel droplet rate
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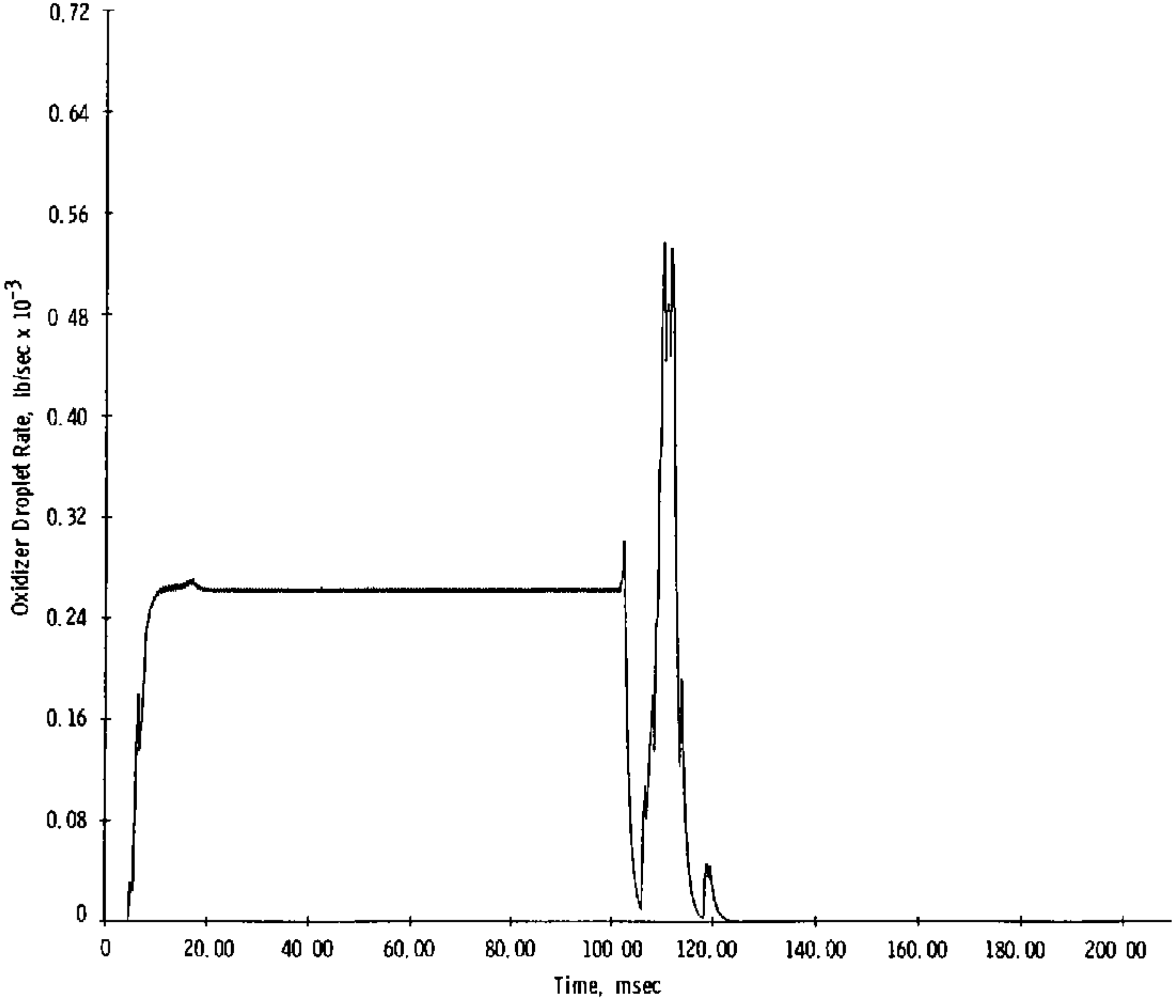

c. Oxidizer droplet rate
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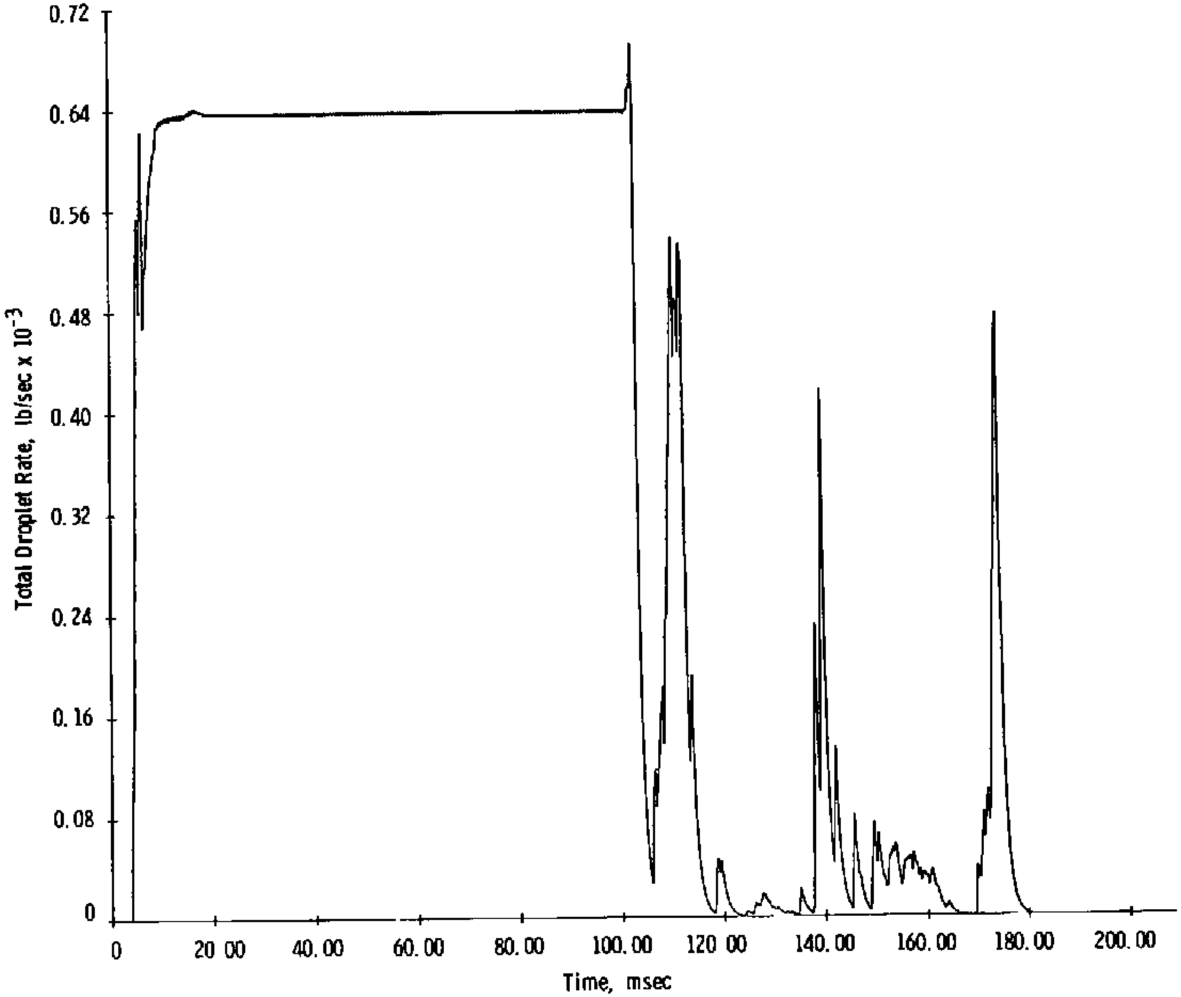

d. Total droplet rate
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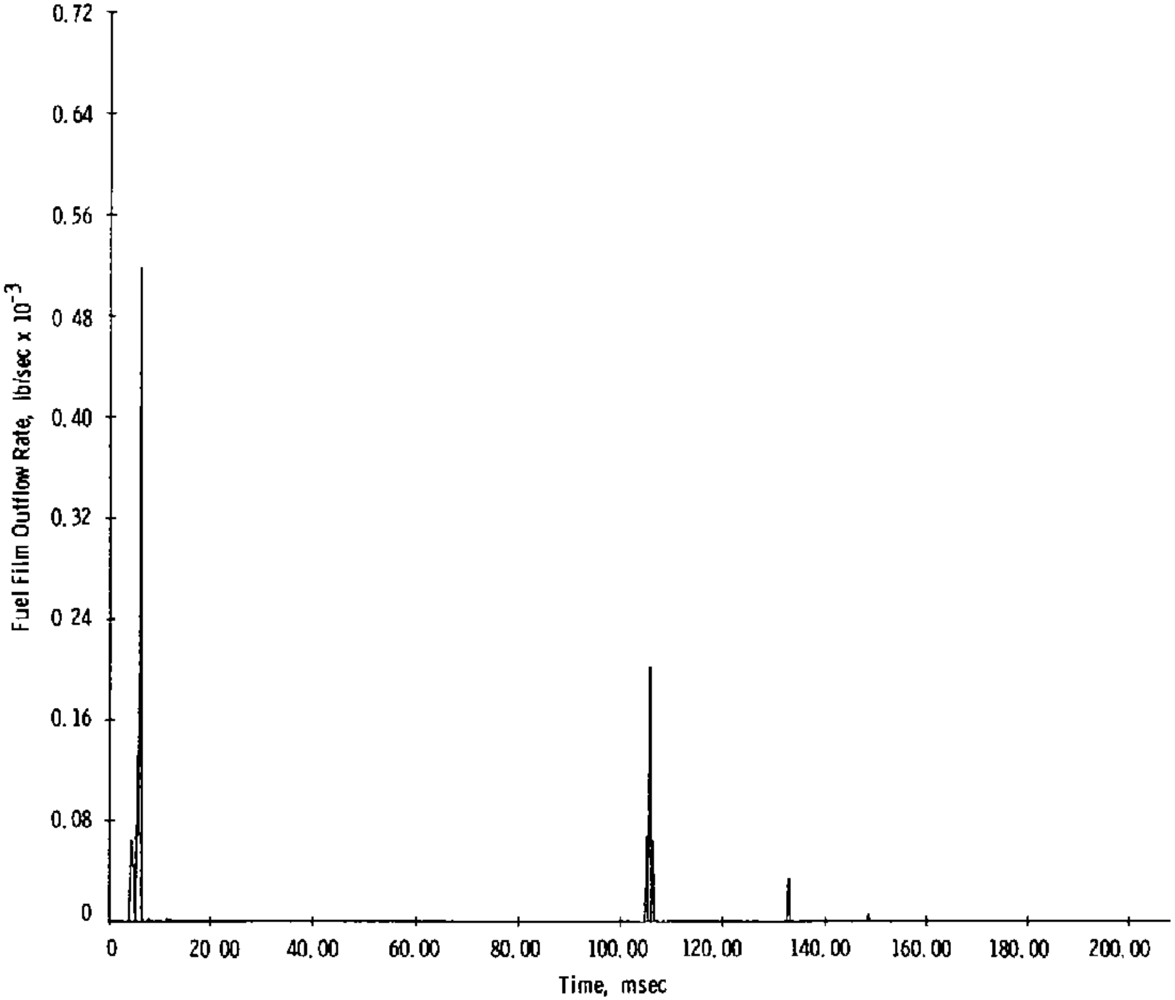

e. Fuel film outflow rate
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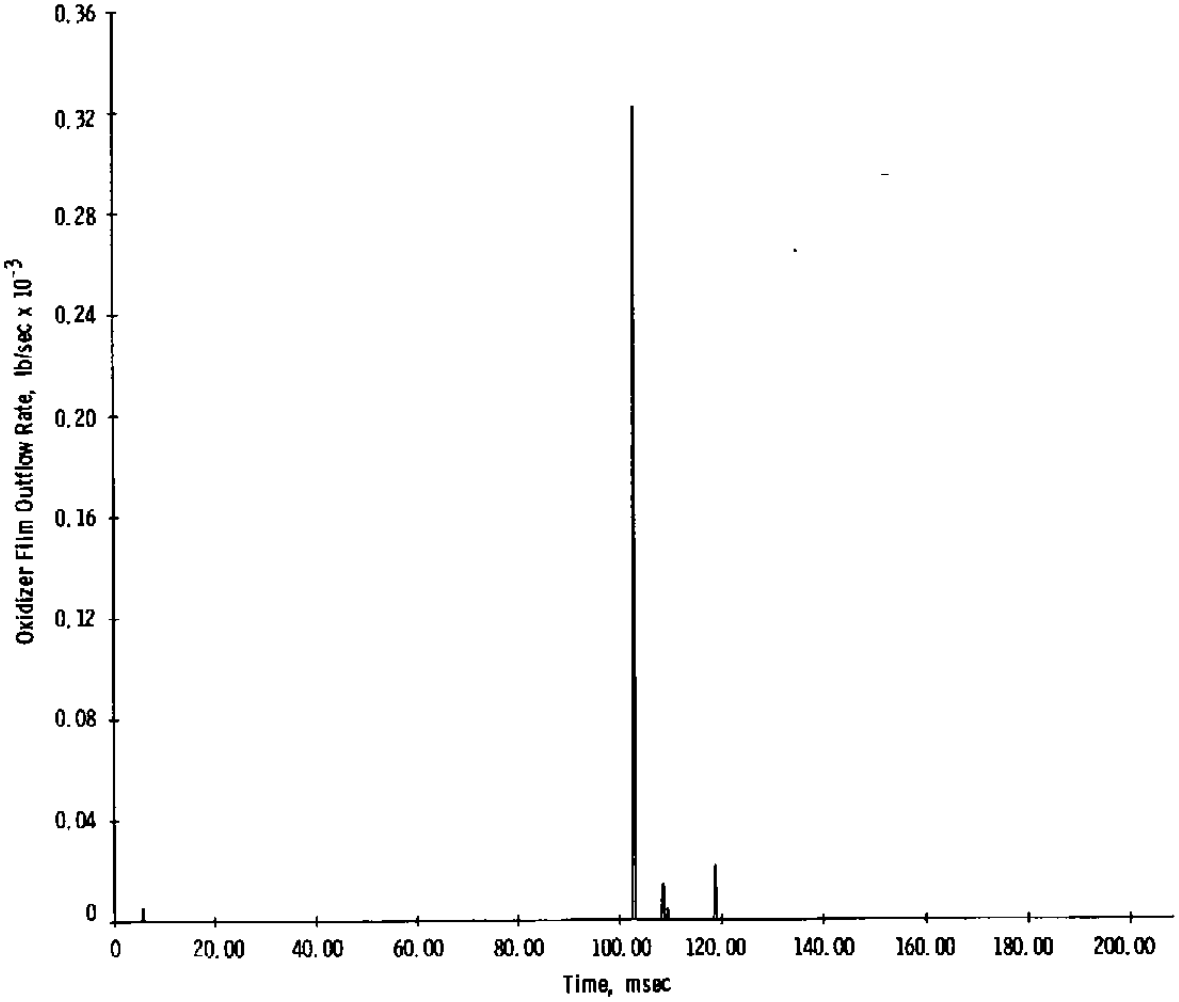

f. Oxidizer film outflow rate

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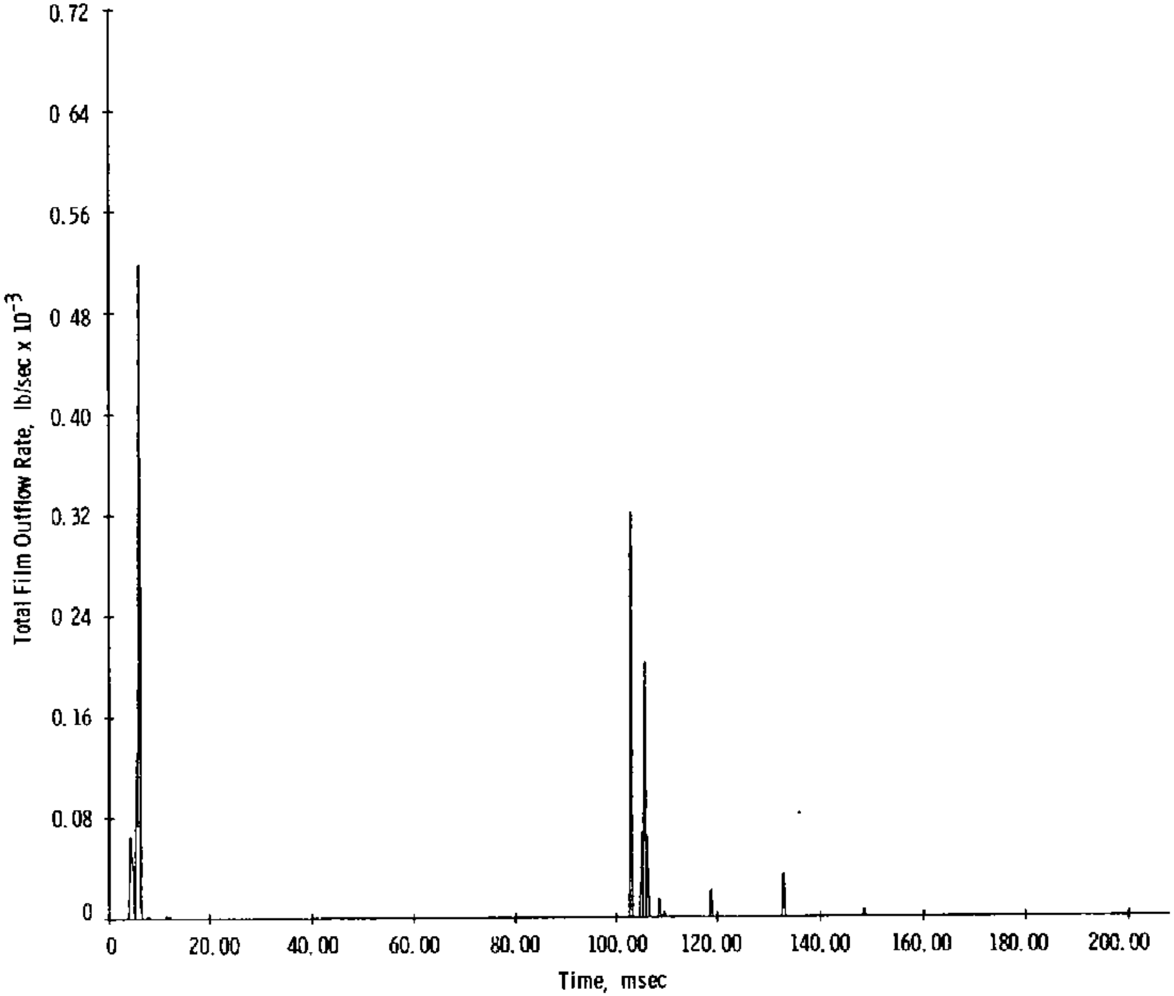

g. Total film outflow rate
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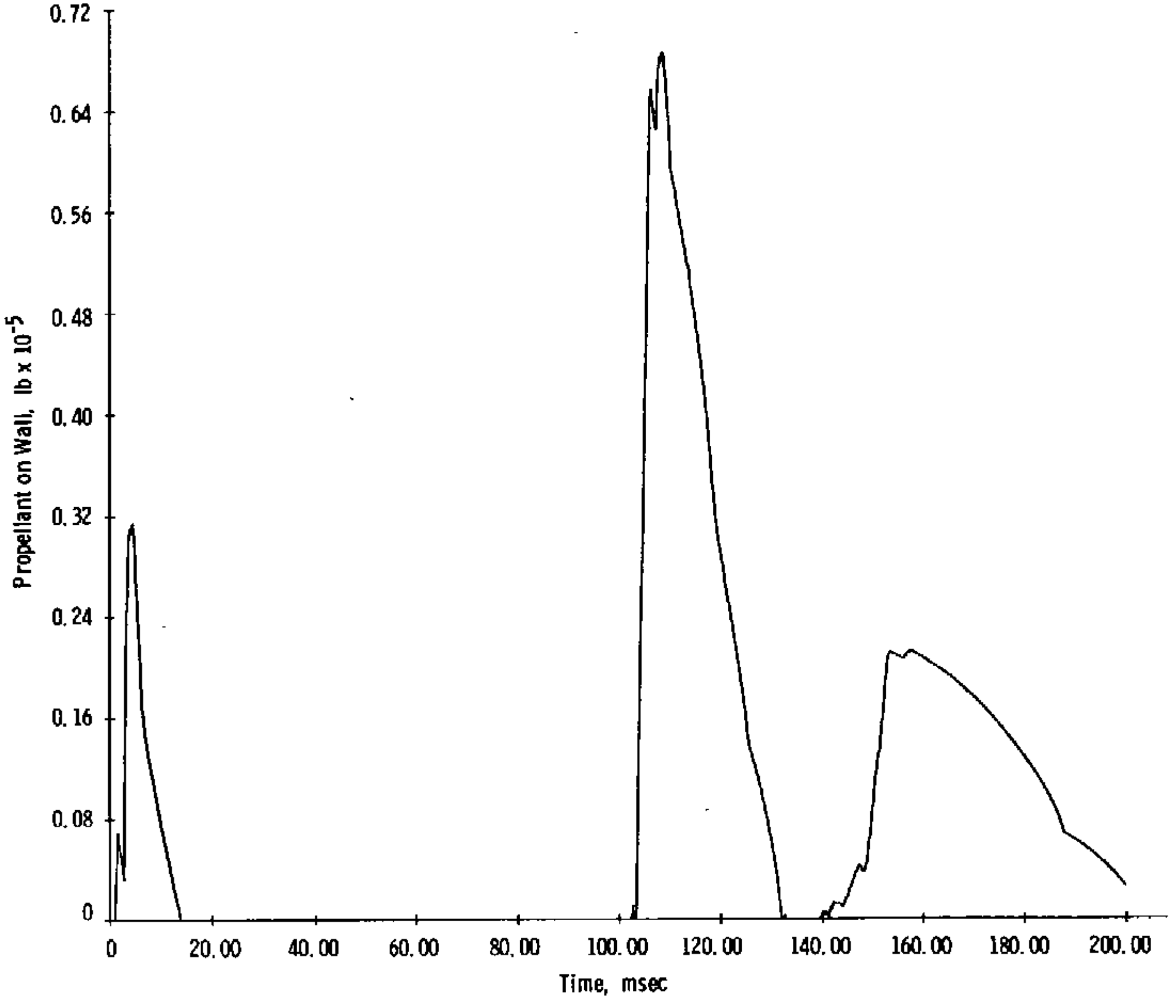

h. Propellant on wall
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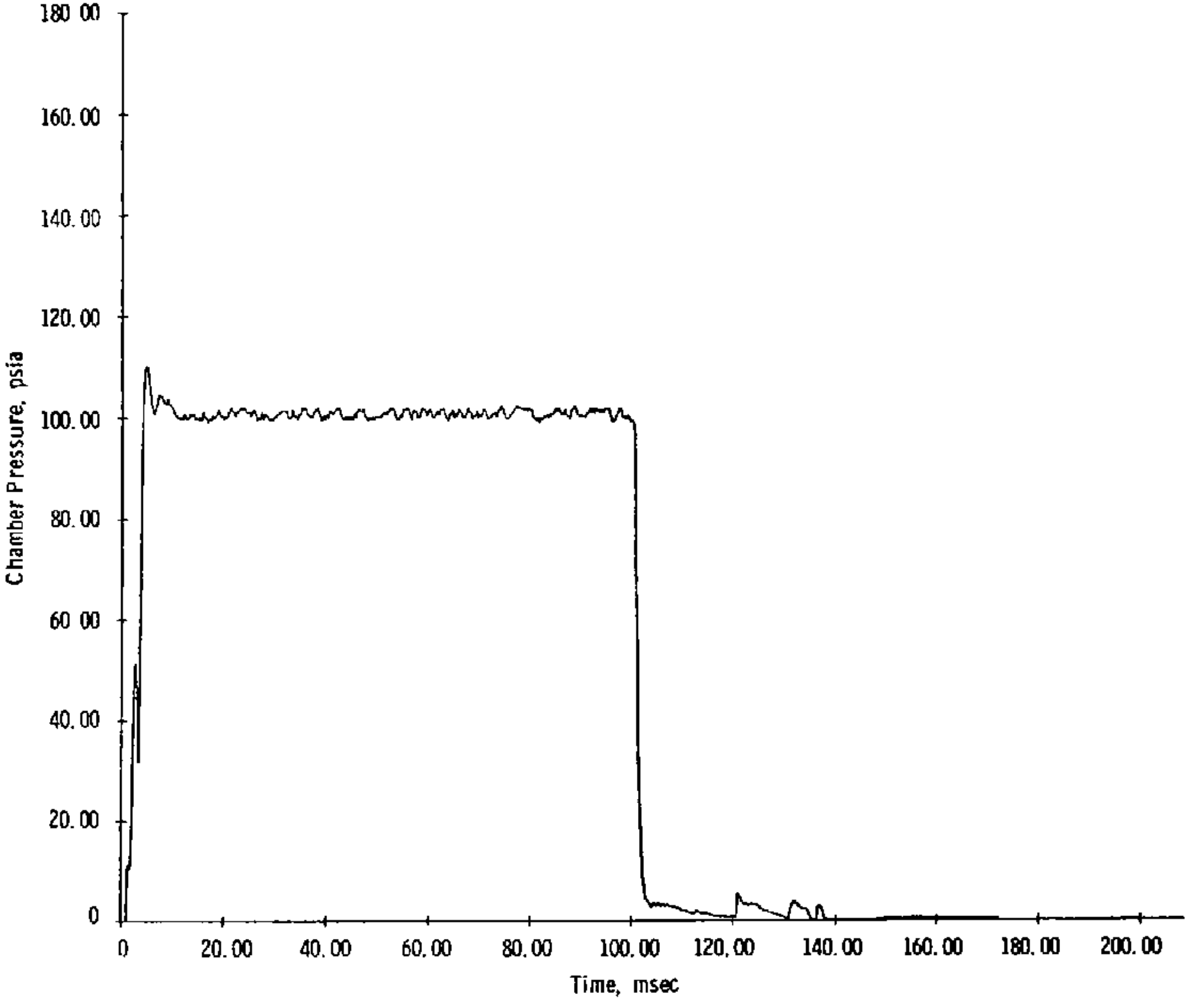
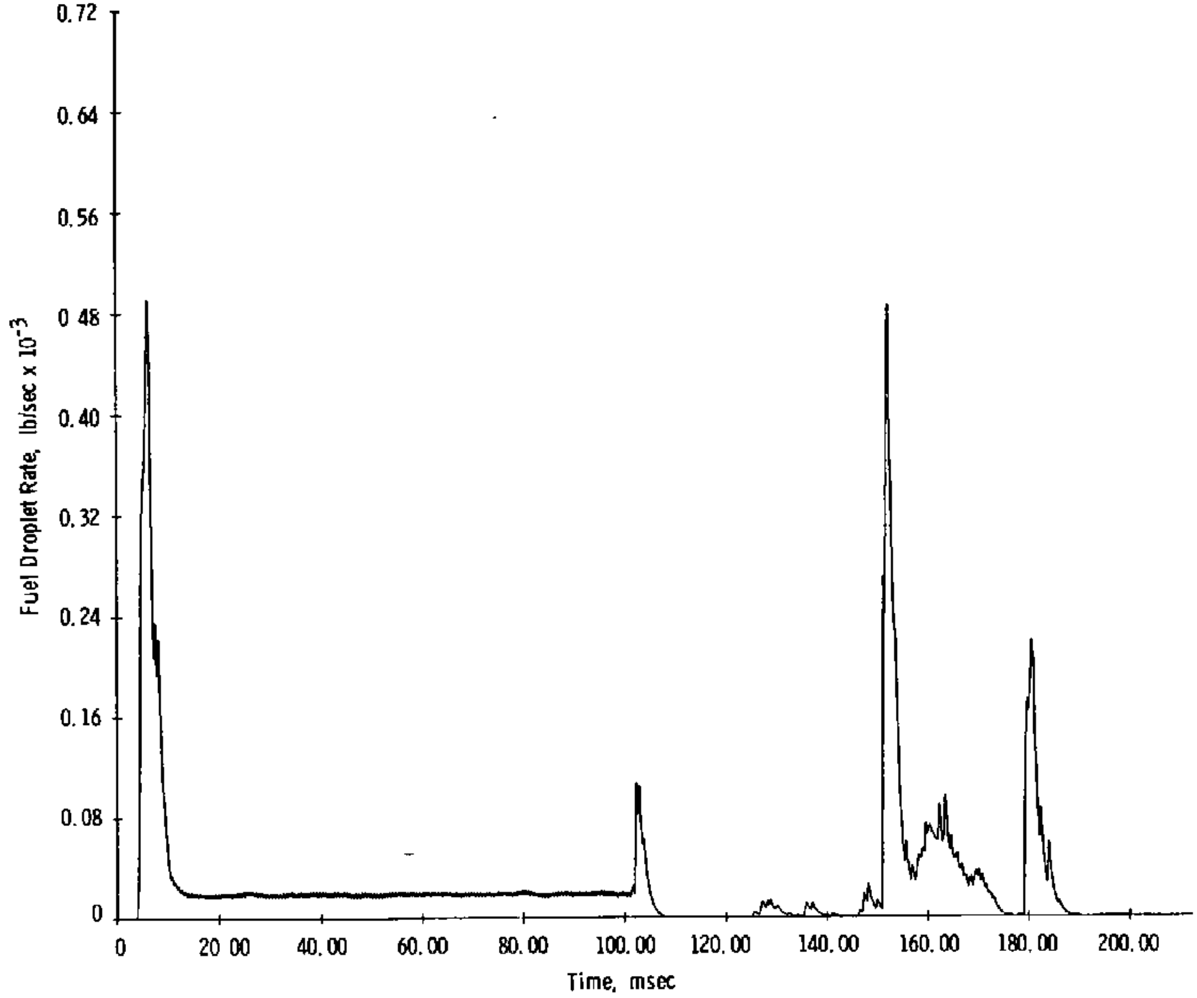
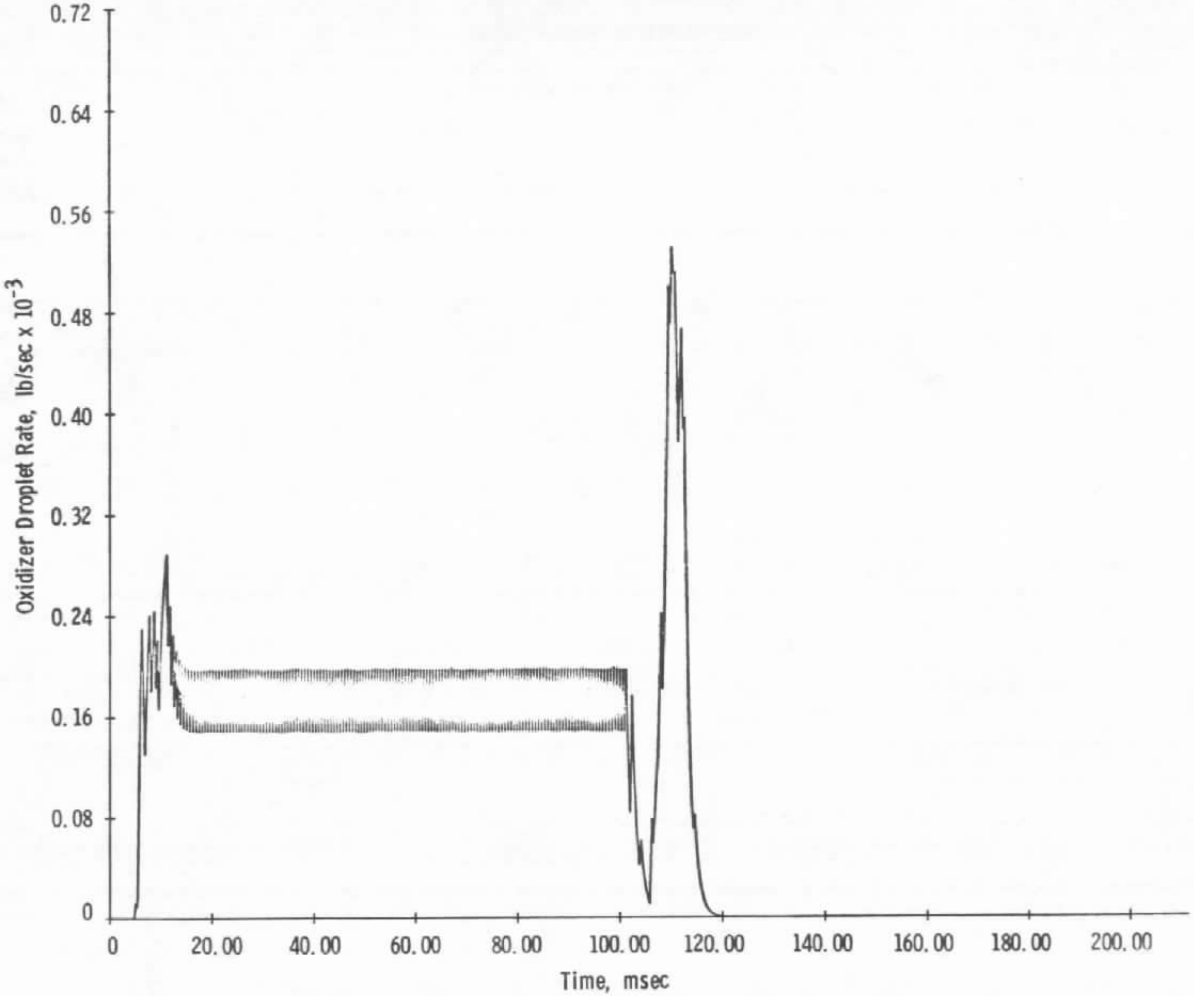


a. Chamber pressure

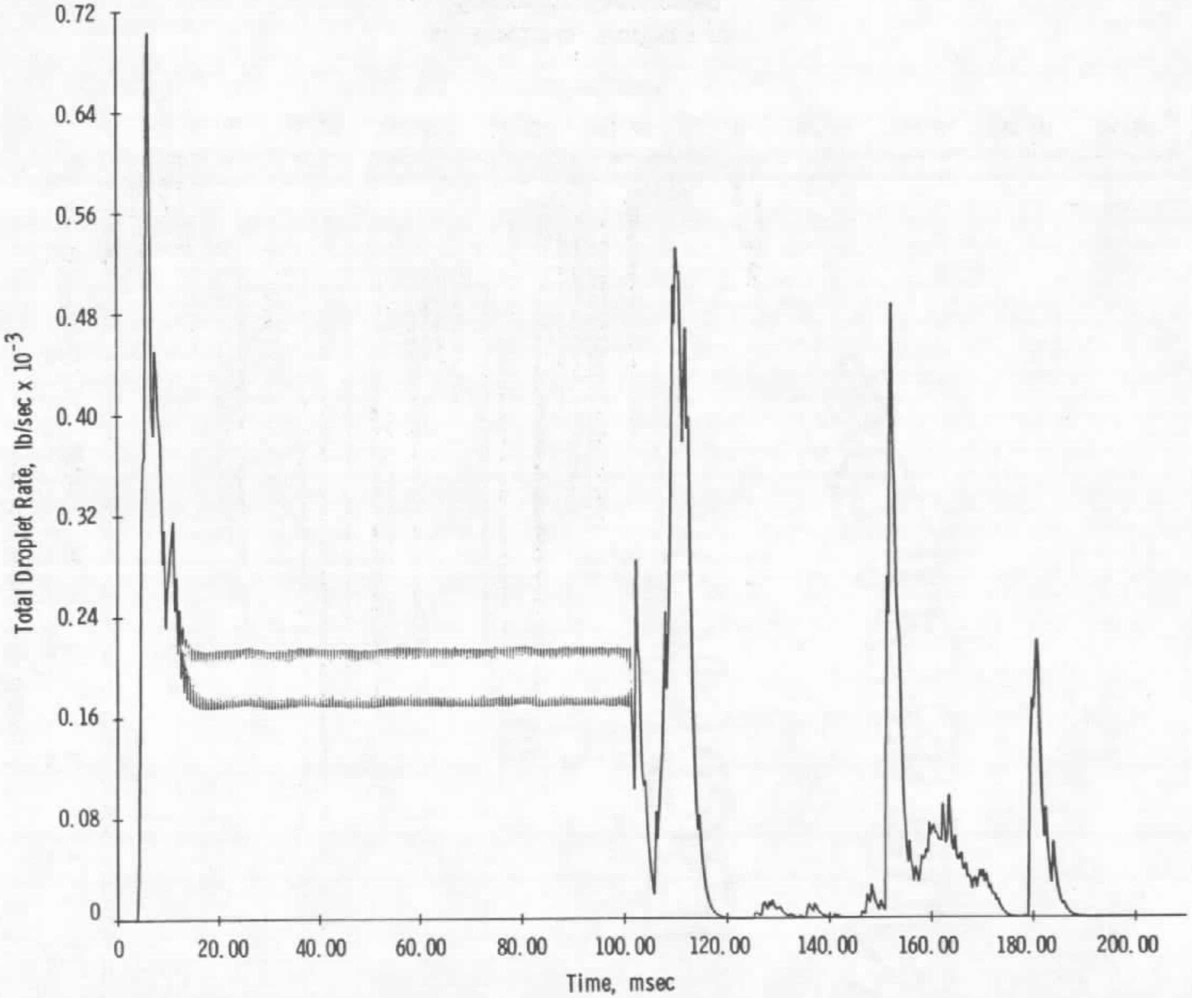
Figure 5. Case D results for AJ10-181-2.



