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TECHNICAL REPORT RD-80-12

INVESTIGATION OF PLUME INDUCED SEPARATION
ON A FULL-SIZE MISSILE AT SUPERSONIC VELOCITIES

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20 June 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A large amount of data to determine plume effects have been obtained from various simulation techniques. To provide data for evaluating the adequacy of these simulations, a test utilizing a rocket sled to measure surface pressures on a full-size, live, high thrust rocket at Mach number up to $M=1.6$. Selected portions of the data are presented to show Mach number and thrust level effects		

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I. INTRODUCTION

The development of high performance missiles usually implies a rocket motor that develops high thrust with a corresponding underexpanded plume. This plume continues to expand after exiting from the rocket nozzle and exceeds the base area of the missile. The presence of the plume acts as an obstacle to the free-stream flow over the aft portion of the missile and flow separation takes place. At that location flow separation is highly destabilizing when nonsymmetrical and resulting flight attitude tend to further promote this activity. The performance of stabilizing or controlling surfaces located in this region are degraded by being partially submerged in the separated flow. Therefore an understanding of plume induced separation is necessary to avoid adverse influences to high performance missiles.

Numerous studies have been conducted to define this effect. The theoretical approach was unable to adequately describe the highly transient conditions within the exhaust flow and the complex mixing between the plume and the free-streams. The experimental approaches have been simulations which failed to produce complete confidence in the results. These simulations have been in the use of sub-scale models and the use of cold gases to simulate the rocket exhaust.

To provide data for evaluating the large data base obtained from previous simulations, a sled test was conducted. These tests were conducted by firing a live full-size motor aboard a sled propelled to supersonic velocities to produce the proper external flow conditions. The tests were conducted at Holloman Air Force Base on the High Speed Test Track.

II. APPARATUS

A description of the High Speed Test Track at Holloman Air Force Base may be found in Reference 1.

A photograph showing the test article mounted atop the test sled and the pusher sled with Nike Rocket Motors installed is shown in Figure 1. Figure 2 presents a general arrangement of the test sled and the test missile. In an attempt to improve the quality of the data, two missile configurations were used in this test program and the sled-missile orientation was varied.

The basic test missile was composed of an existing 6-inch diameter motor case and nozzle to provide an exit Mach No. of 2.53, half-angle of expansion of 10.40, and a maximum thrust > 20,000 pounds. The nozzle exit to base area ratio was 0.927. This motor was mated to a sled attachment section, a three caliber tangent ogive nose and a tail section to provide a typical aerodynamic shape 135 inches long. This body was mounted above the sled through a supporting pylon. A flat plate was mounted on top of the sled to shield the test missile from flow disturbance emanating from the sled.

The instruments incorporated in the test article were a number of surface pressure orifices installed in the rear 3 caliber portion of the tail

¹"6585 Test Group Facilities and Capabilities," Armament Development Center, 6585 Test Group, Holloman Air Force Base, New Mexico.

section, in the missile base region and a pressure measurement in the motor combustion area. The pressure measurements were telemetered from the sled during each run.

The first version of the test missile utilized the 6-inch rocket motor case as the overall missile diameter with the pressure lines and electrical leads routed from the rear through an external tunnel to the forward portion of the missile. In order to improve the flow quality over the rear portion, the missile body was redesigned to encircle the motor case and instrumentation lines within a 7-inch diameter body sleeve. The nozzle exit to base area ratio for this version of the test missile was 0.80. The pylon mounting was also modified so that the test missile was moved upward and forward from its original position.

The test missile contained provisions to allow fins to be installed and angle-of-attack changes.

III. DISCUSSION OF DATA

Data presented in Figure 5 (Top center line pressures) is typical of the data obtained from runs conducted with the 6-inch diameter test missile. The velocity range and thrusting interval employed (Figure 4) represent the prime region of interest - transonic velocities where plume induced separation effects are known to be greatest. The burn time available from the test motor was approximately one second and it was fired to yield test data over the Mach number range of 0.8 to 1.4. The data presented in Figure 5 was obtained during this firing time as the sled was accelerating to maximum velocity and for the non-firing values, during the corresponding Mach number range as the sled decelerated.

Inspection of the non-firing data reveals the presence of unwanted influences. It was determined that these were disturbances emanating from various surfaces on the sled and impinging on the test article (see Figure 5). Examination of these data shows this interference to move rearward as Mach number increased and clear the missile body at Mach numbers ≥ 1.5 . The motor firing data showed a large influence on local pressures due to the presence of the plume.

It was decided that meaningful data to provide insight into these plume effects could be obtained by modifying the test objectives and altering the test vehicle. The emphasis was shifted from transonic velocities to the region above which interference free data could be obtained. A redesign effort attempted to reconfigure the test apparatus so that the Mach number at which sled induced disturbances that obscured test results could be lowered.

To improve the flow quality of the test, this missile support pylon was lengthened to position the missile approximately 5.3 inches higher and 6.0 inches forward of its original position. The leading edge was extended and fences were affixed to the flat plate sides in an attempt to constrain disruptive flow from the sled region thereby promoting better flow characteristic and lessen disturbances on the test article. Additionally, the change in test missile diameter, mentioned previously to improve local flow over the missile, was undertaken. The resulting increase in base area was counter

to original test aims, demonstration of plume induced separation, by lowering the effect of thrust density (base area/thrust).

The test regime used after these alterations were made is shown in Figure 6. The sled trajectory was unchanged but the test rocket firing was delayed to insure data acquisition at interference free Mach numbers.

Data acquired at this Mach number range for two runs is presented in Figures 7 and 9. The test conditions were identical for each run ($\alpha = 0$, no fins) with the exception that the motor fired to obtain Figure 9 data was preheated prior to firing to produce slightly higher thrust values. The maximum thrust obtained in Figure 7 was 26,000 pounds as contrasted with 22,000 pounds for Figure 5.

Inspection of the data in these Figures reveal that the redesign of the test article expanded the available Mach number range. What effect the presence of disturbances on the missile at the time firing was initiated, and the existence of these disturbances aft of the missile in the wake area during data acquisition, is not known. Still, insight into the interrelationship of Mach number, thrust level and plume effects is provided in these data.

Comparison of the higher thrust data (Figure 9 with Figure 7) shows the surface pressures to be higher, denoting greater flow separation for the increased thrust run. Shown in both sets of data is the sensitivity of the separation effects to Mach number increases. This is apparent for locations forward of the base region ($x/d > 0.20$) where the increase in surface pressures during firing disappear, although thrust levels remain reactively constant at small Mach number increases. The separation produced by the higher thrust run (Figure 9) is seen to persist to a higher Mach number but breaks down just as abruptly for slight Mach number increases.

Photographs illustrating the mechanism producing measurable differences in the separated region in the two sets of data are presented in Figure 10. These photographs were taken at essentially the same Mach number but with different thrust levels showing the luminous portion of the plume. Measurements made on these films show the plume to be approximately 1.6 body diameters, one diameter downstream of the base, for the lower thrust level. The higher thrust run shows plume dimensions of approximately 2 body diameters at that location.

IV. CONCLUSIONS

The data presented in this report is only a portion of the information obtained during tests of the two versions of the missile-sled arrangement. The remainder of the data are published in Technical Report TR-RD-80-14. Data in that report include the following: missile at angle-of-attack, missile with fins installed, pressures recorded on upper and lower surfaces, a constant Mach number trajectory ($M=1.2$), and a run with no rocket firing. This data is not included herein because the results are clouded by the presence of sled generated disturbances.

It is considered that a redesign of the current test configuration would provide a further increase in acceptable Mach number range. Additional data could be obtained which would allow a more meaningful interpretation of

the data described above. Additional testing could be performed to evaluate other parameters influencing plume induced separation.

Currently no wind tunnel data exist for an exact-case comparison. Future plans of this organization include a wind tunnel test modeled to duplicate the nozzle geometry-base geometry and thrust levels employed in these sled tests. Comparison of these results with available wind tunnel test of similar conditions do not reveal any gross differences in the data.

