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VORTEX FLOW AND EROSION IN ROCKET NOZZLES DUE TO WARM-GAS INJECTION FOR THRUST VECTOR CONTROL

by G. Louis Smith

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VORTEX FLOW AND EROSION IN ROCKET NOZZLES DUE TO WARM-GAS INJECTION FOR THRUST VECTOR CONTROL

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SUMMARY

Rocket motors with an 1800° F (1255° K) gas secondary injection for thrust vector control have been fired in three ground tests. The thrust level of the primary motors was approximately 2700 pounds (12 000 newtons), and side forces of up to 160 pounds (710 newtons) were generated by a continuous-flow gas secondary-injection system. The duration of each firing was approximately 40 seconds.

Postfiring inspection of the graphite-tape nozzles showed considerable erosion in the region of the secondary-injection ports. The erosion was more pronounced in the nozzle with the secondary-injection ports upstream than in the nozzle with the secondary-injection ports near the exit plane. Photographs of the nozzles and contour maps of the erosion are presented.

Comparison of the erosion contours with pressure measurements and consideration of other flow studies indicate that the erosion is primarily due to the presence of vortices created by the gas secondary injection and that only a small amount of erosion is due to the impingement on the nozzle wall of the shock wave created by the secondary injection.

Erosion due to gas secondary injection is a factor which should be considered in the design of flight-weight nozzles. From the viewpoint of erosion, the secondary-injection ports should be as far downstream as possible. Also, consideration should be given to the vortices in the formulation of analytical descriptions of secondary injection.

INTRODUCTION

Many methods of steering rocket vehicles by thrust vector control have been proposed and used with varying degrees of success. Currently one of the most promising methods is hot-gas secondary injection (ref. 1). In order to study control-position properties, such as linearity and hysteresis, and in order to increase the understanding of the phenomena involved, the Langley

Research Center of NASA has conducted a joint program with two contractors. Because of the current state of the art in hardware for handling hot gases (at temperatures of 5000° F (3033° K) or greater), this program was concerned with warm gas (at temperatures of about 1800° F (1255° K)) for the secondary injectant. Under this program, the contractors designed, built, and tested a series of identical rocket motors with warm-gas secondary-injection thrust-vector-control systems.

Postfiring inspection of the rocket nozzles showed that considerable erosion had occurred as a result of the warm-gas secondary injection. The purpose of this report is to present data and to explain the causes of the erosion in terms of the nature of the flow field which is strongly influenced by the presence of vortices.

Measurements for the present investigation were taken in U.S. Customary Units. Equivalent values are indicated herein parenthetically in the International System of Units (SI). Details concerning the use of SI, together with physical constants and conversion factors, are given in reference 2.

APPARATUS AND TESTS

The warm-gas secondary-injection thrust-vector-control system, shown schematically in figure 1, is of the continuous-flow type, with control in one plane only. The primary rocket motor has a 22-inch-diameter (56 centimeters) end-burning grain, which uses a highly aluminized double-base propellant. The construction of the nozzle of the primary motor is shown in figure 2. The diverging portion of the nozzle is fabricated as follows: An insert was made from a single width of graphite-cloth-phenolic tape and asbestos-phenolic tape circumferentially wrapped in layers parallel to the center line. The insert was cured by a vacuum-bagging hydroclave technique, and then the 15° half-angle cone was machined. The throat section was made from a high-density graphite. Nominal values for the more important parameters of this motor and nozzle are listed in table I. The secondary injectant is a warm gas (1800° F or 1255° K) provided by an ammonium nitrate solid-propellant gas generator at a rate of 0.6 pound/sec (0.27 kilogram/sec). The gas flows from the gas generator into a proportional dividing valve, where it is divided and sent through the right and left secondary-injection ports. (See fig. 1.) The proportional dividing valve was programed to vary the mass flow of the warm gas through each secondary-injection port, so that the valve position moved through a series of steps and sine waves.

Three secondary-injection port configurations were tested; the primary nozzle construction was identical in each test. For nozzle 1, the secondary-injection ports were alined perpendicular to the center line of the primary nozzle at station 0.75 ($x/l = 0.75$ in fig. 2), and sonic injection was used. For nozzle 2, the secondary-injection ports were moved upstream to station 0.56, and a secondary-injection Mach number of 1.40 was used. The secondary-injection ports for nozzle 2 were also alined perpendicular to the center line of the primary nozzle. For nozzle 3, however, the secondary-injection ports were alined at an angle of 70° to the nozzle center line, exhausting upstream into the primary nozzle. The secondary-injection ports of nozzle 3 were at station 0.75, and a secondary-injection Mach number of 1.56 was used.

TABLE I.- NOMINAL VALUES OF PARAMETERS OF PRIMARY ROCKET MOTOR AND NOZZLE

Average thrust	2680 lbf	(1.19×10^4 N)
Mass flow rate	11.5 lbm/sec	(5.2 kg/sec)
Chamber pressure	550 psia	(3.78×10^6 N/m^2)
Combustion temperature	6290° F	(3750° K)
Specific-heat ratio		1.17
Burning time		40 sec
Throat area	3.008 in^2	(1.94×10^{-3} m^2)
Exit area	24.010 in^2	(1.55×10^{-2} m^2)
Nozzle expansion ratio		8:1
Percent aluminum		21.3

The rocket motor and its secondary-injection thrust-vector-control system were mounted on a six-component test stand. Measurements were taken of injector pressures, primary-motor chamber pressures, and nozzle wall pressures at a number of places. Injector and primary-motor temperatures were also measured.

RESULTS AND DISCUSSION

Postfiring inspection of each primary nozzle showed definite erosion patterns around the injection ports due to the warm-gas secondary injection. During the tests, side forces of up to 160 pounds (710 newtons) were generated by the secondary-injection thrust-vector-control system, giving a thrust-vector angle of approximately 3.5°. The right and left injector pressures and side forces are shown in figures 3, 4, and 5 for nozzles 1, 2, and 3, respectively.

Photographs showing the portions of the primary nozzle eroded by the warm-gas secondary injection are presented in figures 6(a) to 6(f). These photographs were taken by lighting the nozzle so as to accentuate the erosion and show the main features of the erosion pattern. The valve was programed so that the right port had a greater net flow than did the left port. Consequently, the erosion around the right port was somewhat greater than that around the left port; this difference can be seen by comparing figures 6(a) and 6(b). The predominant feature of the erosion patterns is a deep valley which extends around the upstream side of the injection port and trails back downstream. A fainter line shows the location of the bow shock-wave impingement on the primary-nozzle wall. The region between the valley and the line of the shock-wave impingement appears to have a coarser surface than the region outside the shock wave; this difference is particularly noticeable in figures 6(b) and 6(c). One feature peculiar to figure 6(a) is a sharp built-up ridge beside the valley, downstream of the injection port.

For each of the three nozzles, measurements were made of the difference in radius between various points of the nozzle wall influenced by the secondary-injection flow and points at the same longitudinal stations but well outside the influence of the secondary-injection flow. These measurements were thus of the erosion which occurred in excess of the erosion normally found in rocket nozzles, and as such indicate relative rather than absolute erosion. The measurements were used to construct contour maps of the erosion patterns, which are shown in figures 7(a) to 7(f). Areas where the surface flaked off are indicated by short-dash lines, and the positions of the shock waves for full secondary-injection flow are indicated by long-dash lines. The shock-wave positions were determined from pressure measurements at the nozzle wall. As can be seen in figure 7(d), up to 0.2 inch (0.5 centimeter) more erosion occurs in the vicinity of the secondary-injection ports than in other sections of the rocket nozzle.

The erosion contour diagrams show quantitatively the features seen in the photographs. The greatest erosion occurs well behind the shock wave and does not appear to be caused by the shock wave. Also, comparison of figures 7(a) and 7(b) with figures 7(c) and 7(d) shows that the erosion is twice as great for the secondary-injection ports upstream as for the secondary-injection ports near the exit plane.

The erosion patterns in the vicinity of the secondary-injection ports are a direct result of the nature of the flow induced by secondary injection. In reference 1, the flow field due to gas secondary injection is considered to consist of a secondary injectant which turns sharply to follow the primary-nozzle wall, a separated region ahead of the secondary-injection port, and an accompanying oblique separation shock. References 3 and 4 point out that behind the shock wave there are vortices in the flow which start at the secondary-injection port and extend downstream almost parallel to the primary-nozzle wall. Reference 4 further points out that the shear on the wall adjacent to the vortex is high because of the high velocity induced by the vortex. The erosion contours of figures 7(a) to 7(d) are very similar to the oil-film streaklines and lines of constant ratio of pressure of figures 4 and 5 in reference 4. It is seen then that the valleys constituting the most prominent part of the erosion pattern may be attributable to the vortices. The vortex is seen to have a significant influence on the flow field; however, this effect has not been considered in the formulation of known analytical models. The side force generated by secondary injection may be significantly affected by this vortex, and this possibility should be considered in the formulation of analytical models of secondary injection.

The erosion in configuration 2, in which the secondary-injection port is well upstream (station 0.56), is much more severe than in configuration 1, in which the secondary-injection port is at the longitudinal station 0.75. This increase in erosion is due to the higher pressure and temperature at the upstream position. The design of a nozzle with a hot- or warm-gas secondary-injection thrust-vector-control system would have to provide a sufficient thickness of the nozzle in the regions of severe erosion. Because additional nozzle material for an upstream secondary-injection port would increase the weight, it would be advantageous to have this port close to the exit plane.

The difficulty of estimating the erosion depth with a high degree of assurance is exemplified in figure 7(f). The symmetry of the other erosion patterns, which would be expected, is missing from this figure; the erosion on one side is double that on the other side. The cause of this anomaly is unknown, but it is possibly due to small variations in the material and construction of the nozzle.