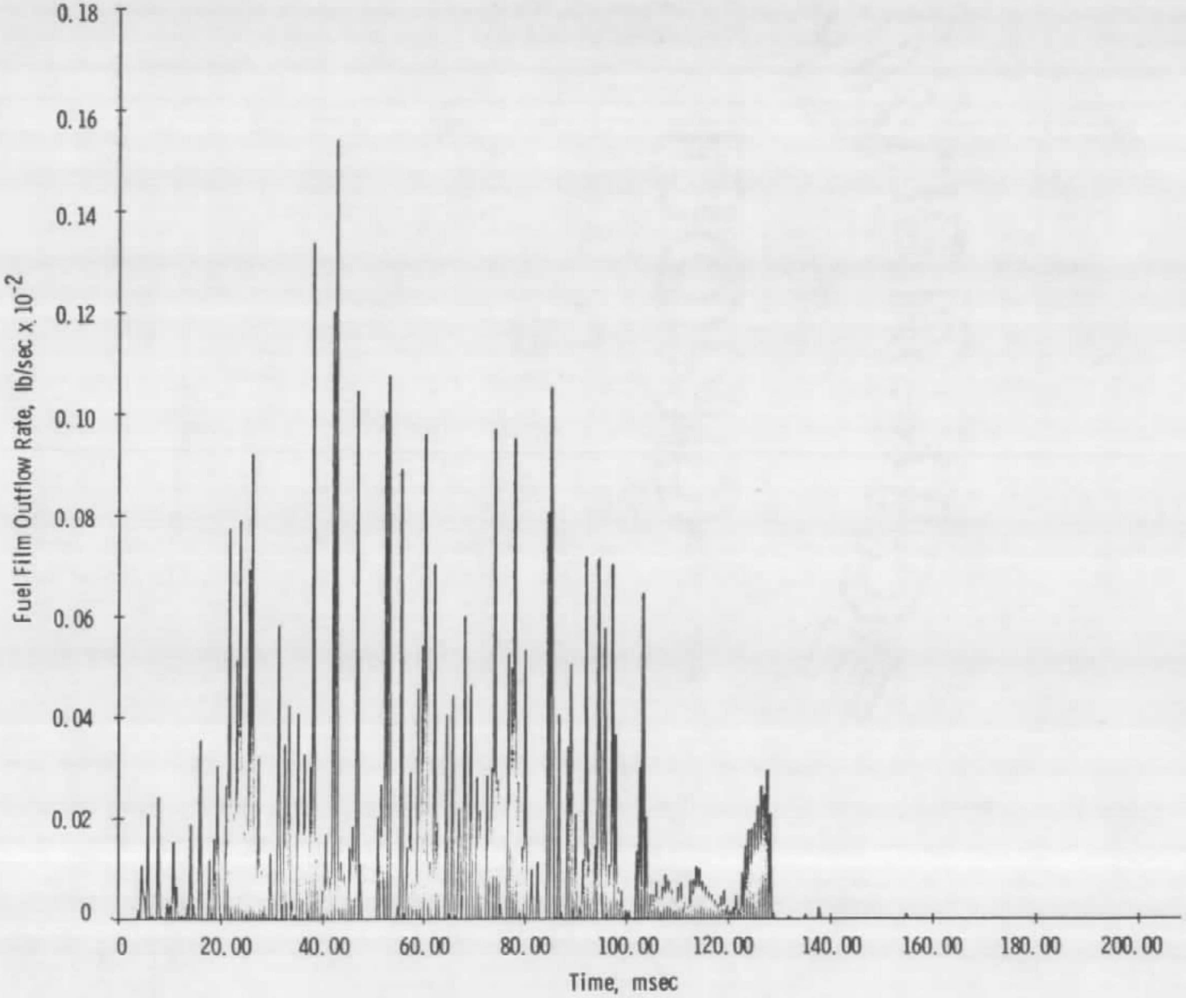
b. Fuel droplet rate
Figure 5. Continued.



c. Oxidizer droplet rate
Figure 5. Continued.

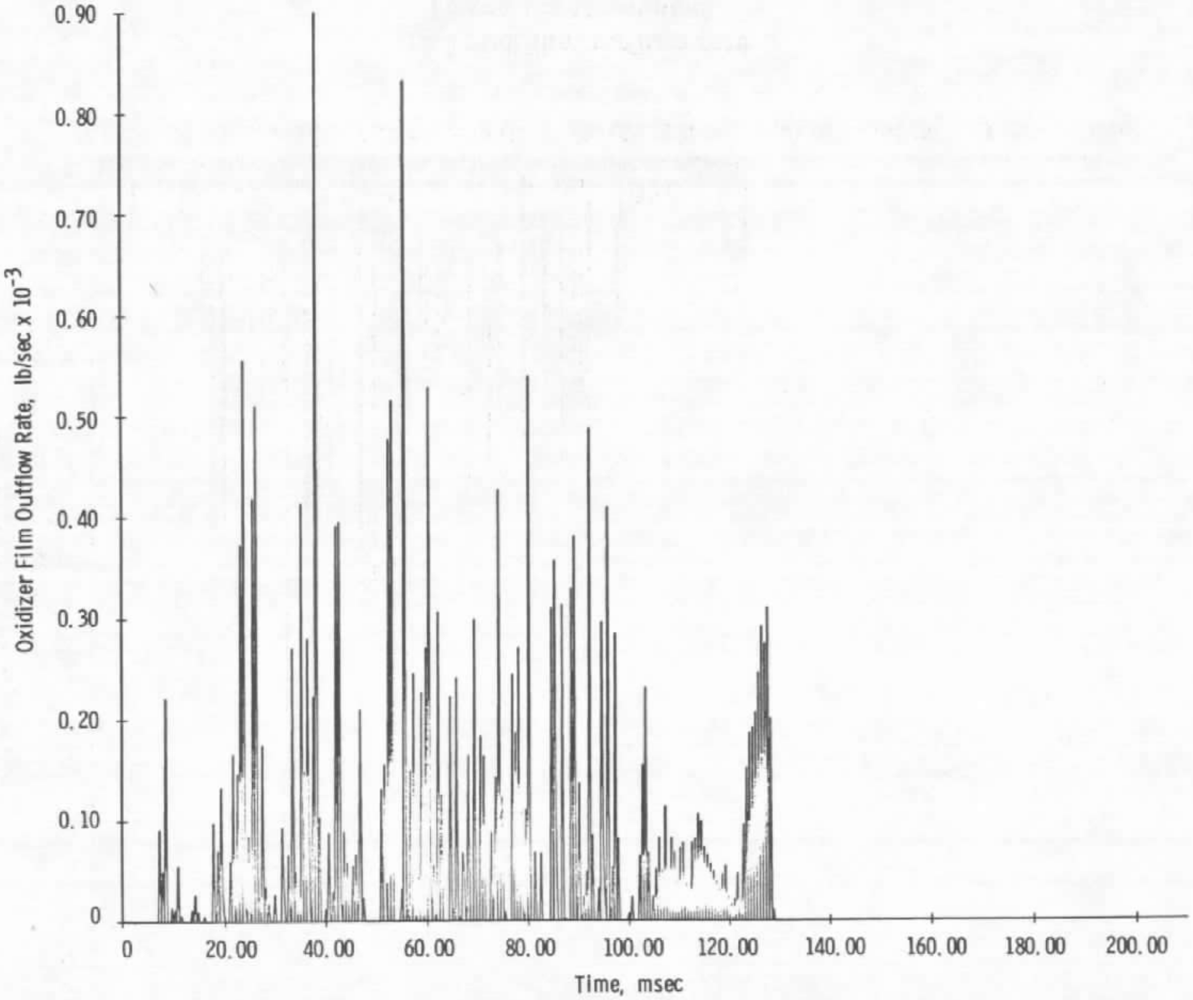


d. Total droplet rate
Figure 5. Continued.

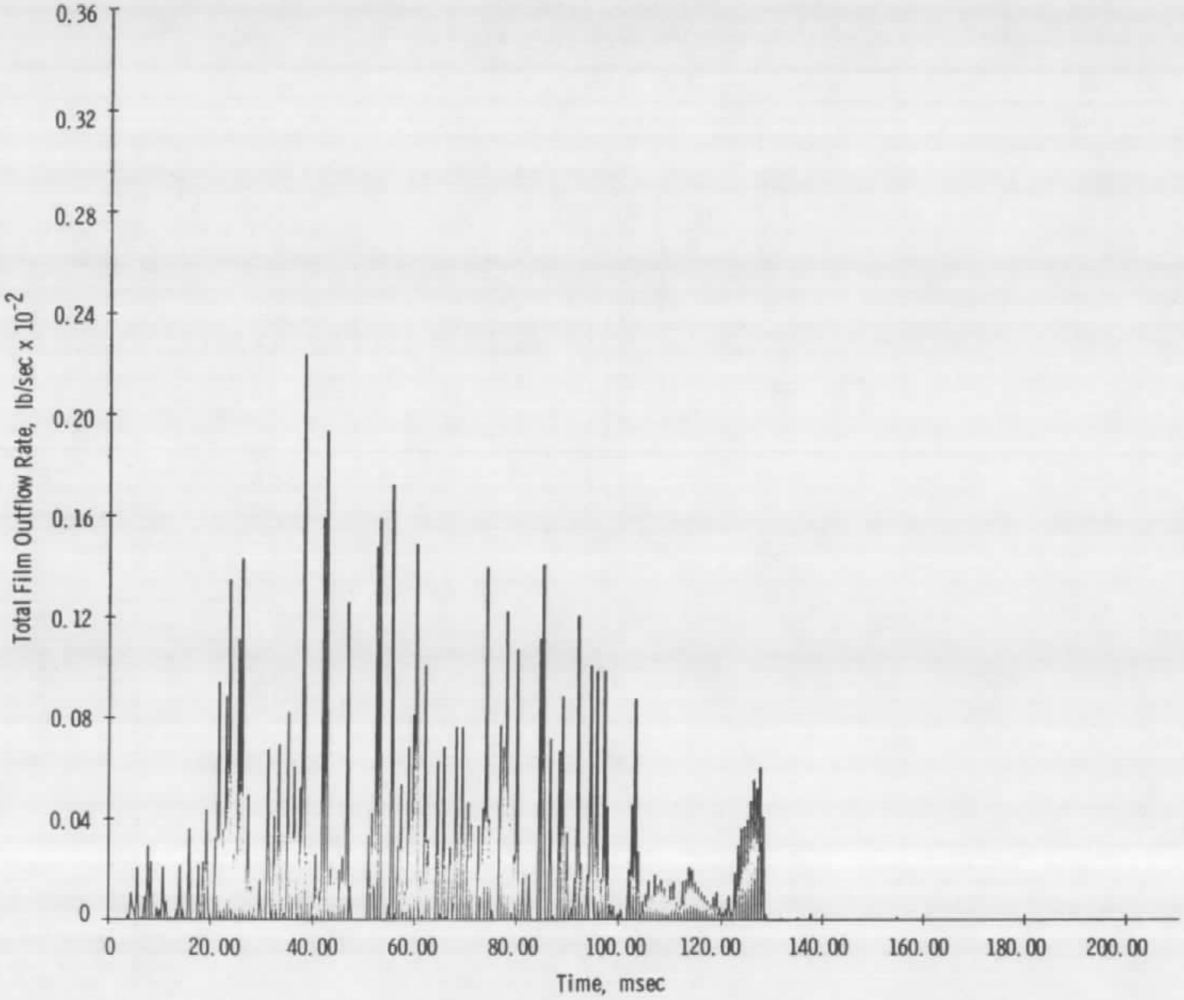


e. Fuel film outflow rate

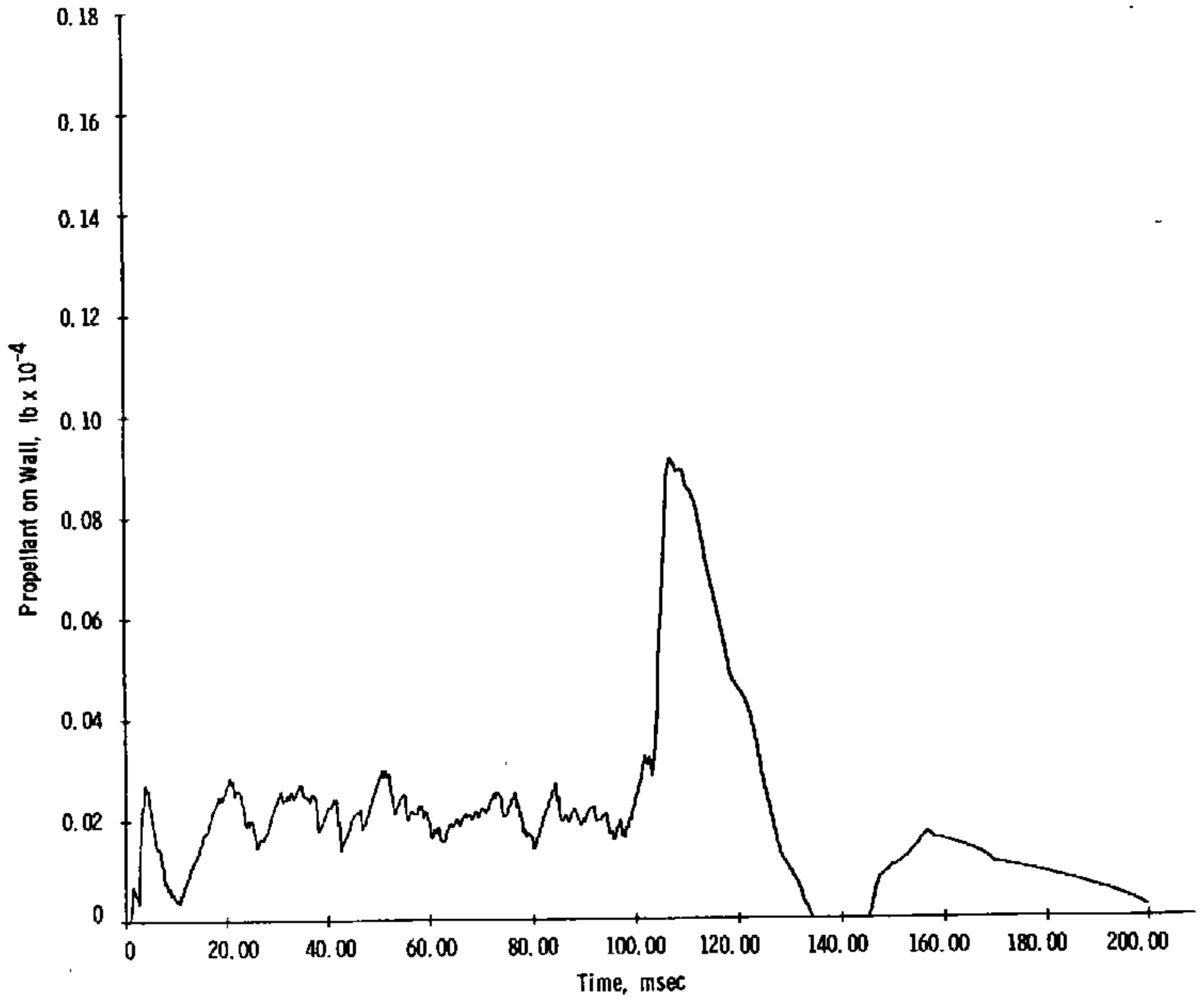
Figure 5. Continued.



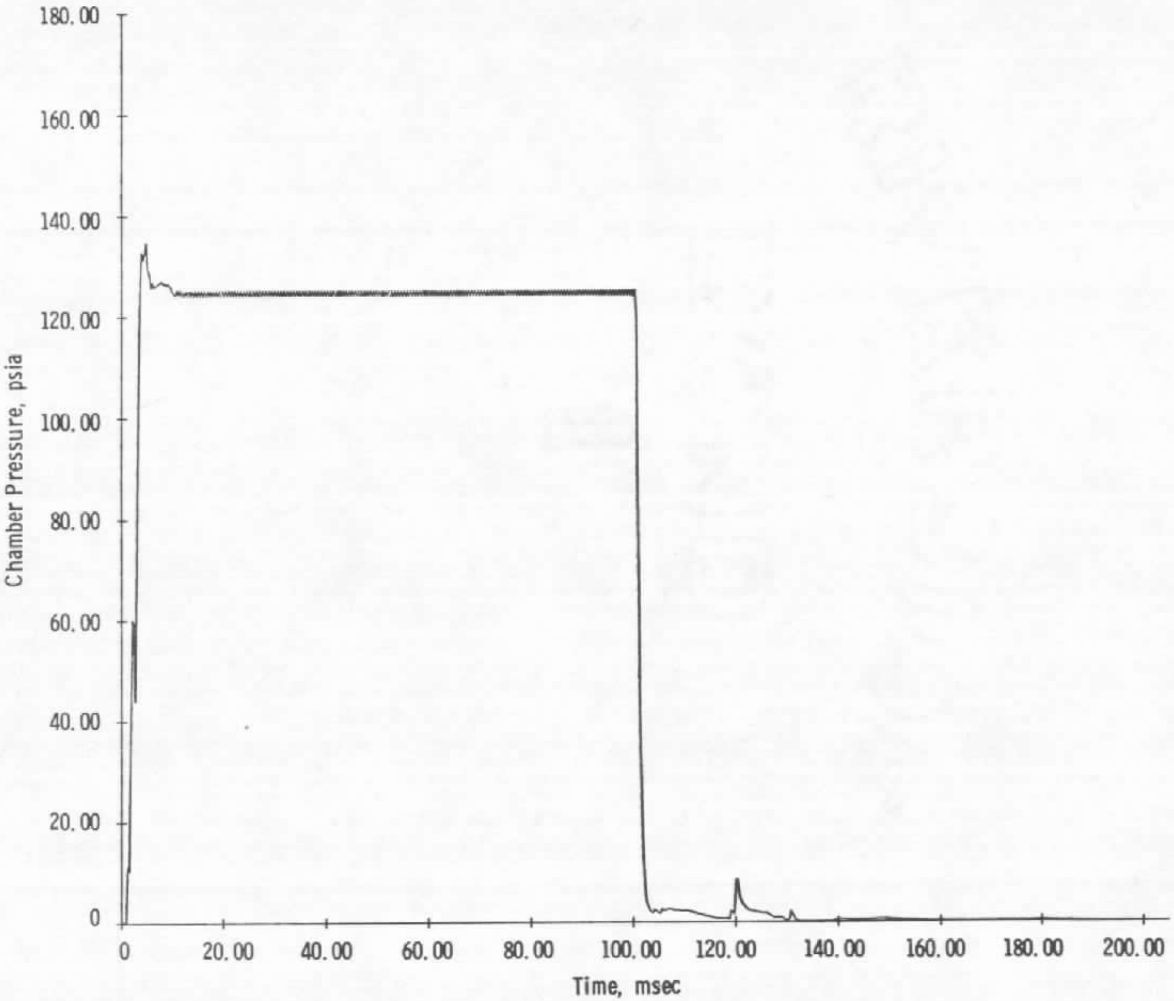
f. Oxidizer film outflow rate
Figure 5. Continued.



g. Total film outflow rate
Figure 5. Continued.

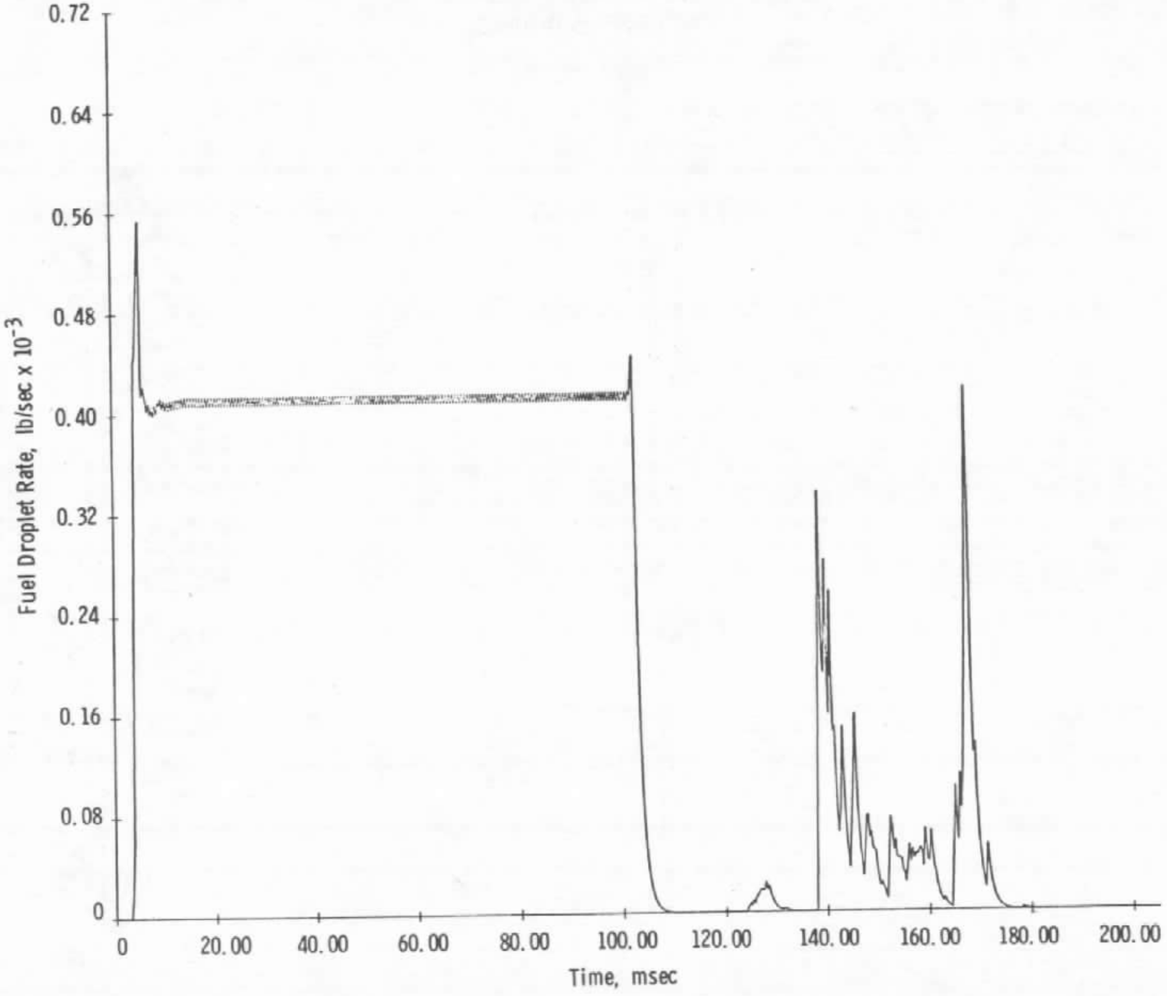


h. Propellant on wall
Figure 5. Concluded.

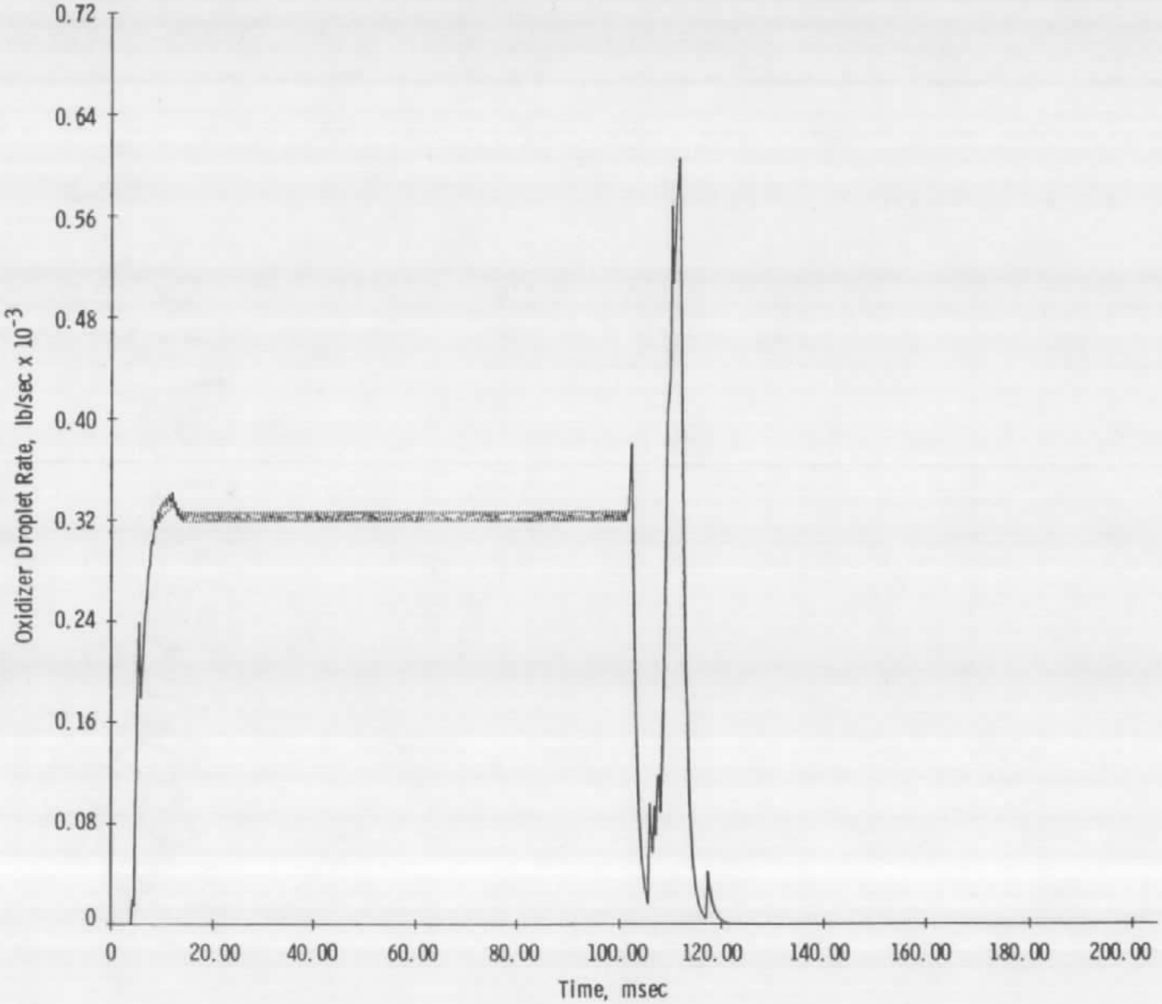


a. Chamber pressure

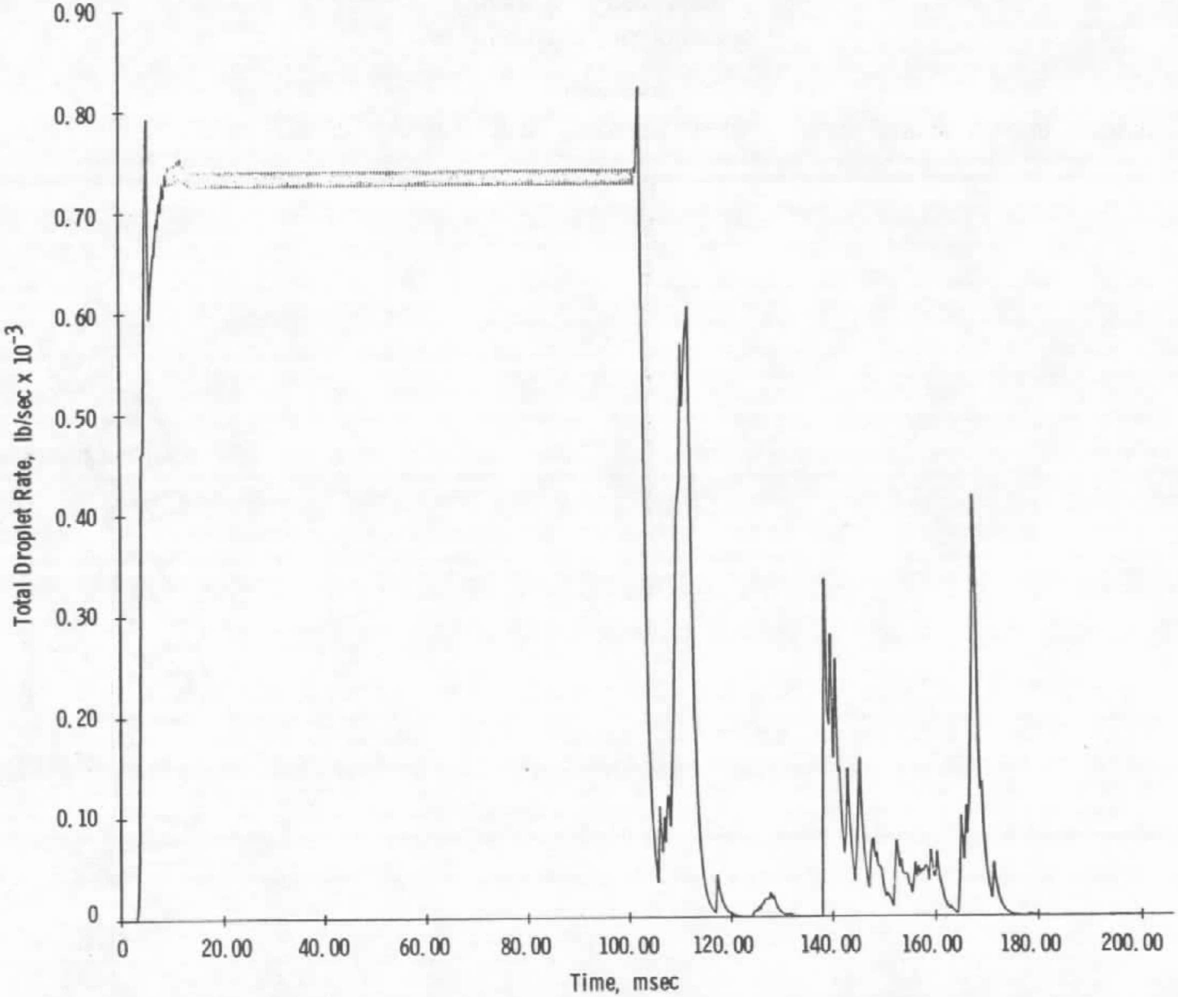
Figure 6. Case E results for AJ10-181-2.



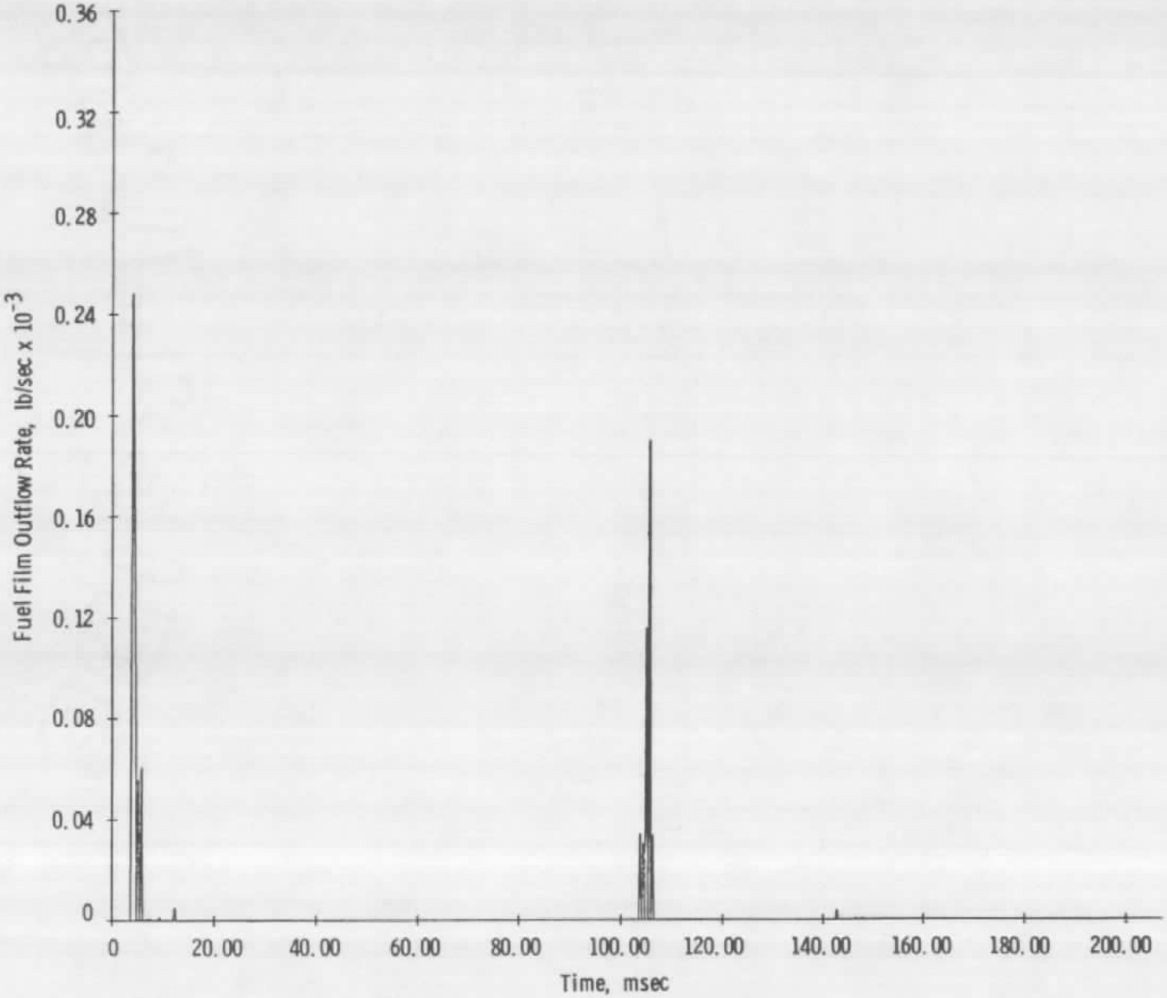
b. Fuel droplet rate
Figure 6. Continued.