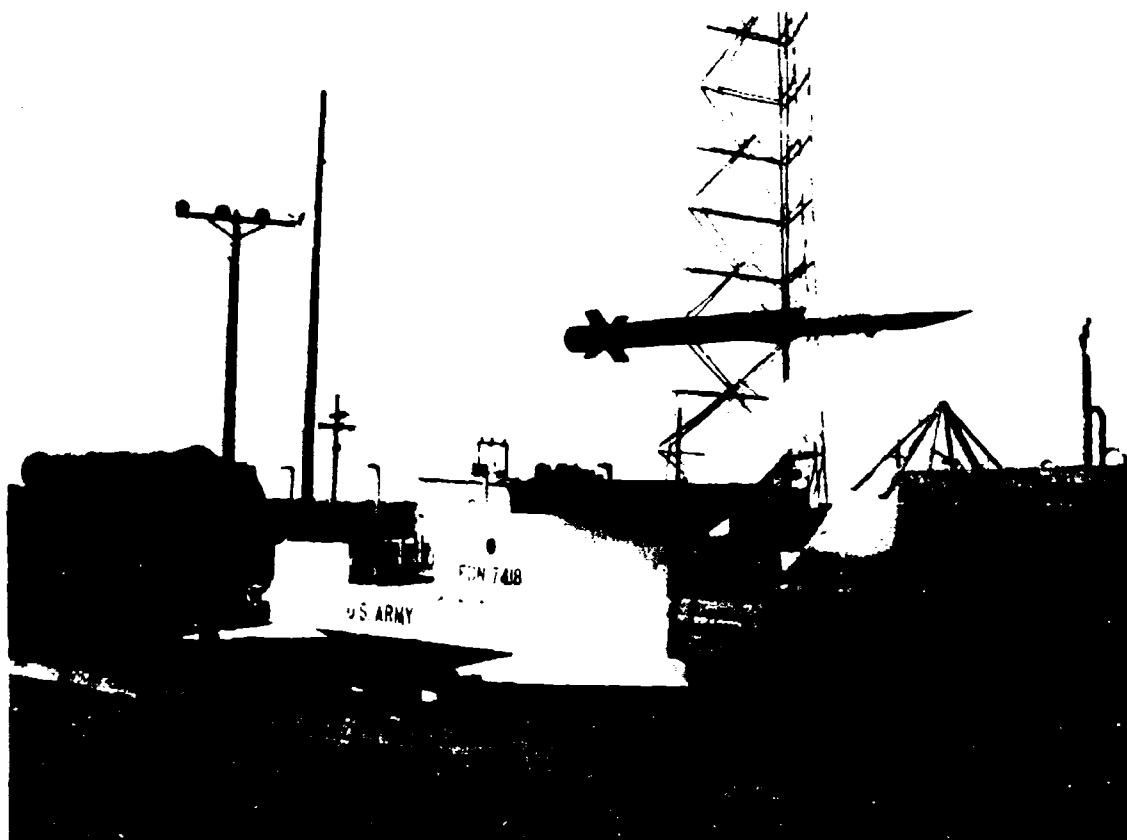


Figure 1. Photograph of test missile and sled train

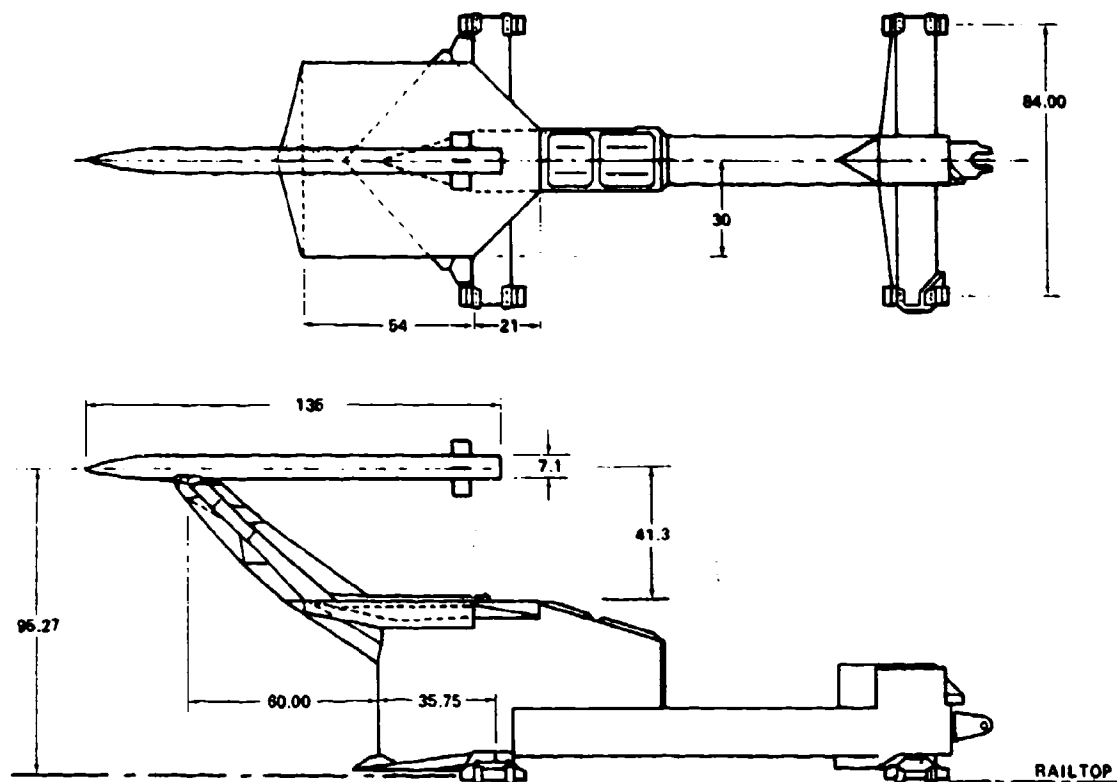


Figure 2. General arrangement of test missile and test sled

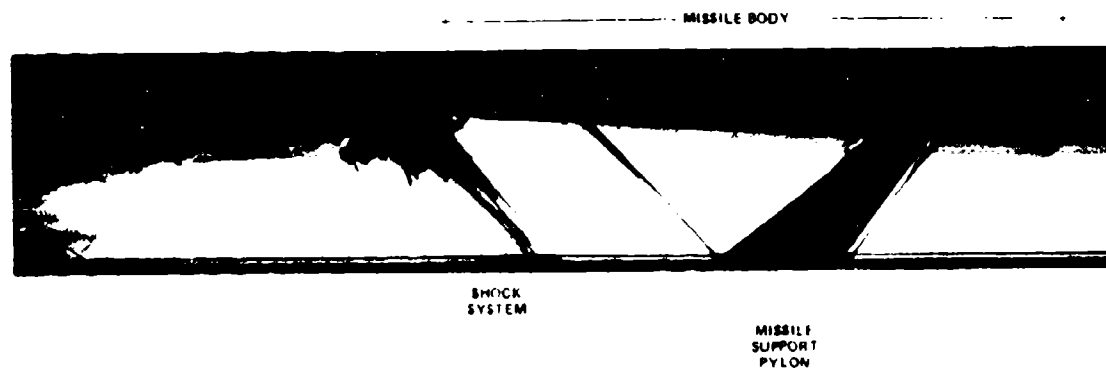


Figure 3. Shadowgraph showing shock from sled body impinging on test article

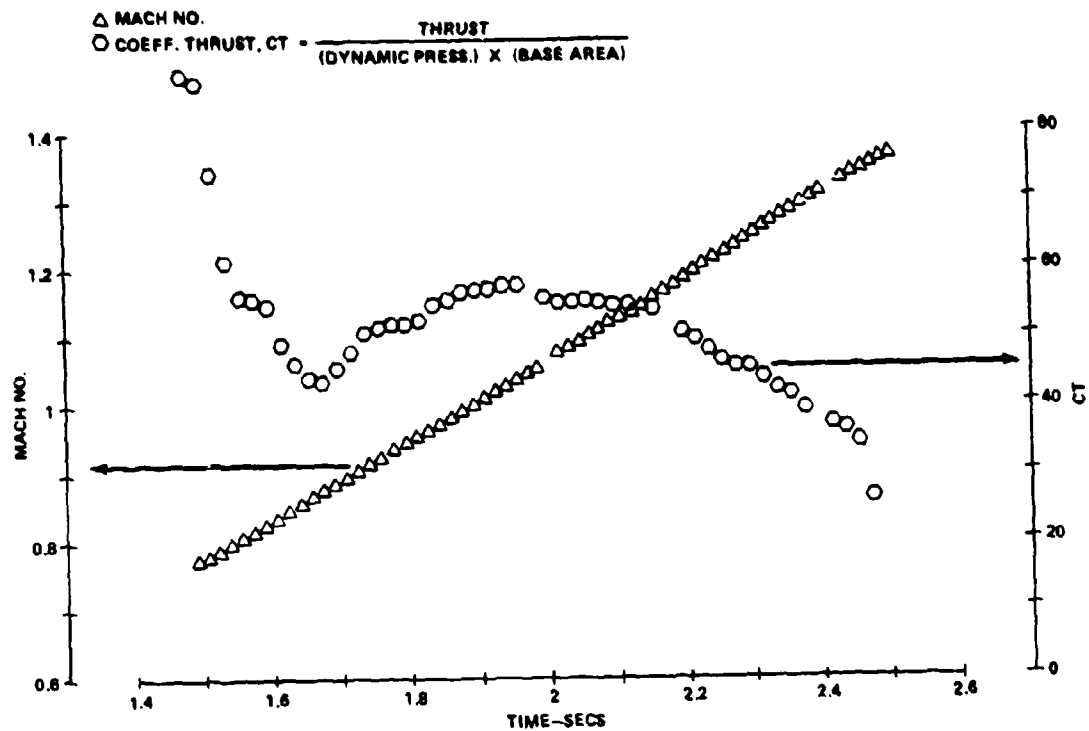
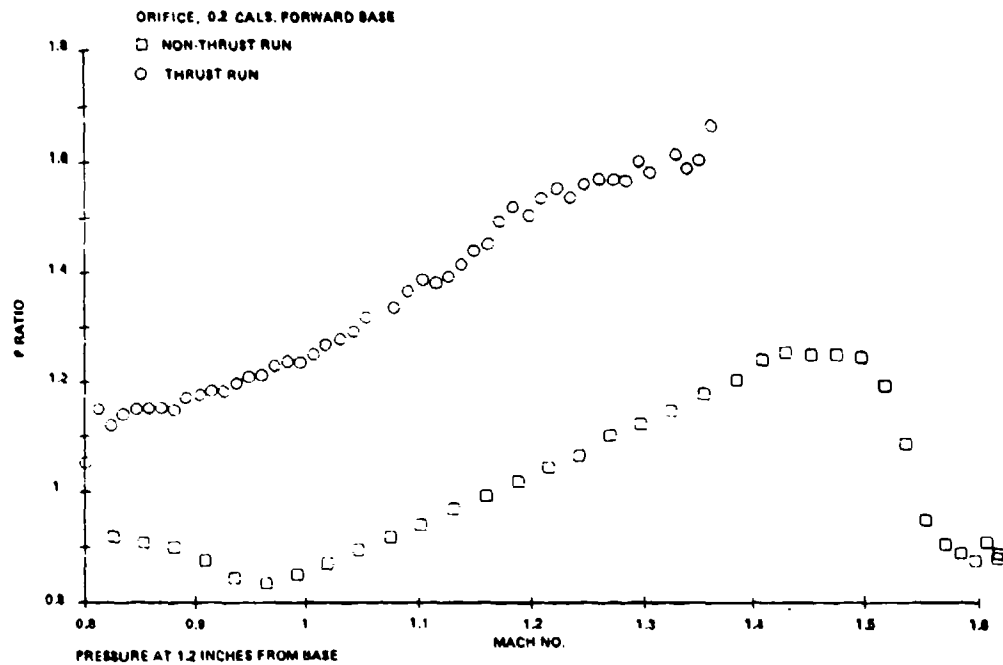
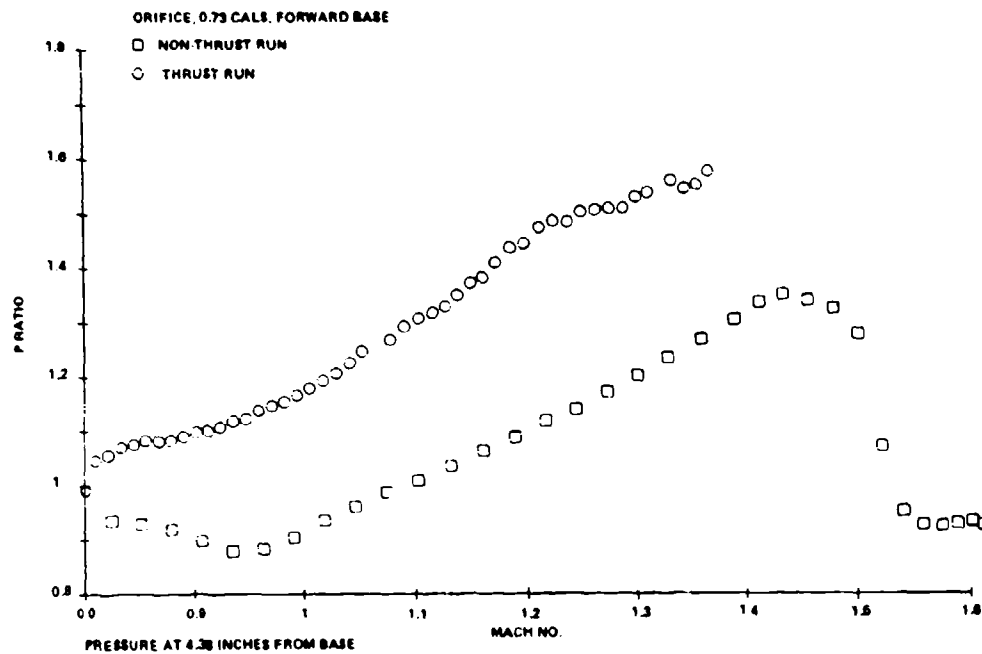