CONCLUSIONS

A study has been made of the erosion due to the use of secondary injection in a rocket nozzle for thrust vector control. Three different secondary-injection port configurations were tested and the following conclusions were made:

1. A warm-gas secondary injection in the nozzle of a rocket motor causes considerable erosion.

2. For the present tests, up to 0.2 inch (0.5 centimeter) more erosion occurs in the vicinity of the secondary-injection ports than in other sections of the rocket nozzle.

3. The erosion is not directly due to the shock wave formed in the nozzle by secondary injection, but appears to be due to the presence of a vortex induced by the secondary injection.

4. The erosion should be considered in the design of a nozzle with a hot- or warm-gas secondary-injection system.

5. Consideration of the increased erosion for configurations with the secondary-injection port upstream indicates that the hot- or warm-gas secondary-injection ports should be placed as close to the exit plane of the nozzle as possible.

6. Some consideration should be given to the presence of vortex flow in formulating analytical descriptions of secondary injection.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 4, 1965.

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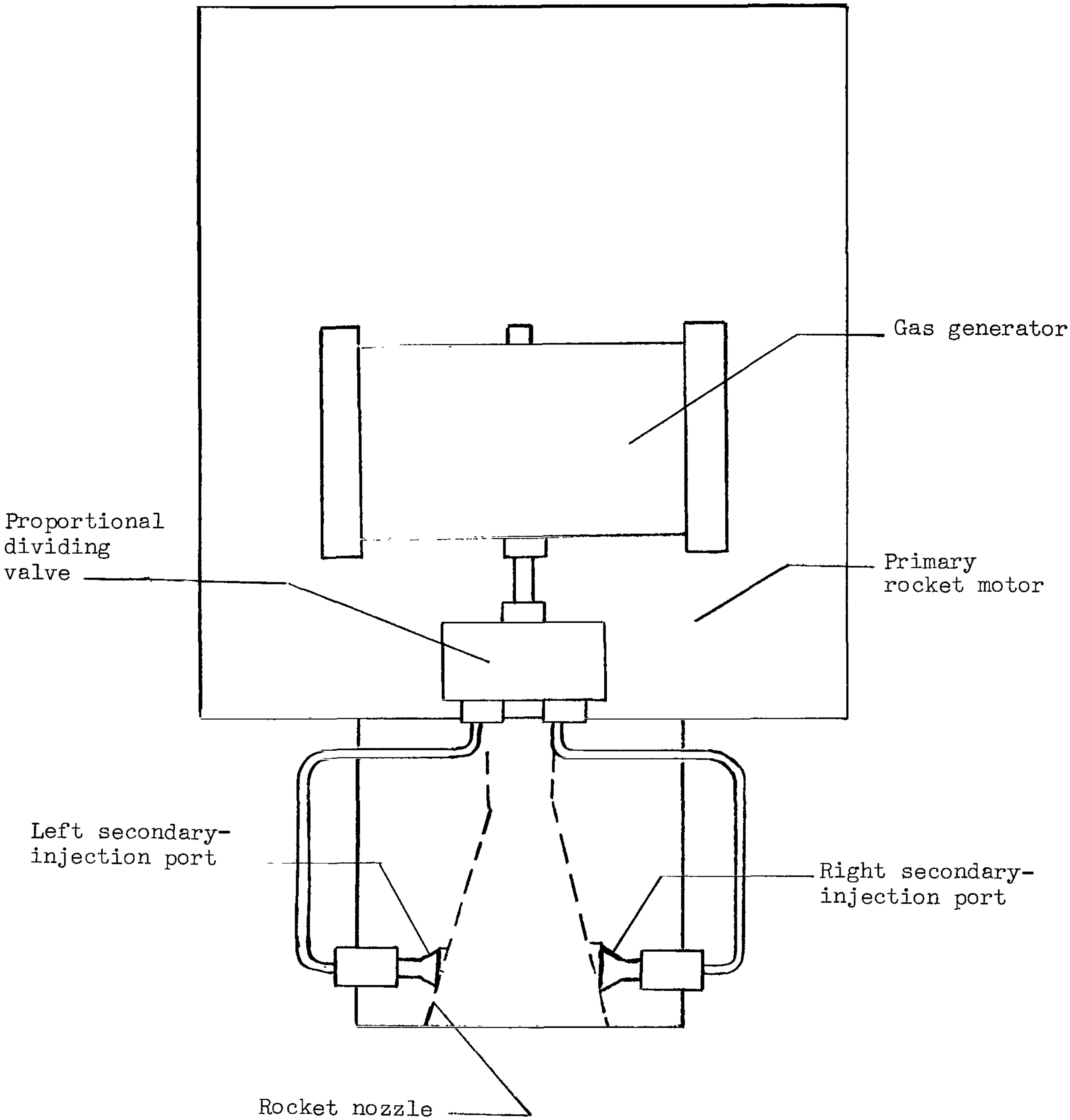
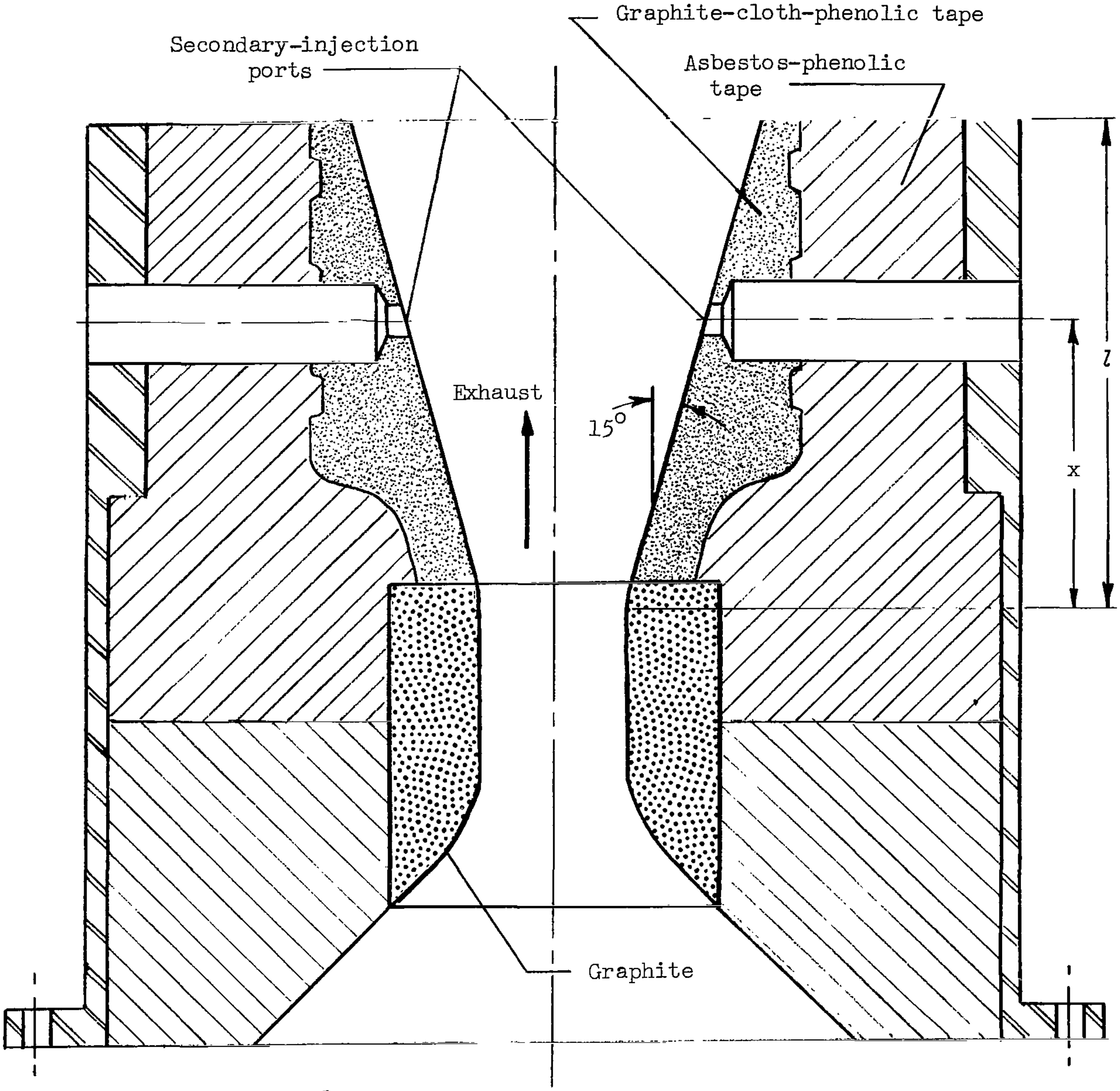


Figure 1.- Schematic drawing of warm-gas secondary-injection thrust-vector-control system mounted on primary rocket motor.



Nozzle	x/l
1	0.75
2	.56
3	.75

Figure 2.- Rocket nozzle with secondary-injection ports.