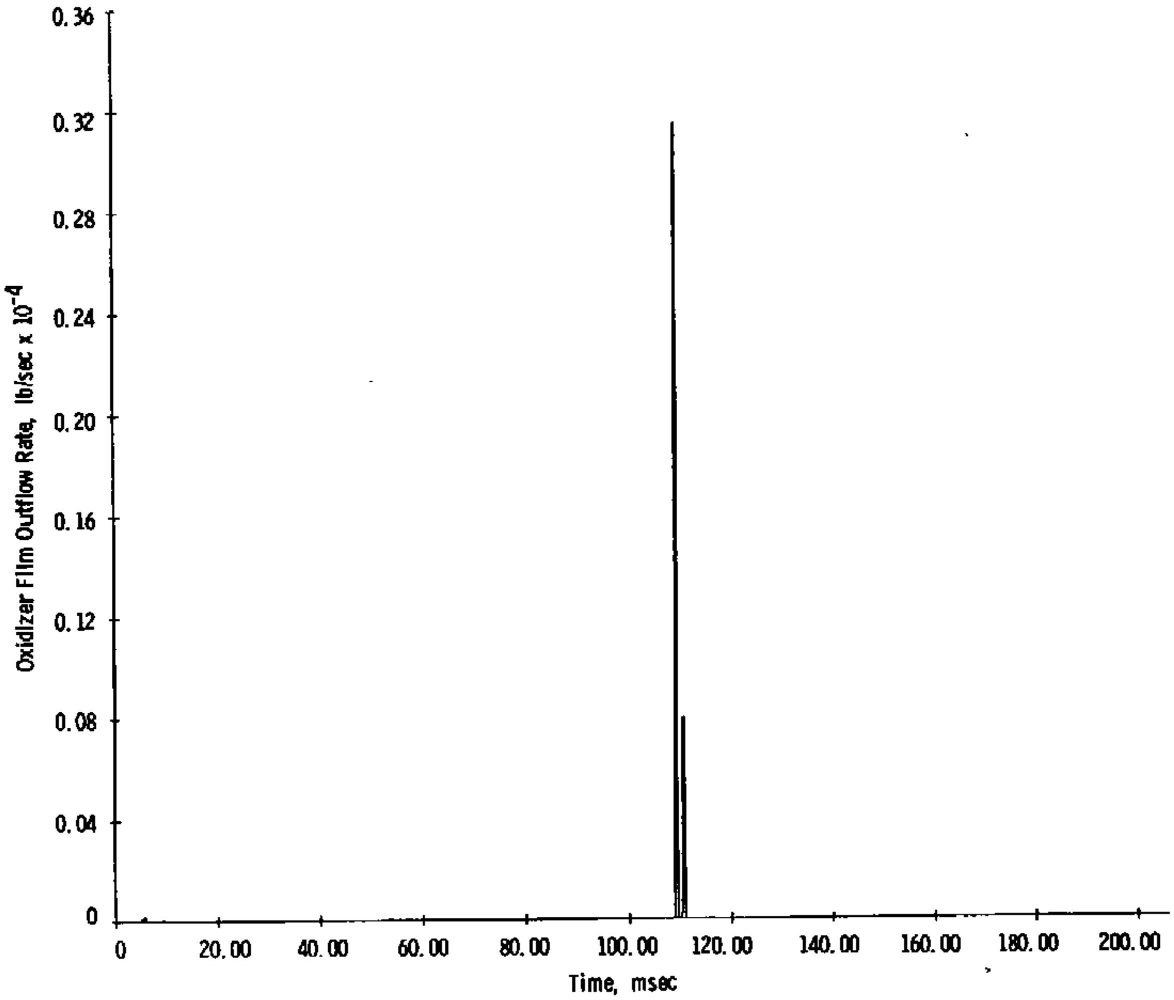
c. Oxidizer droplet rate
Figure 6. Continued.



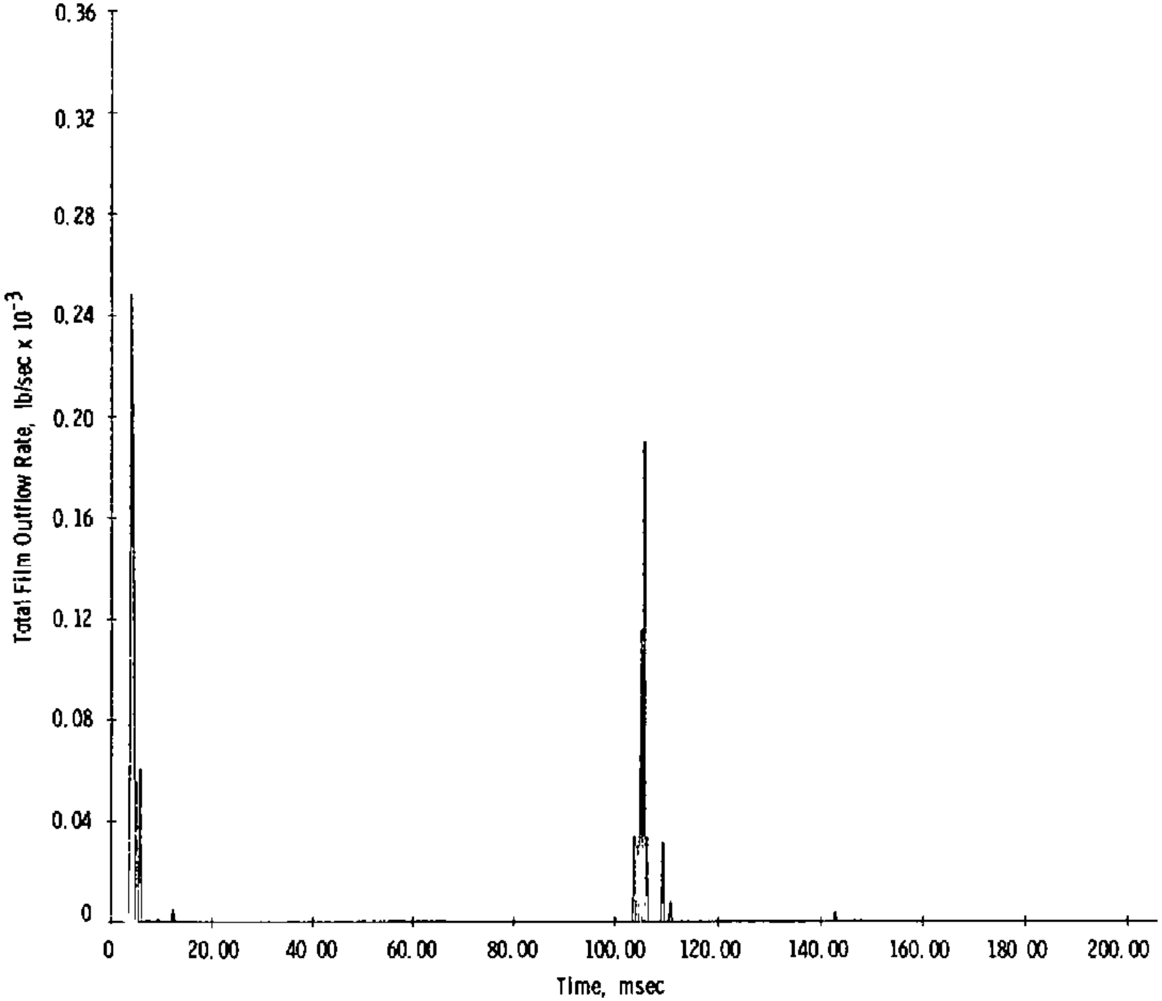
d. Total droplet rate
Figure 6. Continued.



e. Fuel film outflow rate
Figure 6. Continued.

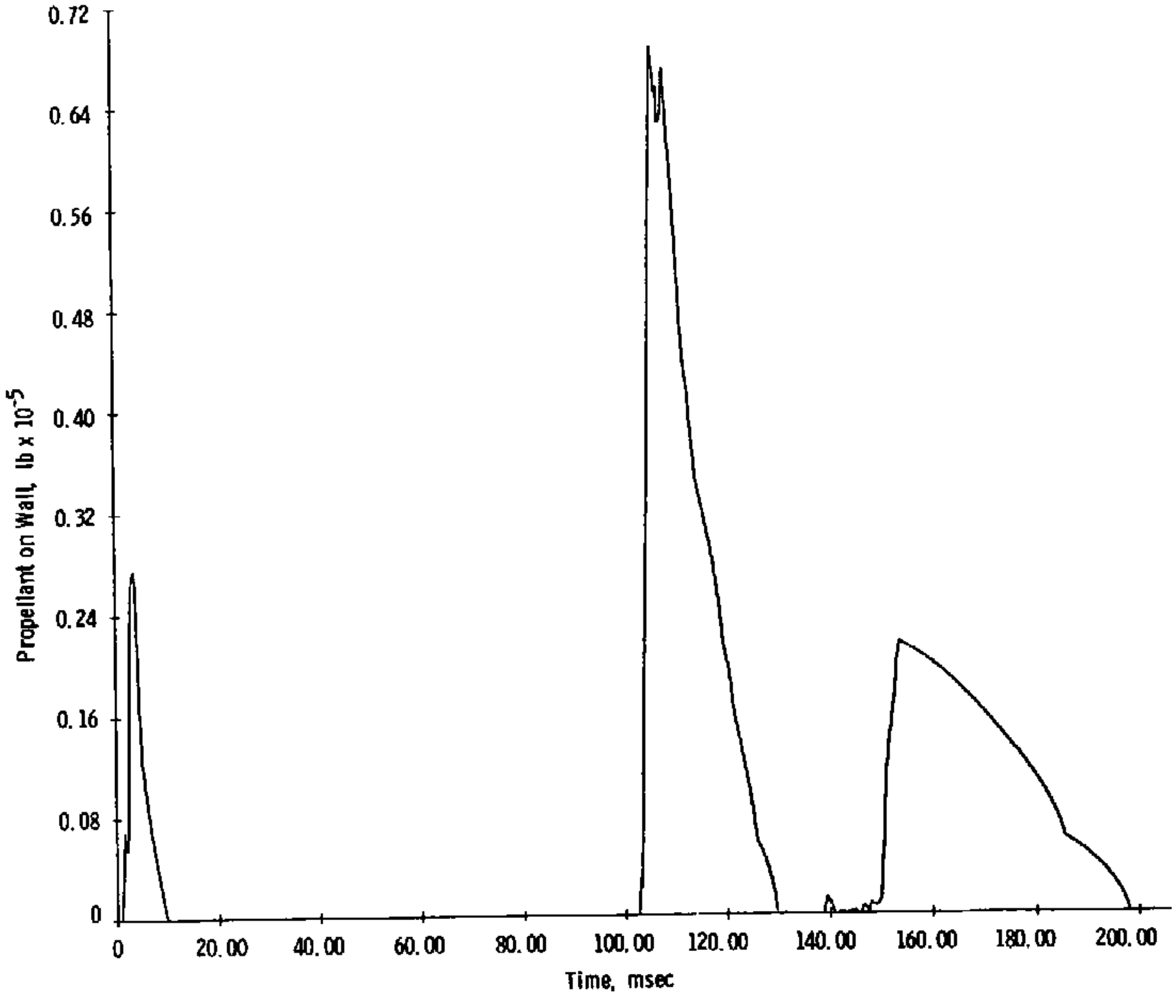


f. Oxidizer film outflow rate
Figure 6. Continued.

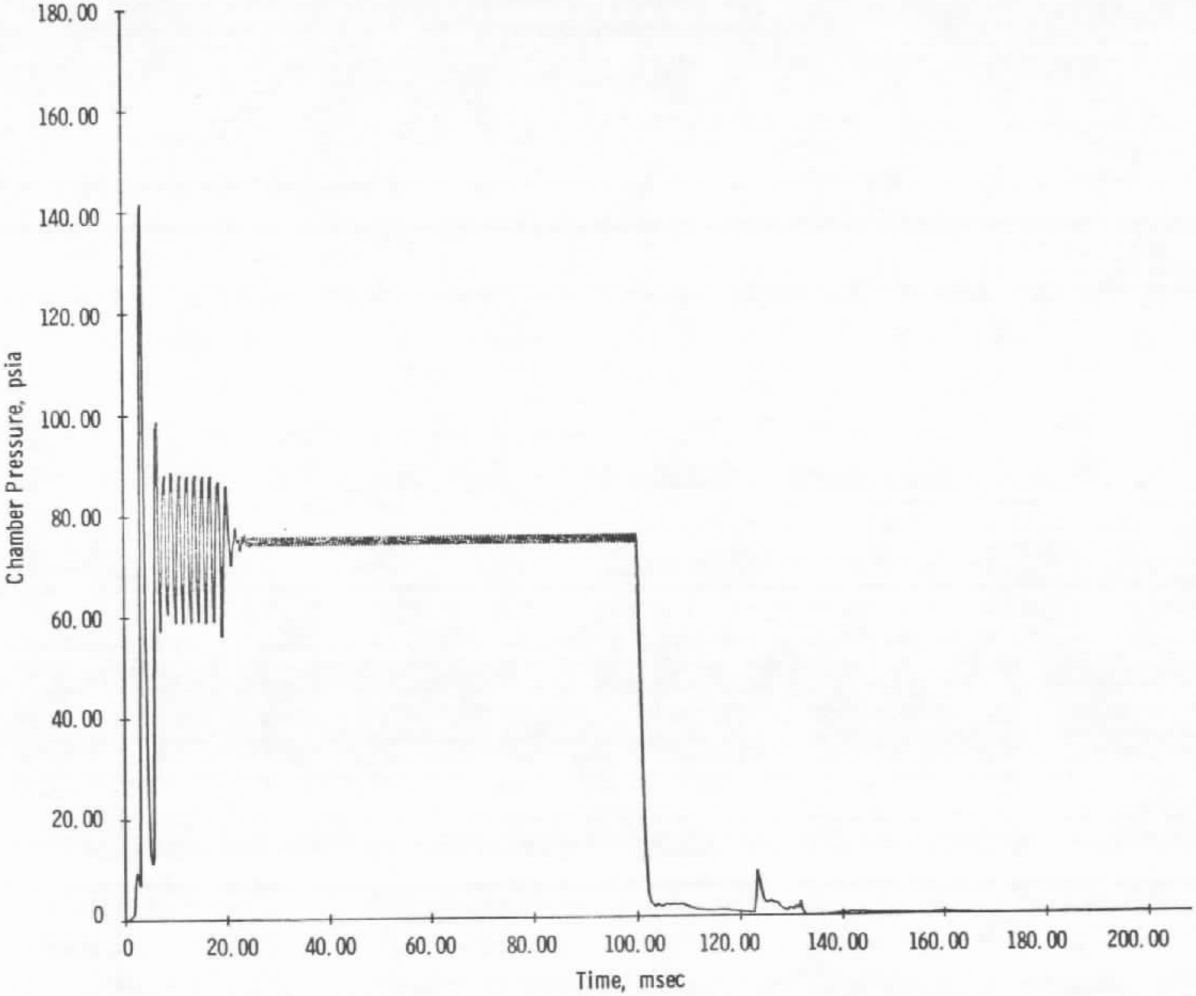


g. Total film output rate

Figure 6. Continued.

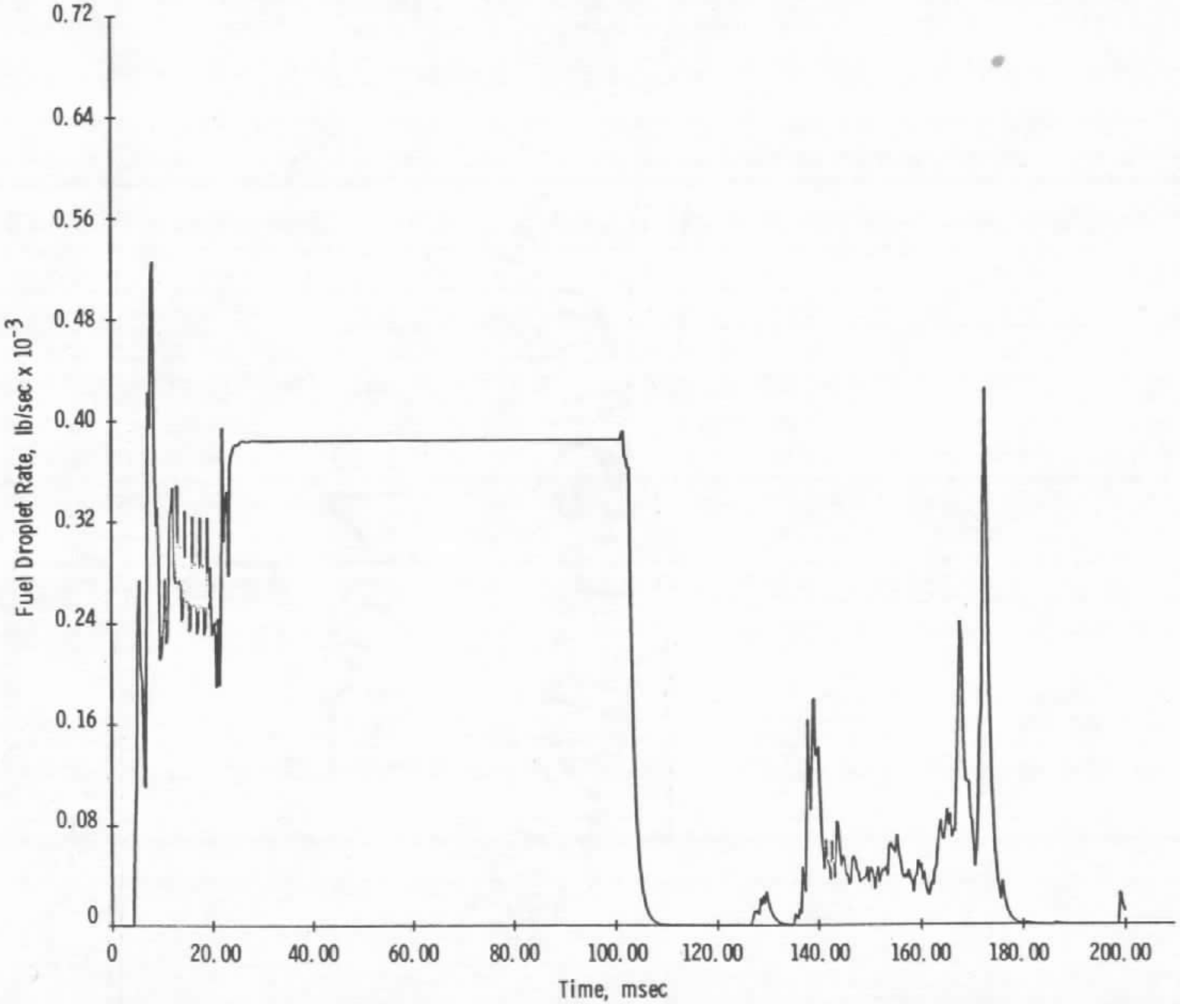


h. Propellant on wall
Figure 6. Concluded.

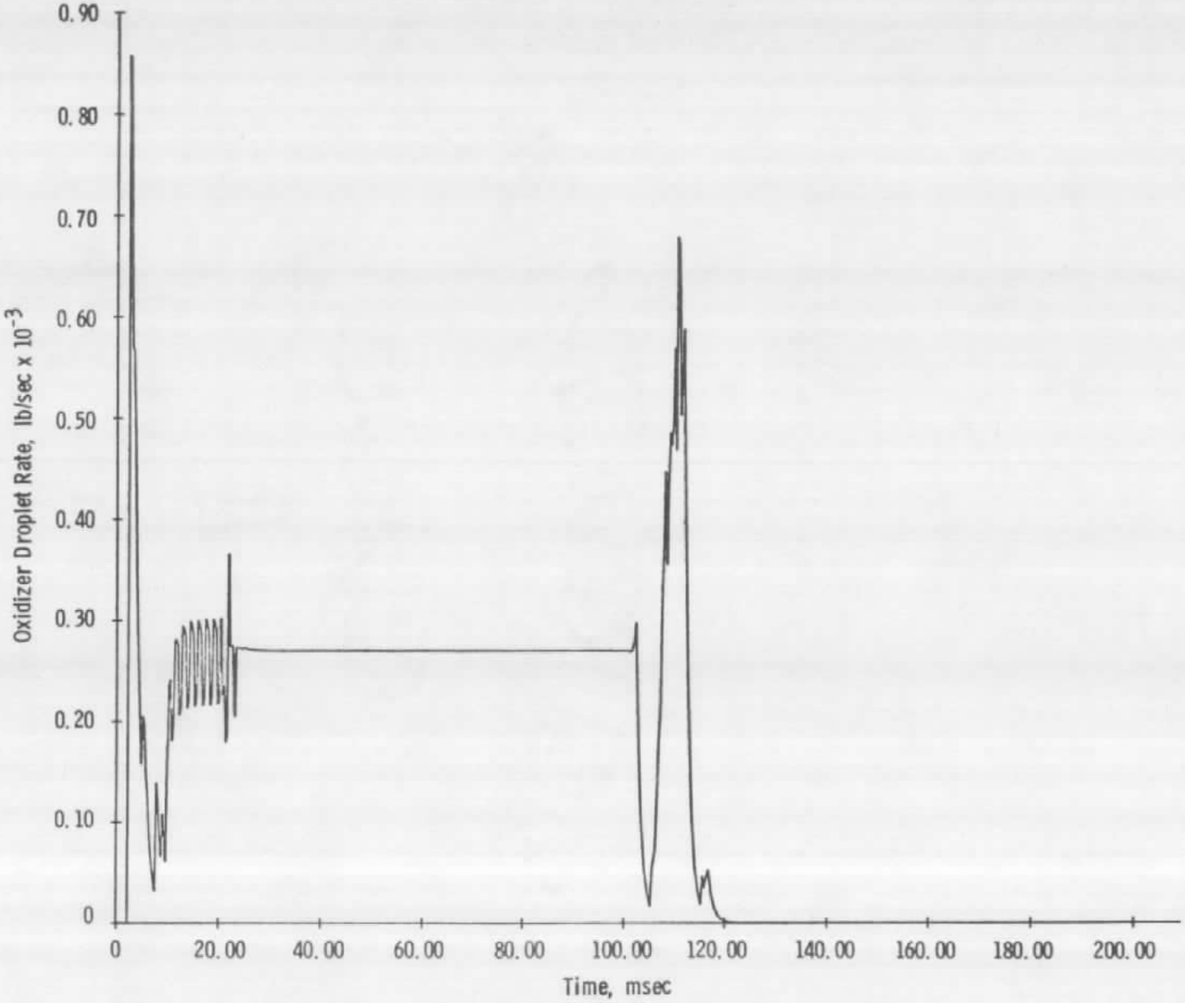


a. Chamber pressure

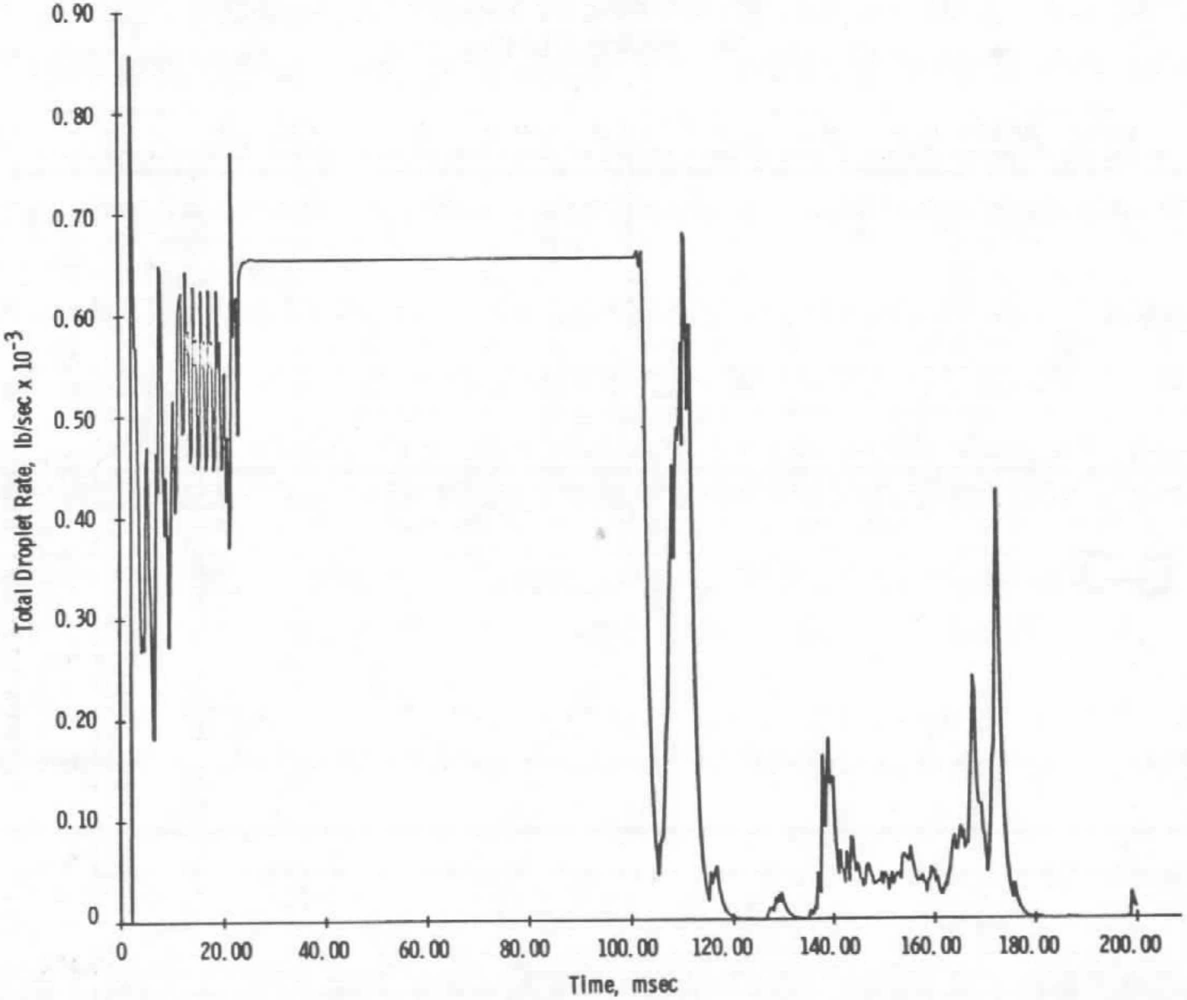
Figure 7. Case G results for AJ10-181-2.



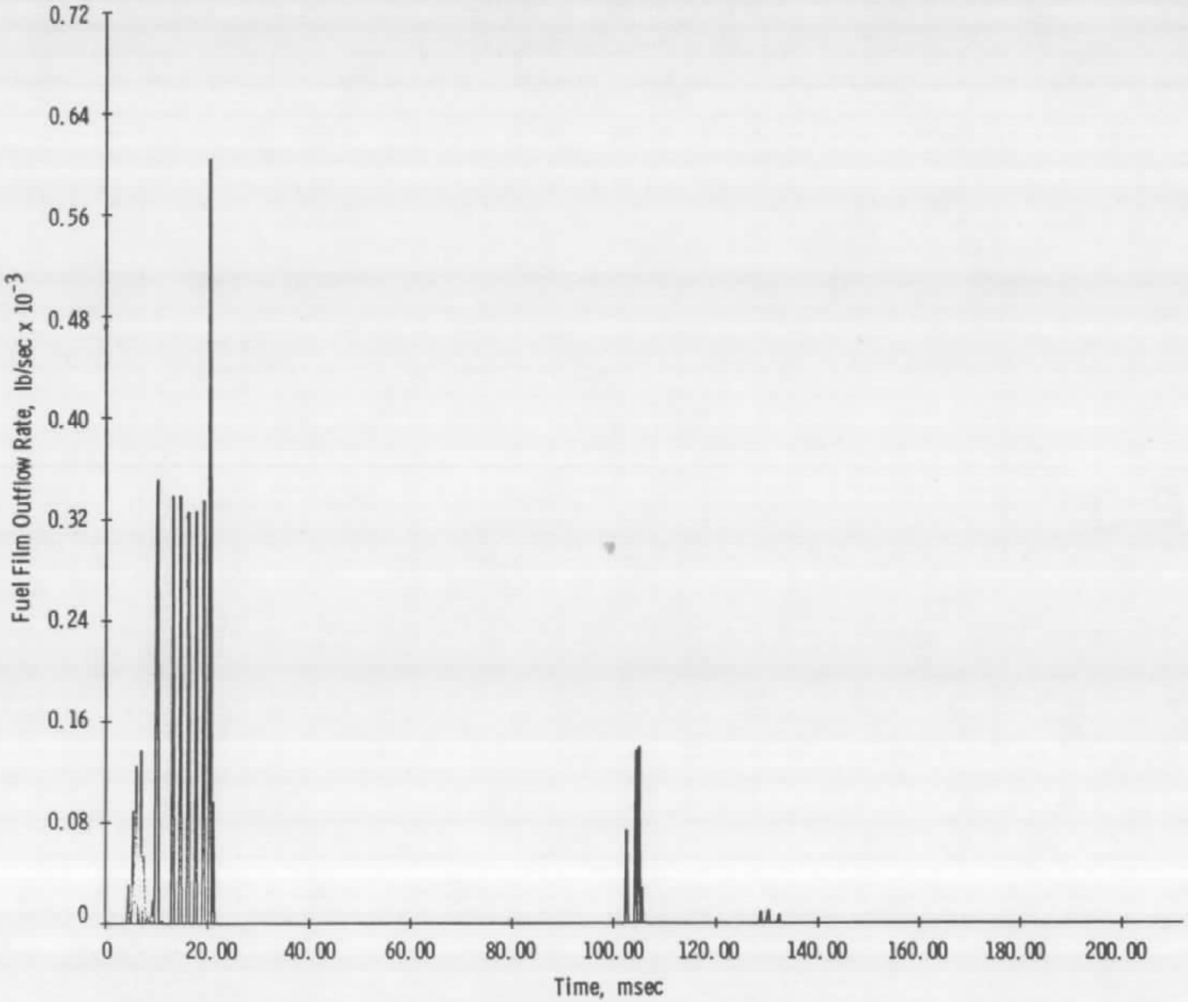
b. Fuel droplet rate
Figure 7. Continued.



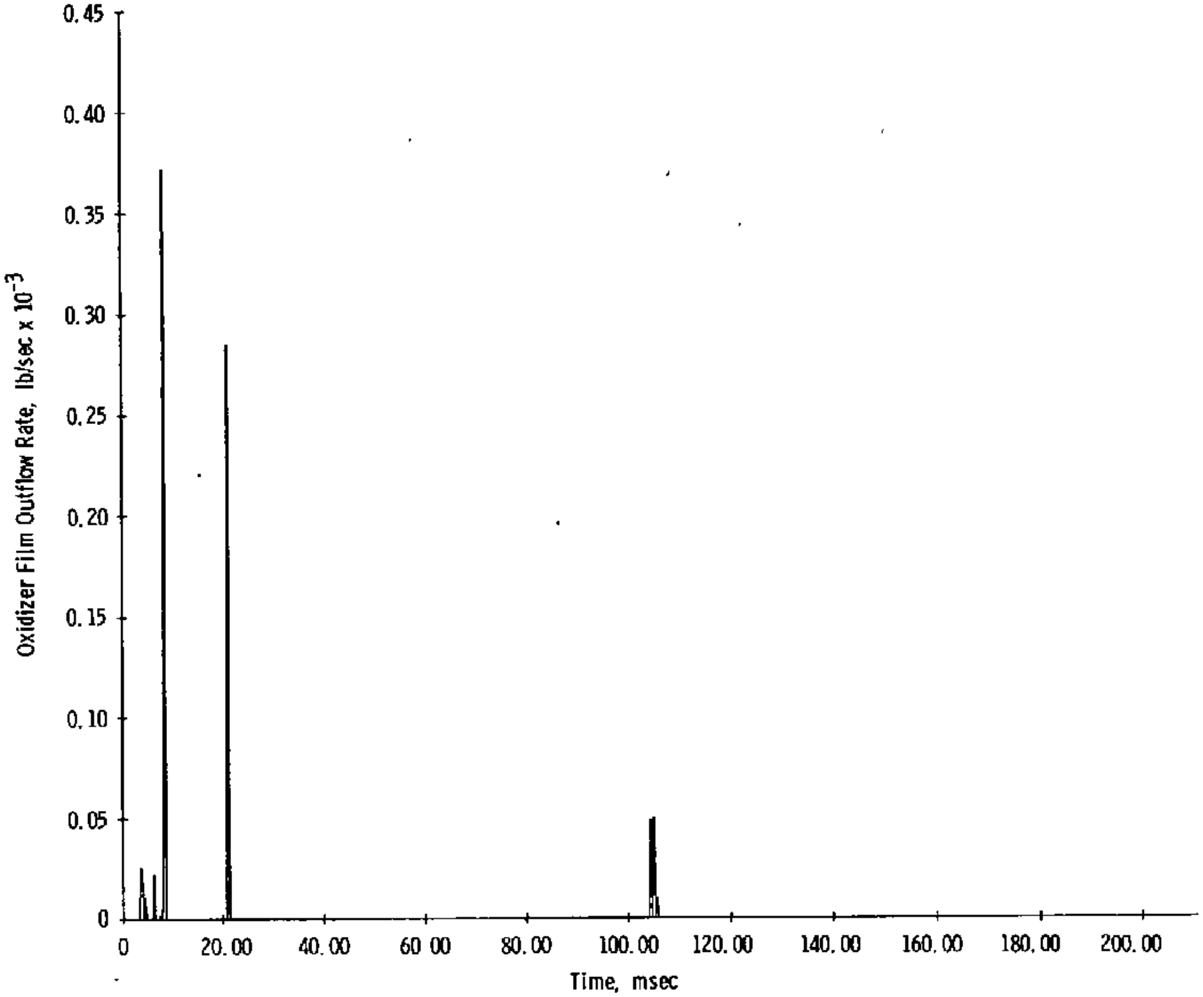
c. Oxidizer droplet rate
Figure 7. Continued.



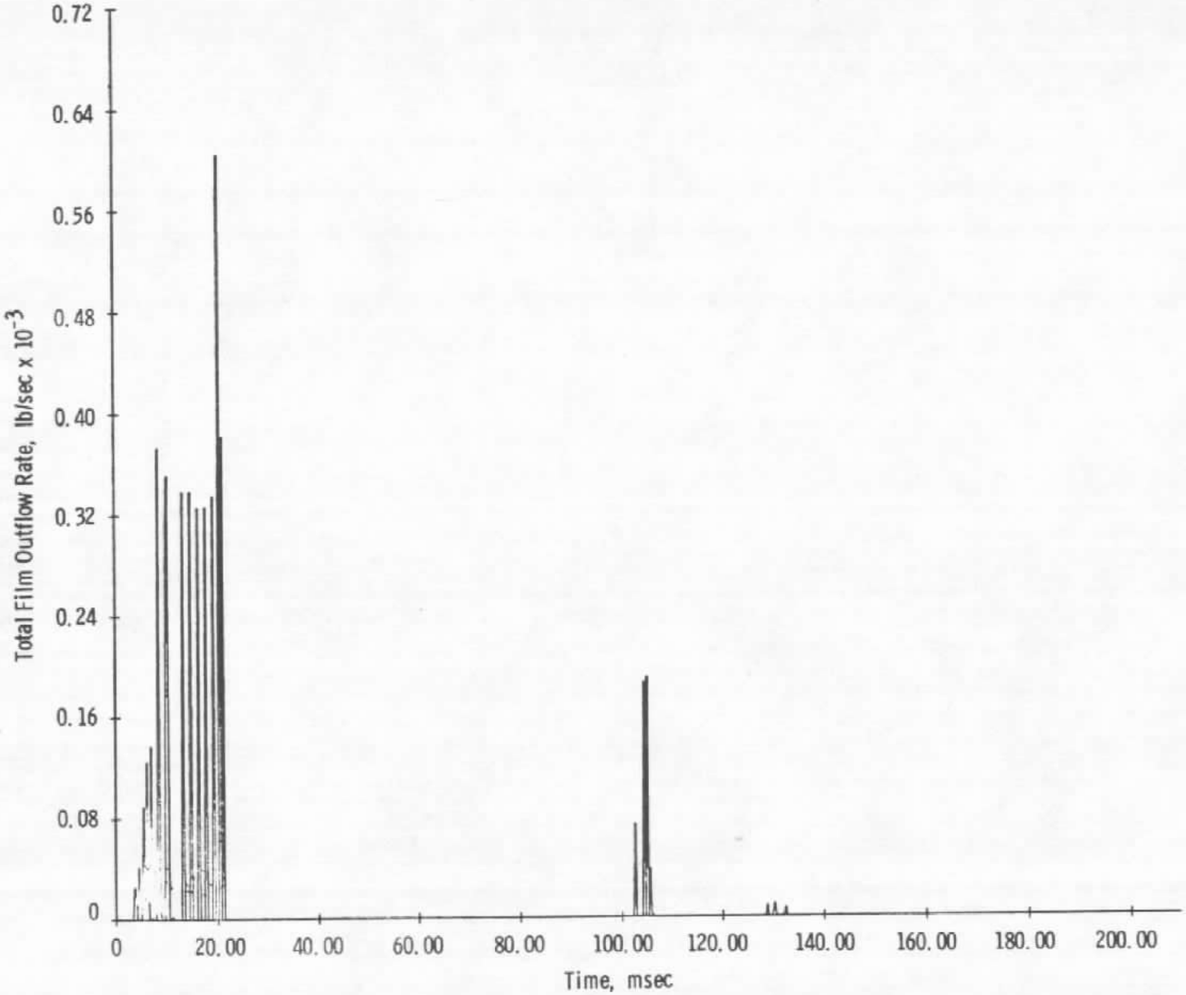
d. Total droplet rate
Figure 7. Continued.