Figure 4. Mach number and thrust history of firing portion of run A-1

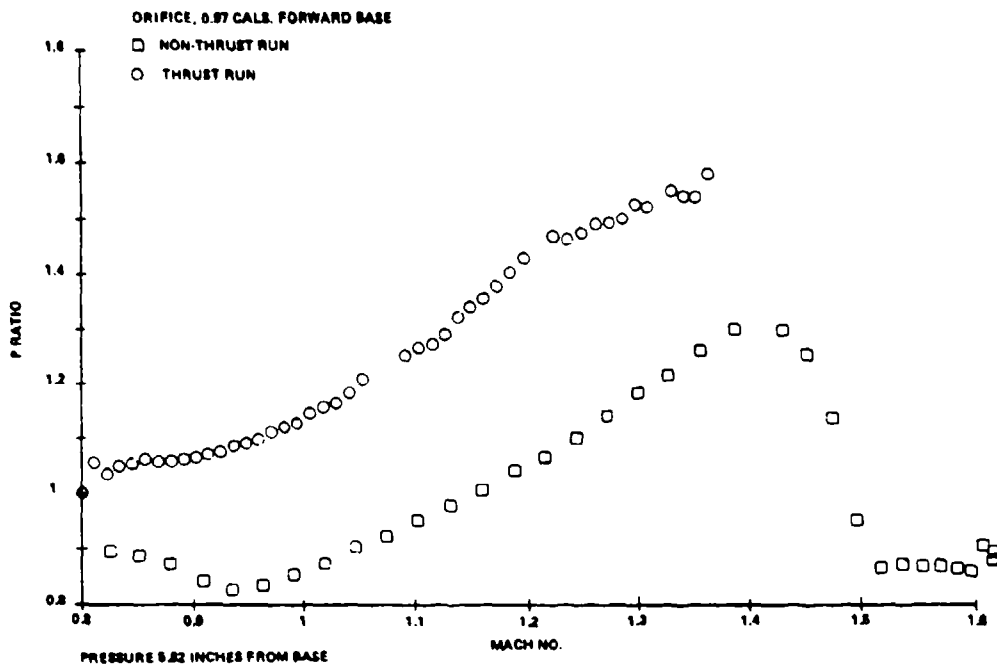


a. Pressure at 1.2 inches from base

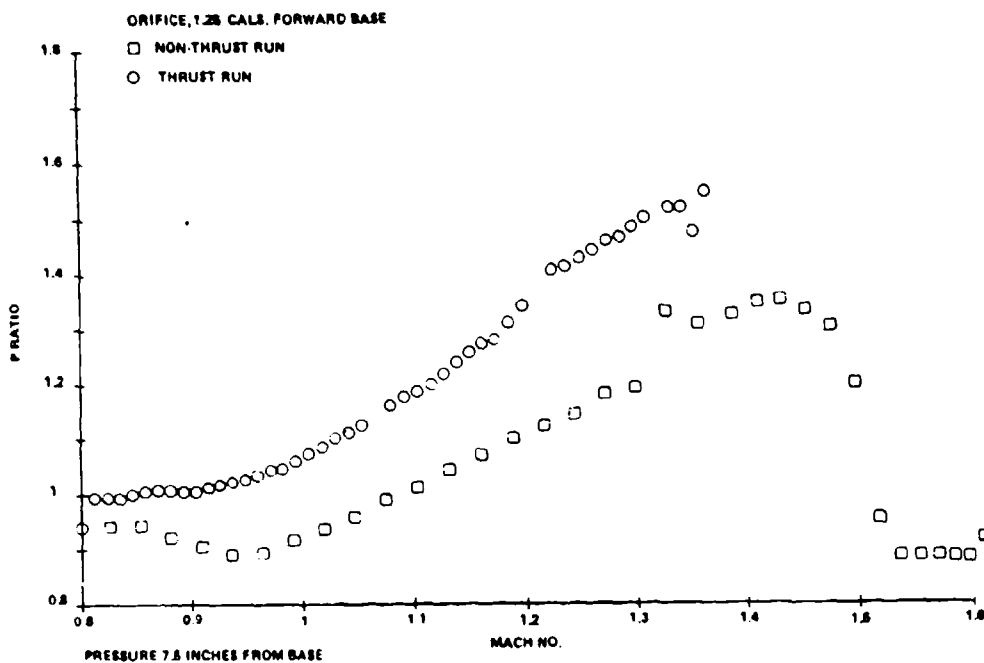


b. Pressure at 4.38 inches from base

Figure 5. Ratio of surface pressures to ambient pressure measured during run A-1

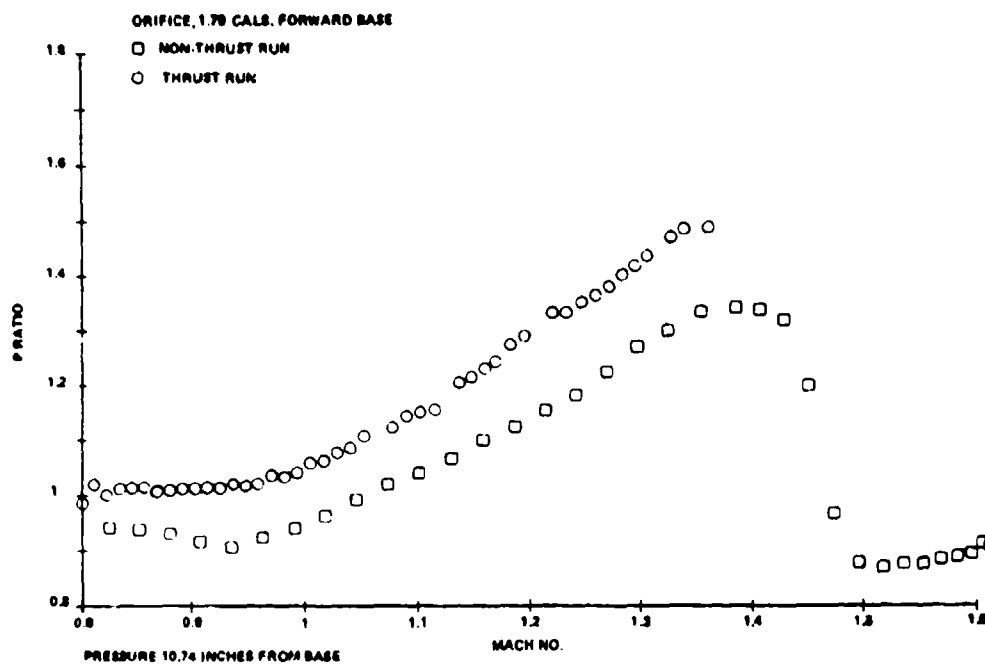


c. Pressure 5.82 inches from base