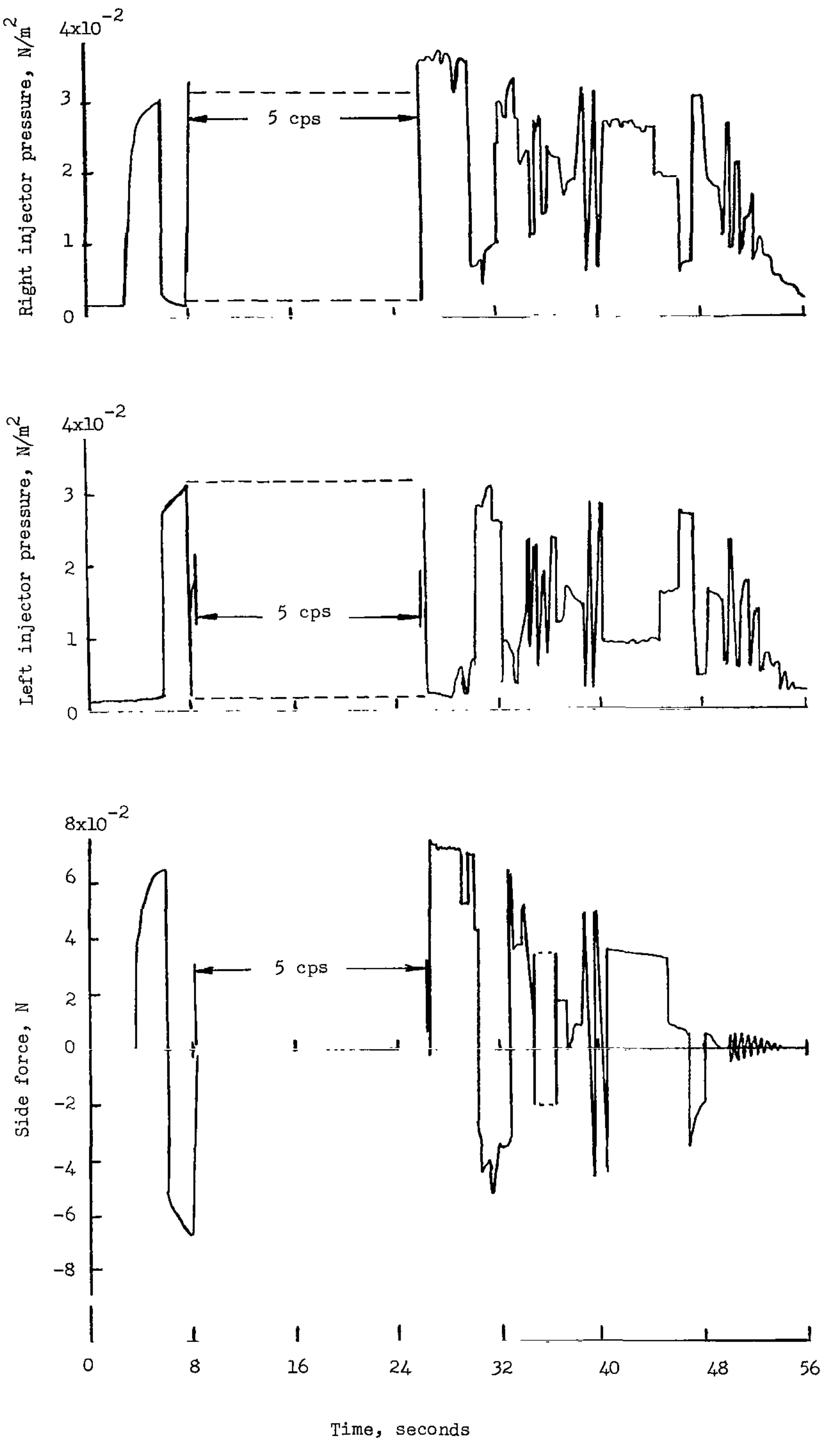


Figure 3.- Injector pressures and side force measured during testing of nozzle 1.

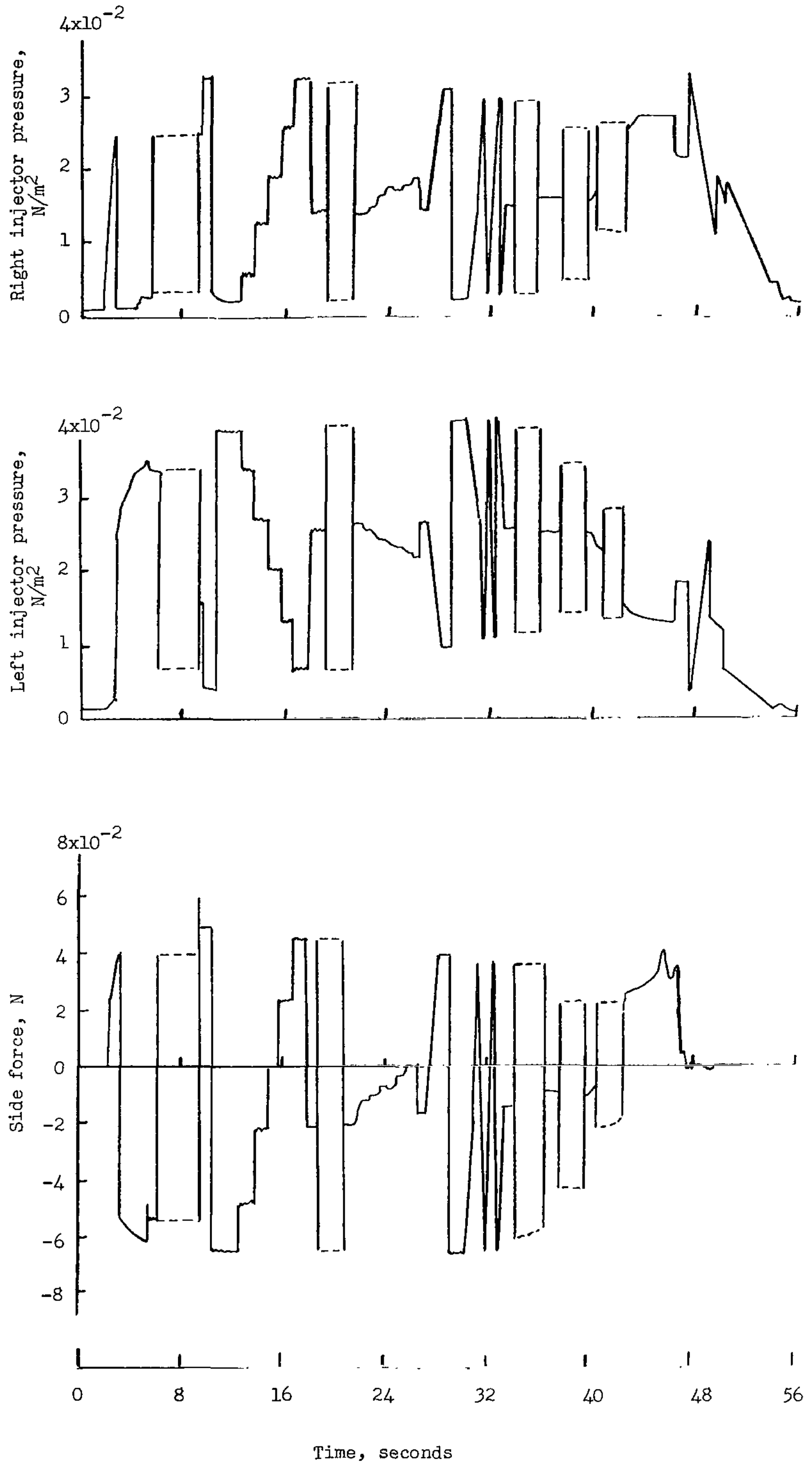


Figure 4.- Injector pressures and side force measured during testing of nozzle 2.