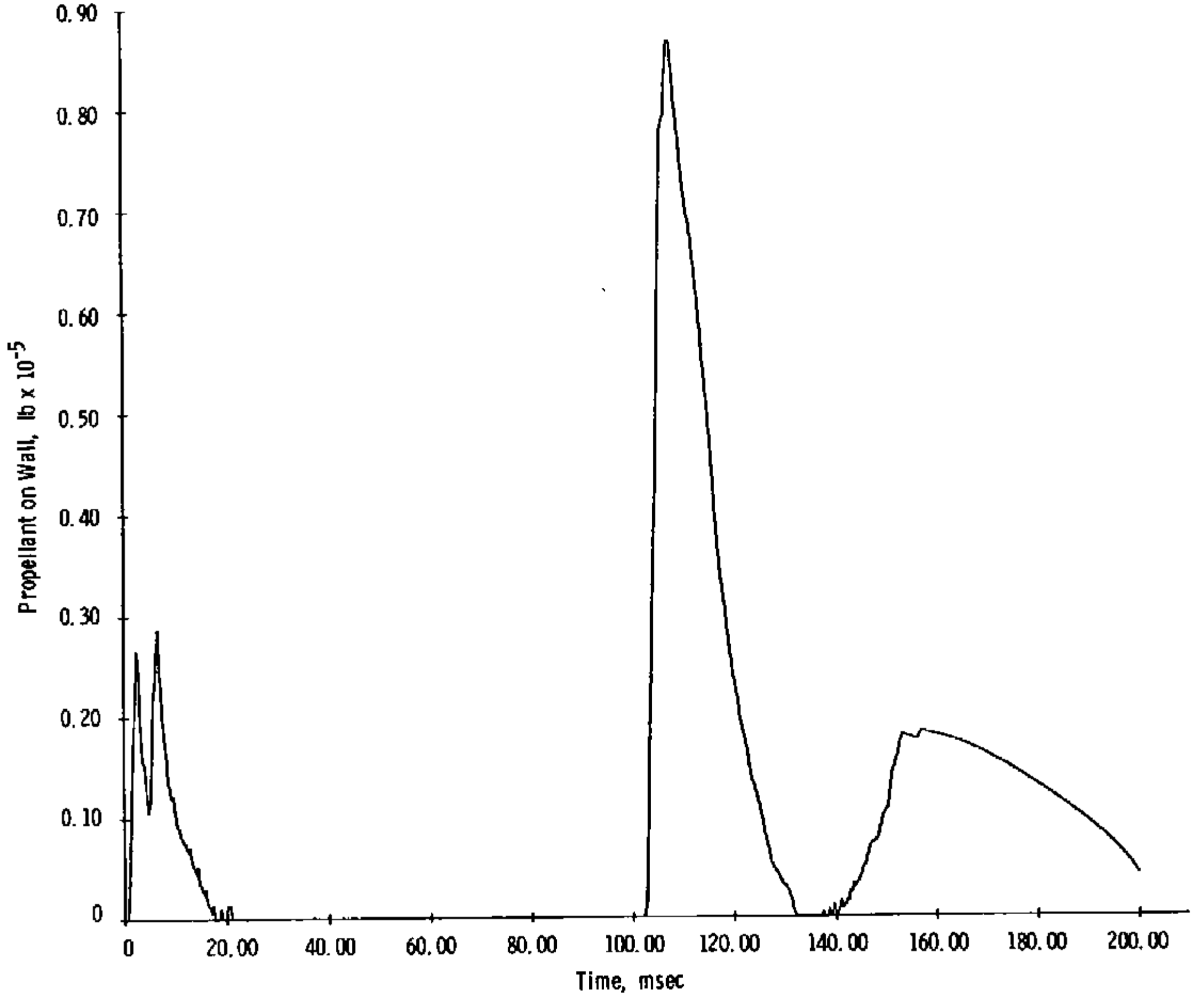
e. Fuel film outflow rate
Figure 7. Continued.



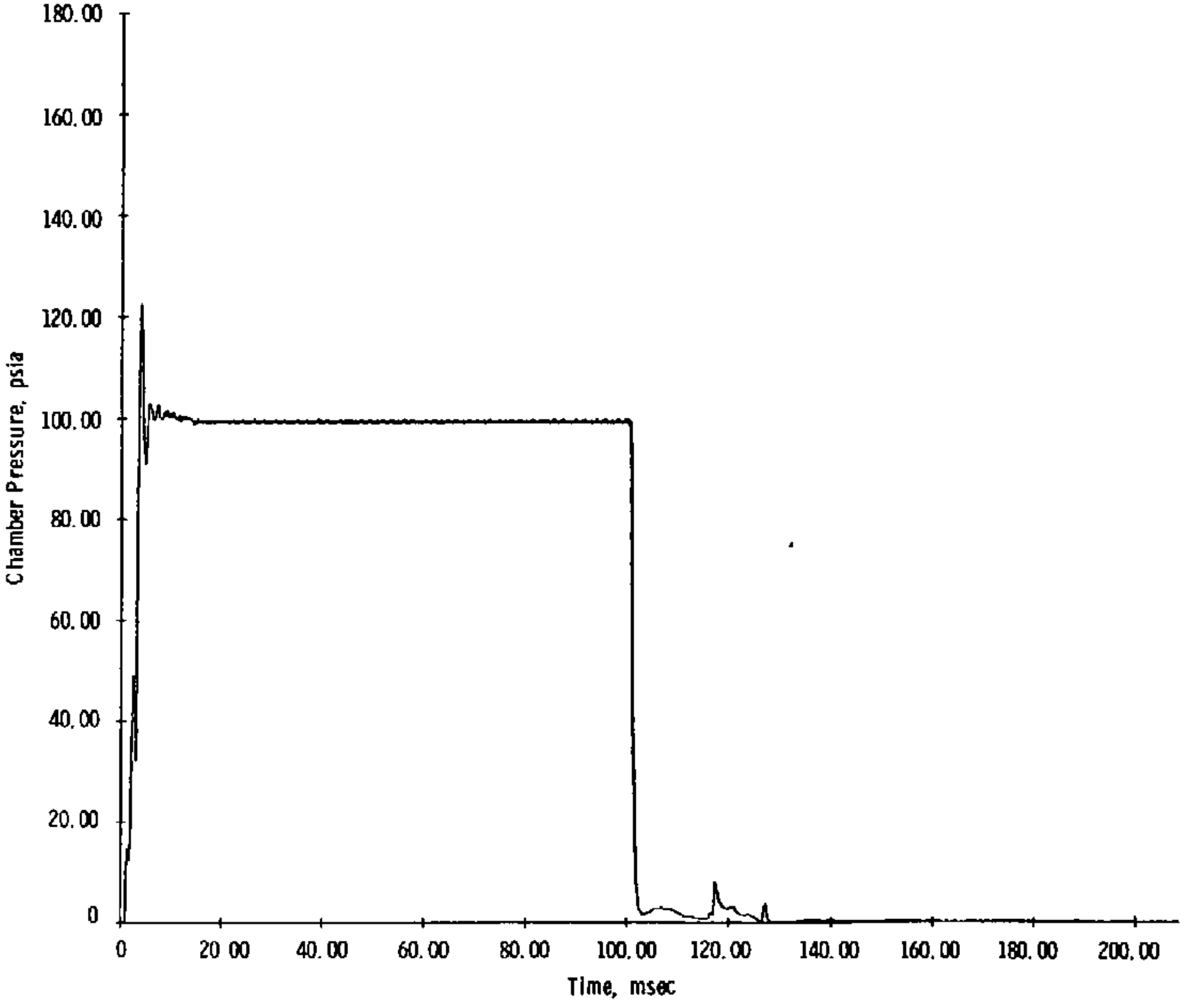
f. Oxidizer film outflow rate
Figure 7. Continued.



g. Total film outflow rate
Figure 7. Continued.

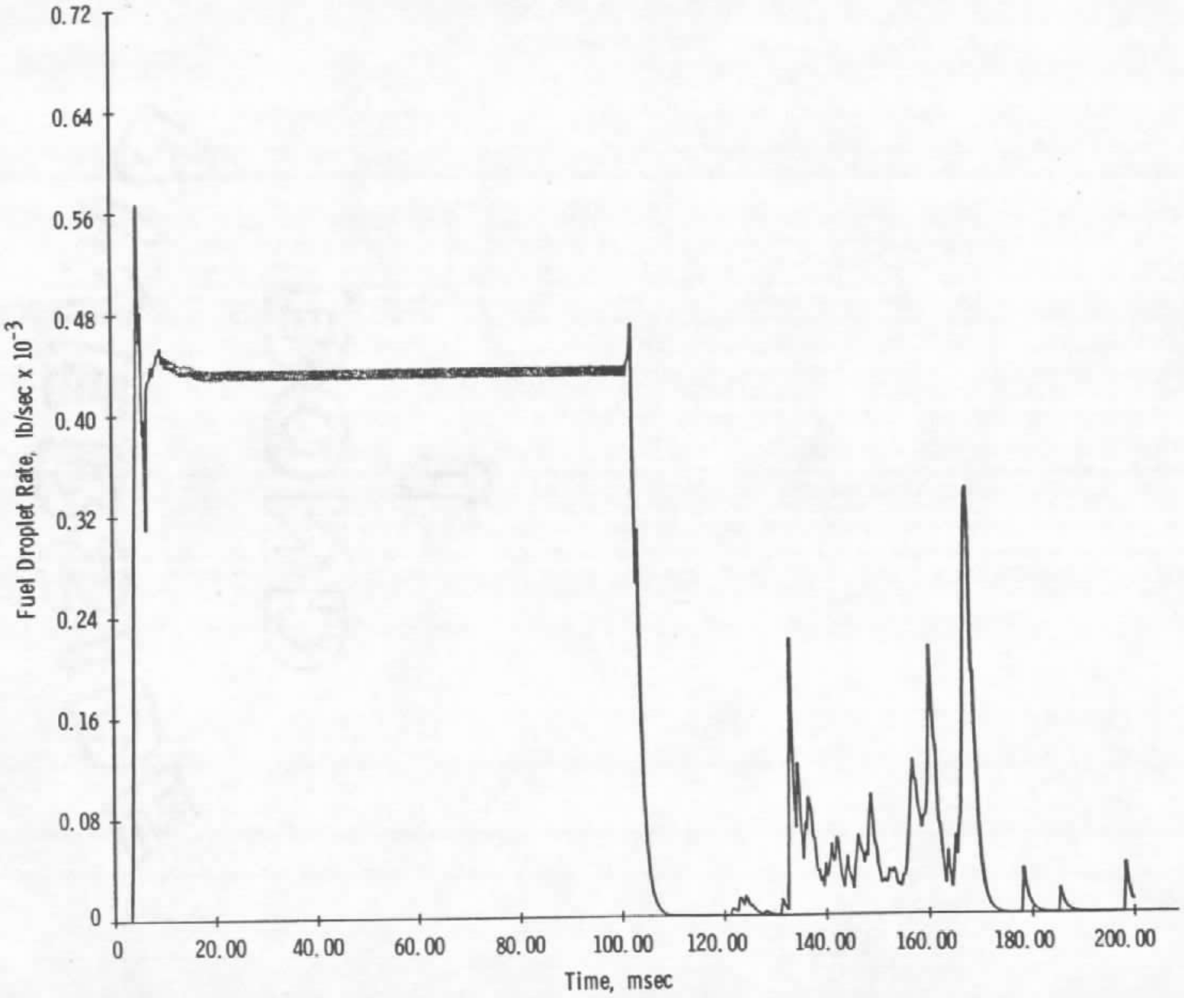


h. Propellant on wall
Figure 7. Concluded.

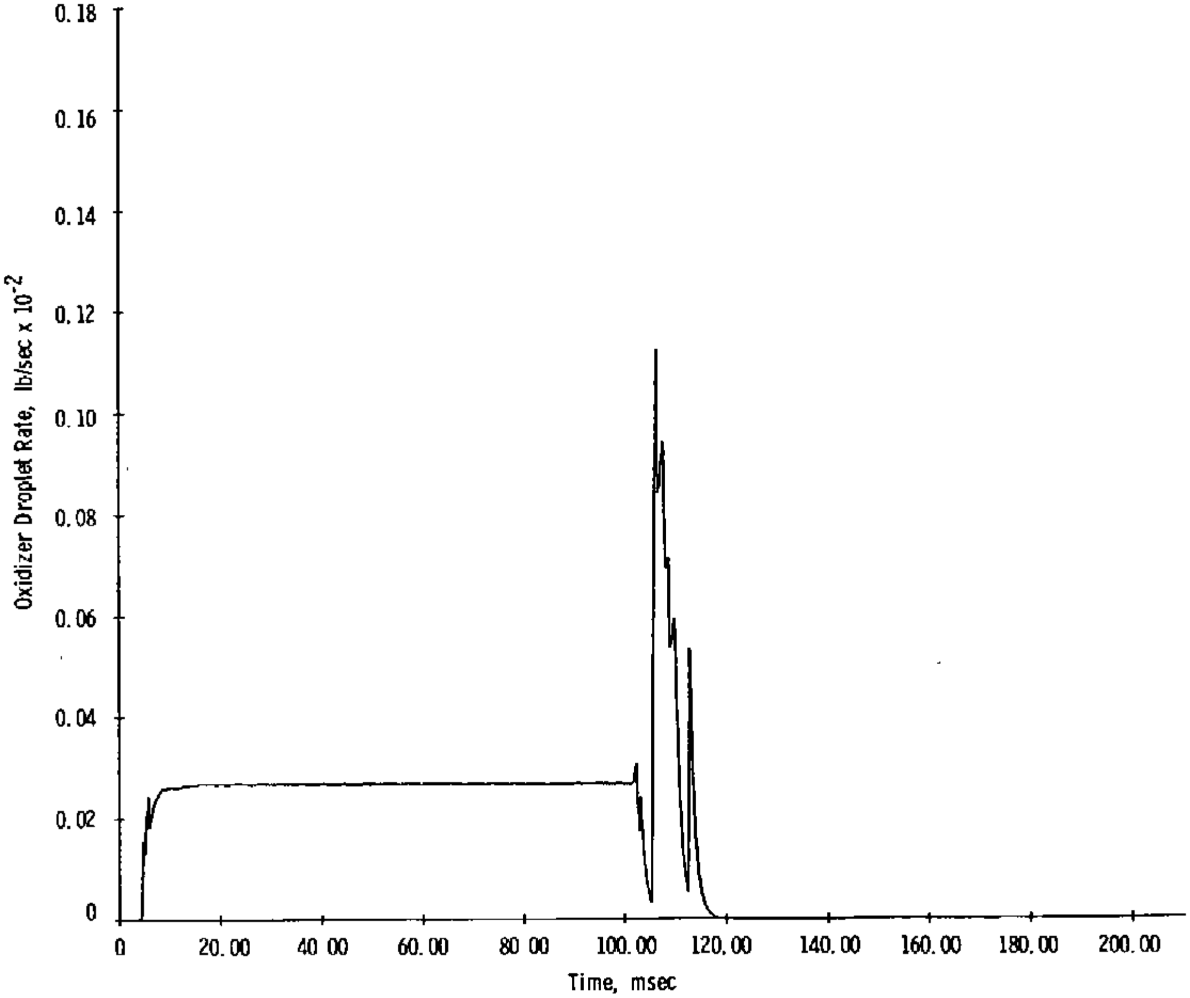


a. Chamber pressure

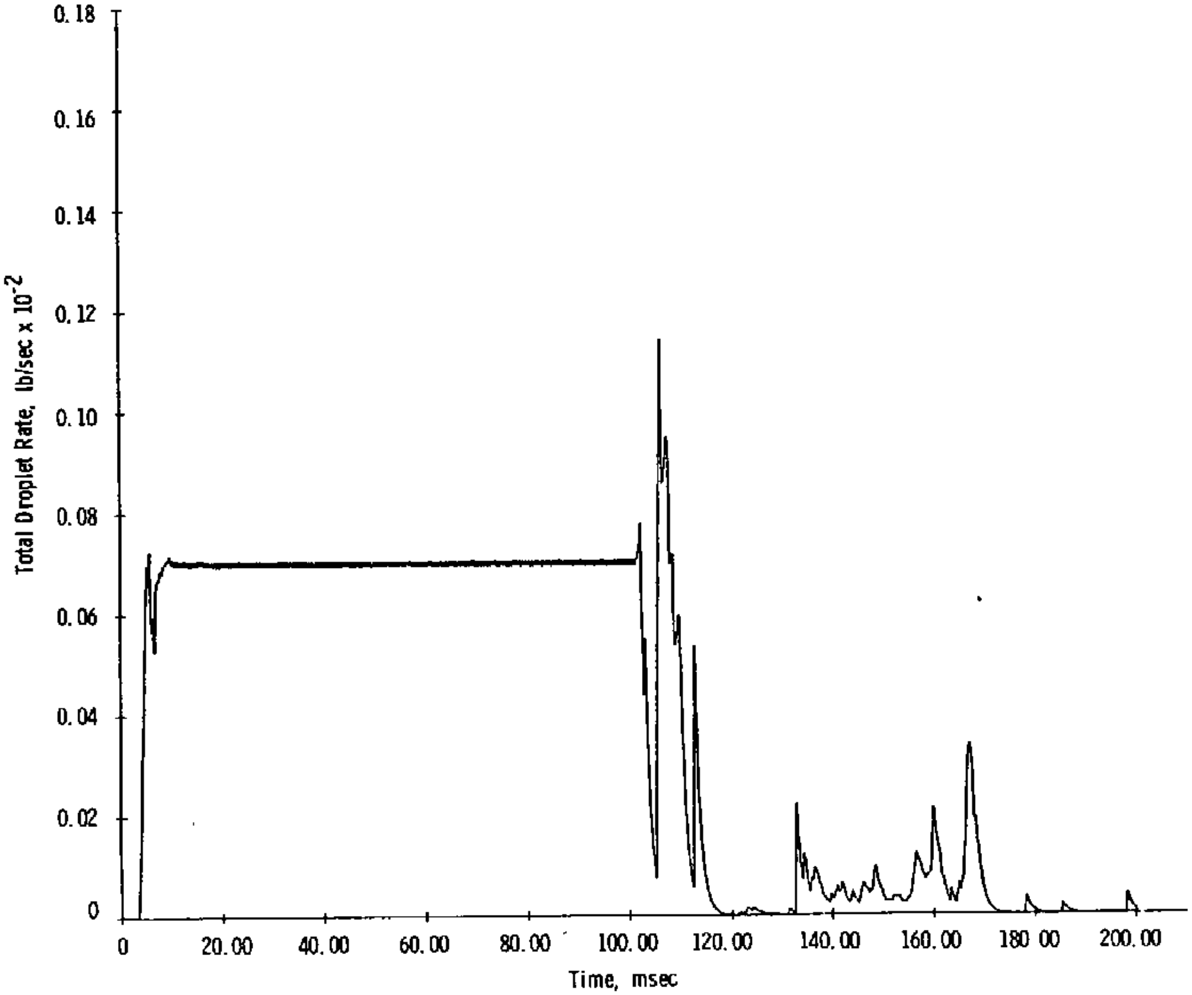
Figure 8. Case H results for AJ10-181-3.



b. Fuel droplet rate
Figure 8. Continued.

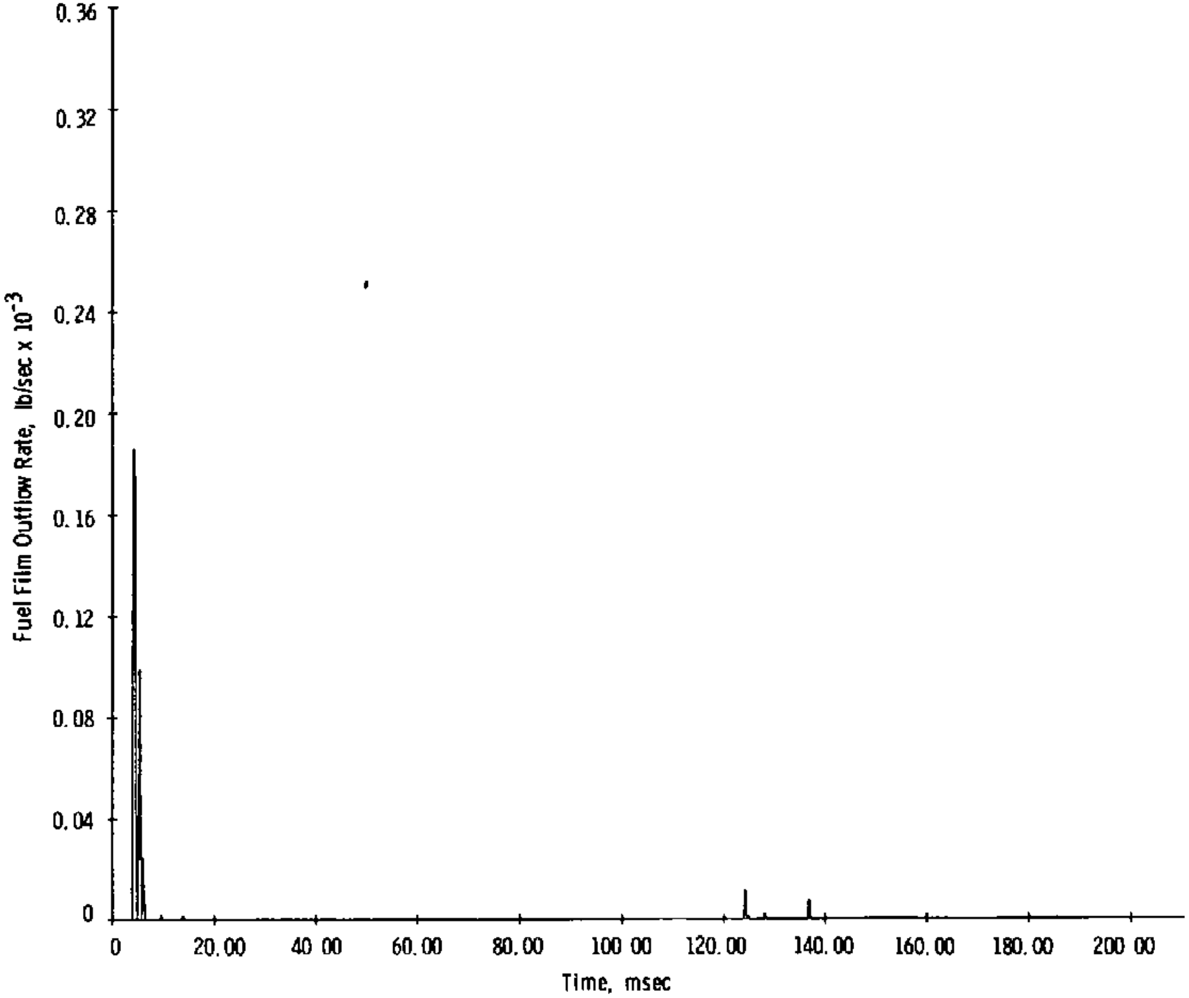


c. Oxidizer droplet rate
Figure 8. Continued.

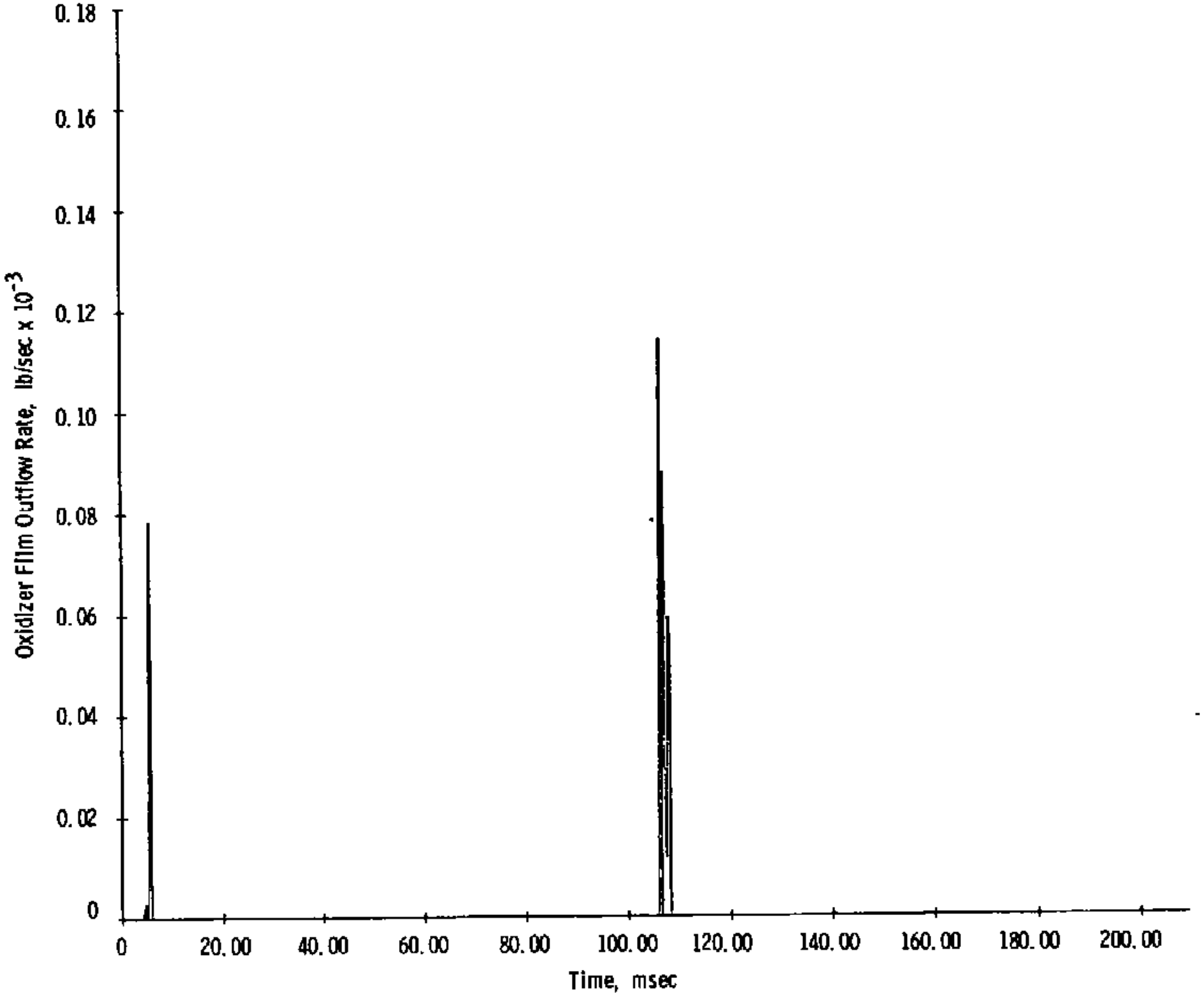


d. Total droplet rate

Figure 8. Continued.

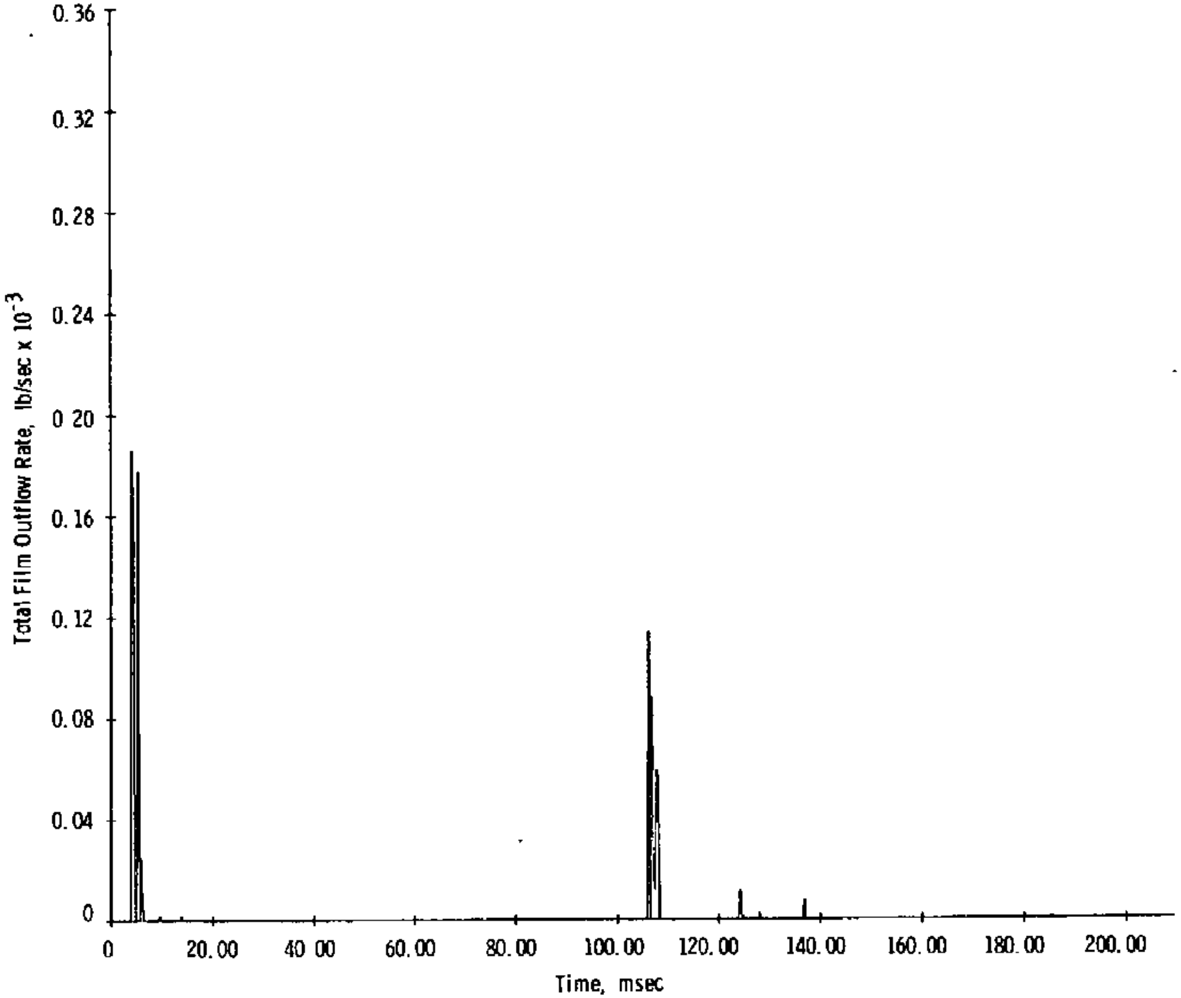


e. Fuel film outflow rate
Figure 8. Continued.

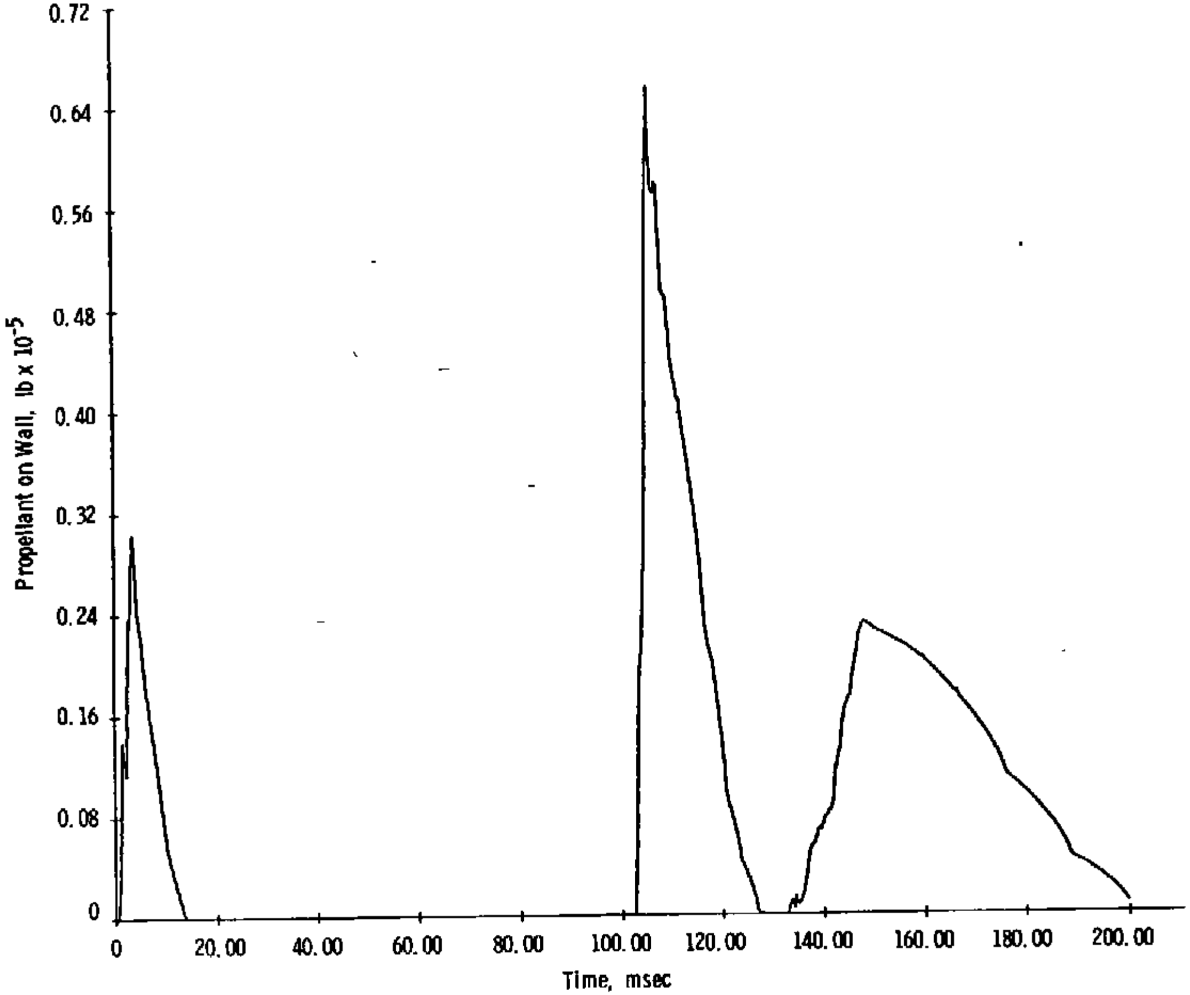


f. Oxidizer film outflow rate

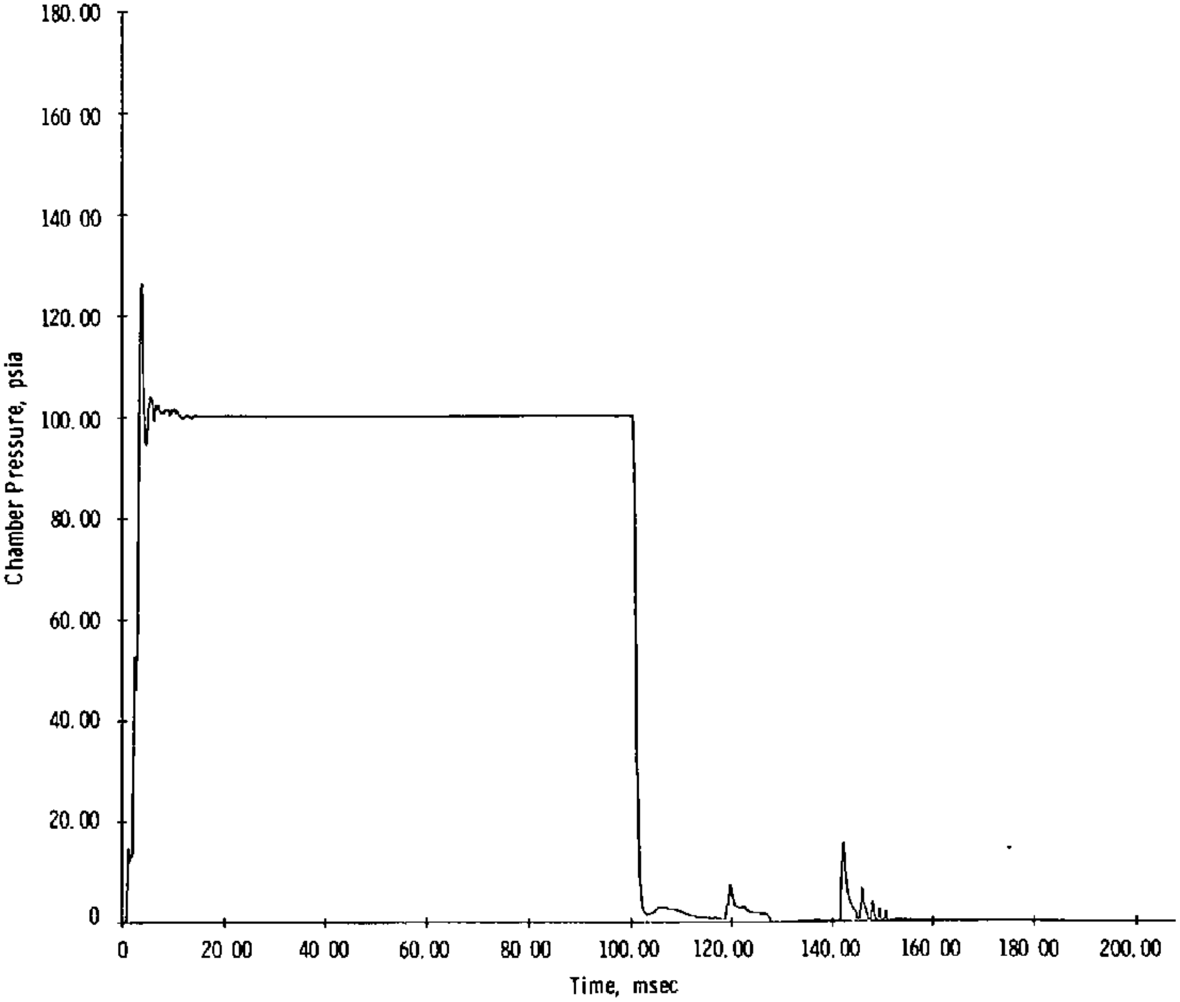
Figure 8. Continued.



g. Total film outflow rate
Figure 8. Continued.