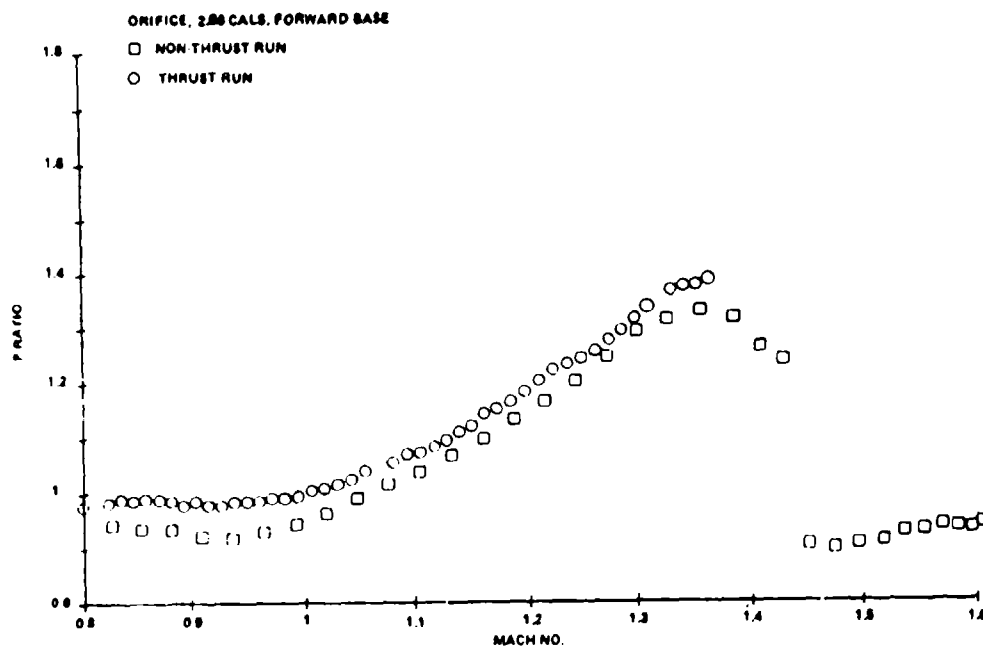


d. Pressure 7.5 inches from base

Figure 5. Continued

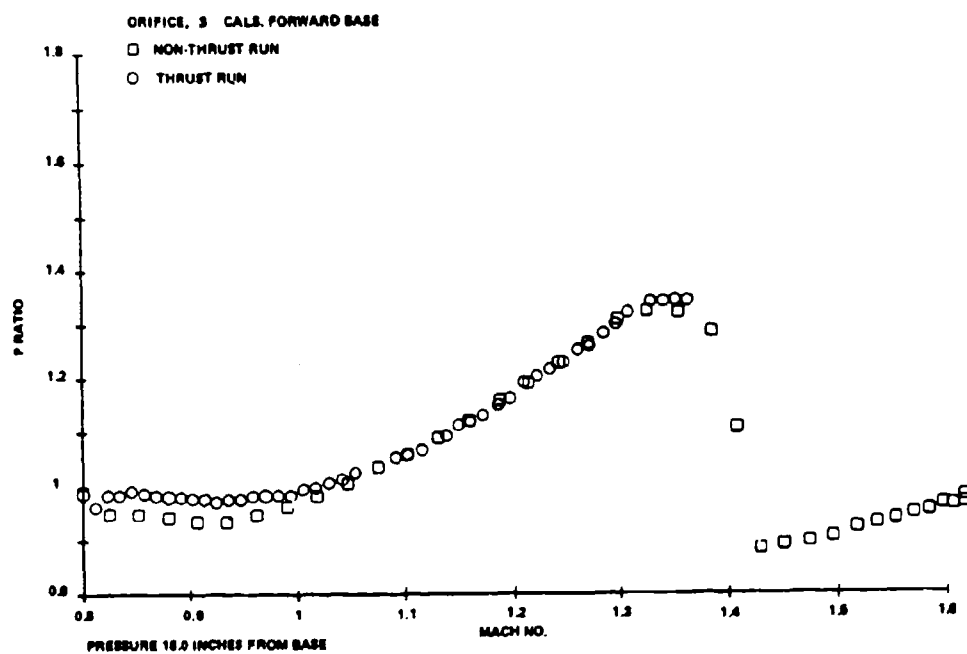


e. Pressure 10.74 inches from base



f. Pressure 15.36 inches from base

Figure 5. Continued



g. Pressure 18.0 inches from base

Figure 5. Continued

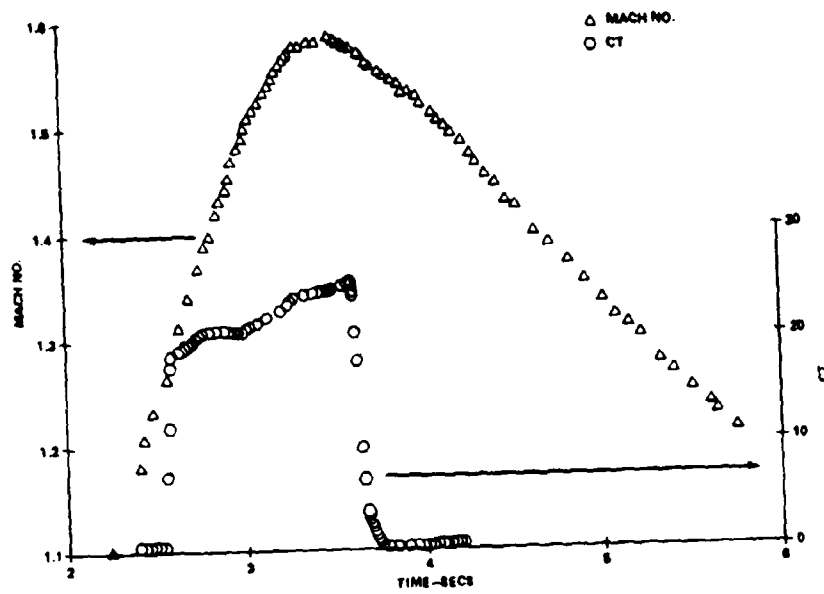
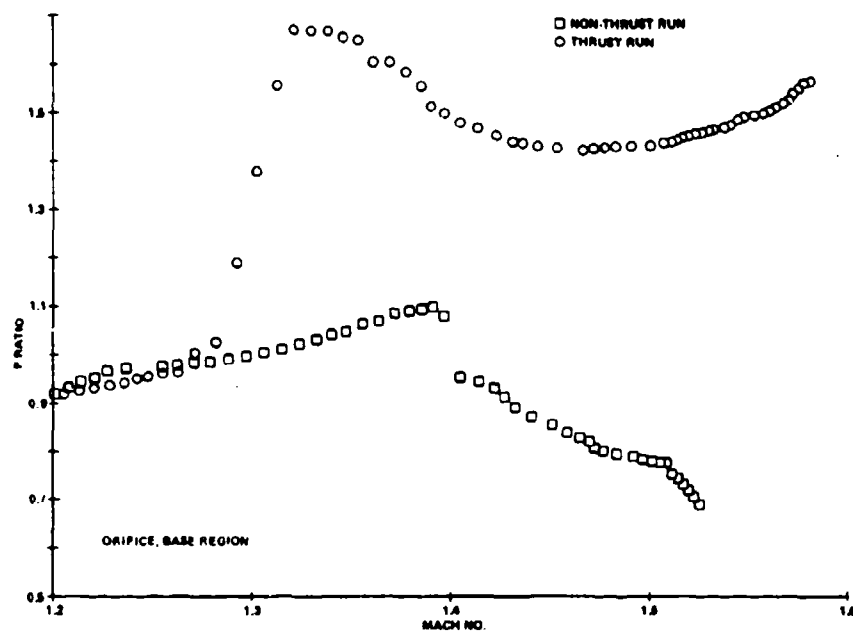
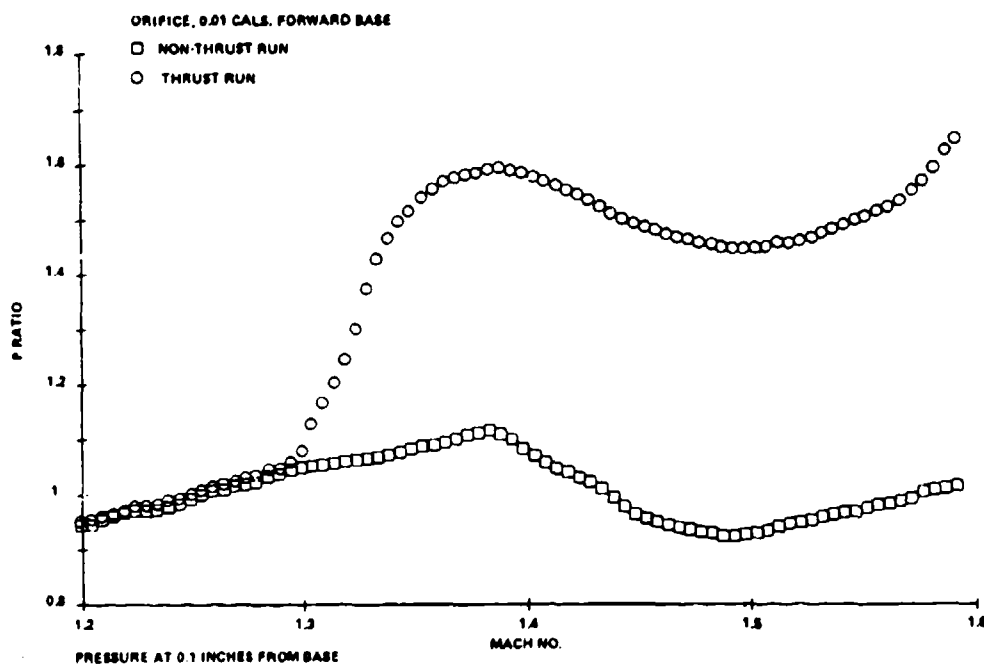