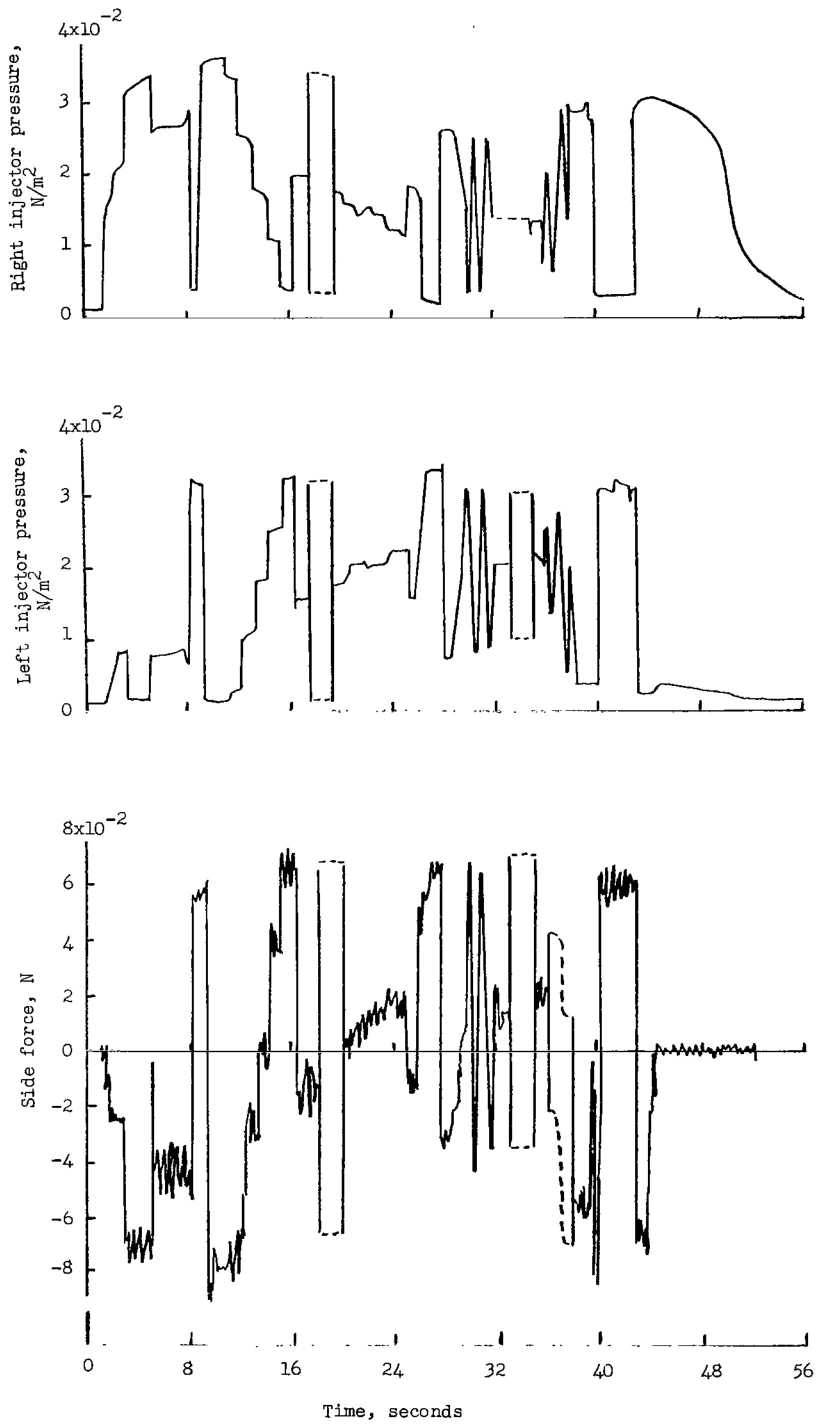
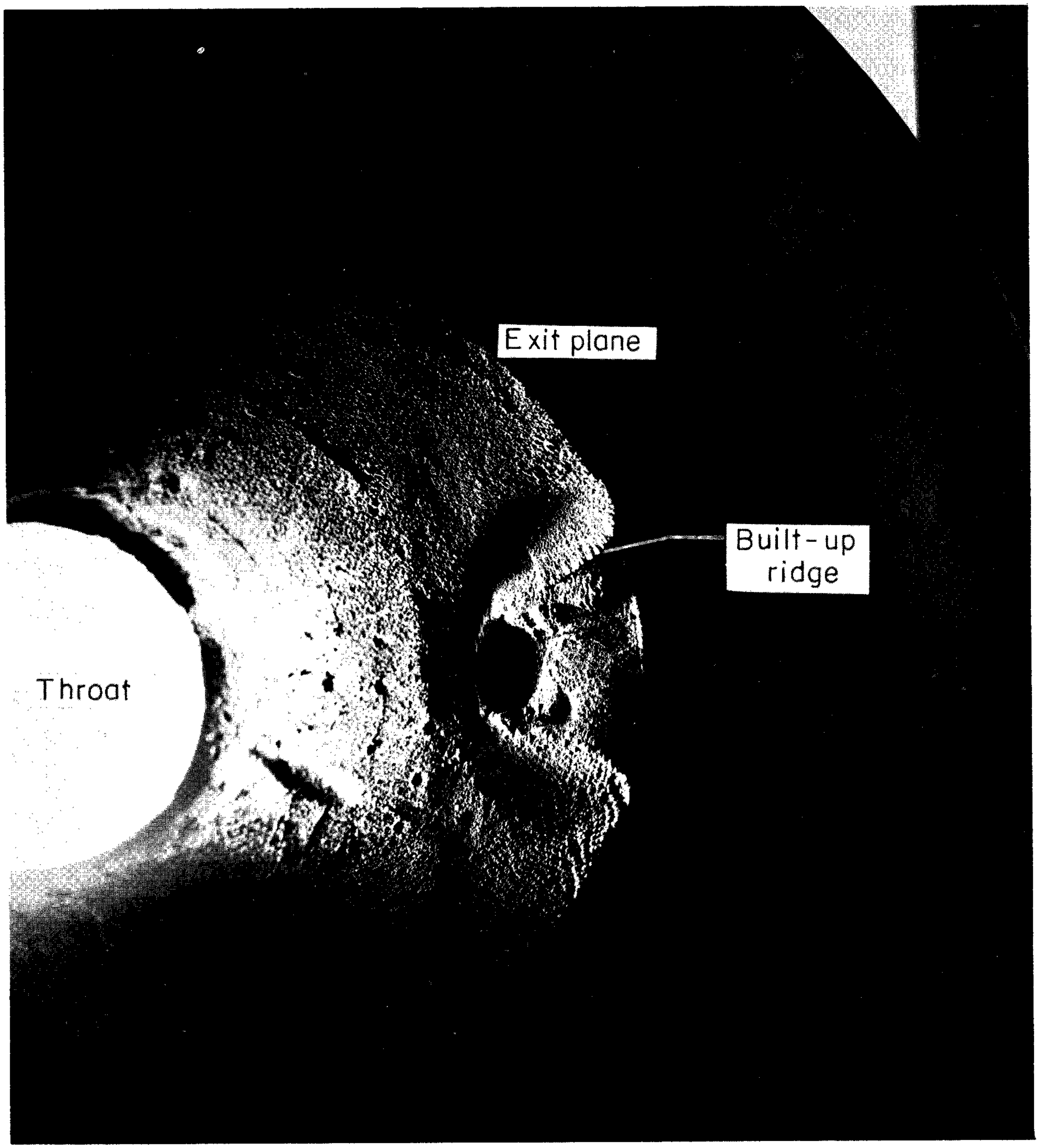
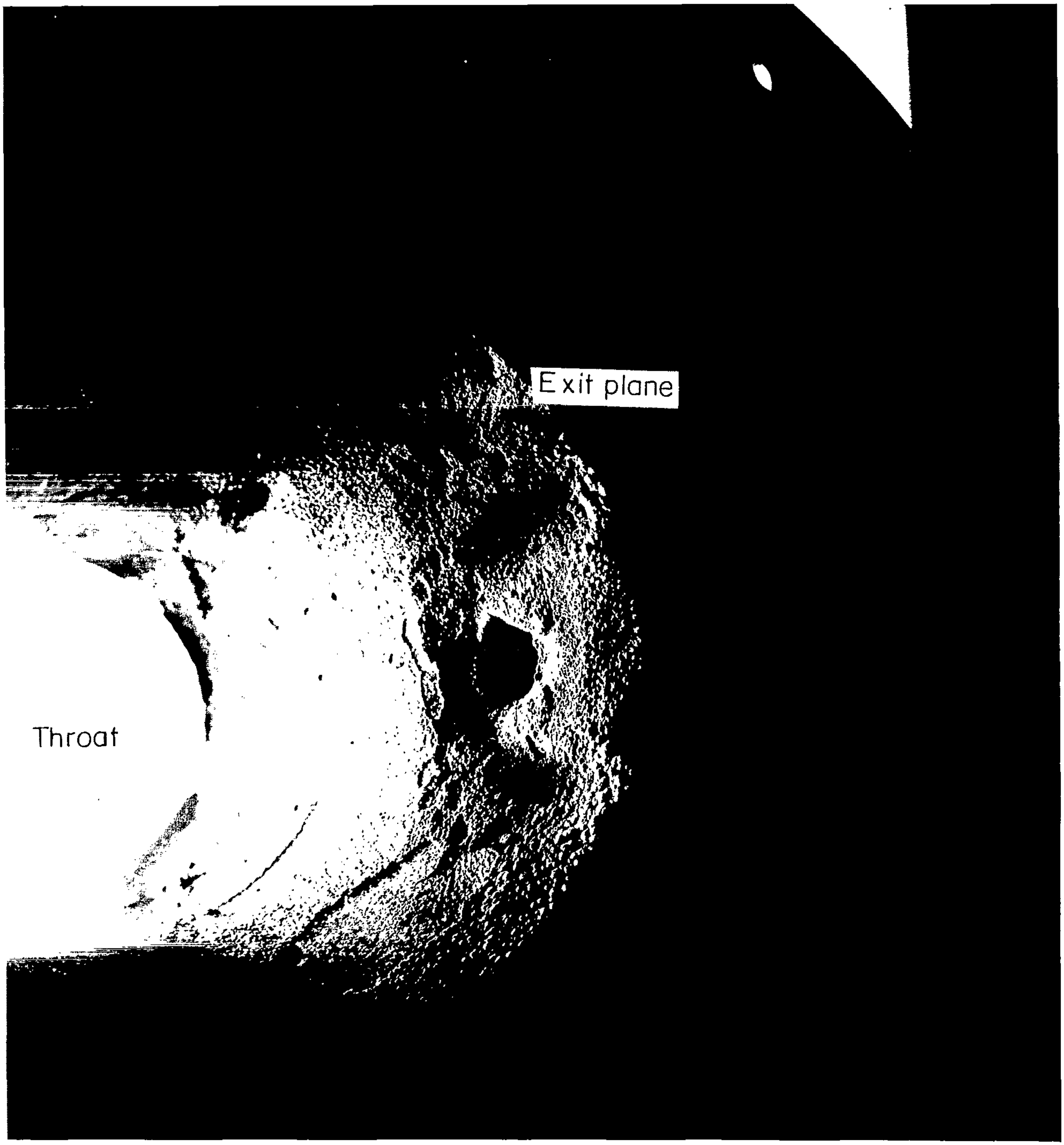


Figure 5.- Injector pressures and side force measured during testing of nozzle 3.