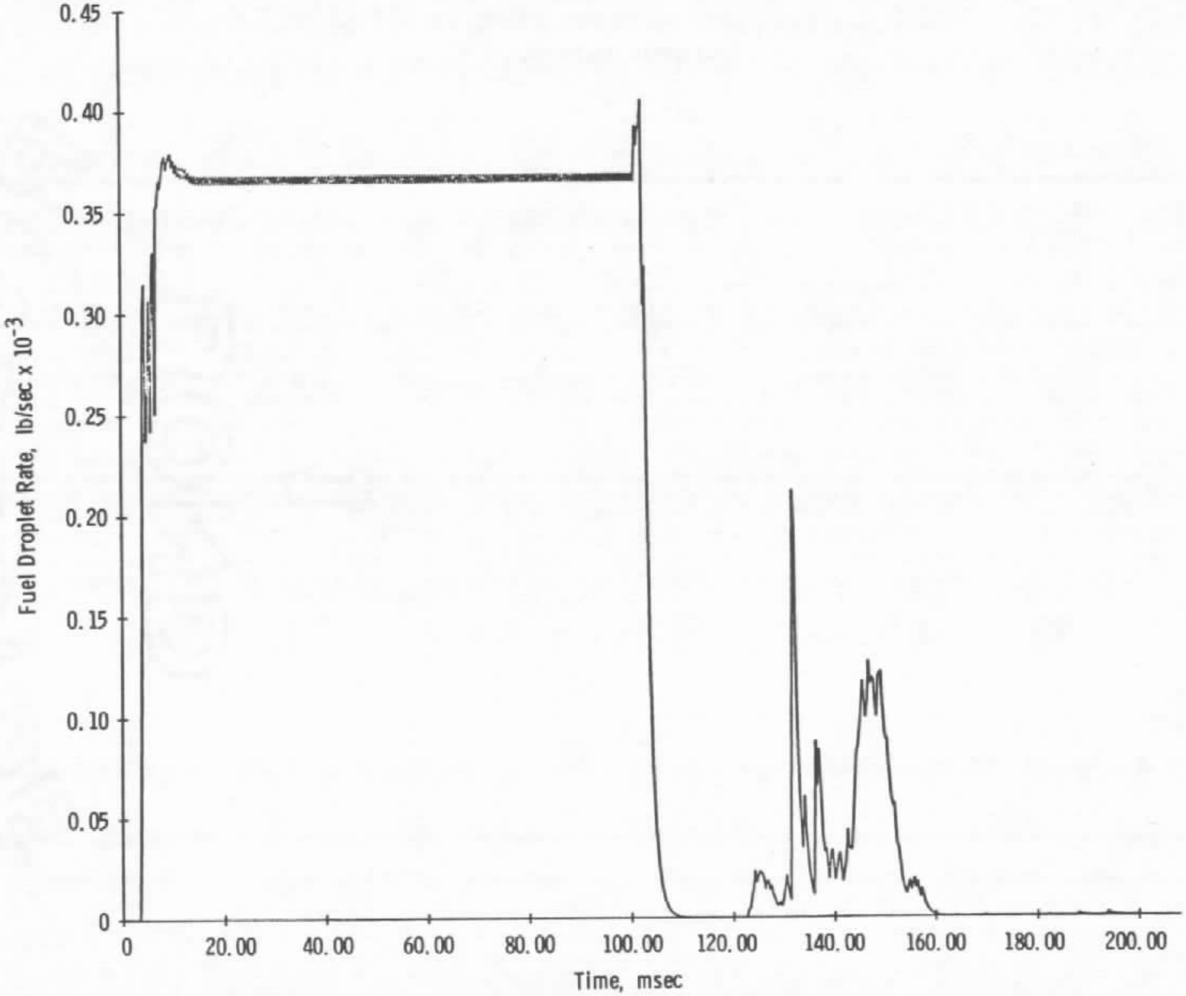


h. Propellant on wall
Figure 8. Concluded.

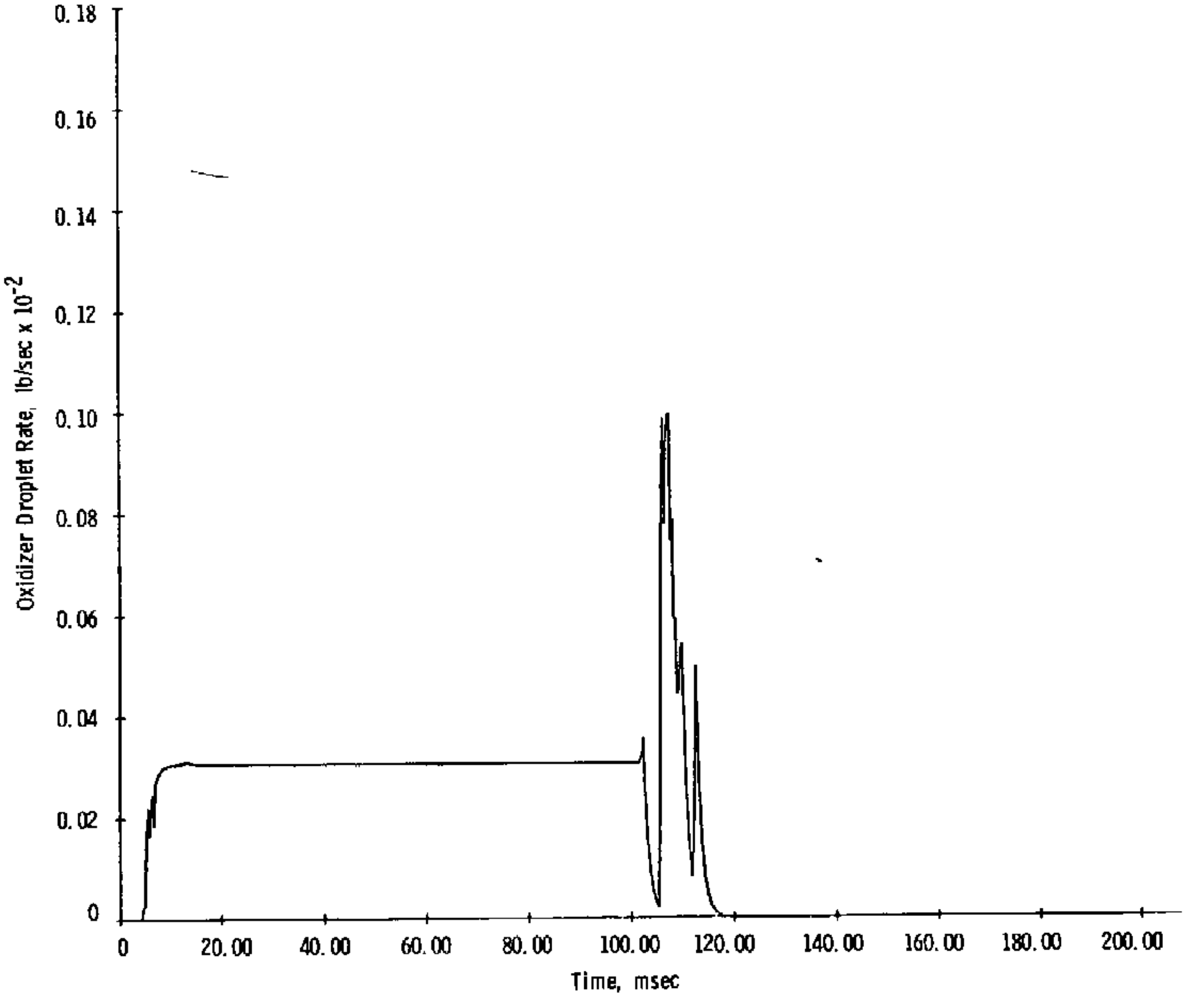


a. Chamber pressure

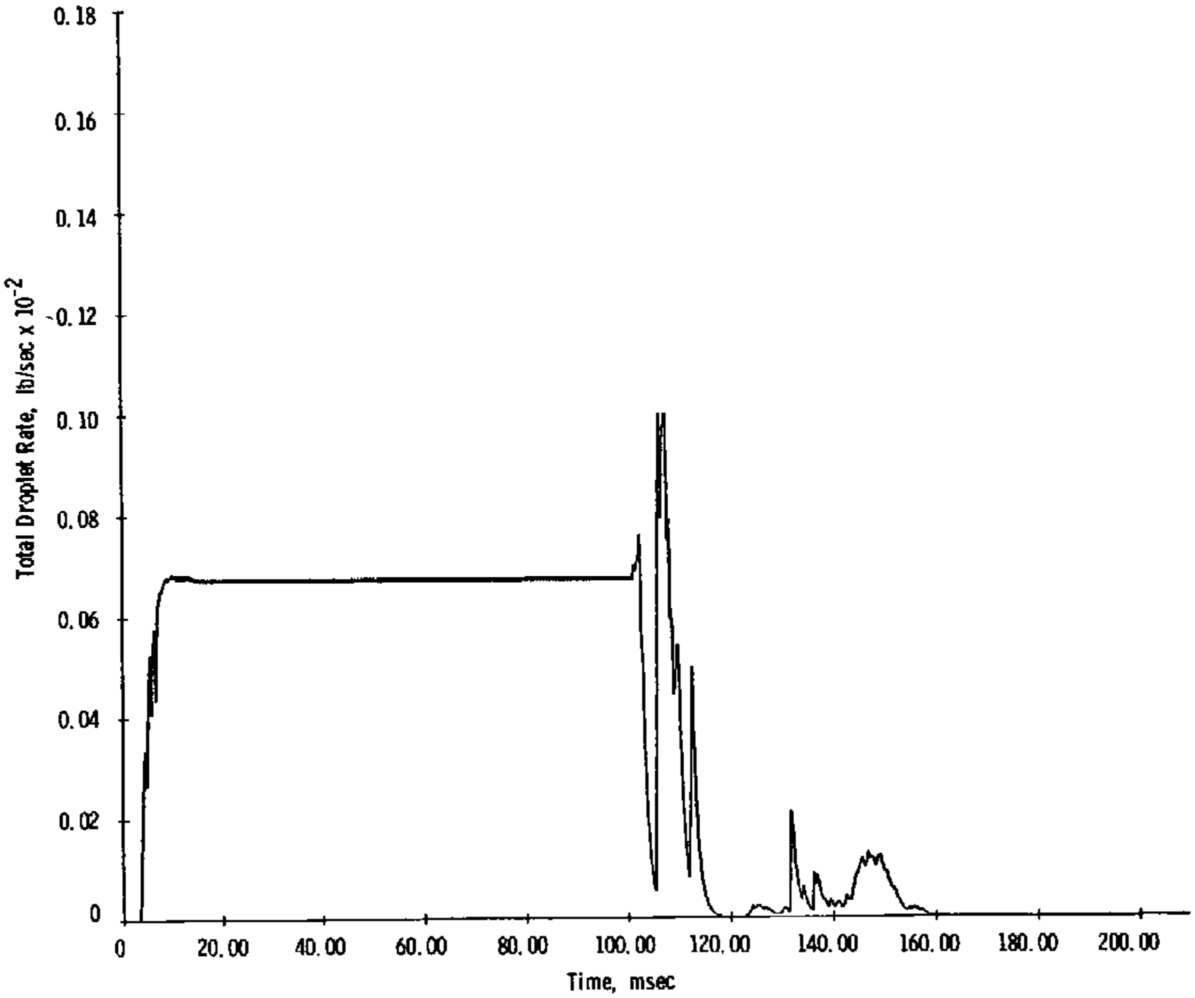
Figure 9. Case I results for AJ10-181-3.



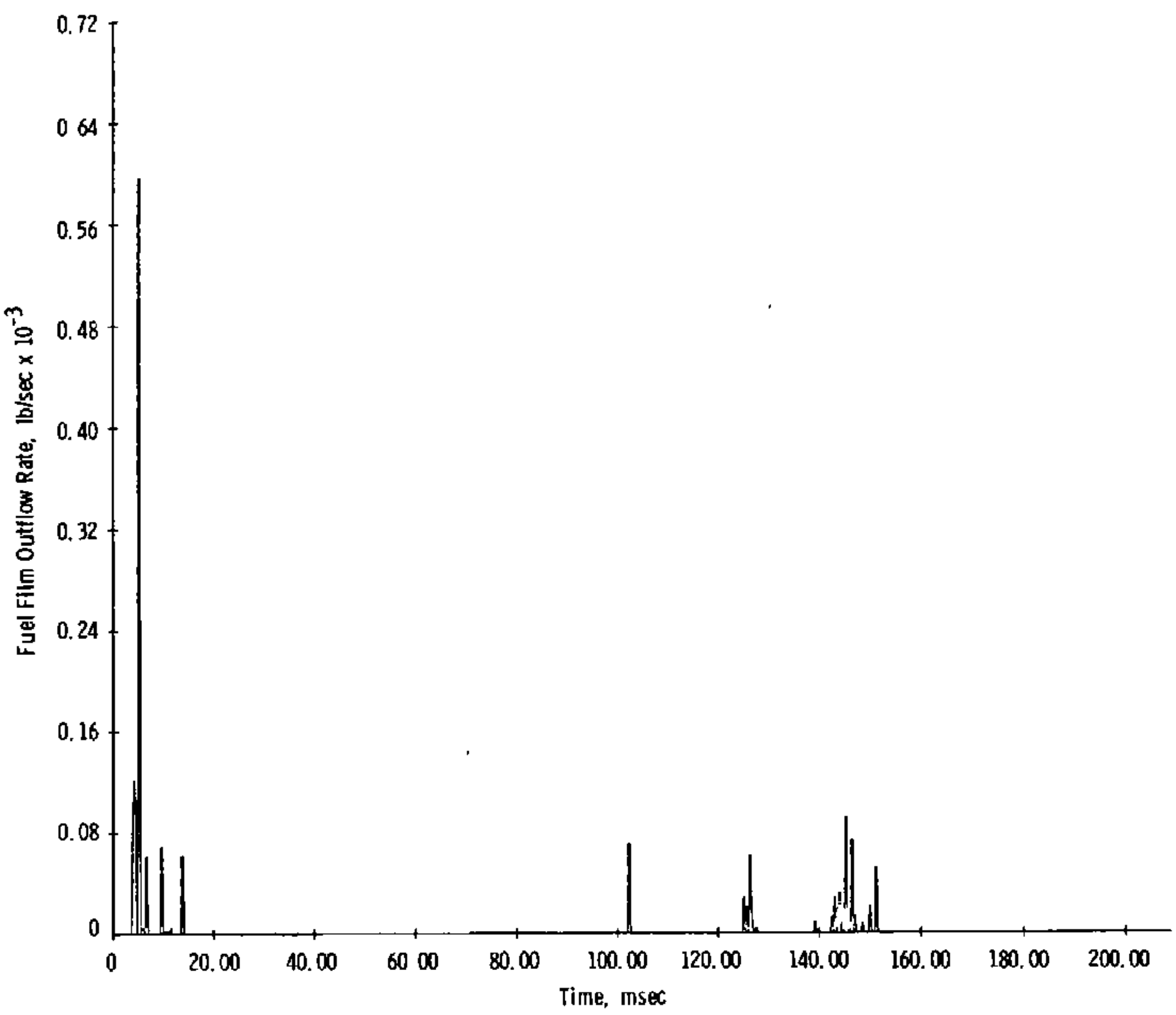
b. Fuel droplet rate
Figure 9. Continued.



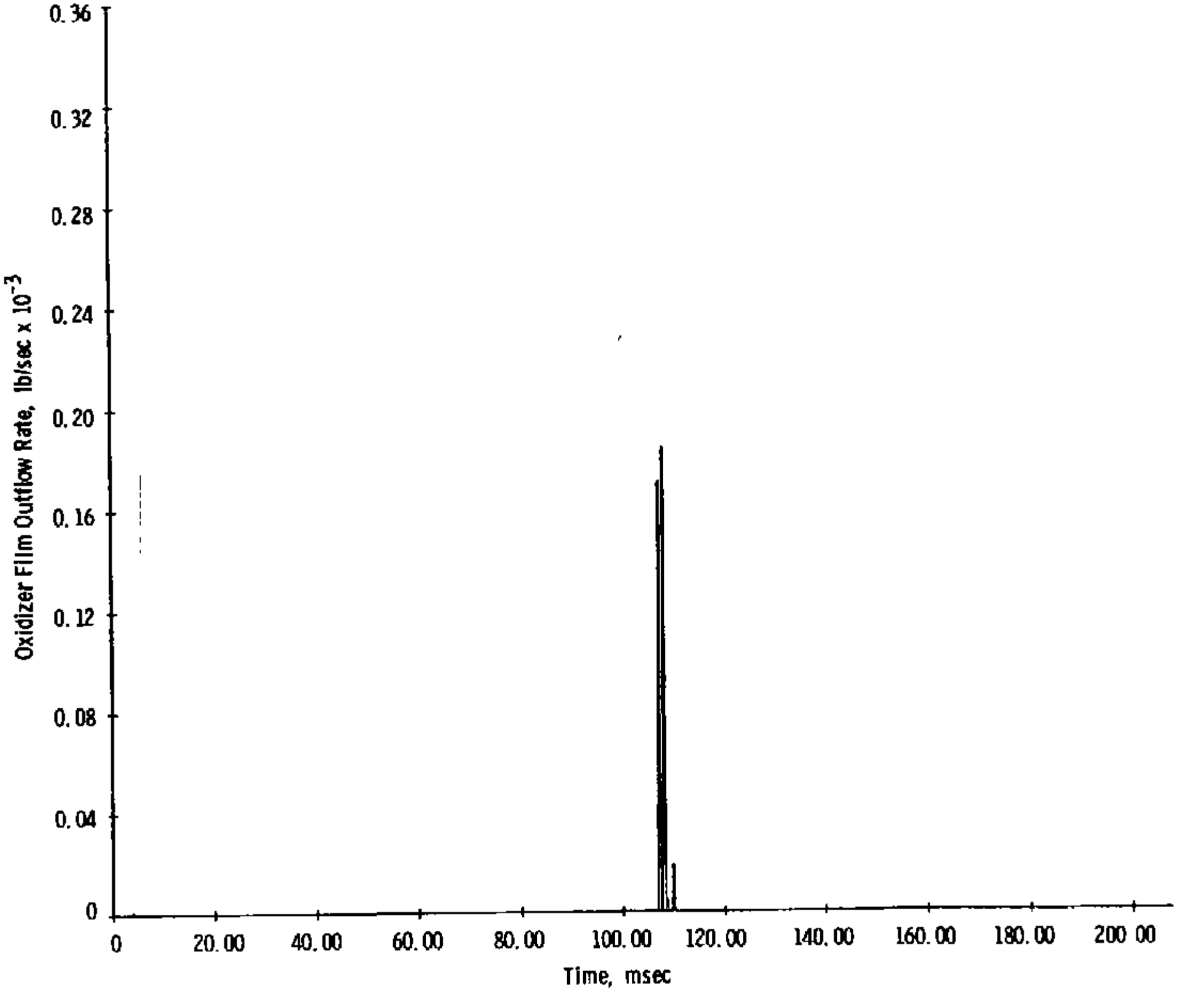
c. Oxidizer droplet rate
Figure 9. Continued.



d. Total droplet rate
Figure 9. Continued.

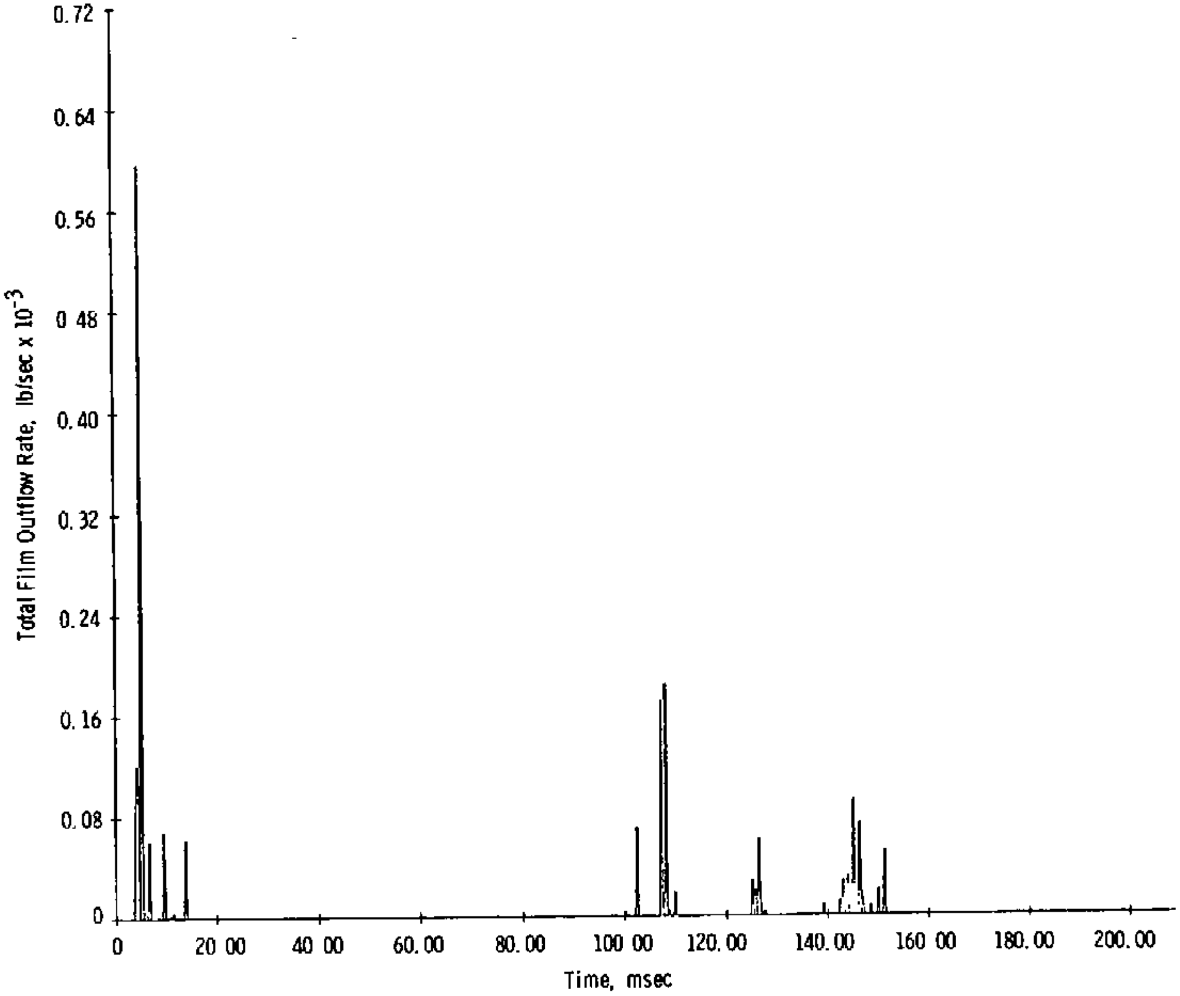


e. Fuel film outflow rate
Figure 9. Continued.

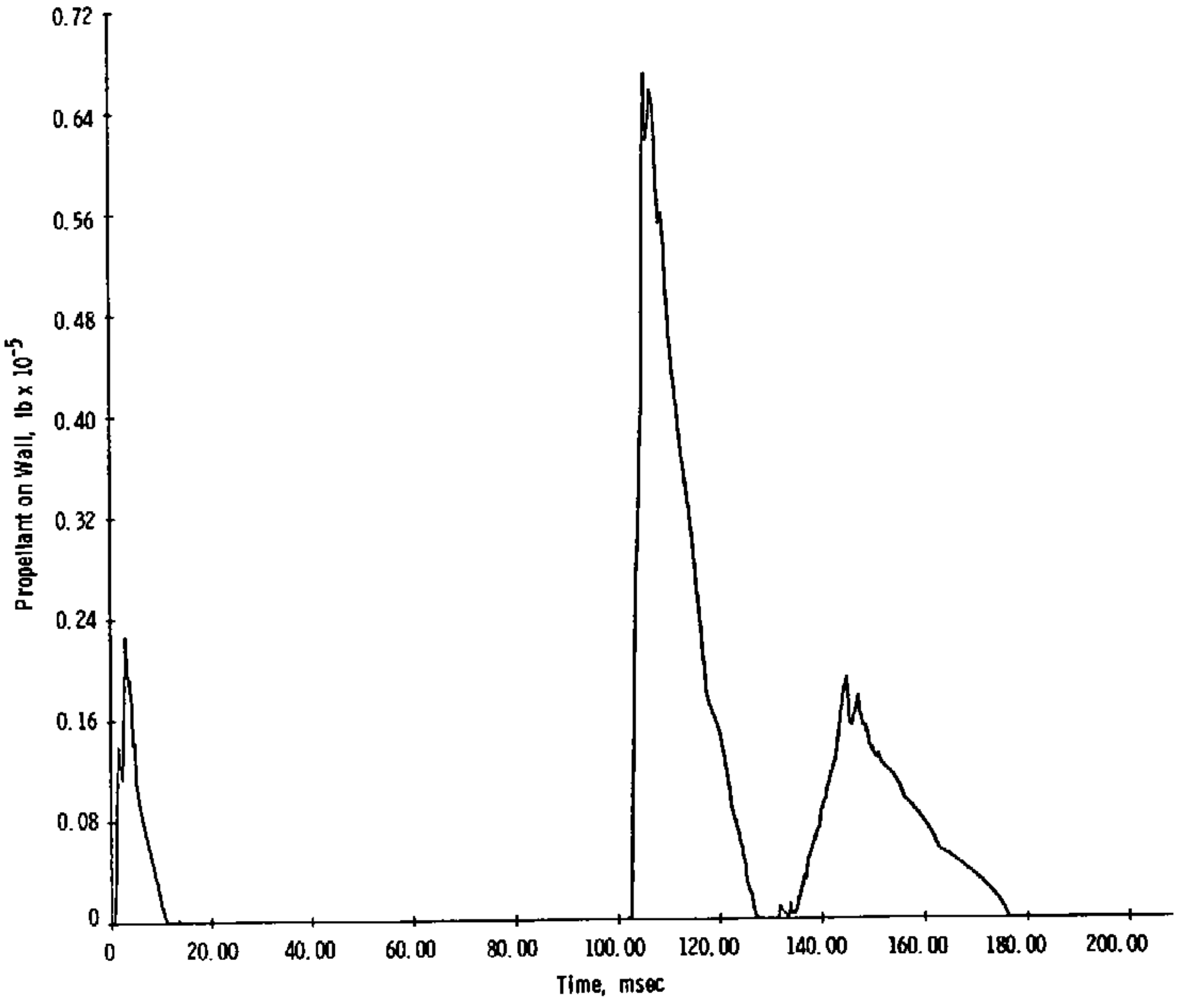


f. Oxidizer film outflow rate

Figure 9. Continued.

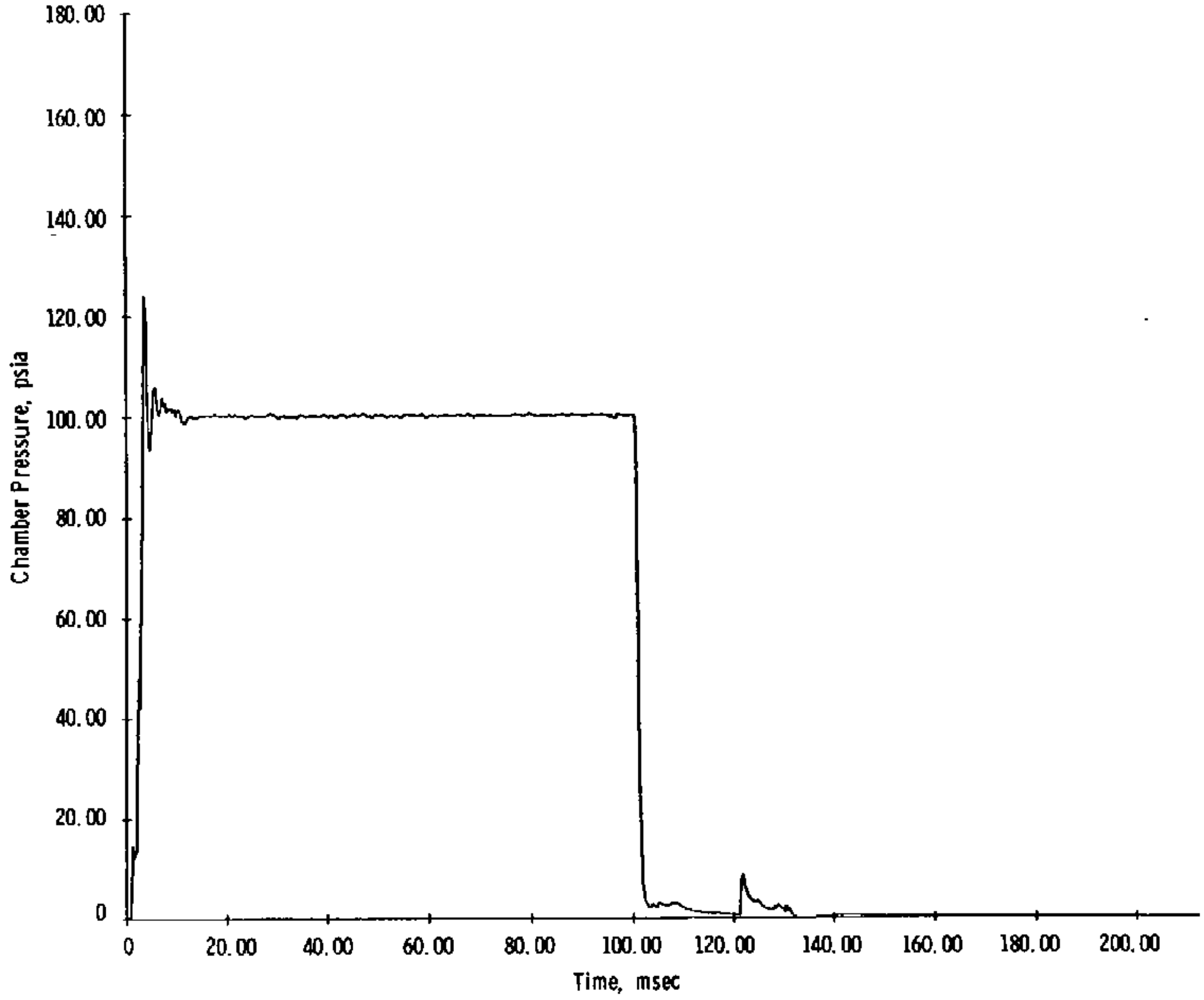


g. Total film outflow rate
Figure 9. Continued.



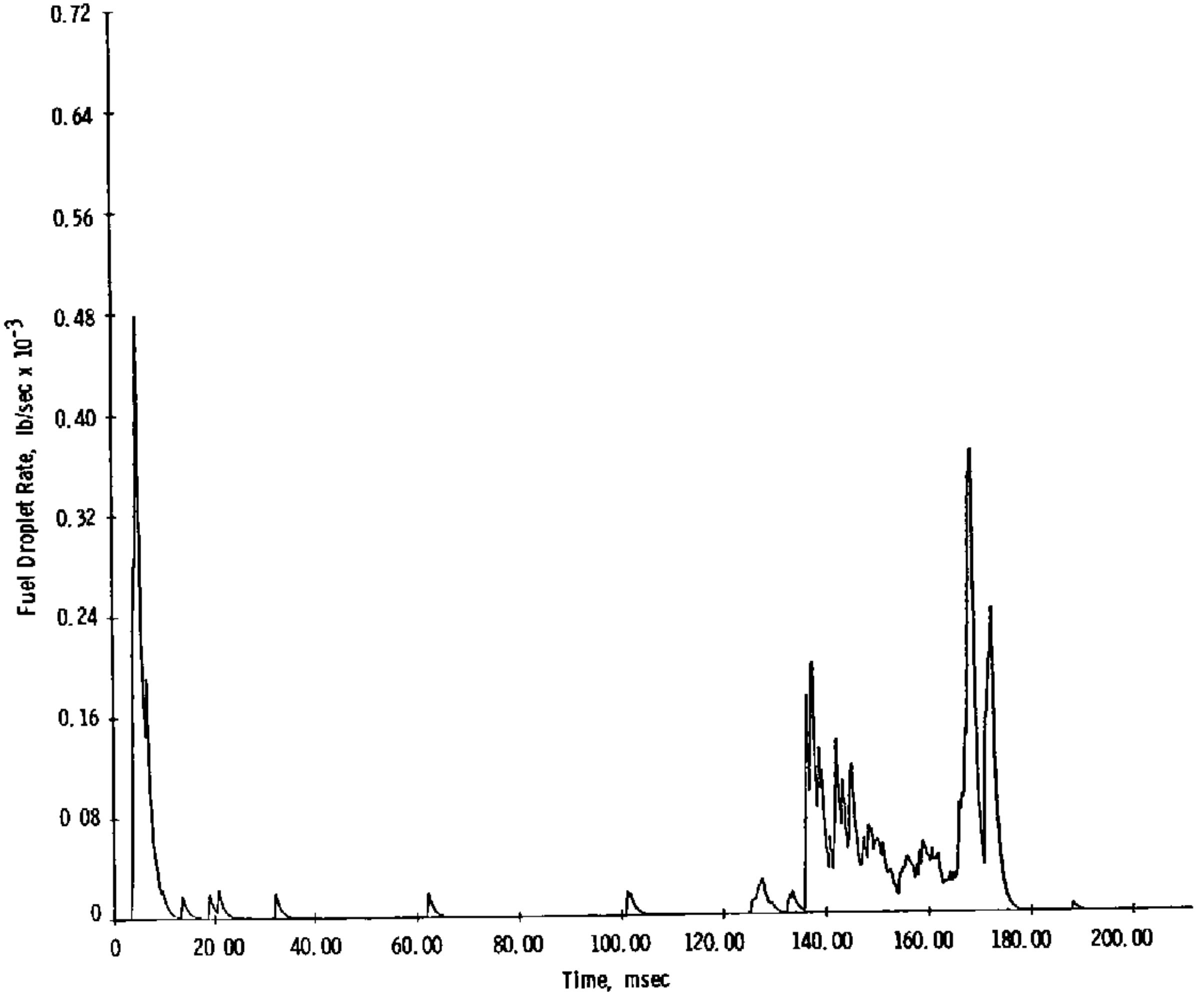
h. Propellant on wall

Figure 9. Concluded.