Figure 6. Mach no. and thrust history of run B-1

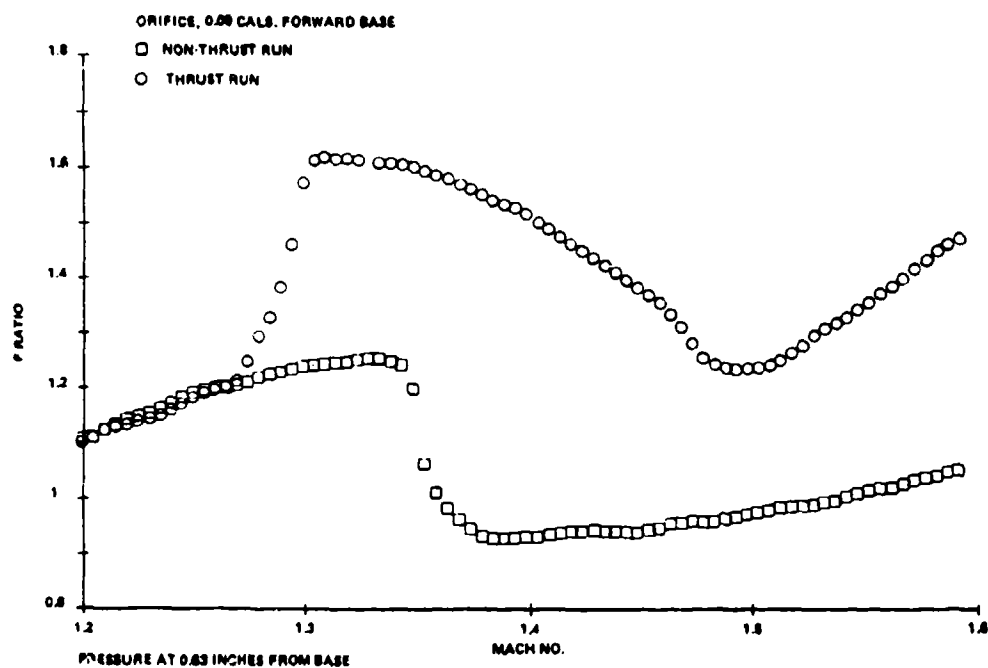


a. Base pressure

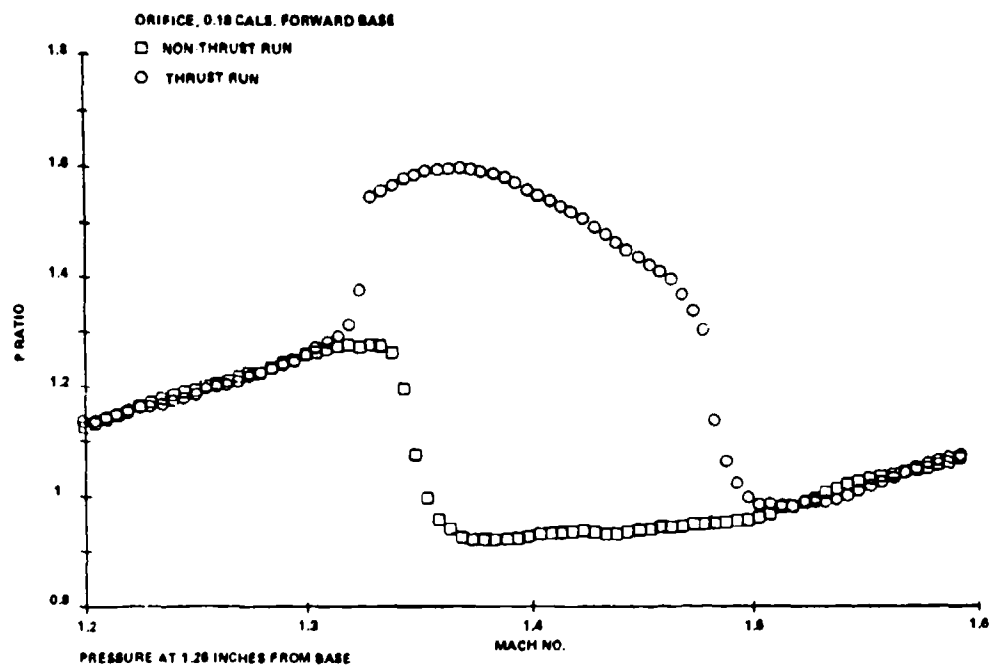


b. Pressure at 0.1 inches from base

Figure 7. Ratio of surface pressure to ambient pressure measured during run B-1

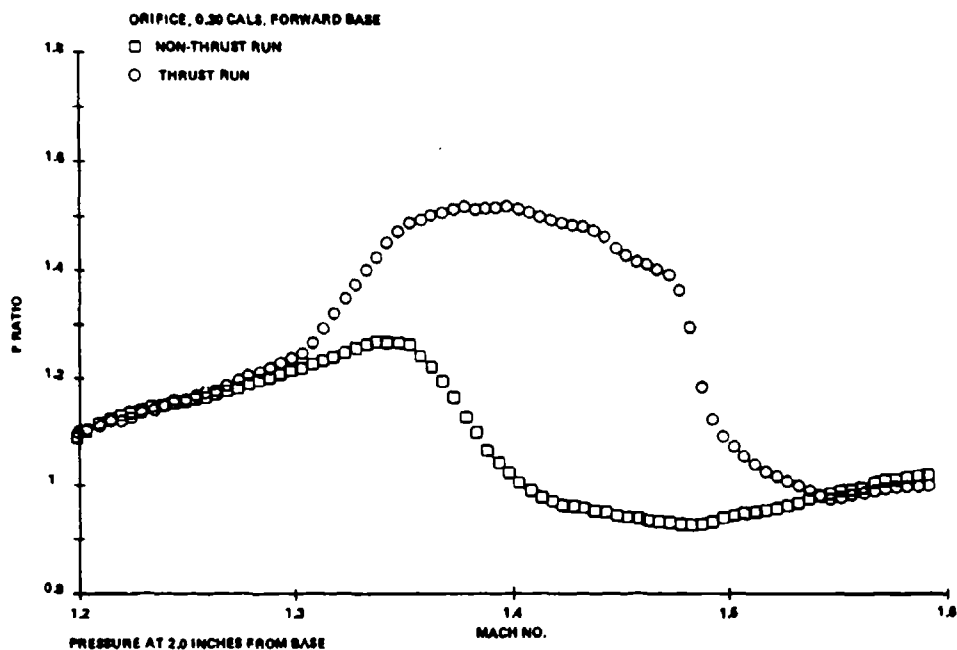


c. Pressure at 0.63 inches from base

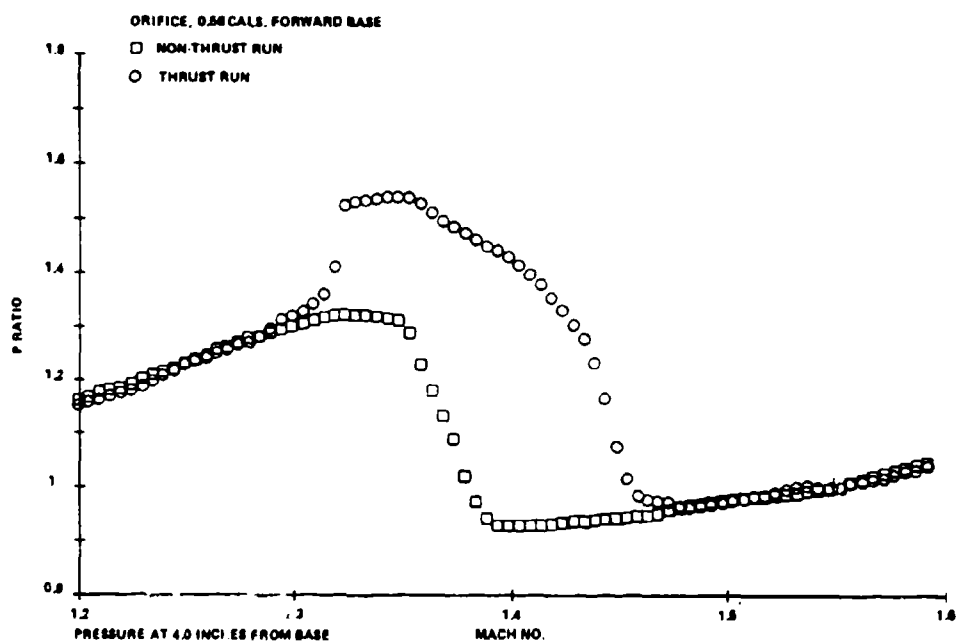


d. Pressure at 1.26 inches from base