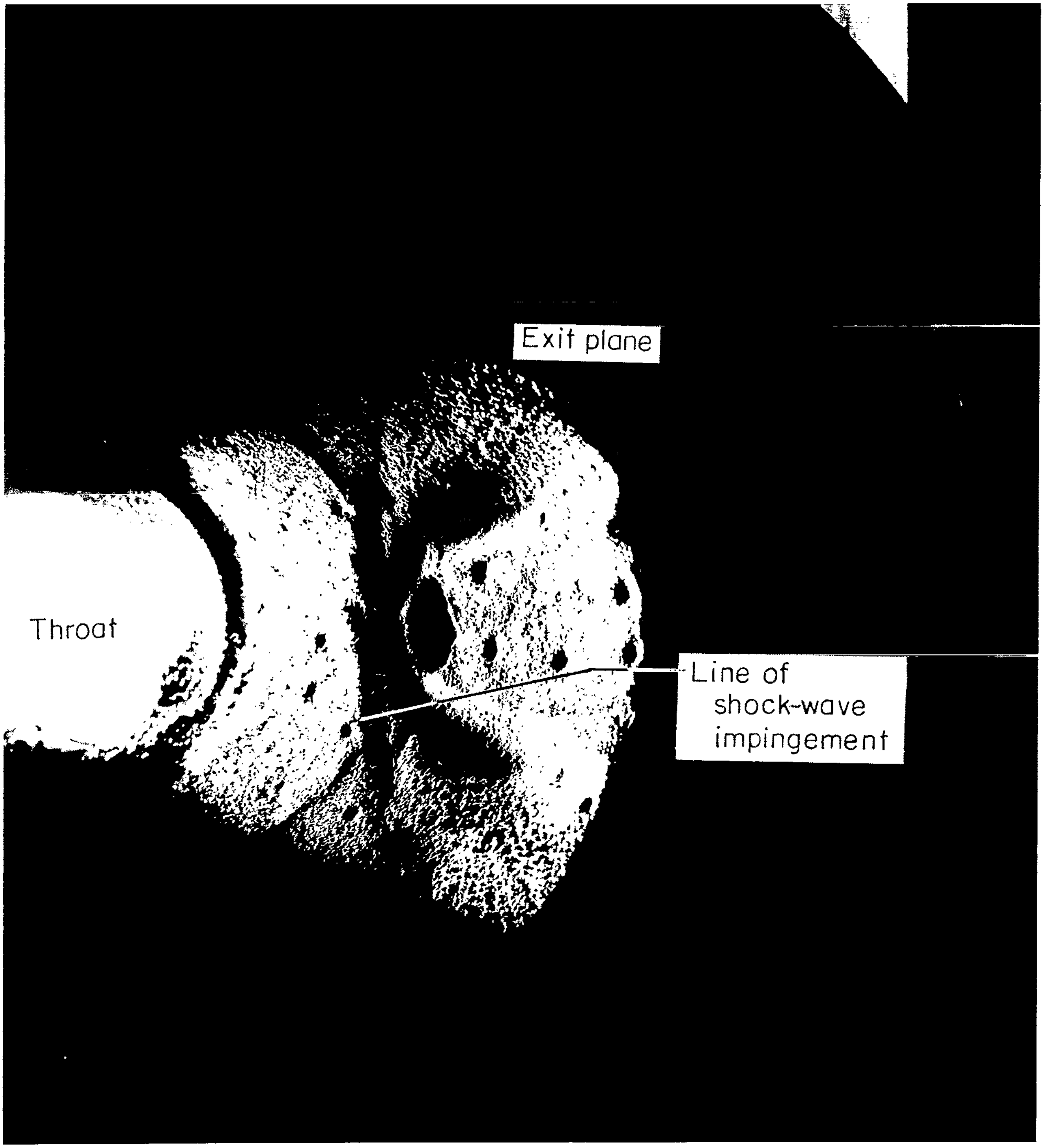
(a) Vicinity of right injection port of nozzle 1. L-65-1076.1

Figure 6.- Photographs showing erosion due to warm gas secondary injection; view looking upstream.



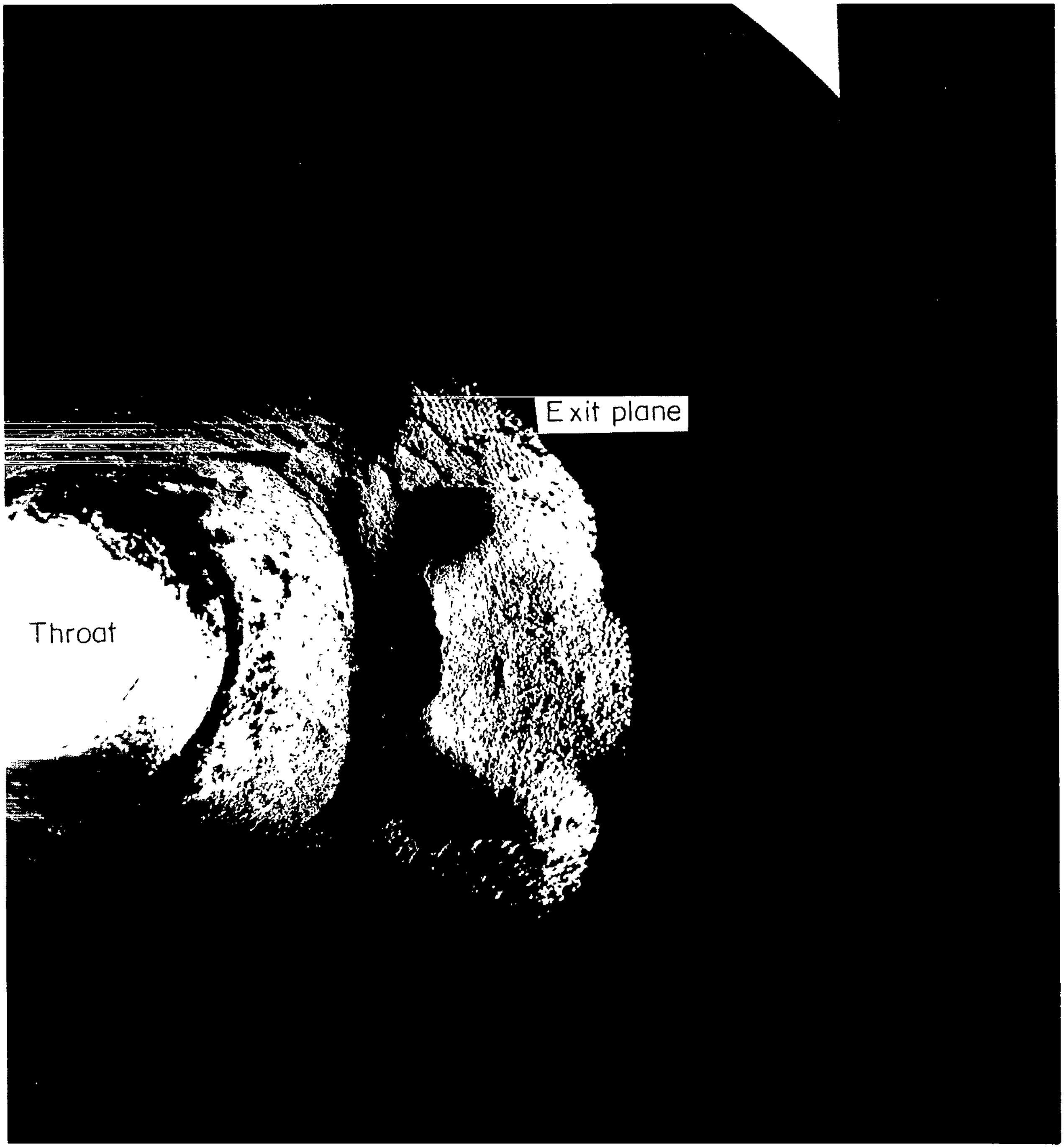
(b) Vicinity of left injection port of nozzle 1. L-65-1077.1

Figure 6.- Continued.



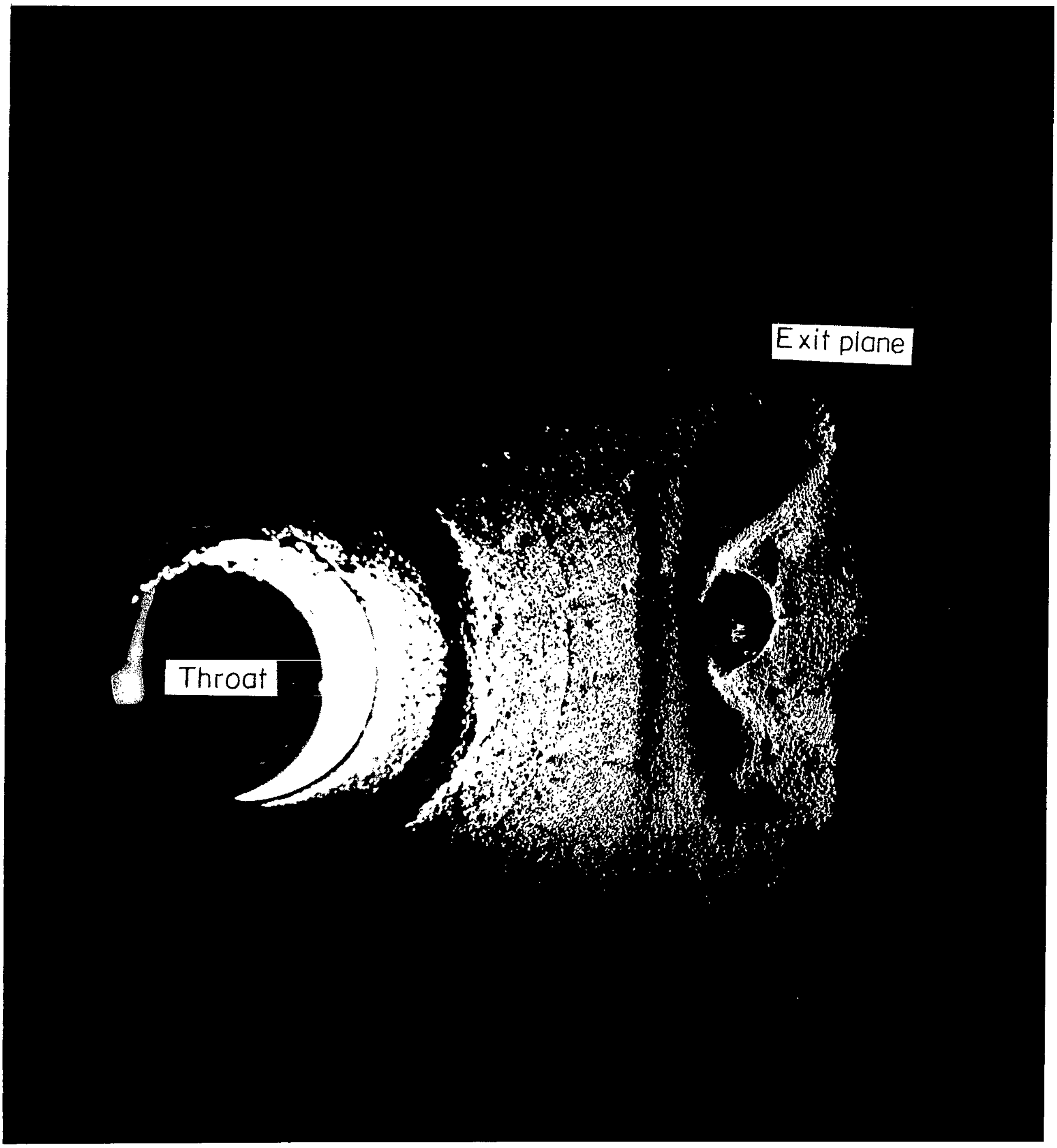
(c) Vicinity of right injection port of nozzle 2. L-65-1075.1

Figure 6.- Continued.