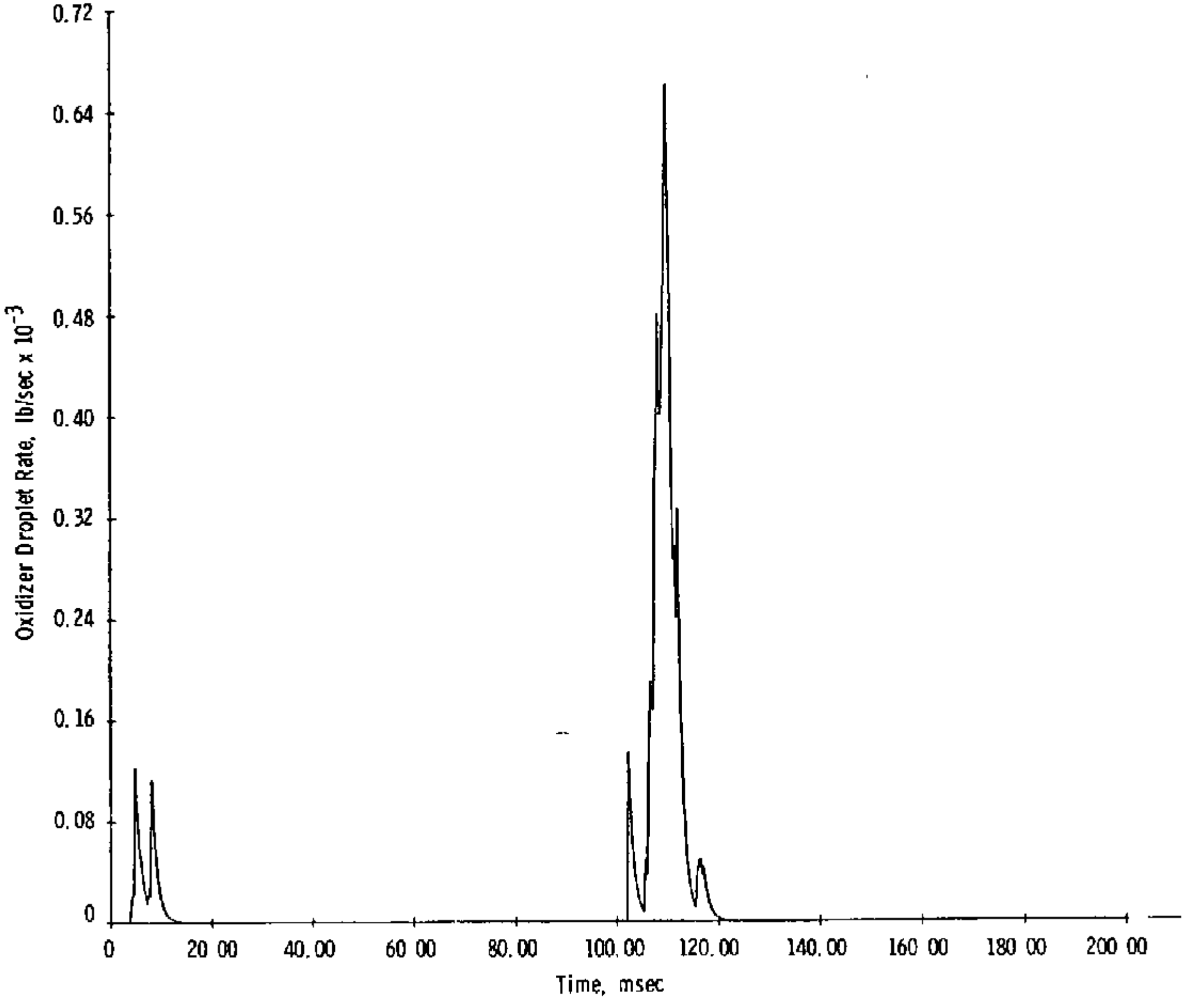


a. Chamber pressure

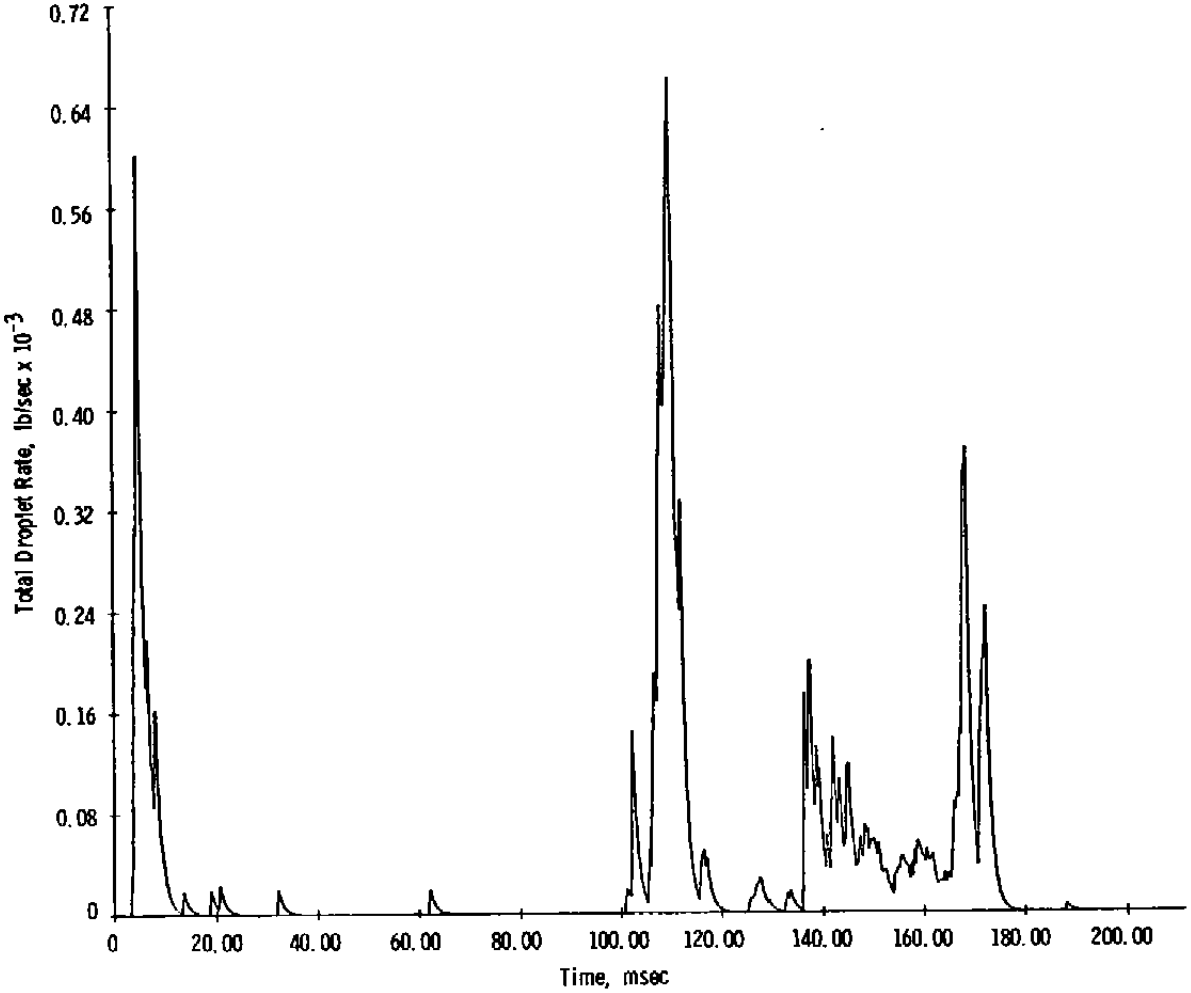
Figure 10. Case J results for AJ10-181-3.



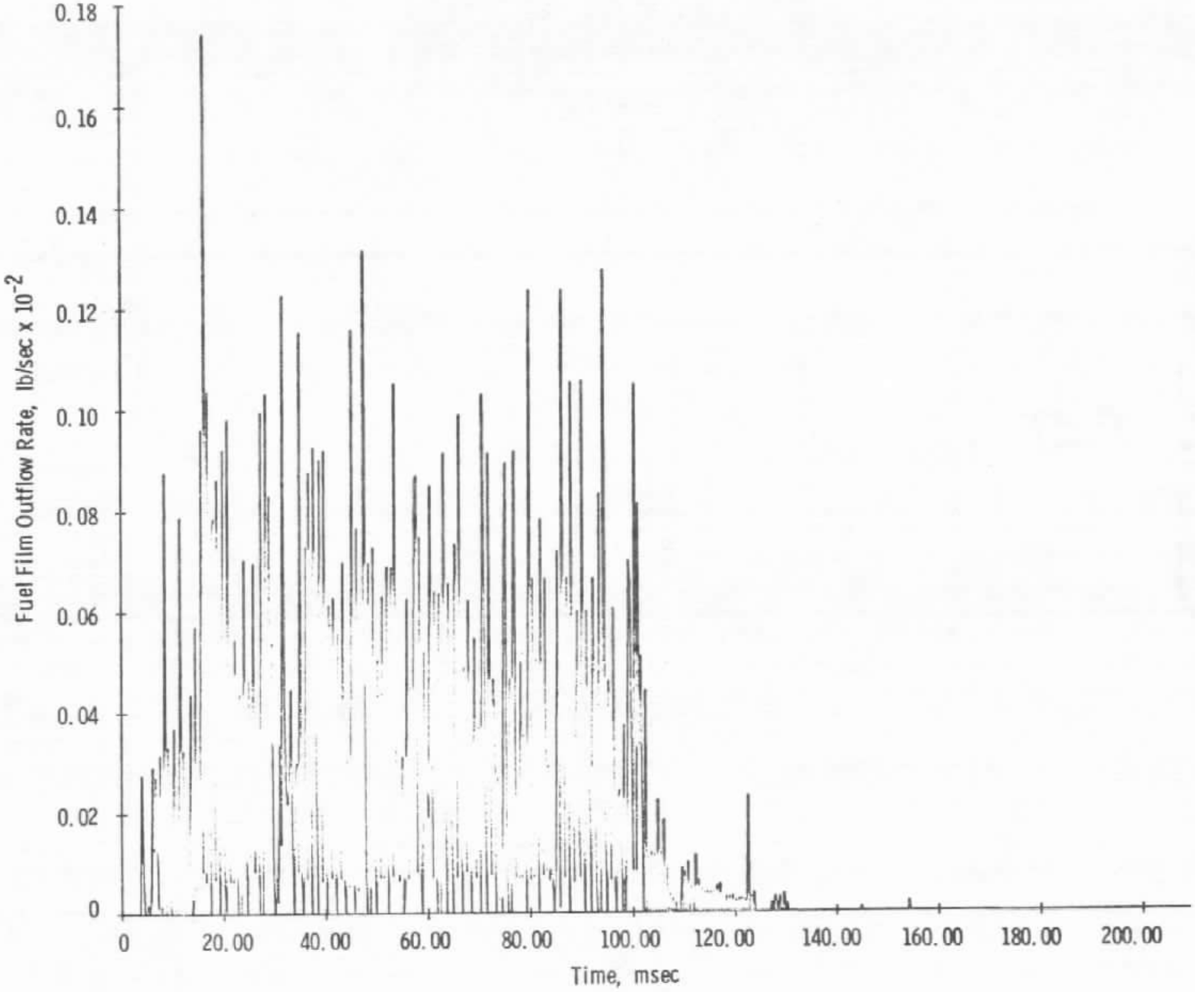
b. Fuel droplet rate
Figure 10. Continued.



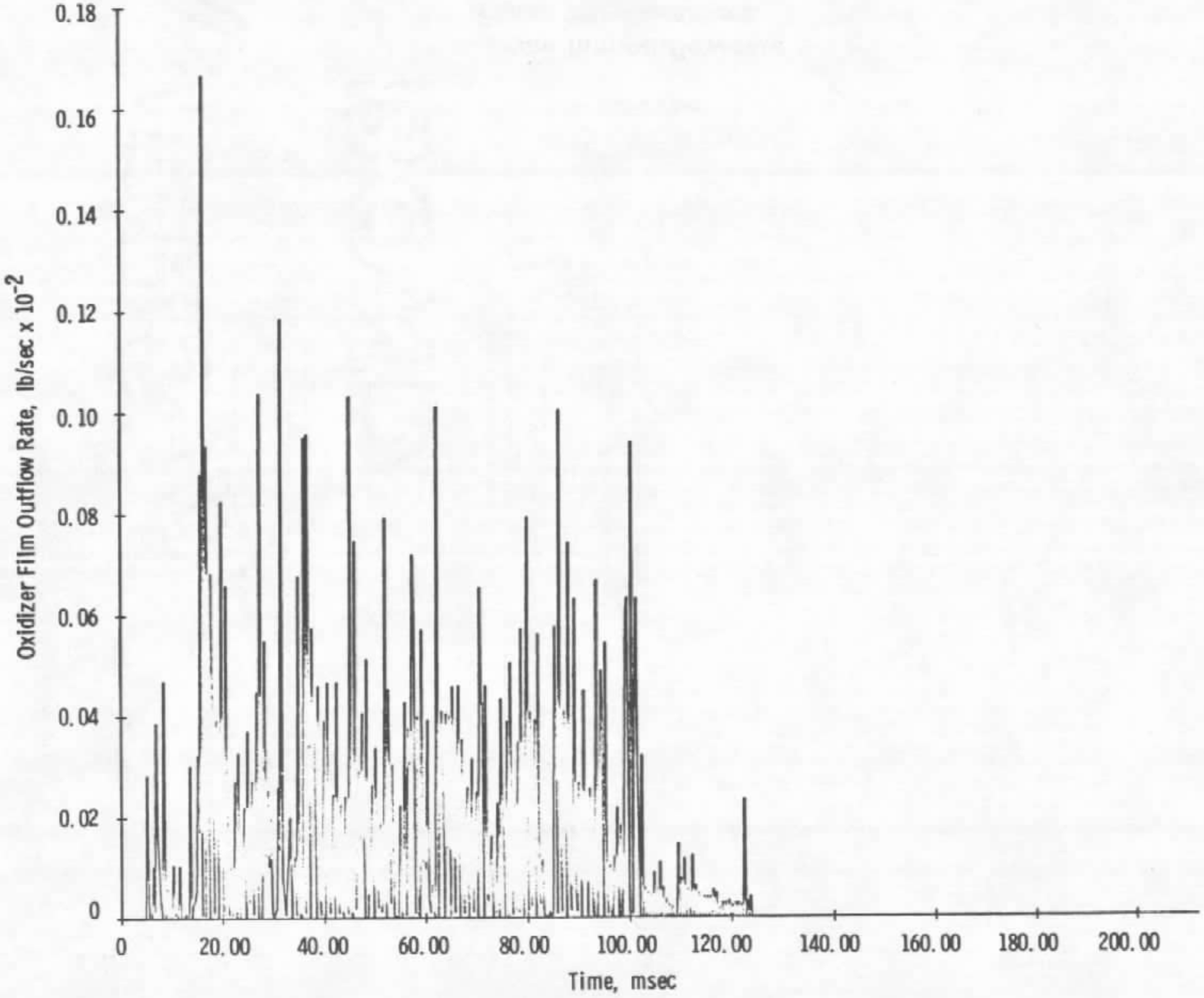
c. Oxidizer droplet rate
Figure 10. Continued.



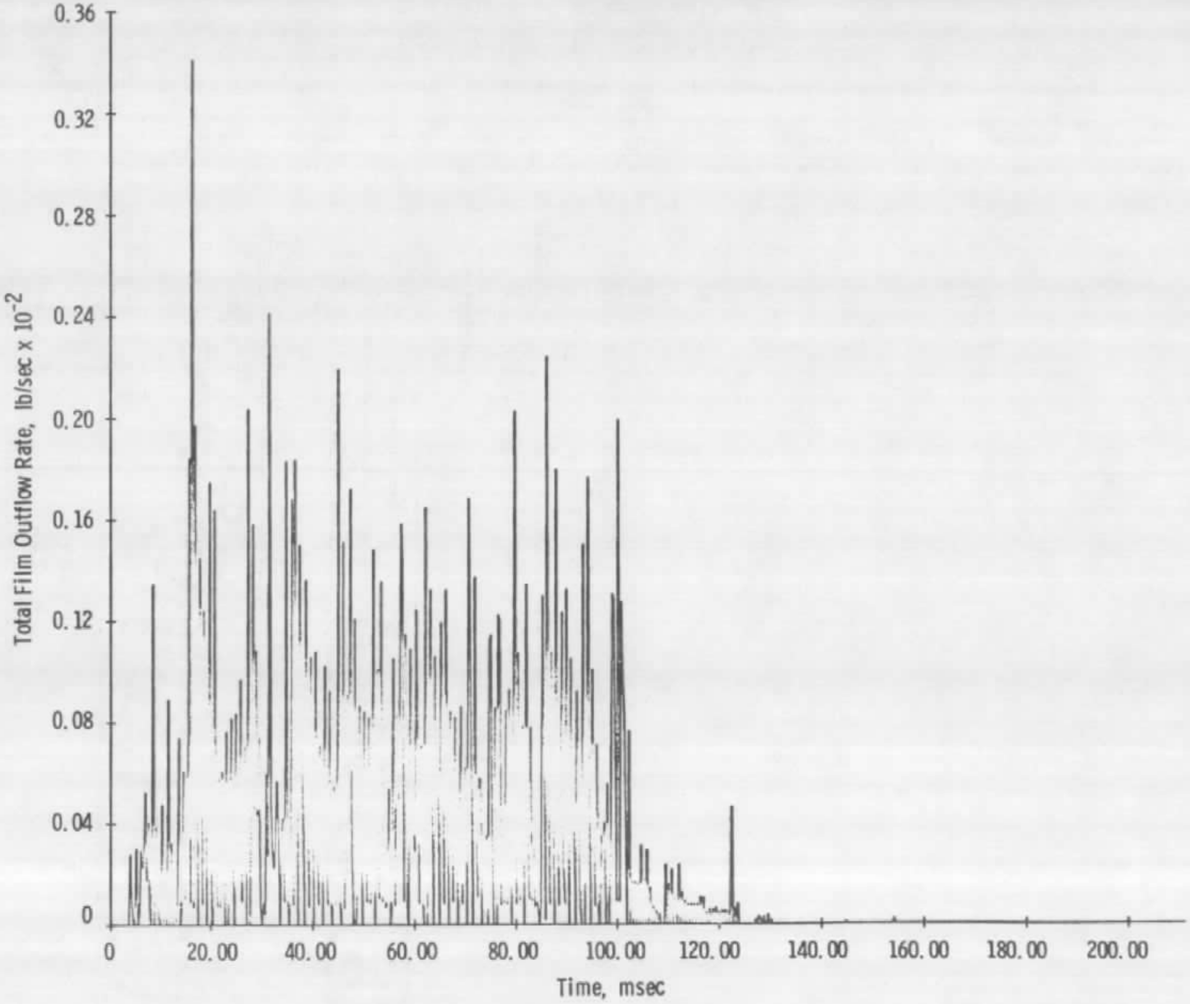
d. Total droplet rate
Figure 10. Continued.



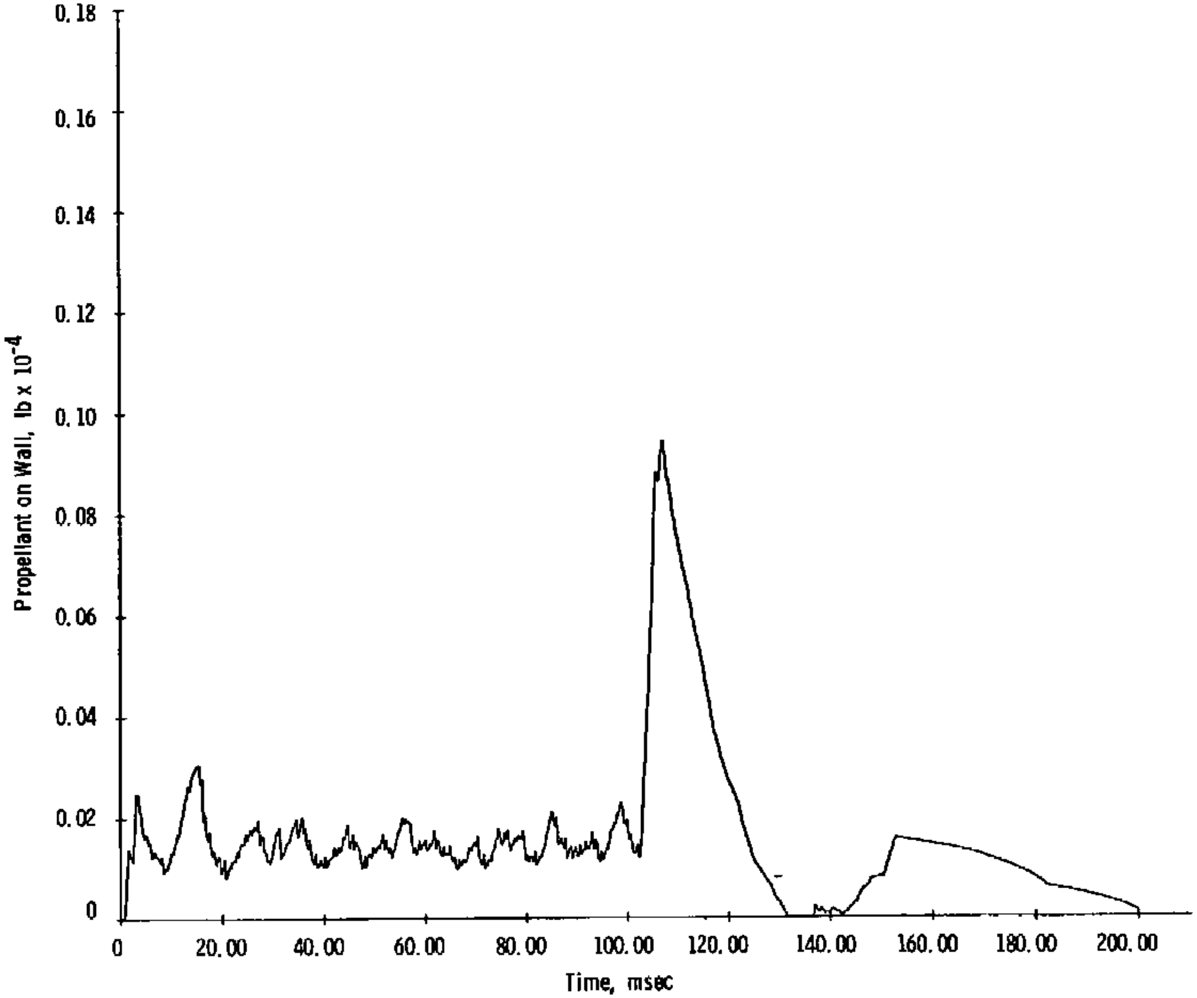
e. Fuel film outflow rate
Figure 10. Continued.



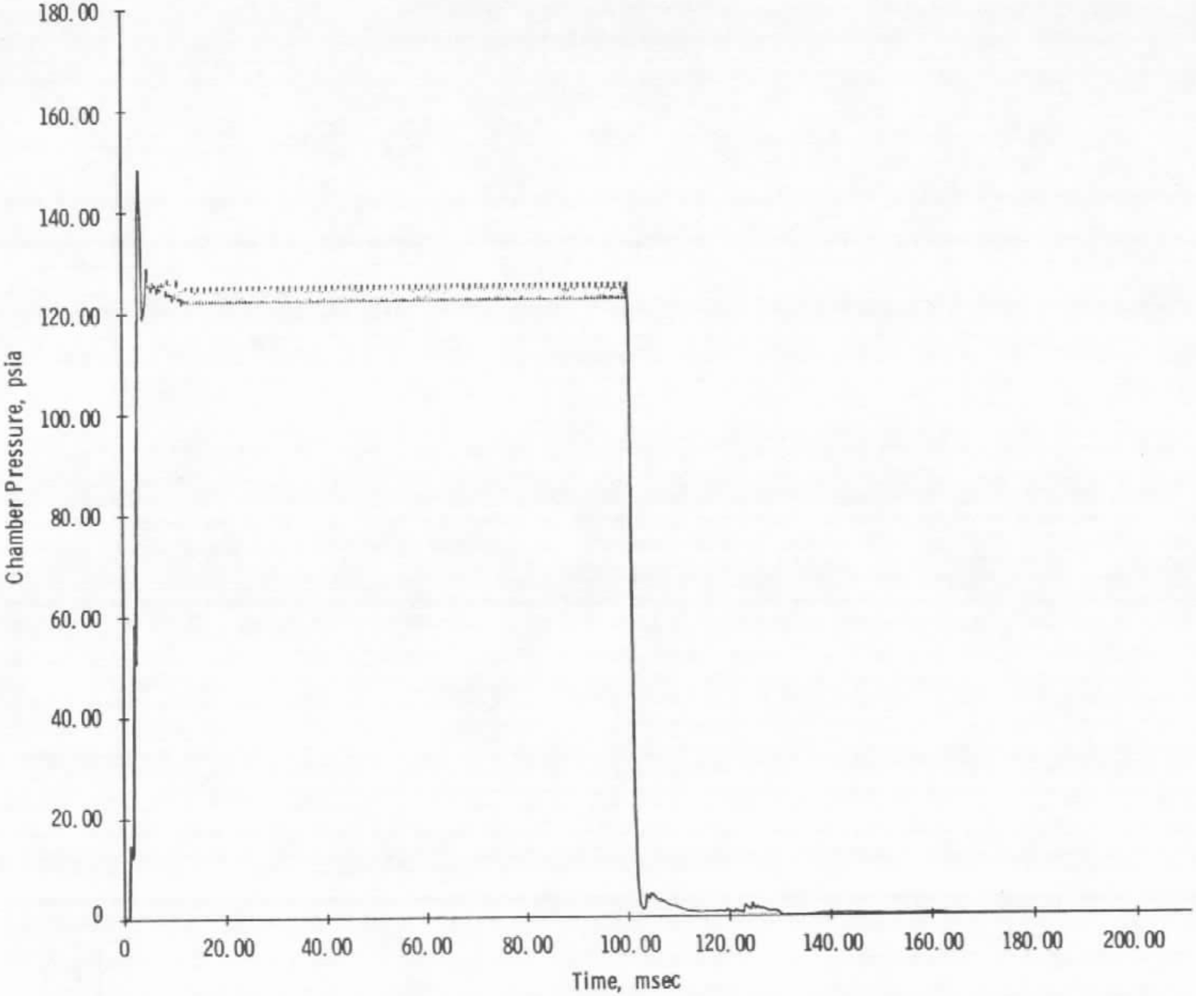
f. Oxidizer film outflow rate
Figure 10. Continued.



g. Total film outflow rate
Figure 10. Continued.

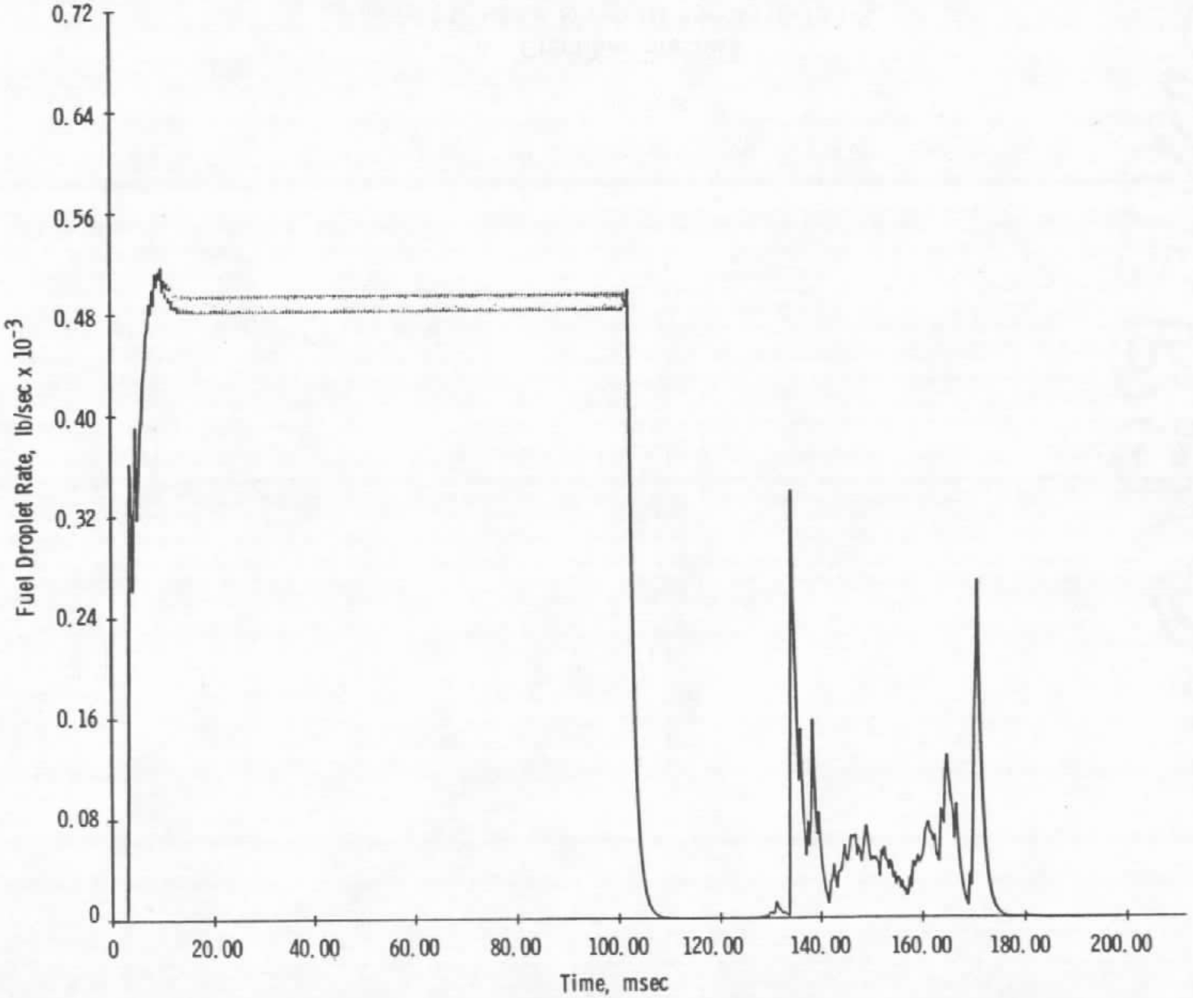


h. Propellant on wall
Figure 10. Concluded.

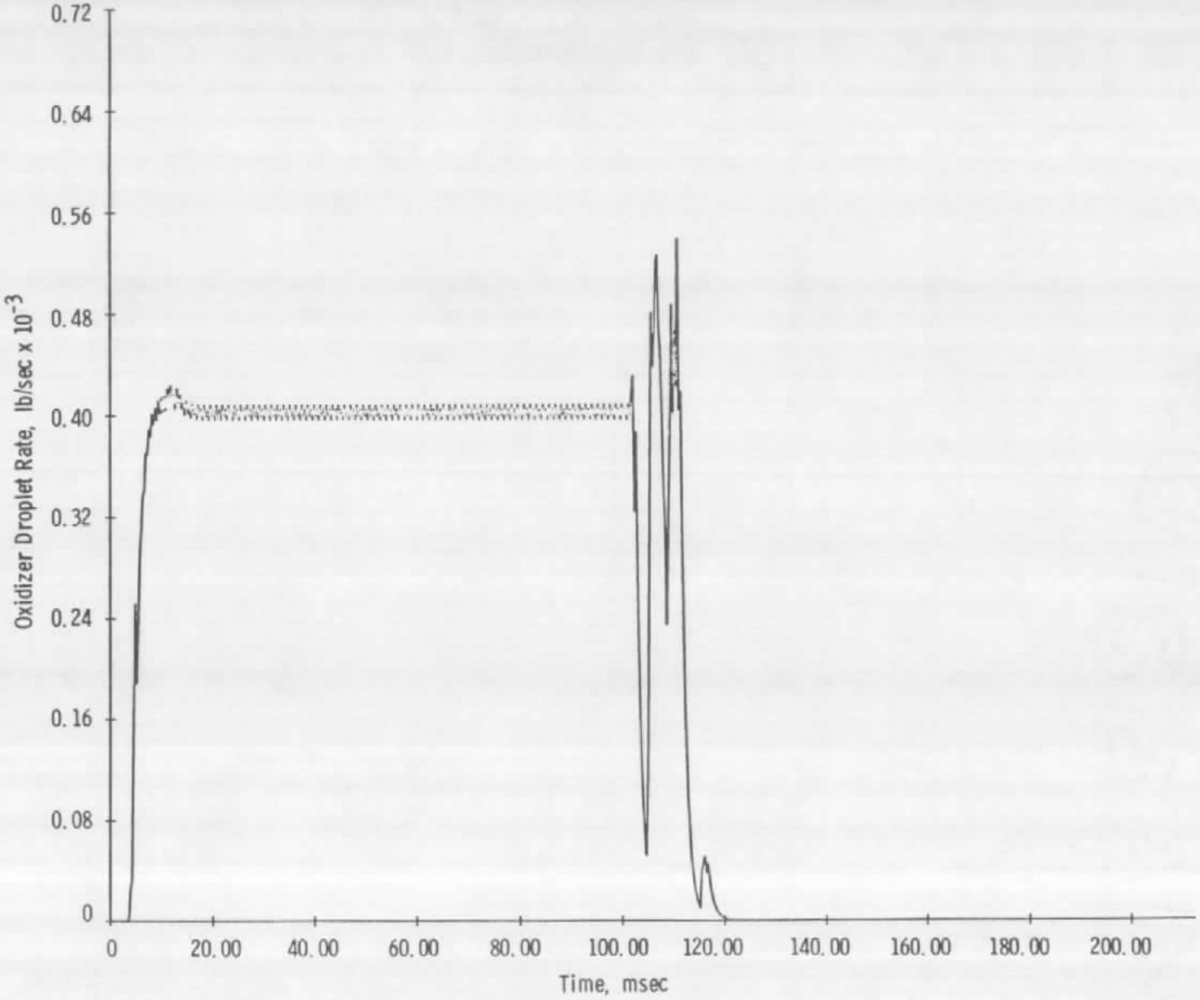


a. Chamber pressure

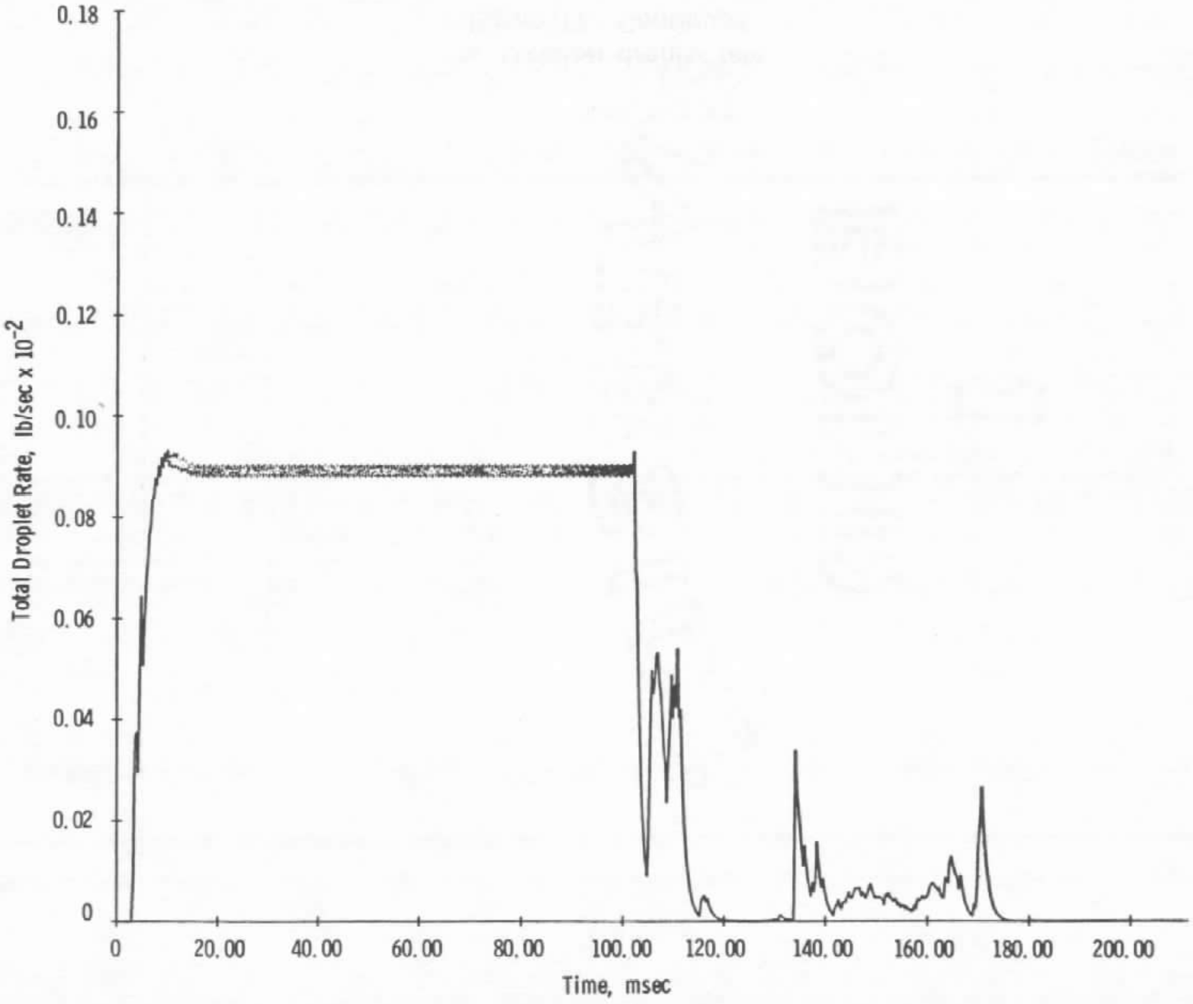
Figure 11. Case K results for AJ10-181-3.