Figure 7. Continued

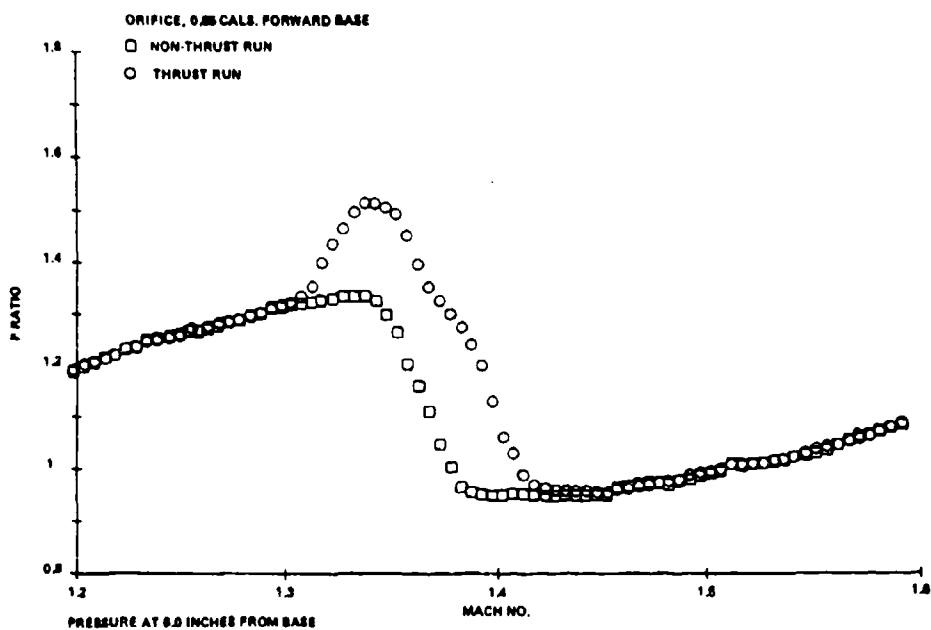


e. Pressure at 2.0 inches from base

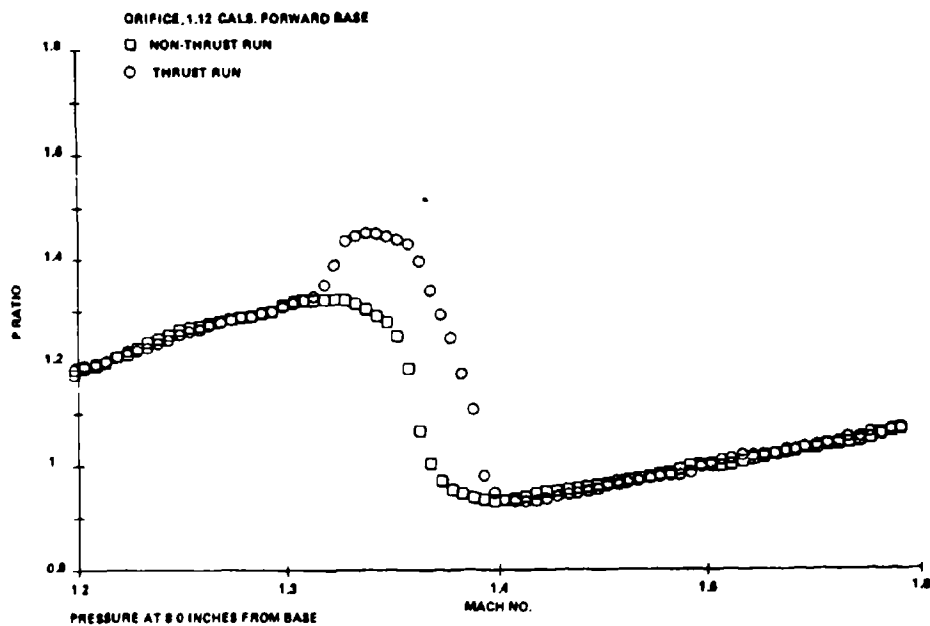


f. Pressure at 4.0 inches from base

Figure 7. Continued



g. Pressure at 6.0 inches from base



h. Pressure at 8.0 inches from base

Figure 7. Continued

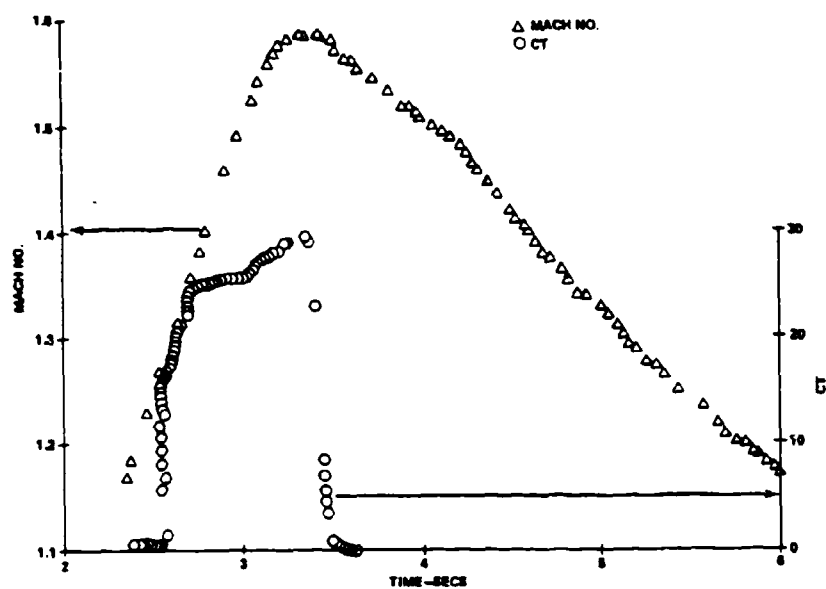
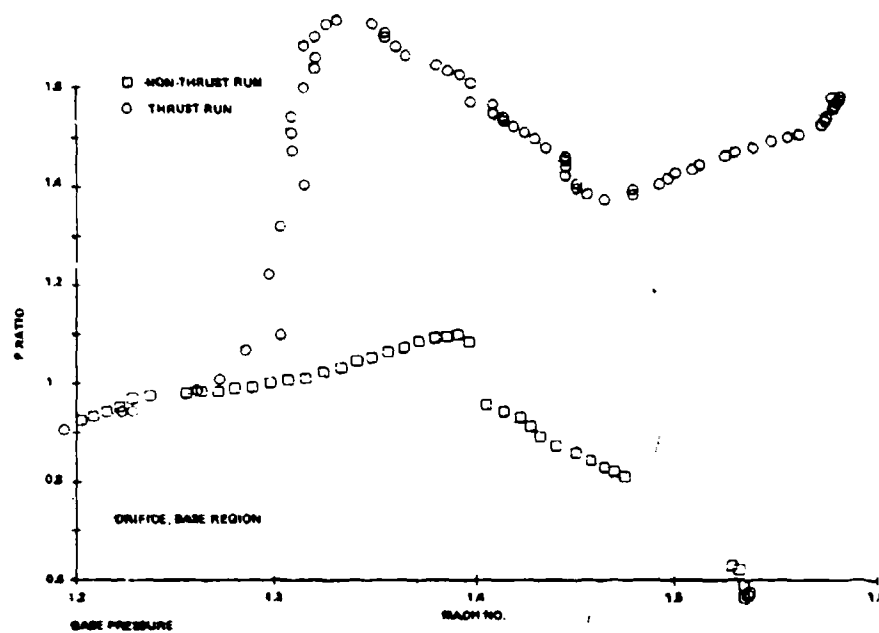
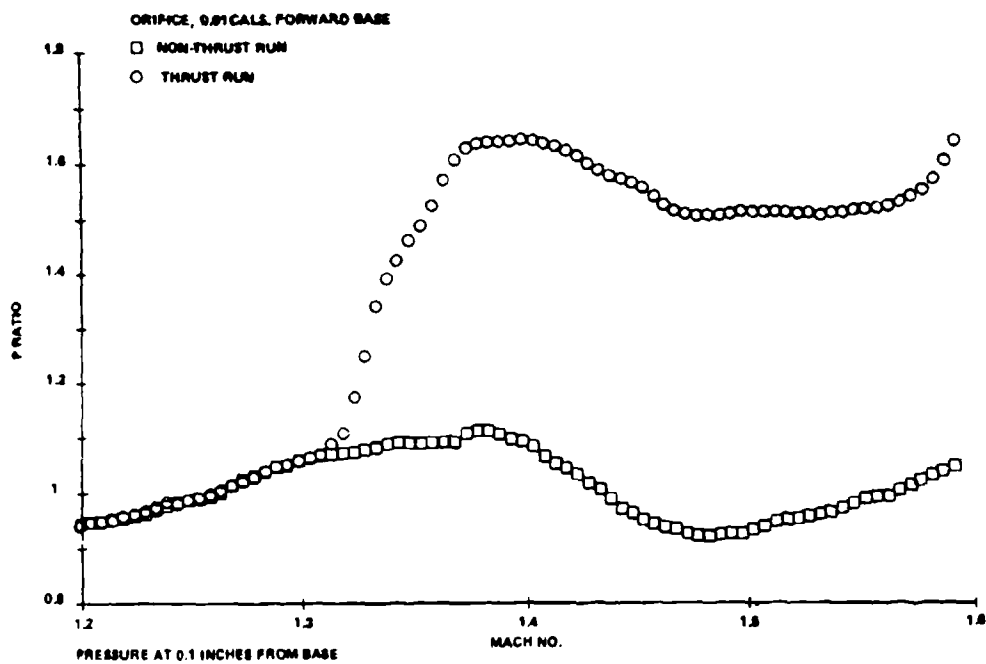