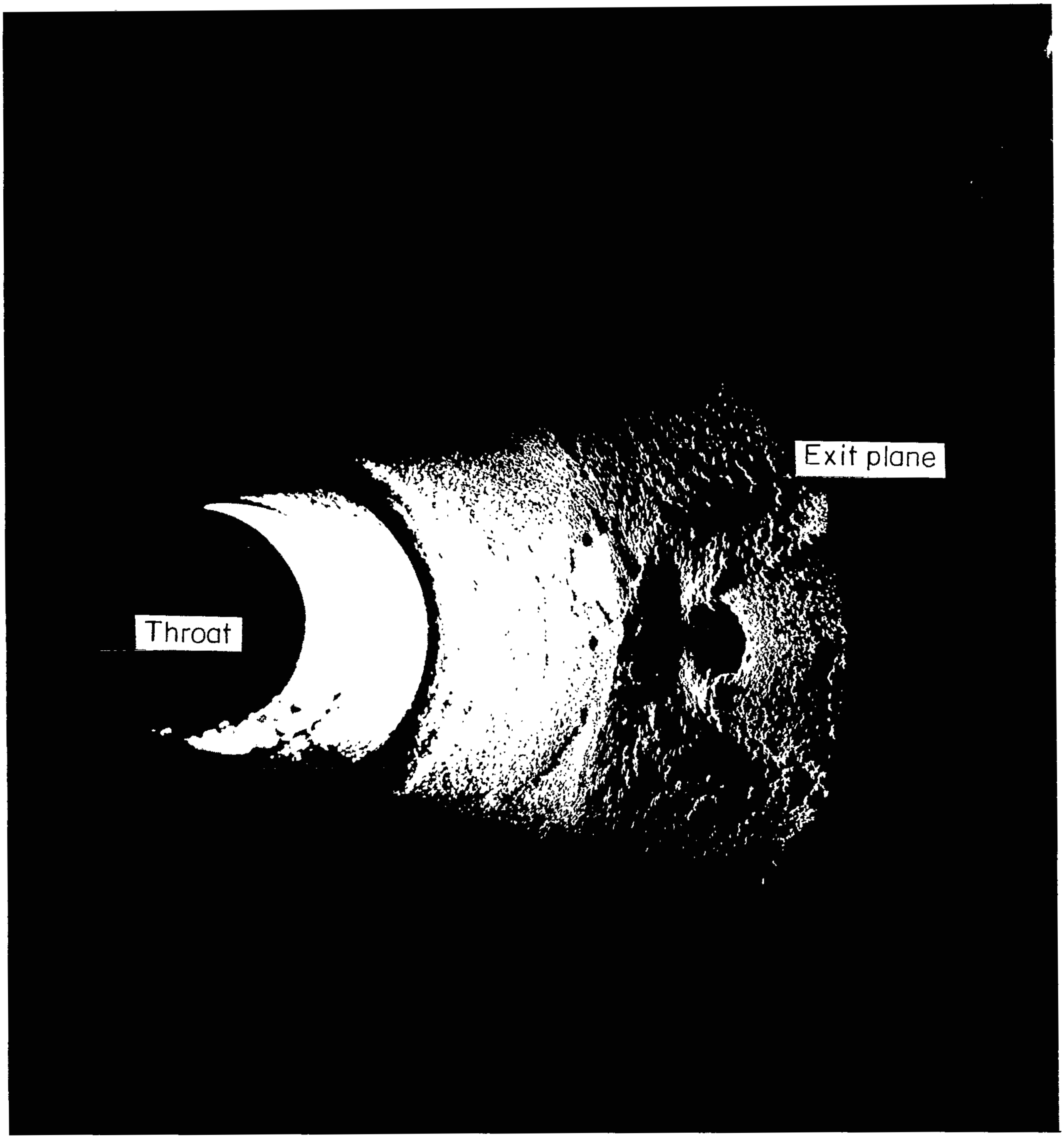
(d) Vicinity of left injection port of nozzle 2. L-65-1078.1

Figure 6.- Continued.



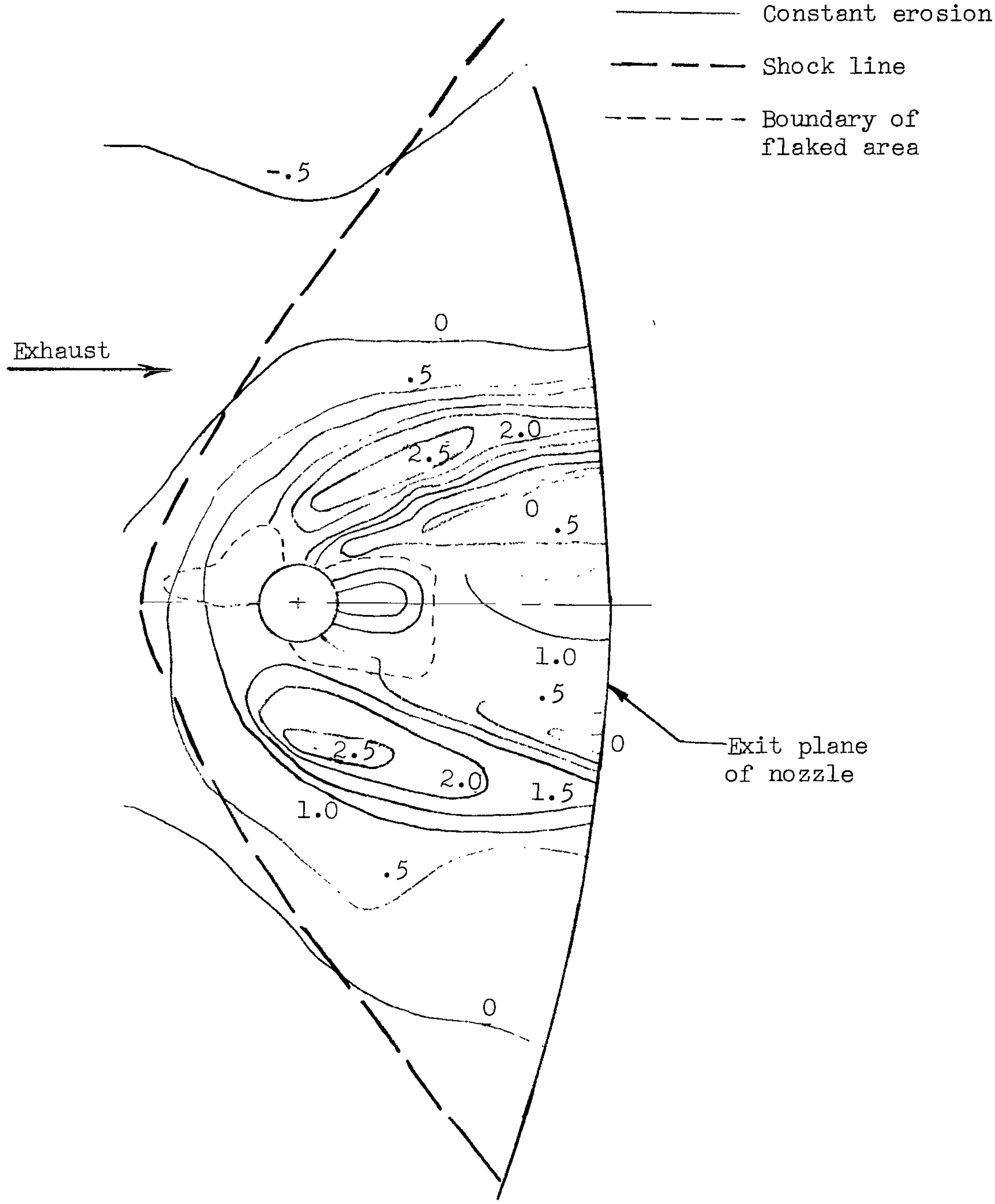
(e) Vicinity of right injection port of nozzle 3. L-65-2156.1

Figure 6.- Continued.