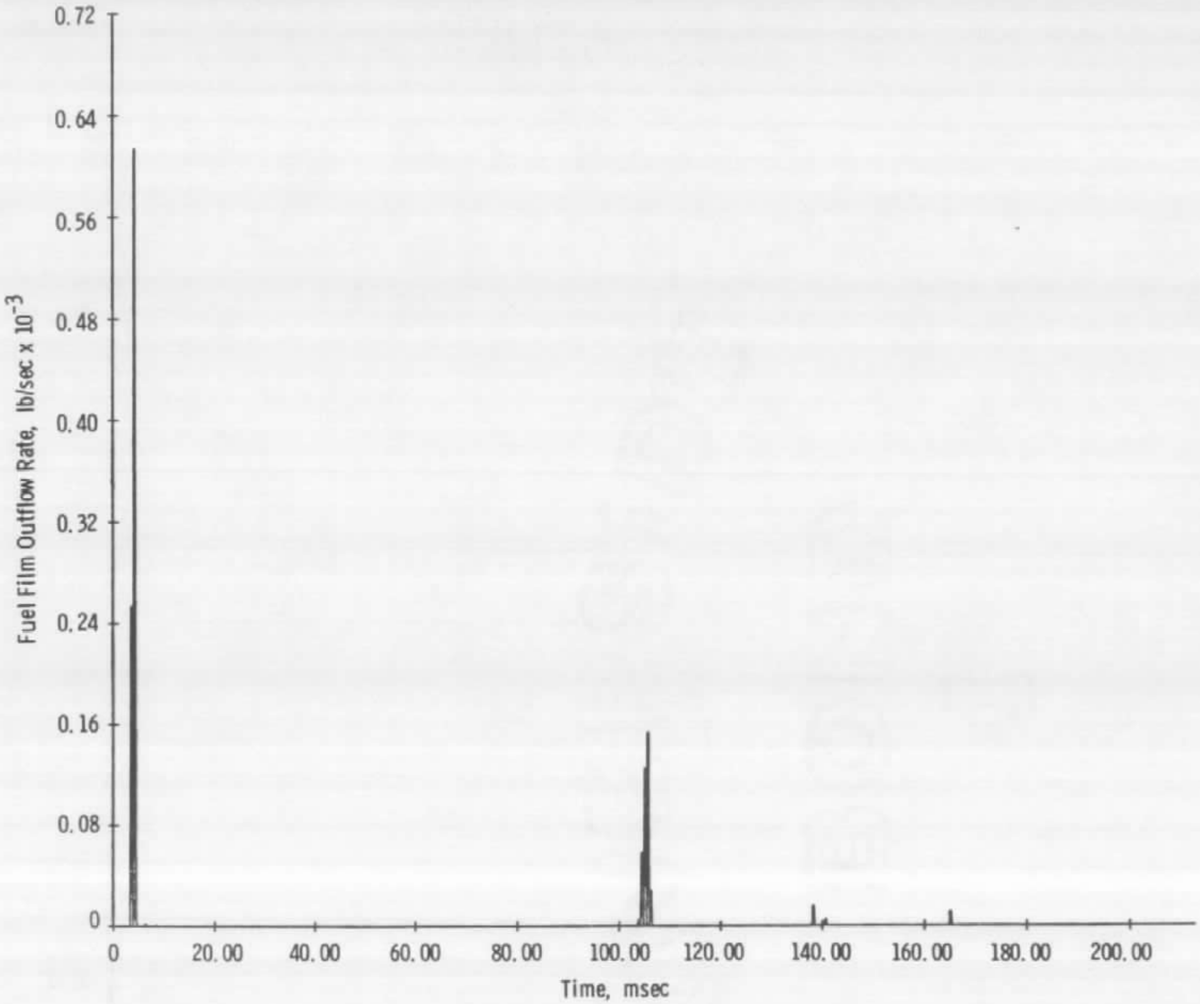
b. Fuel droplet rate
Figure 11. Continued.



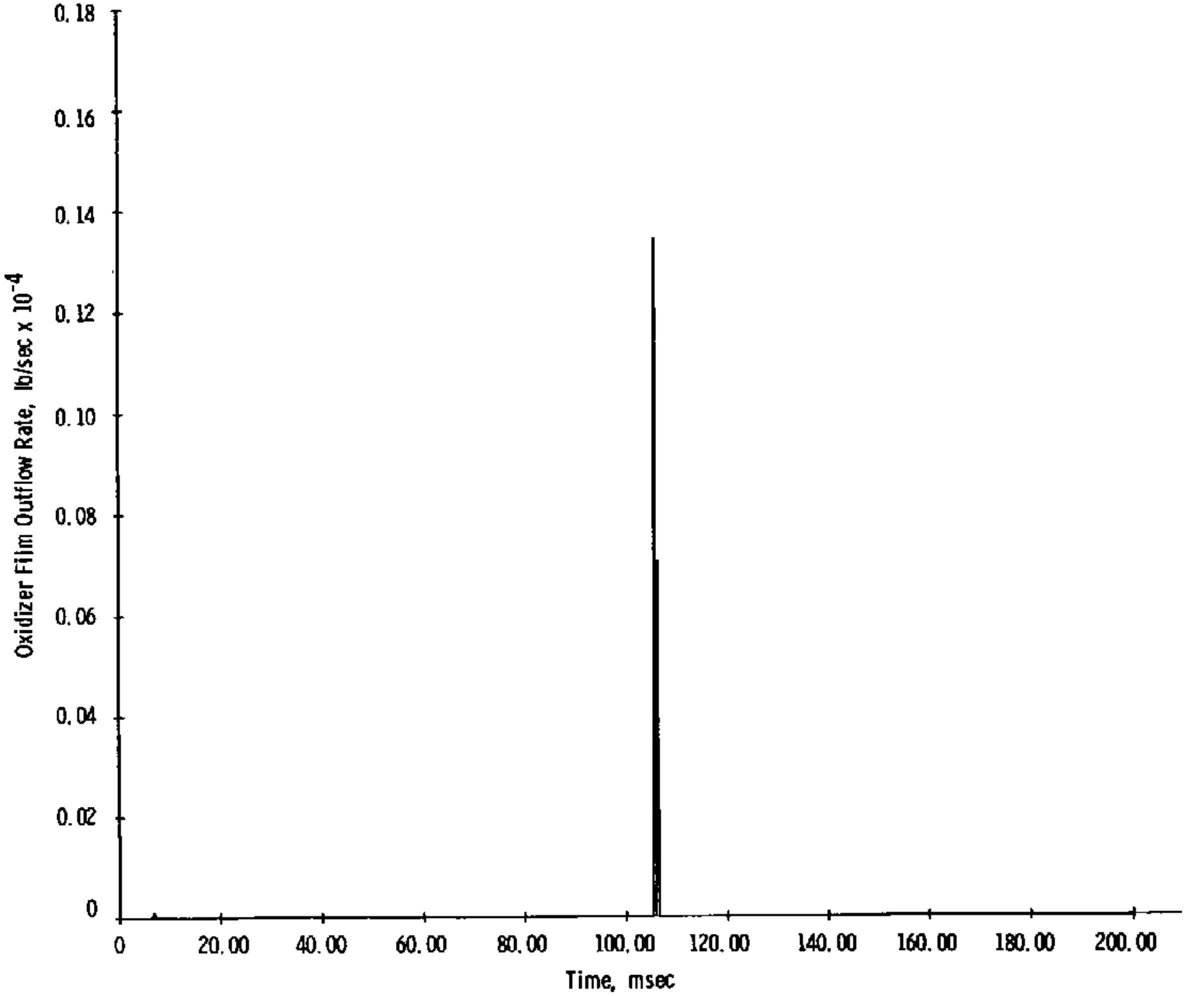
c. Oxidizer droplet rate
Figure 11. Continued.



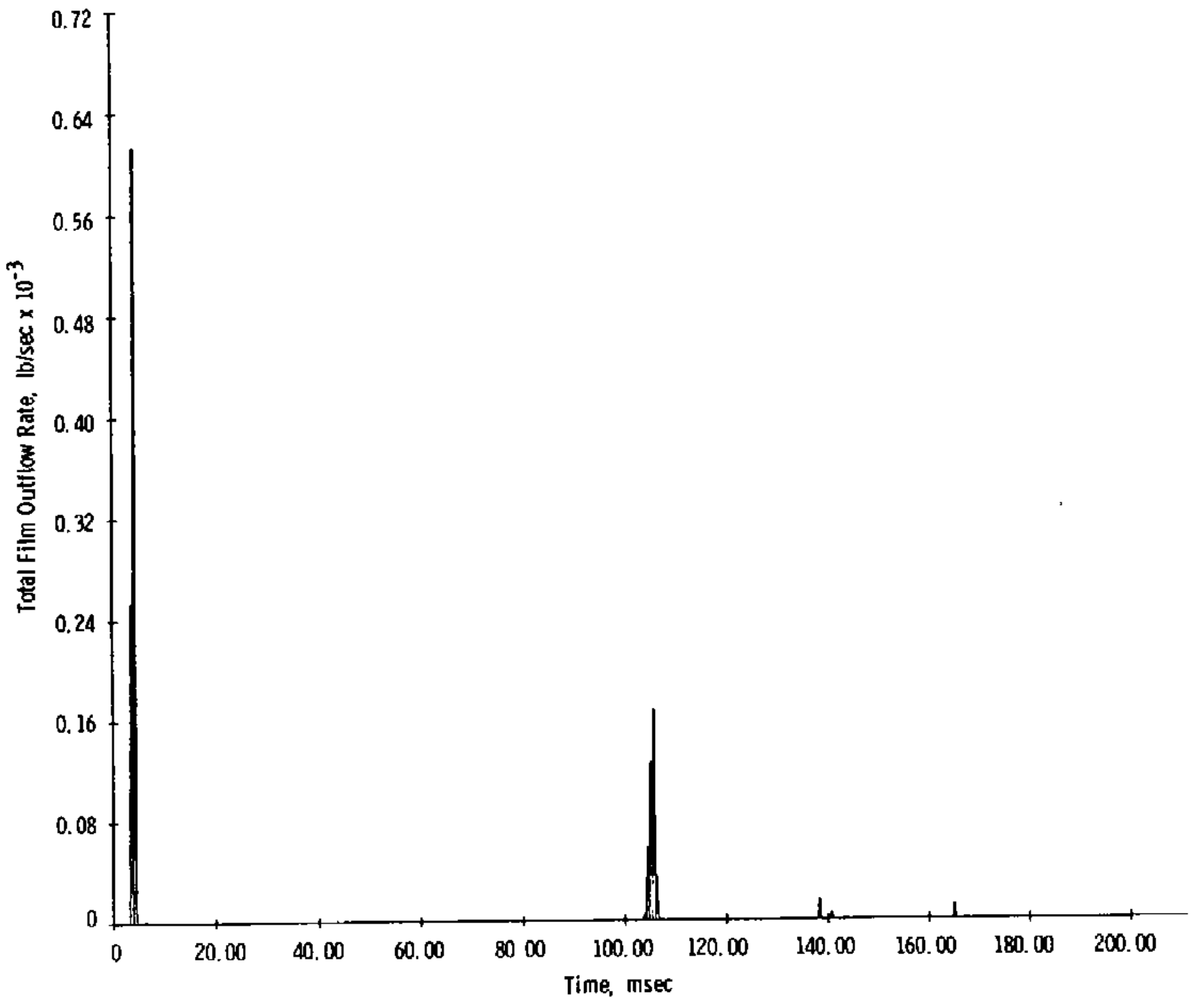
d. Total droplet rate
Figure 11. Continued.



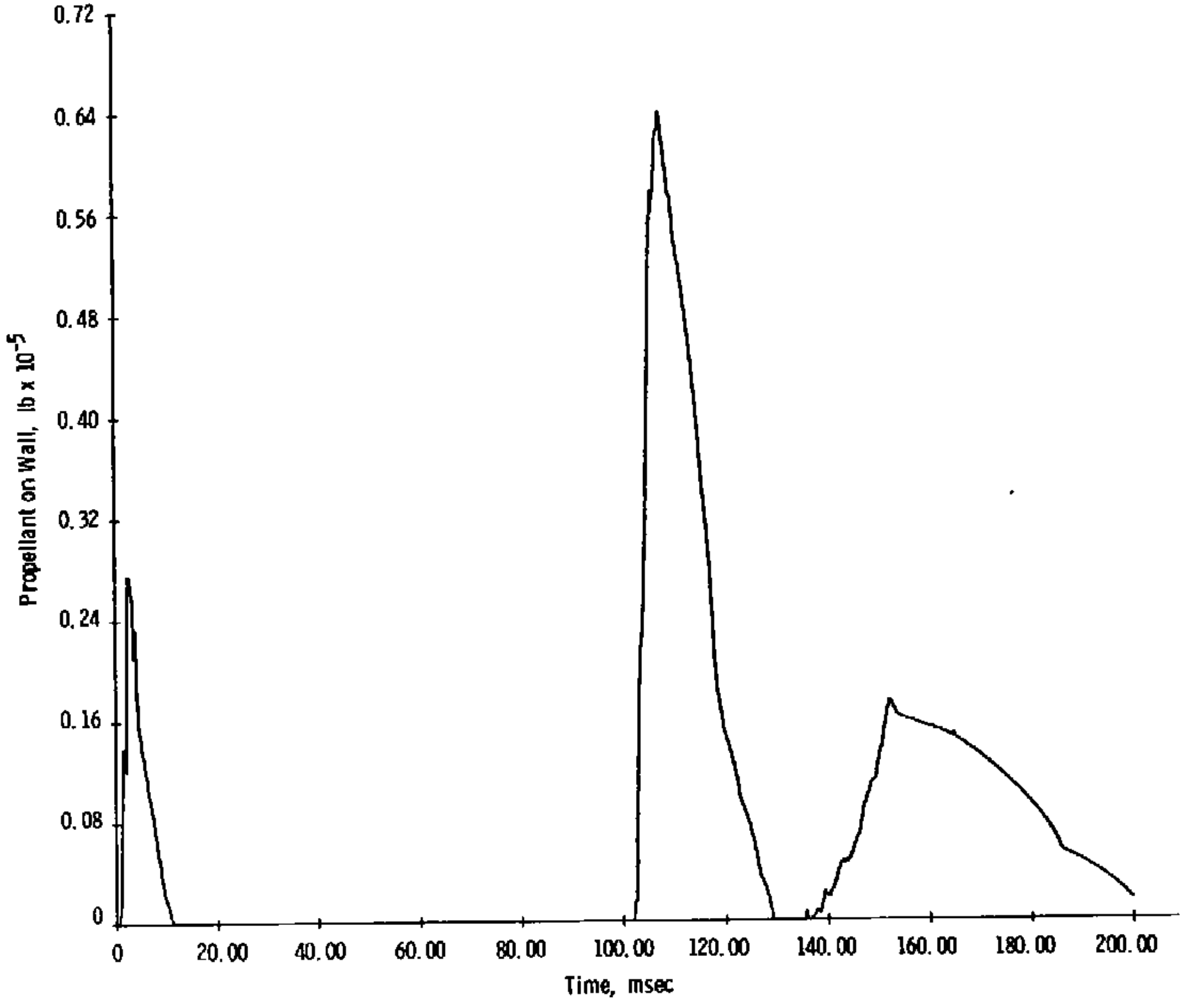
e. Fuel film outflow
Figure 11. Continued.



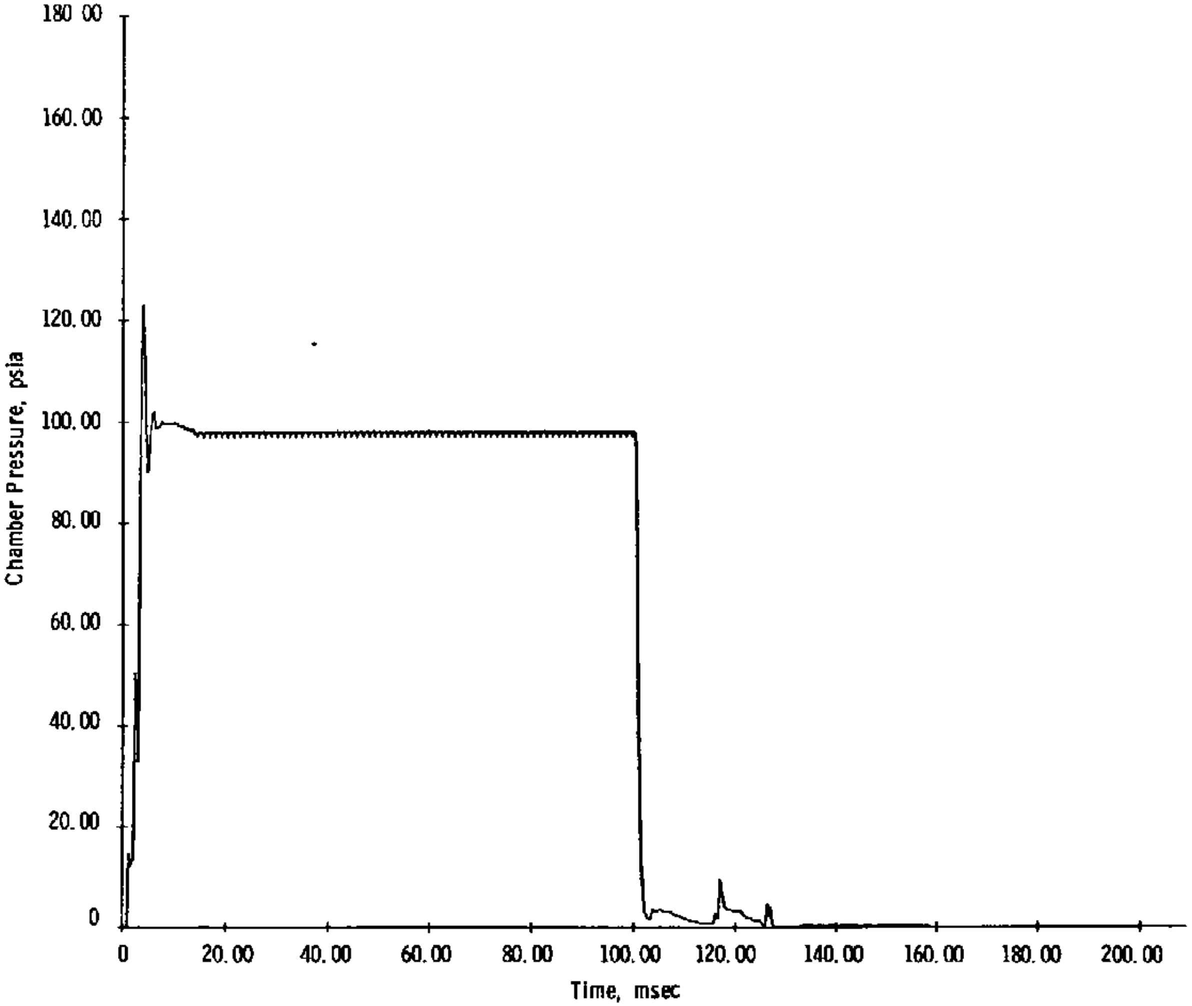
f. Oxidizer film outflow rate
Figure 11. Continued.



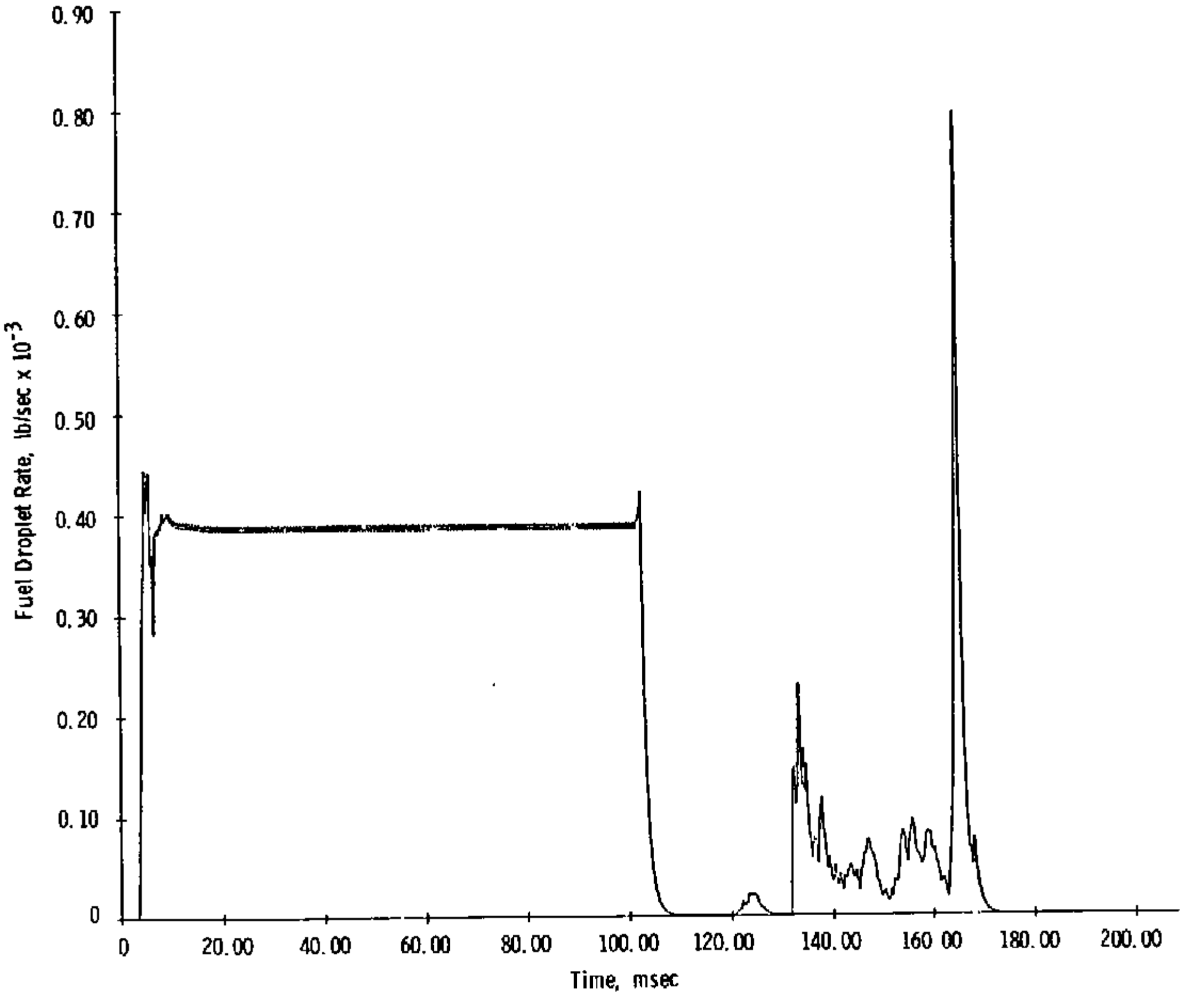
g. Total film outflow rate
Figure 11. Continued.



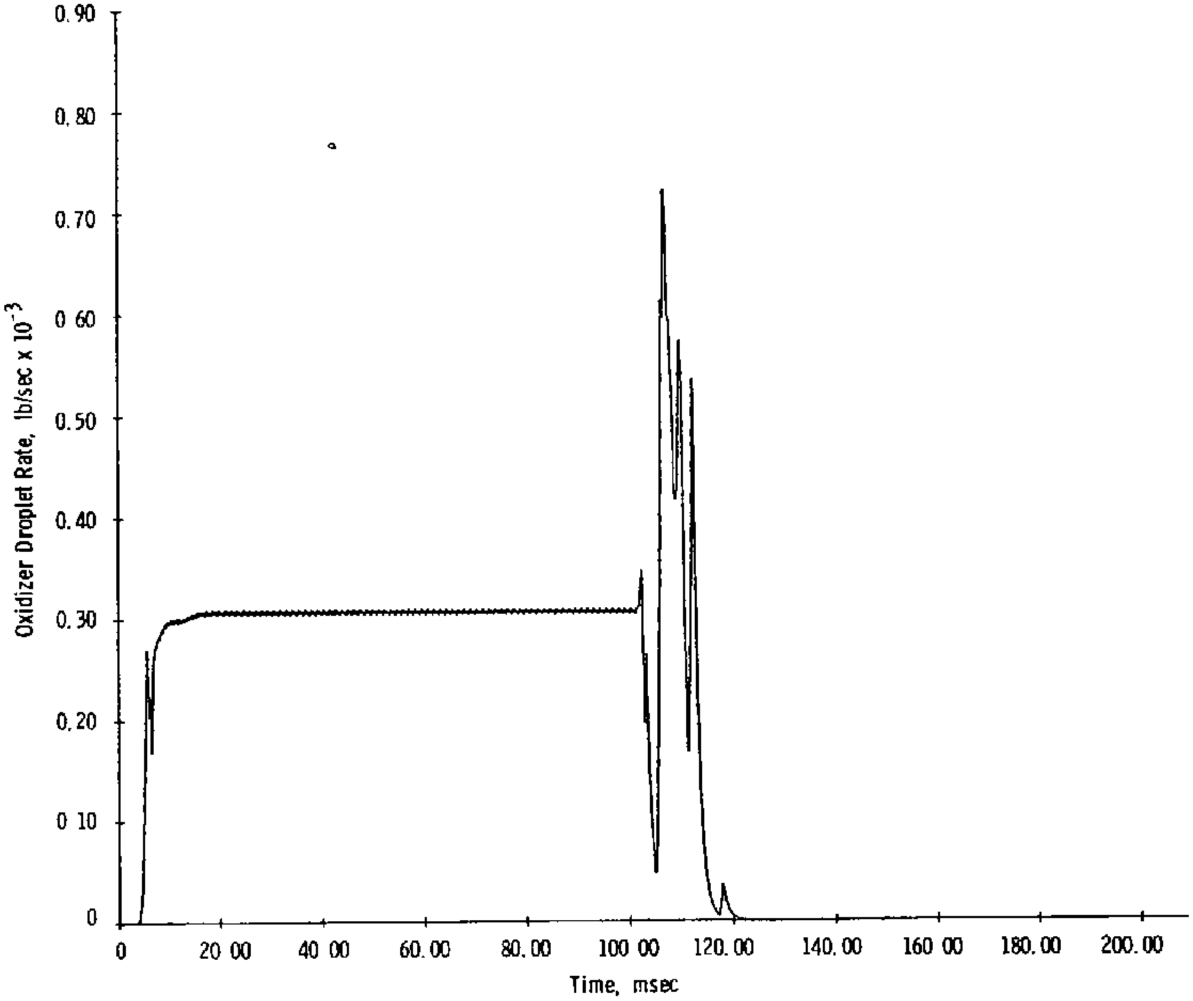
h. Propellant on wall
Figure 11. Concluded.



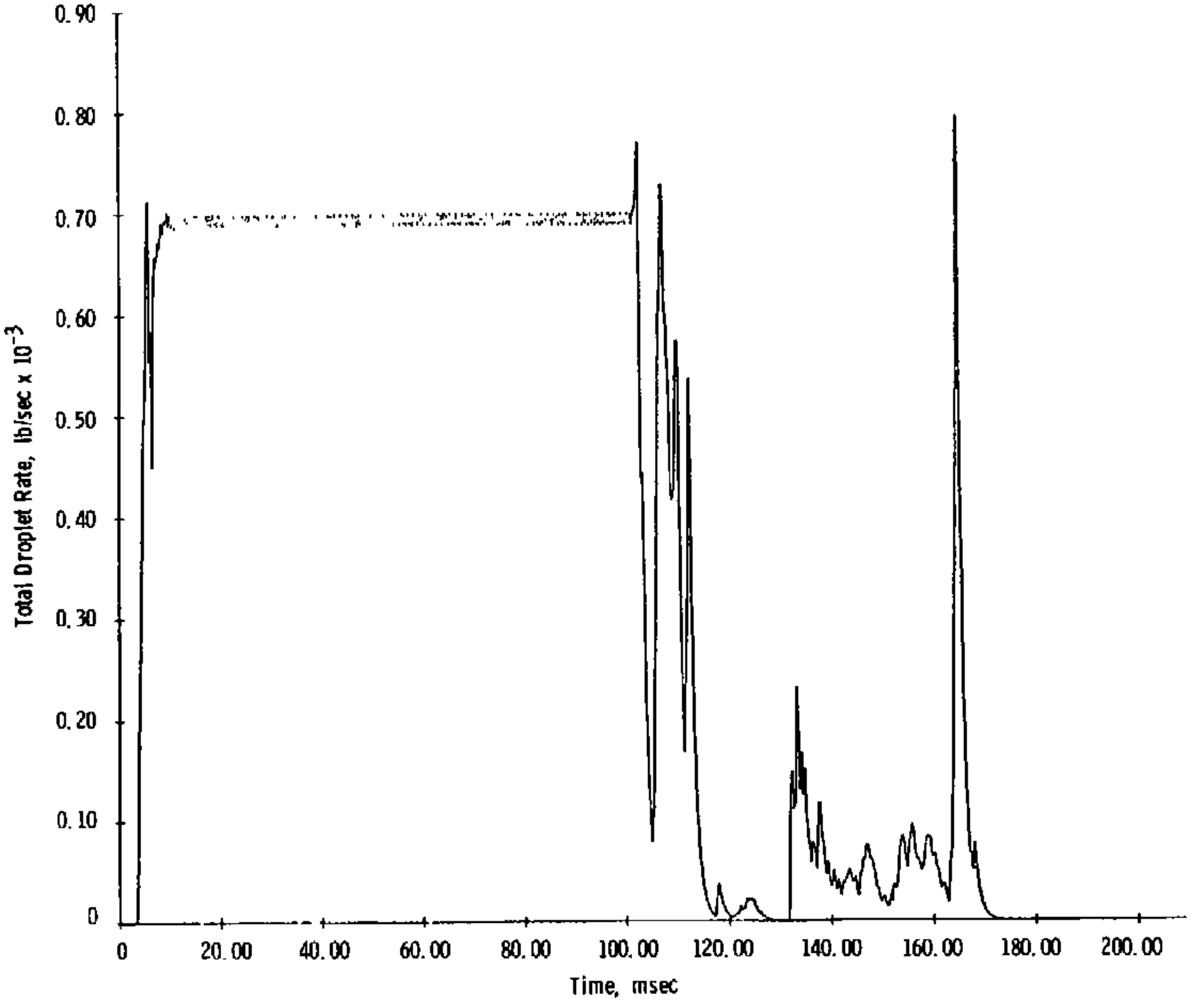
a. Chamber pressure
Figure 12. Case L results for AJ10-181-3



b. Fuel droplet rate
Figure 12. Continued.

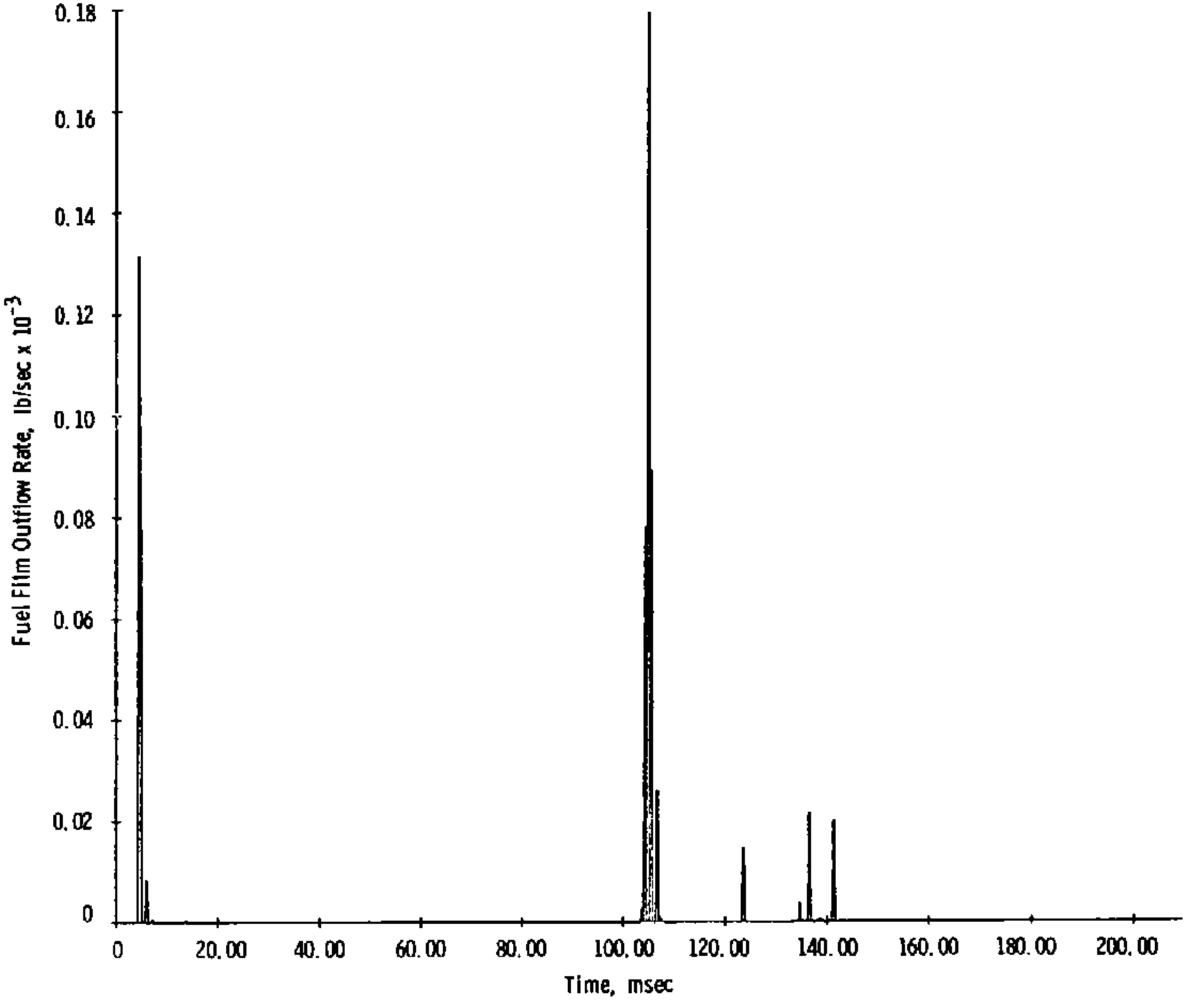


c. Oxidizer droplet rate
Figure 12. Continued.