Figure 8. Mach no. and thrust history of run B-2

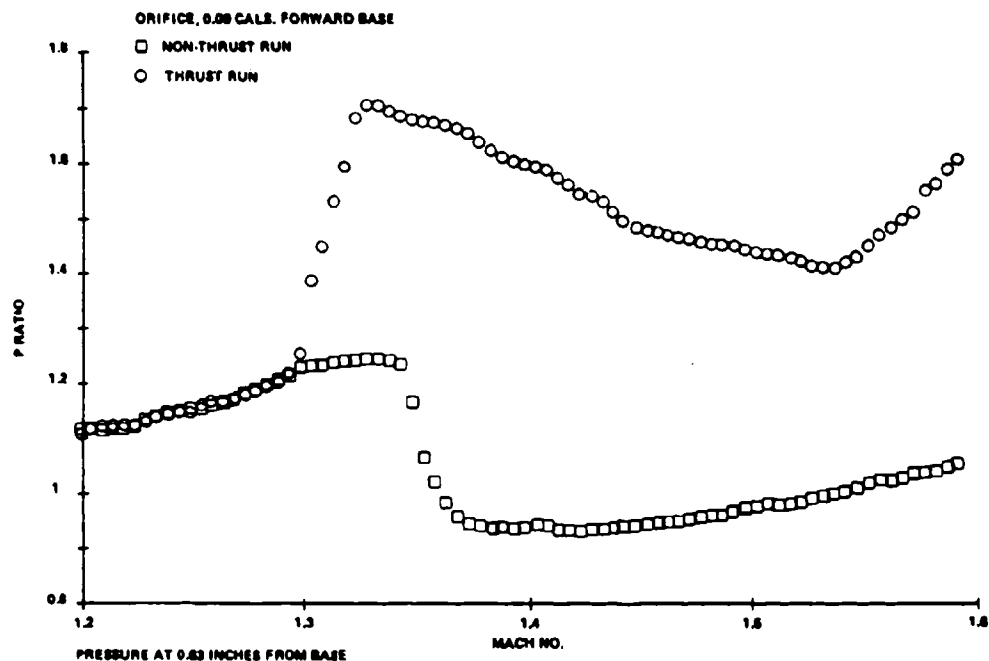


a. Base pressure

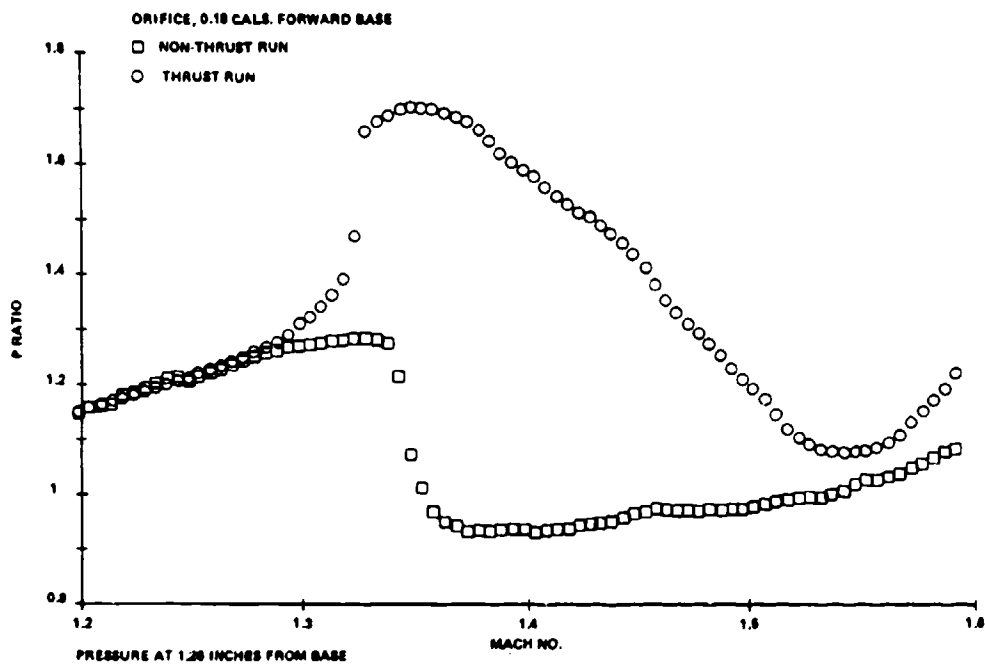


b. Pressure at 0.1 inches from base

Figure 9. Ratio of surface pressure to ambient pressure measured during run B-2

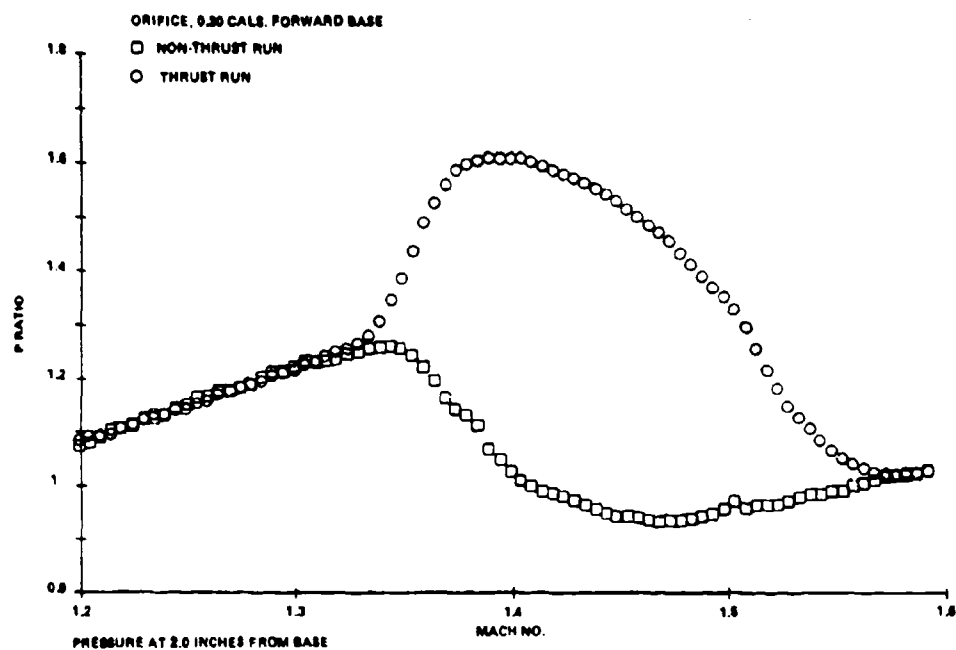


c. Pressure at 0.63 inches from base

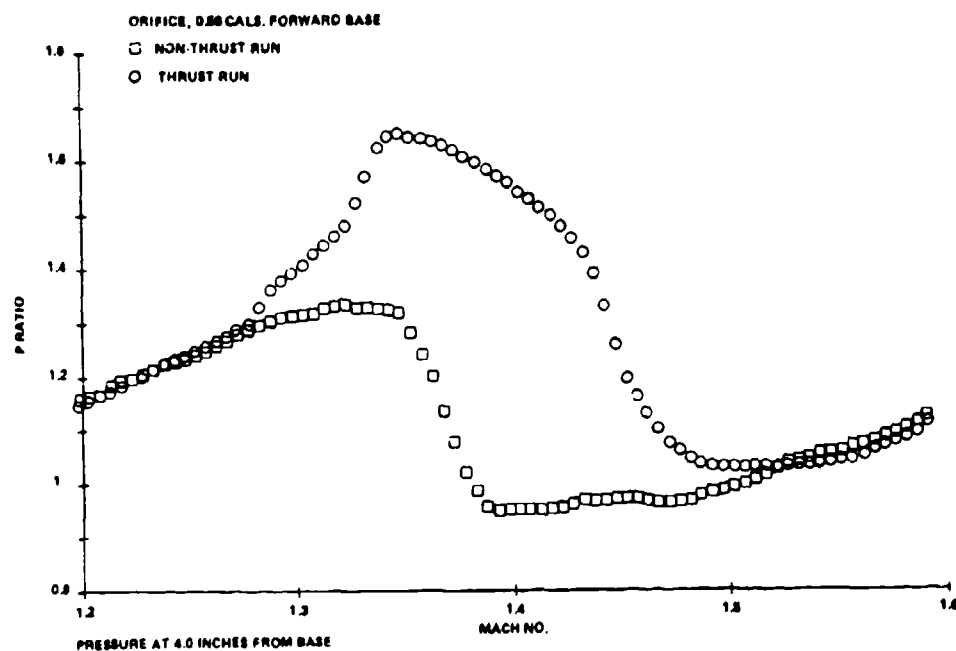


d. Pressure at 1.26 inches from base

Figure 9. Continued

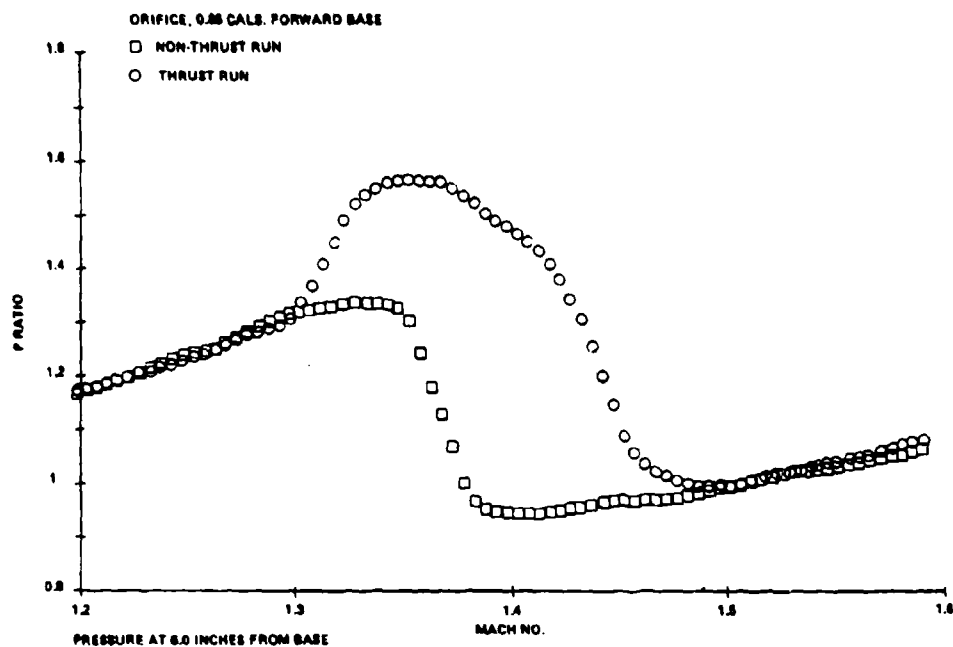