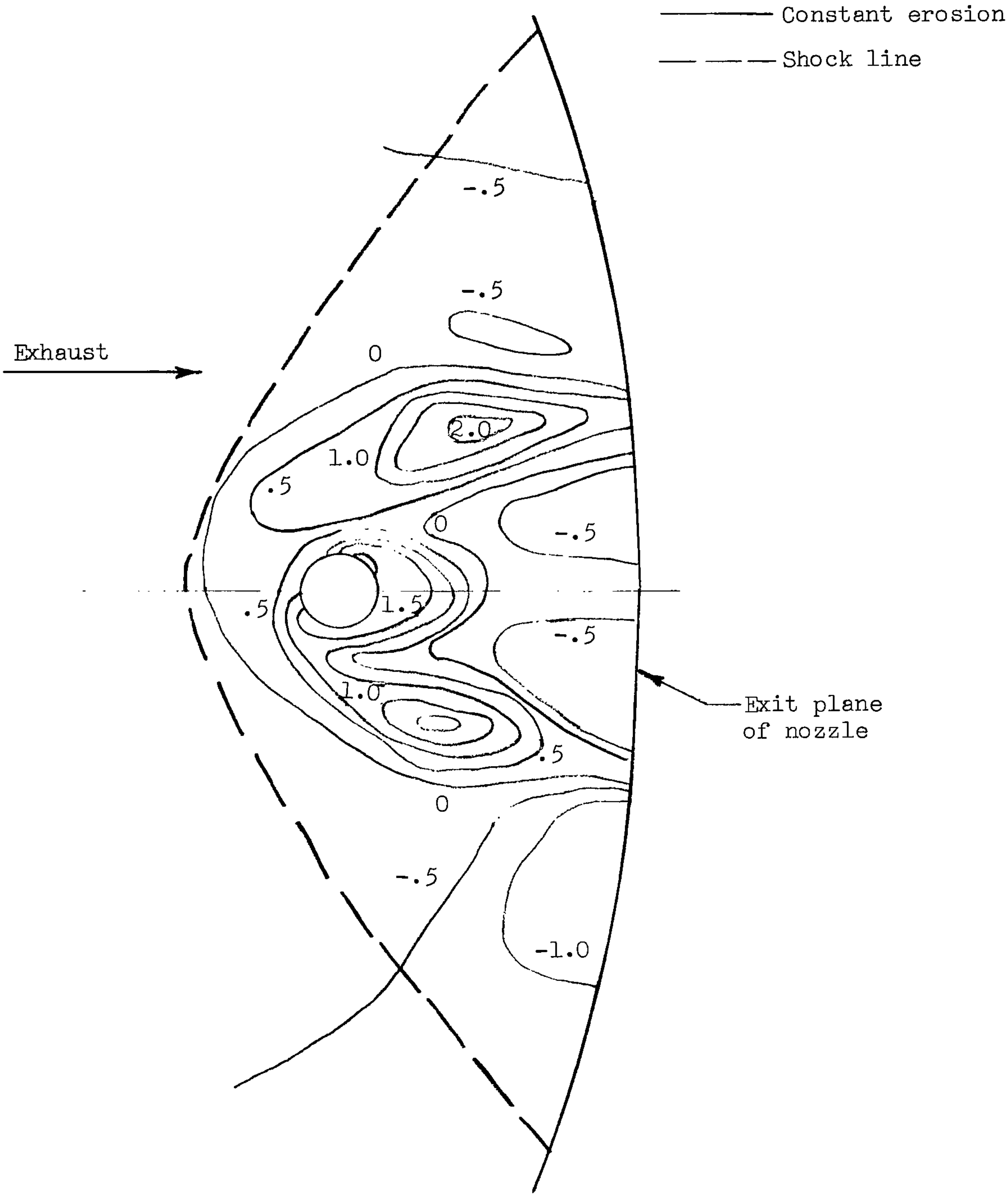
(f) Vicinity of left injection port of nozzle 3. L-65-2155.1

Figure 6.- Concluded.



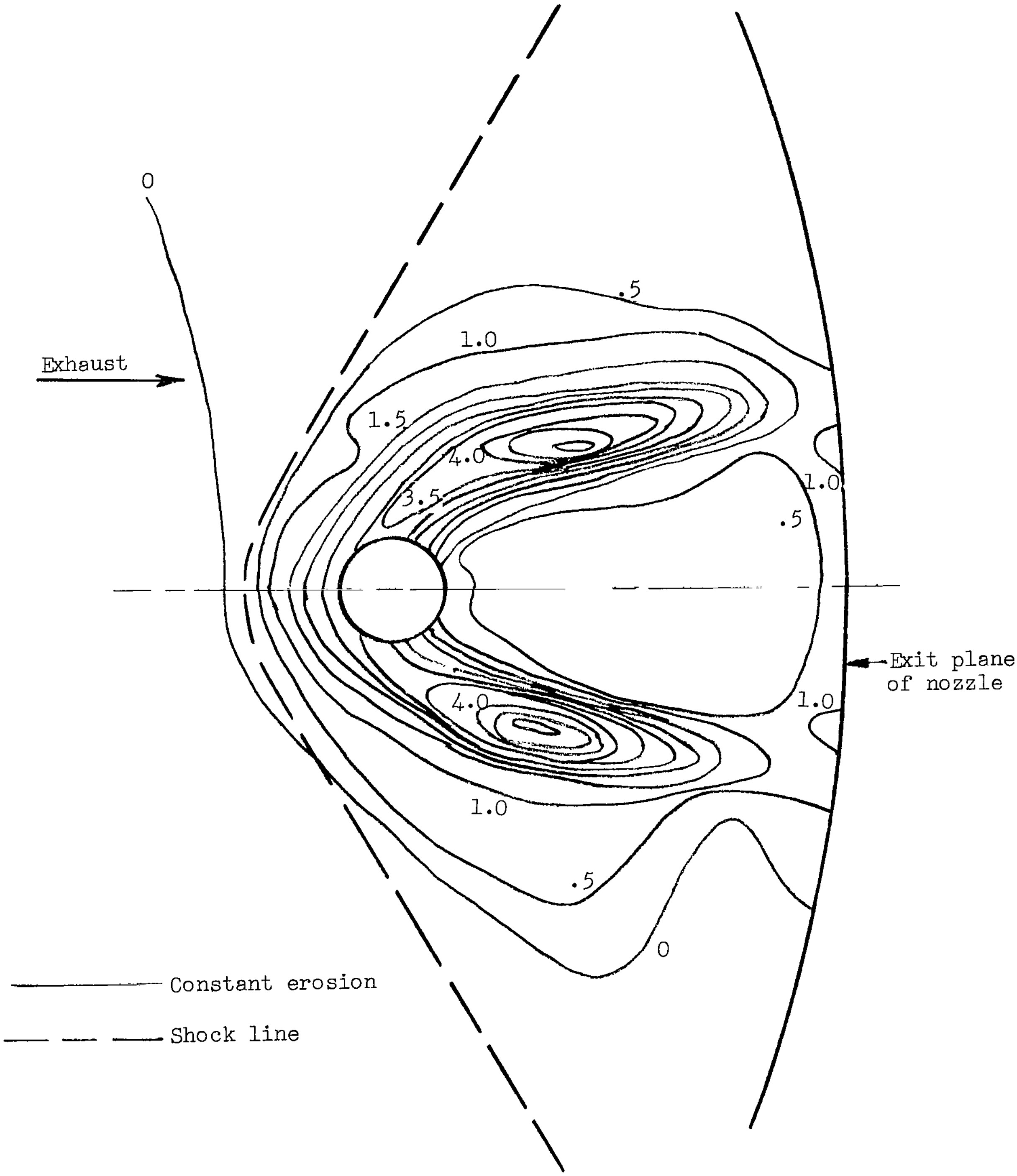
(a) Vicinity of right injection port of nozzle 1.

Figure 7.- Contour lines of constant erosion. Positive numbers indicate depth of erosion in millimeters; negative numbers indicate raised areas.



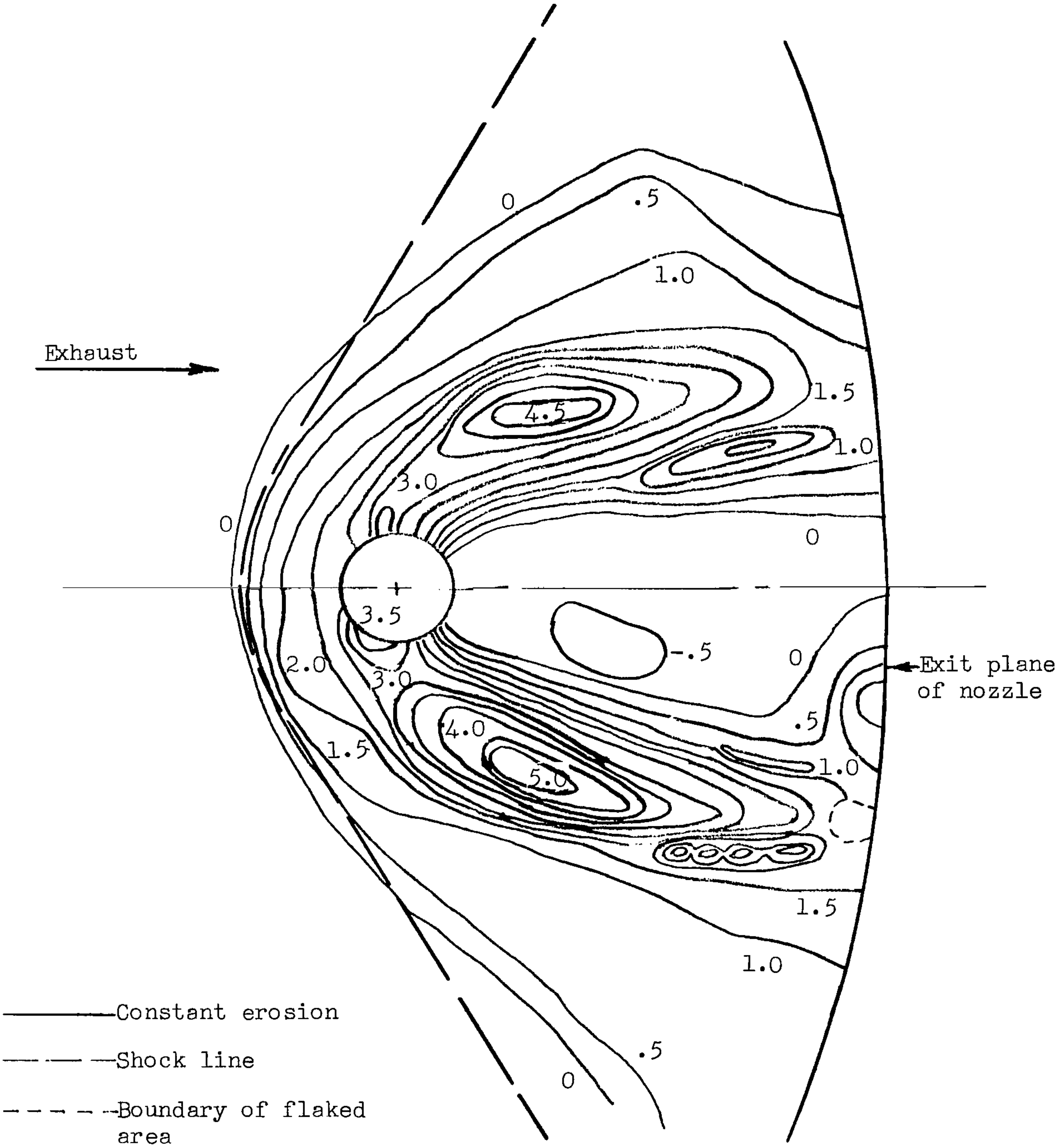
(b) Vicinity of left injection port of nozzle 1.