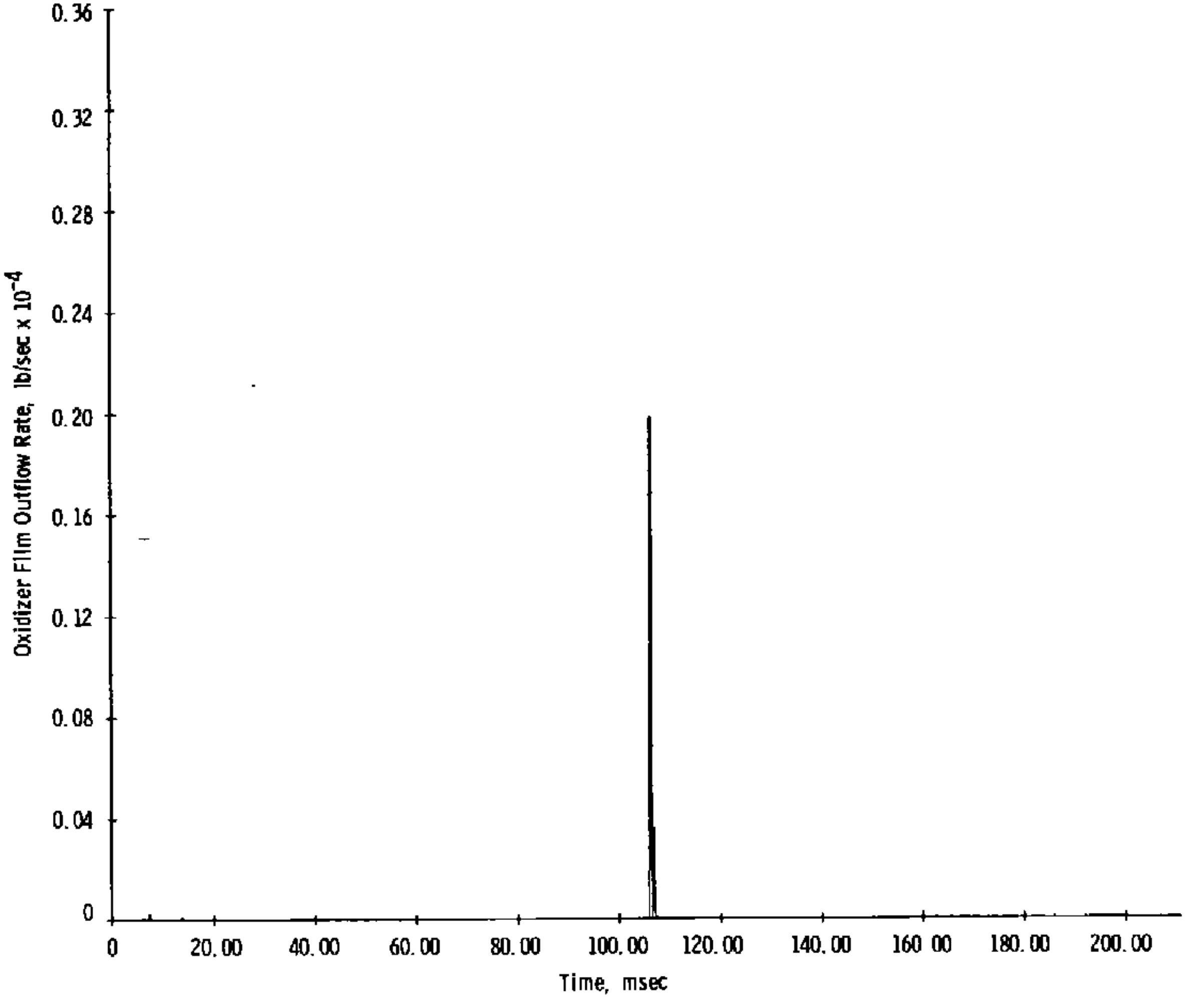


d. Total droplet rate

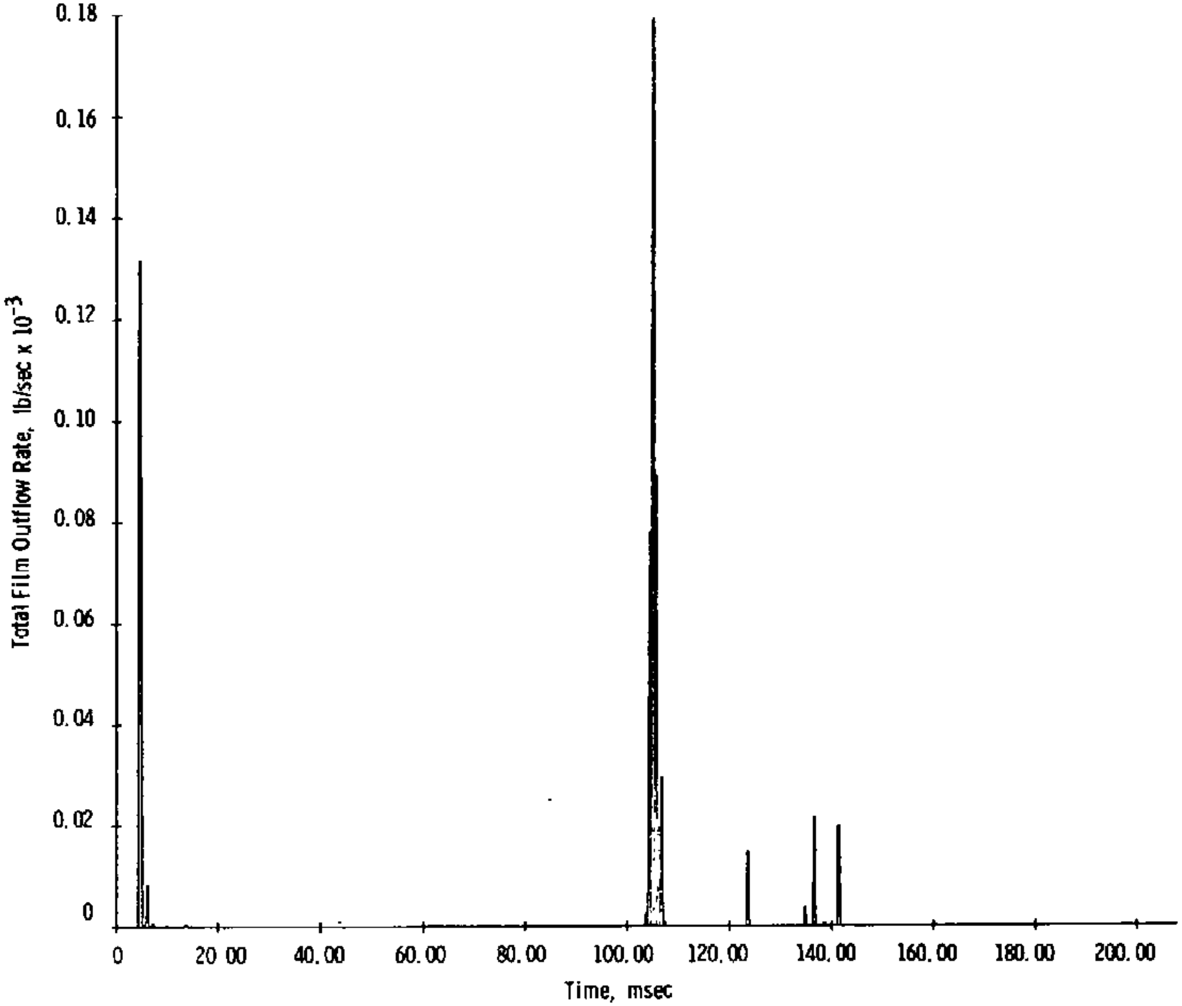
Figure 12. Continued.



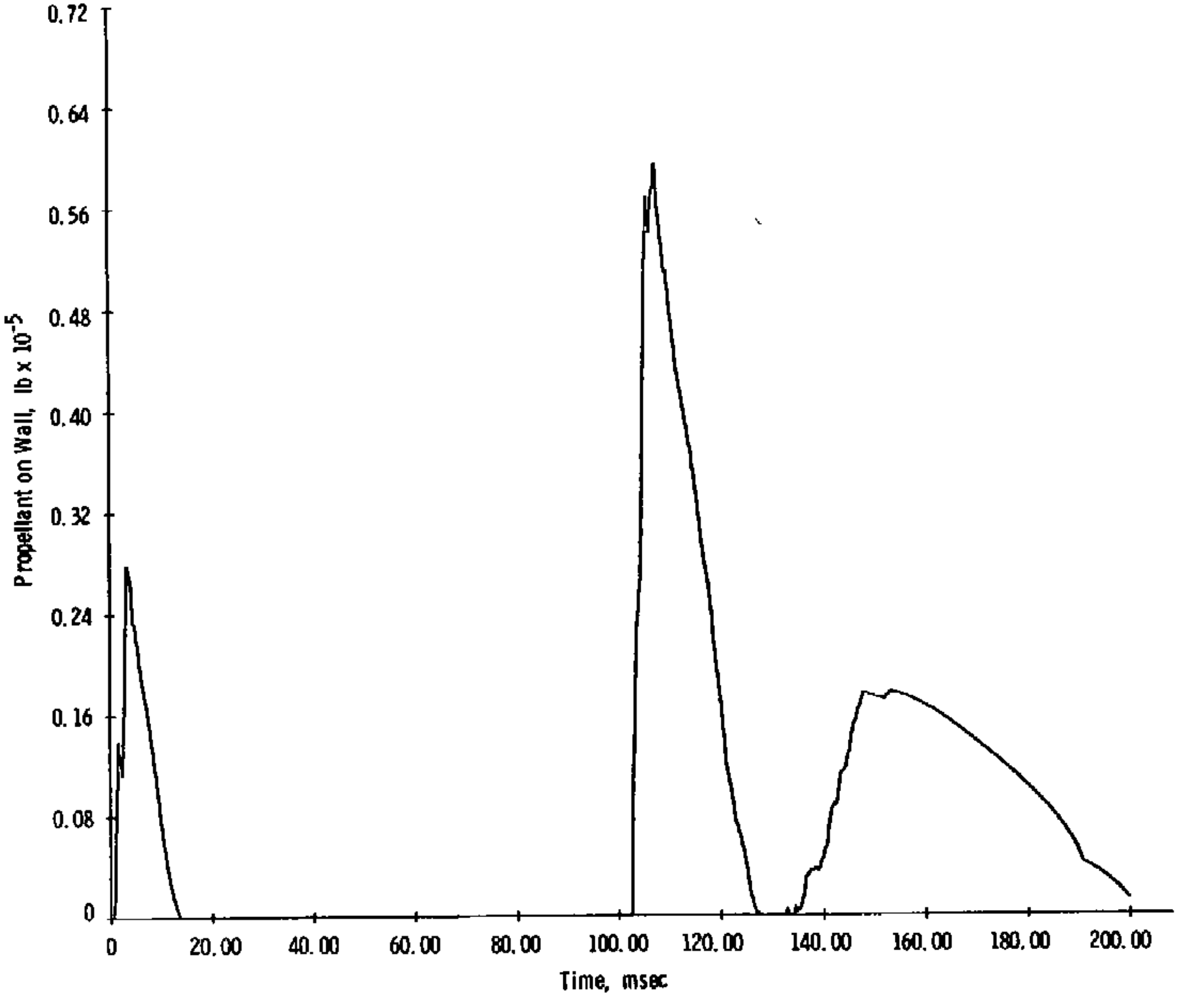
e. Fuel film outflow rate
Figure 12. Continued.



f. Oxidizer film outflow rate
Figure 12. Continued.



g. Total film outflow rate
Figure 12. Continued.



h. Propellant on wall
Figure 12. Concluded.

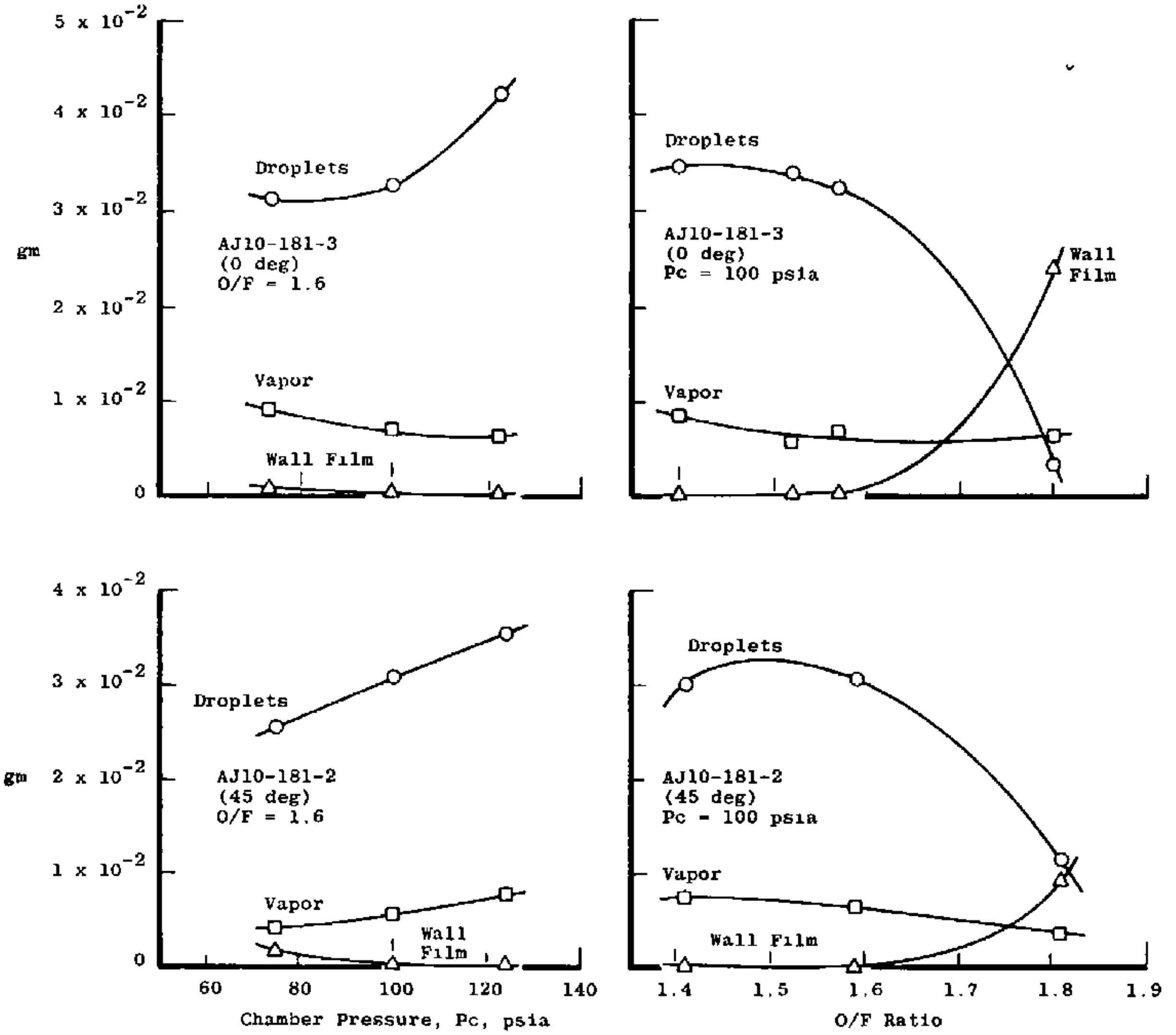


Figure 13. Unburned Propellant Ejected from Chamber for 0.1-sec firing.

Table 1. Chamber 10V Nominal Test Conditions

Engine	AJ10-181-2					AJ10-181-3					
Designation	A	B	C	D	E,F	G	H	I	J	K	L
Chamber Pressure, Pc, psia	75	100	100	100	125	75	100	100	100	128.5	98
Fuel Flow Rate $\dot{w}_F$ lb/sec	0.00363	0.00513	0.00473	0.00436	0.00585	0.0340	0.00478	0.00449	0.00410	0.00531	0.00449
Oxidizer Flow Rate $\dot{w}_O$ lb/sec	0.00585	0.00722	0.00755	0.00792	0.00945	0.00538	0.00661	0.00704	0.00739	0.00859	0.00680
O/F Ratio	1.61	1.41	1.60	1.82	1.62	1.58	1.38	1.57	1.80	1.64	1.52

Table 2. Computer Printout of Typical TCC Input

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                 THE INPUT DATA FOR THIS CASE ARE AS FOLLOWS

                              PROBLEM DESCRIPTION
       (* AEROJET AJ-10-181 ENGINE - SAMPLE TEST CASE FOR TCC * )

                              GENERAL INSTRUCTIONS

 PUNCH FOR RESTART    WORK FROM TAPE              KBUG         NO MOVIE TAPE
 (  9)     0.0        ( 10)     0.0       ( 11)  200.000000 ( 12)     0.0

          STOP TIME      TIME INTERVAL  PRINT ONE OUT OF   PLOT ONE OUT OF
 (201)     0.120000 (202)     0.000300 (203)    10.000000 (204)    25.000000

 FILM VERT. EXAG.  START MOVIE ITER.   END MOVIE ITER.   DATA REVIEW ONLY
 (205)    20.000000 (206)    10.000000 (207)    12.000000 (208)     0.0

                        TIME-AVERAGE PERFORMANCE VALUES

        START TIME 1       FINISH TIME 1       START TIME 2      FINISH TIME 2
 (313)     0.0      (314)     0.008000 (315)     0.008000 (316)     0.010000

        START TIME 3      FINISH TIME 3
 (317)     0.010000 (318)     0.025000 (

                             DROPLET TRAJECTORY PLOT

   FUEL SIZE  GROUP  OXID SIZE  GROUP    INJECTION TIME     INJECTOR RING
 (209)     3.000000 (210)     0.0       (211)     0.005000 (212)     2.000000

                              FLOW RATE OVERRIDES

   FUEL FLOW RATE   TOTAL PRESS DROP   VALVE PRESS DROP     INJ PRESS DROP
 (213)     0.0      (214)     0.0      (215)     0.0      (216)     0.0

   PERCENT RING 1     PERCENT RING 2     PERCENT RING 3
 ( 61)     0.0      ( 62)     0.0      ( 63)     0.0      ( 64)     0.0

   OXID FLOW RATE   TOTAL PRESS DROP   VALVE PRESS DROP     INJ PRESS DROP
 (217)     0.0      (218)     0.0      (219)     0.0      (220)     0.0

   PERCENT RING 1     PERCENT RING 2     PERCENT RING 3
 ( 85)     0.0      ( 86)     0.0      ( 87)     0.0      ( 88)     0.0

                              OPERATING CONDITIONS

   FUEL TANK PRESS    FUEL TANK TEMP FUEL TANK PSI/SEC EXTERNAL PRESSURE
 ( 13)  184.000000 ( 14)  294.000000 ( 15)     0.0      ( 16)     0.000001

   OXID TANK PRESS    OXID TANK TEMP OXID TANK PSI/SEC
 ( 17)  177.000000 ( 18)  294.000000 ( 19)     0.0      ( 20)     0.0

  INJECT INIT TEMP  THROAT INIT TEMP
 ( 21)  294.000000 ( 22)  294.000000 ( 23)     0.0      ( 24)     0.0

  INJECT MAX. TEMP    HALF-RISE TIME  INJECT MIN. TEMP    HALF-FALL TIME
 ( 25)  350.000000 ( 26)     5.200000 ( 27)  294.000000 ( 28)    74.000000

  THROAT MAX. TEMP    HALF-RISE TIME  THROAT MIN. TEMP    HALF-FALL TIME
 ( 29) 1439.000000 ( 30)     5.200000 ( 31)  294.000000 ( 32)    75.000000
```

Table 2. Continued

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                           IGNITION DESCRIPTION

  ASSIGNED DELAY IGNITER PORT LOC.    FUEL FLOW RATE    OXID FLOW RATE
( 33)      0.0   ( 34)      0.0     ( 35)    0.0      ( 36)    0.0

ACTIVATION ENERGY  FREQ. FACT. X Q    PERFECT MIXING    NO AXIAL MIXING
( 37) 5200.000000 ( 38)0.340000E 15 ( 39)    0.0      ( 40)    0.0

                             FUEL FEED SYSTEM

       LINE LENGTH          LINE DIAM   RESTRICTOR DIAM      VENTURI DIAM
( 41)   52.000000 ( 42)   0.180000 ( 43)    0.012740 ( 44)     0.0

       VALVE AREA      CHECK VALVES      VALVE OPEN DT     VALVE CLOSE DT
( 45)    0.000314 ( 46)    0.0        ( 47)    0.000500 ( 48)    0.000500

INIT. VOID VOLUME                     TRANSITION VOLUME    DRIBBLE VOLUME
( 57)    0.000400 ( 58)    0.0        ( 59)    0.0      ( 60)    0.000340

                           OXIDIZER FEED SYSTEM

       LINE LENGTH          LINE DIAM   RESTRICTOR DIAM      VENTURI DIAM
( 65)   39.000000 ( 66)    0.180000 ( 67)    0.013590 ( 68)    0.0

       VALVE AREA      CHECK VALVES      VALVE OPEN DT     VALVE CLOSE DT
( 69)    0.000550 ( 70)    0.0        ( 71)    0.000500 ( 72)    0.000500

INIT. VOID VOLUME                     TRANSITION VOLUME    DRIBBLE VOLUME
( 81)    0.000400 ( 82)    0.0        ( 83)    0.0      ( 84)    0.000390

                         ATOMIZATION PARAMETERS

 FUEL DROP FACTOR  OXID DROP FACTOR  FUEL FAN MIN L/D  OXID FAN MIN L/D
( 89)    0.500000 ( 90)    0.500000 ( 91)    3.000000 ( 92)    3.000000

HOLD AT TRIPLE PT  NO INIT. DRIBBLE  FLASH CONE ANGLE SINGLE STREAM L/D
( 93)    1.000000 ( 94)    0.0      ( 95)   30.000000 ( 96)   10.000000

       DROP SIZE 1       DROP SIZE 2       DROP SIZE 3       DROP SIZE 4
( 97)    0.198000 ( 98)    0.759000 ( 99)    1.000000 (100)    1.230000

       DROP SIZE 5  NO WALL BREAKUP  DROP RESTITUTION FRACTION STICKING
(101)    2.304500 (102)    0.0      (103)    1.000000 (104)    0.500000

     NO FUEL FLASH    NO OXID FLASH    NO ENTRAINMENT DELETE DROP MEANS
(105)    0.0      (106)    0.0      (107)    0.0      (108)    0.0

                             FUEL PROPERTIES

     BOILING POINT    FREEZING POINT    CRITICAL TEMP.   CRITICAL PRESS.
(109)  360.000000 (110)  222.000000 (111)  594.000000 (112) 1195.000000

         VAPOR CP.        LIQUID CP.                         MOL. WEIGHT
(113)    0.995000 (114)    0.690000 (115)    0.0      (116)   46.073990

  LATENT HEAT VAP.  LATENT HEAT FUS. LIQ. THERM. COND.     ACCOM. COEFF.
(117)  210.000000 (118)   67.500000 (119)    0.000545 (120)   -1.000000
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Table 2. Continued.

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   REFERENCE TEMP.                 DENSITY            VISCOSITY    SURFACE TENSION
 (121)  300.000000 (122)     0.880000 (123)      0.010400 (124)     47.000000

     BURNING RATE K    MONO. INTERCEPT MONO. COEFFICIENT     MONO. EXPONENT
 (125)     0.032500 (126)    0.0         (127)    0.0         (128)    0.0

                          OXIDIZER PROPERTIES

    BOILING POINT      FREEZING POINT     CRITICAL TEMP.    CRITICAL PRESS.
 (129)  294.000000 (130)  262.000000 (131)  431.000000 (132) 1470.000000

         VAPOR CP.          LIQUID CP.                              MOL. WEIGHT
 (133)     0.298000 (134)     0.360000 (135)     0.0        (136)   46.007996

 LATENT HEAT VAP.  LATENT HEAT FUS. LIQ. THERM. COND.      ACCOM. COEFF.
 (137)   99.000000 (138)   39.199997 (139)     0.000306 (140)     1.000000

   REFERENCE TEMP.                 DENSITY            VISCOSITY   SURFACE TENSION
 (141)  300.000000 (142)     1.450000 (143)      0.004460 (144)    28.000000

     BURNING RATE K    MONO. INTERCEPT MONO. COEFFICIENT     MONO. EXPONENT
 (145)     0.027000 (146)    0.0         (147)    0.0         (148)    0.0

                          PRODUCT PROPERTIES

 TABULAR PROPERTY DATA IS FOR FUEL FRACTIONS OF 0.0, 0.1, 0.2 - - - 1.0

                      EQUILIBRIUM GAS TEMPERATURE

            TEMP. 1             TEMP. 2             TEMP. 3             TEMP. 4
 (149)  300.000000 (150) 2103.000000 (151) 3084.000000 (152) 3397.000000

            TEMP. 5             TEMP. 6             TEMP. 7             TEMP. 8
 (153) 3061.000000 (154) 2368.000000 (155) 1705.000000 (156) 1433.000000

            TEMP. 9            TEMP. 10            TEMP. 11
 (157) 1344.000000 (158) 1266.000000 (159) 1190.000000 (160)    0.0

                      EQUILIBRIUM GAS MOL. WEIGHT

          MOL. WT. 1          MOL. WT. 2          MOL. WT. 3          MOL. WT. 4
 (161)   46.007996 (162)   28.789993 (163)   26.409988 (164)   23.389999

          MOL. WT. 5          MOL. WT. 6          MOL. WT. 7          MOL. WT. 8
 (165)   19.879990 (166)   16.750000 (167)   14.410000 (168)   13.910000

          MOL. WT. 9         MOL. WT. 10         MOL. WT. 11
 (169)   14.000000 (170)   14.099999 (171)   14.290000 (172)    0.0

                        EQUILIBRIUM GAS GAMMA

             GAMMA 1             GAMMA 2             GAMMA 3             GAMMA 4
 (173)    1.120000 (174)    1.250000 (175)    1.219999 (176)    1.216999

             GAMMA 5             GAMMA 6             GAMMA 7             GAMMA 8
 (177)    1.235000 (178)    1.268000 (179)    1.308999 (180)    1.299000

             GAMMA 9            GAMMA 10            GAMMA 11
 (181)    1.270000 (182)    1.247000 (183)    1.228000 (184)    0.0
```

Table 2. Continued

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                           THRUST COEFFICIENT TABLE

                       EQUILIBRIUM THRUST COEFFICIENT

           CF VAC 1          CF VAC 2          CF VAC 3          CF VAC 4
(221)     1.924000 (222)    1.802799 (223)    1.908199 (224)    1.961699

           CF VAC 5          CF VAC 6          CF VAC 7          CF VAC 8
(225)     1.846999 (226)    1.812200 (227)    1.867999 (228)    1.933100

           CF VAC 9         CF VAC 10         CF VAC 11     EXP. AREA RATIO
(229)     1.929399 (230)    1.922400 (231)    1.895900 (232)   40.000000

                              ADDUCT PROPERTIES

           DENSITY          VAPOR CP.       LATENT HEAT      DECOMP. TEMP.
(185)     1.000000 (186)    1.000000 (187)  100.000000 (188)  500.000000

                           CONTAMINANT VISCOSITY

         VISCOSITY 1       VISCOSITY 2       VISCOSITY 3       VISCOSITY 4
(189)     0.004460 (190)    0.024000 (191)    0.043000 (192)    0.068000

         VISCOSITY 5       VISCOSITY 6       VISCOSITY 7       VISCOSITY 8
(193)     0.081000 (194)    0.100000 (195)    0.082000 (196)    0.064000

         VISCOSITY 9       VISCOSITY 10      VISCOSITY 11
(197)     0.046000 (198)    0.029000 (199)    0.010400 (200)    0.0

                           FIRST BURN VALVE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(233)     0.0      (234)    0.0      (235)    0.100000 (236)    0.100000

                             SECOND PULSE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(237)     0.0      (238)    0.0      (239)    0.0      (240)    0.0

                              THIRD PULSE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(241)     0.0      (242)    0.0      (243)    0.0      (244)    0.0

                             FOURTH PULSE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(245)     0.0      (246)    0.0      (247)    0.0      (248)    0.0

                              FIFTH PULSE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(249)     0.0      (250)    0.0      (251)    0.0      (252)    0.0

                              SIXTH PULSE TIMING

 FUEL VALVE OPEN   OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
(253)     0.0      (254)    0.0      (255)    0.0      (256)    0.0
```

Table 2. Continued

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                         SEVENTH PULSE TIMING

   FUEL VALVE OPEN    OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
 (257)     0.0      (258)     0.0      (259)     0.0     (260)     0.0

                          EIGHTH PULSE TIMING

   FUEL VALVE OPEN    OXID VALVE OPEN  FUEL VALVE CLOSE  OXID VALVE CLOSE
 (261)     0.0      (262)     0.0      (263)     0.0     (264)     0.0

                          MULTI-RING INJECTOR

                               FIRST RING

                               FUEL HOLES

      HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 ( 49)     0.008000  ( 50)     0.010000  ( 51)     0.0     ( 52)    0.150000

 RADIAL INJ. ANGLE   DISCHARGE COEFF.    NUMBER OF HOLES   TRANSVERSE ANGLE
 ( 53)   -45.000000  ( 54)     0.600000  ( 55)    6.000000 ( 56)     0.0

                            OXIDIZER HOLES

      HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 ( 73)     0.010000  ( 74)     0.010000  ( 75)     0.0     ( 76)    0.050000

 RADIAL INJ. ANGLE   DISCHARGE COEFF.    NUMBER OF HOLES   TRANSVERSE ANGLE
 ( 77)    45.000000  ( 78)     0.600000  ( 79)    6.000000 ( 80)     0.0

                              SECOND RING

                               FUEL HOLES

      HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 (265)     0.0       (266)     0.0       (267)     0.0     (268)     0.0

 RADIAL INJ. ANGLE   DISCHARGE COEFF.    NUMBER OF HOLES   TRANSVERSE ANGLE
 (269)     0.0       (270)     0.0       (271)     0.0     (272)     0.0

                            OXIDIZER HOLES

      HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 (273)     0.0       (274)     0.0       (275)     0.0     (276)     0.0

 RADIAL INJ. ANGLE   DISCHARGE COEFF.    NUMBER OF HOLES   TRANSVERSE ANGLE
 (277)     0.0       (278)     0.0       (279)     0.0     (280)     0.0

                              THIRD RING

                              FUEL HOLES

      HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 (281)     0.0       (282)     0.0       (283)     0.0     (284)     0.0

 RADIAL INJ. ANGLE   DISCHARGE COEFF.    NUMBER OF HOLES   TRANSVERSE ANGLE
 (285)     0.0       (286)     0.0       (287)     0.0     (288)     0.0
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Table 2. Concluded

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                                  OXIDIZER HOLES

     HOLE DIAMETER        HOLE LENGTH      AXIAL LOCATION    RADIAL LOCATION
 (289)      0.0       (290)      0.0      (291)      0.0     (292)      0.0

RADIAL INJ. ANGLE  DISCHARGE COEFF.   NUMBER OF HOLES   TRANSVERSE ANGLE
 (293)      0.0       (294)      0.0      (295)      0.0     (296)      0.0

                             COMBUSTION CHAMBER PROFILE

INJECTOR LOCATION INJECTOR DIAMETER       AXIAL LOC. 2    CHAMBER DIAM. 2
 (297)      0.0       (298)   0.500000 (299)    0.281000 (300)    0.500000

      AXIAL LOC. 3   CHAMBER DIAM. 3      AXIAL LOC. 4    CHAMBER DIAM. 4
 (301)     0.562000 (302)     0.500000 (303)    0.844000 (304)    0.500000

      AXIAL LOC. 5   CHAMBER DIAM. 5      AXIAL LOC. 6    CHAMBER DIAM. 6
 (305)     1.146000 (306)     0.500000 (307)    1.231999 (308)    0.470000

      AXIAL LOC. 7   CHAMBER DIAM. 7      THROAT PLANE     THROAT DIAM.
 (309)     1.379000 (310)     0.242000 (311)    1.500000 (312)    0.155500


     INPUT UNITS ARE INCHES, PSIA, SECONDS AND DEGREES KELVIN.
     PROPELLANT PROPERTIES ARE IN GRAMS/CC, POISE, DYNE/CM.
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Table 3. Important Input Parameters That Were Varied

Engine	AJ10-181-2					AJ10-181-3					
Designation	A	B	C	D	E,F	G	H	I	J	K	L
Fuel Tank Pressure, psia (13)	125	200	185	172	255	123	194	184	170	250.5	181
Oxidizer Tank Pressure, psia (17)	165	237	250	265	360	120	168	177	185	241.5	169
Fuel Restrictor Diameter, in. (43)	0.01317	0.01317	0.01317	0.01317	0.01317	0.01274	0.01274	0.01274	0.01274	0.01274	0.01274
Oxidizer Restrictor Diameter, in. (67)	0.01151	0.01151	0.01151	0.01151	0.01151	0.01359	0.01359	0.01359	0.01359	0.01359	0.01359
Fuel Injector Radial Location, in. (52)	0.140	0.140	0.140	0.140	0.140	0.150	0.150	0.150	0.150	0.150	0.150
Fuel Injector Radial Angle, deg (53)	-35.26	-35.26	-35.26	-35.26	-35.26	-45.0	-45.0	-45.0	-45.0	-45.0	-45.0
Fuel Injector Transverse Angle, deg (56)	35.26	35.26	35.26	35.26	35.26	0	0	0	0	0	0
Oxidizer Injector Radial Location, in. (76)	0.070	0.070	0.070	0.070	0.070	0.050	0.050	0.050	0.050	0.050	0.050
Oxidizer Injector Radial Angle, deg. (77)	35.26	35.26	35.26	35.26	35.26	45.0	45.0	45.0	45.0	45.0	45.0
Oxidizer Injector Transverse Angle, deg (80)	-35.26	-35.26	-35.26	-35.26	-35.26	0	0	0	0	0	0
Chamber Length, in. (311)	2.0	2.0	2.0	2.0	2.0	1.5	1.5	1.5	1.5	1.5	1.5
Nozzle Throat Diameter, in. (312)	0.1611	0.1611	0.1611	0.1611	0.1611	0.1555	0.1555	0.1555	0.1555	0.1555	0.1555
Nozzle Area Ratio (232)	100	100	100	100	100	50	50	50	50	50	50

Note: Numbers in parentheses refer to subscript in TCC input list.

Table 4. Summary of TCC Result for 0.1-sec Firing

Engine		AJ10-181-2					AJ10-181-3					
Designation		A	B	C	D	E,F	G	H	I	J	K	L
Average Chamber Pressure, psia		75.1	99.7	99.0	100.0	123.9	73.9	98.6	99.8	99.6	122.6	97.1
Total Fuel Flow, lb		0.00037	0.00052	0.00048	0.00044	0.00059	0.00035	0.00048	0.00046	0.00042	0.00056	0.00046
Total Oxidizer Flow, lb		0.00059	0.00073	0.00076	0.00080	0.00095	0.00055	0.00068	0.00072	0.00075	0.00088	0.00069
O/F Ratio		1.61	1.41	1.59	1.81	1.61	1.59	1.40	1.57	1.80	1.58	1.52
Disposition of Fuel, percent	Burned	89.0	90.1	90.1	94.1	91.3	86.5	89.0	91.1	89.5	89.5	89.3
	Expelled as Unburned Vapor	1.8	1.3	1.4	1.4	1.2	1.9	1.4	0.5	1.6	1.3	1.4
	Expelled as Drops	8.5	8.4	8.3	1.4	7.4	11.3	9.5	8.3	1.0	9.1	9.2
	Expelled as Wall Film	0.6	0.1	0.1	3.0	0.06	0.3	0.03	0.1	7.9	0.07	0.04
Disposition of Oxidizer, percent	Burned	95.0	95.5	95.3	96.4	95.4	92.2	93.7	93.3	95.9	94.4	94.3
	Expelled as Unburned Vapor	0.5	1.3	1.0	0.3	1.0	2.4	1.7	1.9	1.0	0.8	0.8
	Expelled as Drops	4.2	3.2	3.7	2.5	3.6	5.4	4.6	4.8	0.4	4.8	4.9
	Expelled as Wall Film	0.3	0.001	0.01	0.9	0.001	0.05	0.0002	0.02	2.7	0.001	0.001
Ejected Fuel Drop Diameter, D_{32}, μ		105.0	109.0	96.7	49.6	112.0	90.6	107.0	121.5	65.5	94.5	111.0
Ejected Oxidizer Drop Diameter, D_{32}, μ		86.1	75.6	79.0	88.6	73.8	77.0	68.0	71.6	61.8	73.0	73.6