e. Pressure at 2.0 inches from base

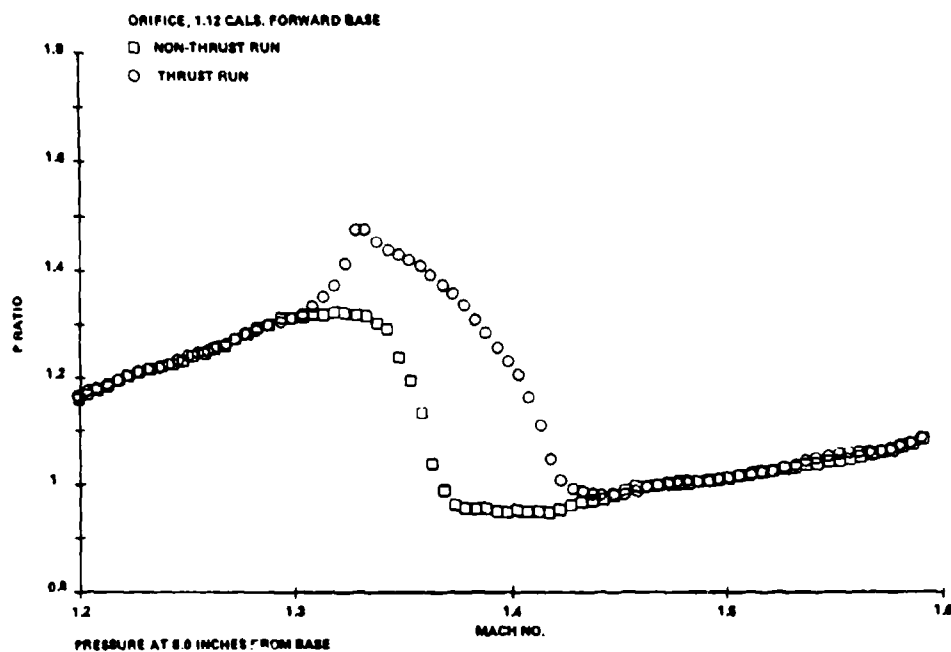


f. Pressure at 4.0 inches from base

Figure 9. Continued



g. Pressure at 6.0 inches from base

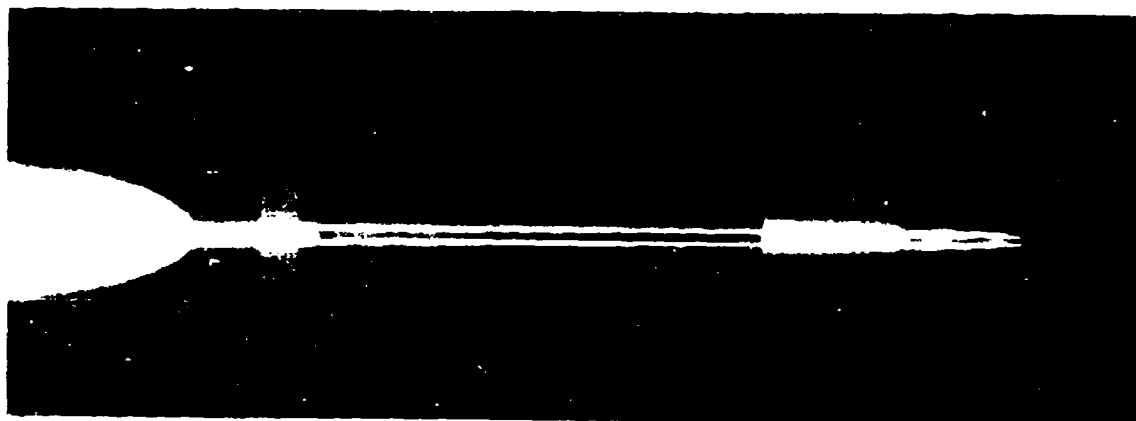


h. Pressure at 8.0 inches from base

Figure 9. Continued



a. Run B-1 ($M_{\infty}=1.410$, $CT=20.7$)



b. Run B-2 ($M_{\infty}=1.424$, $CT=24.6$)

Figure 10. Photographs of plumes produced during run B-1 and B-2

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