Figure 7.- Continued.



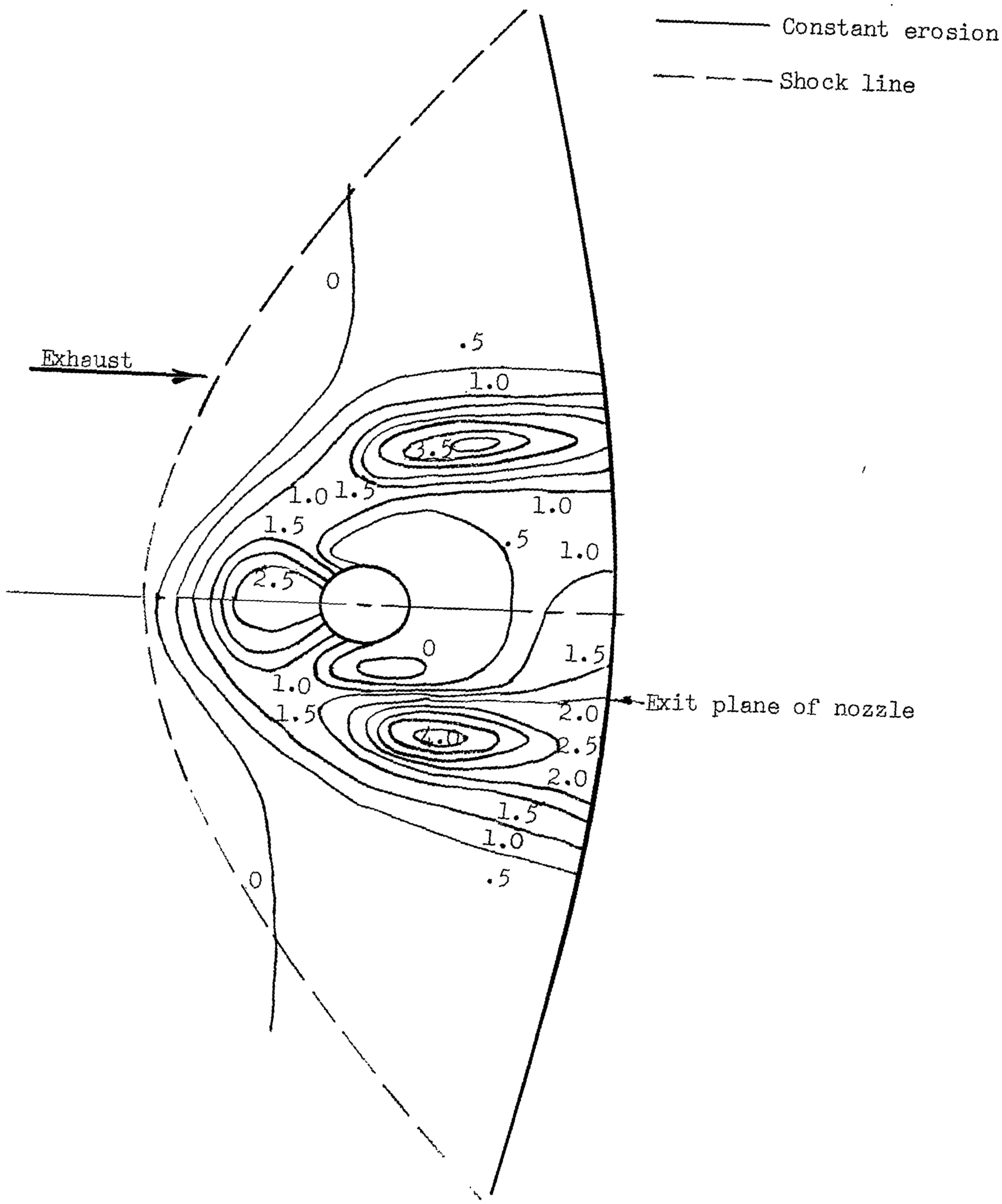
(c) Vicinity of right injection port of nozzle 2.

Figure 7.- Continued.



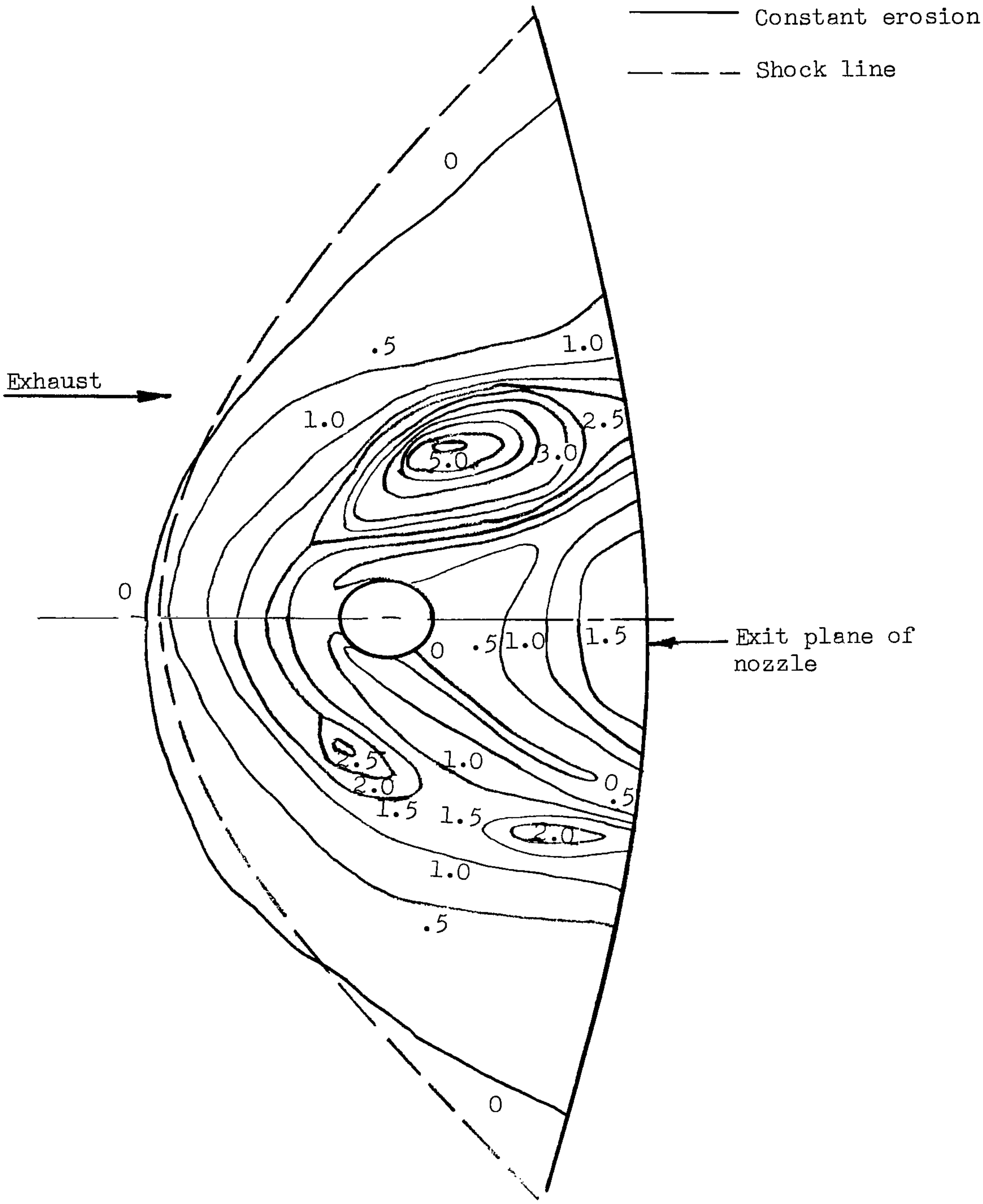
(d) Vicinity of left injection port of nozzle 2.

Figure 7.- Continued.



(e) Vicinity of right injection port of nozzle 3.

Figure 7.- Continued.



(f) Vicinity of left injection port of nozzle 3.

Figure 7.- Concluded.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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