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Report No. 2220A

DUCT-FLOW VISUALIZATION STUDIES
SCALE-MODEL PROGRAM
FOR TEST CELL "D" EXHAUST SYSTEM

August 1962

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MASTER

ROCKET ENGINE OPERATIONS, NUCLEAR

for

Aetron Division
Aerojet-General Corporation
Covina, California

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ABSTRACT

A flow visualization study was made, using a two-dimensional scale model of an ejector duct (which was under consideration for use in Test Cell "D" when testing the NERVA engine) to determine qualitatively phenomena of shock-wave and flow separation. The experimental program consisted of operating the ejector at different chamber pressures, while spark and motion-picture shadow-graphs were being made of the flow. Static pressures along the ejector walls were measured for correlation with the three-dimensional model tests as reported in Aerojet Report 2309. Conclusions are drawn and recommendations are made as a result of the experimental data.

Approved By:

W. D. Stinnett

FOREWORD

This report describes work done in fulfillment of Contract AT (29-2)1060, between June 1961 and December 1961, and is submitted in partial fulfillment of that contract which states in part:

provide the necessary personnel, facilities, and materials to design and fabricate a two-dimensional scale-model exhaust system for visual determination of internal shock structure for Test Cell "D", and to interpret the data.

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I. INTRODUCTION

Test Cell "D" is designed for the static testing of downward-firing, full-scale, nuclear rocket engines. Since the exhaust from a nuclear rocket is highly flammable hydrogen, it must be ducted out of contact with air a considerable distance from the test facility to prevent combustion damage to the reactor and nozzle housings. The exhaust ejector-deflector system for the Test Cell "D" facility is therefore designed to vent the exhaust hydrogen at a safe distance so that it can be burned. A corollary requirement is obviously the restriction that air must be excluded from the exhaust duct to minimize the possibility of a confined hydrogen-oxygen deflagration. The ejector duct contains a right-angle bend which serves both to conduct the gases away from the facility and to reduce the overall height of the equipment.

In order to simulate a space environment at the ground test facility more closely, the exhaust duct system includes a cell which encloses the engine and nozzle. The high kinetic energy of the exhaust stream is used to evacuate the cell and thus causes the nozzle to flow full against a low ambient pressure.

A number of scale-model tests have been conducted at the Azusa test facilities of the Aerojet-General Corp. to evaluate the criteria used in the design of the duct and test-cell nozzle assembly. The first of these programs involved the cold-flow testing with nitrogen of a number of duct and nozzle designs. This program has been recently reported (Ref. 1). These test results led to the selection of two ejector designs for further and more exhaustive testing.

A second program, which utilized a regenerative furnace to heat nitrogen, provides data on heat transfer through the ejector walls, the performance of a secondary ejector design, film cooling, and ejector-purge requirements (Ref. 2).

These hot-flow tests also determined ejector performance under hot-flow conditions.

Shortly after the initiation of the cold-flow test program, it was suggested that an optical study of flow phenomena in selected regions of a typical ejector duct would provide additional information on its operating characteristics. Using both spark shadowgraph and high-speed motion-picture coverage, insight into the structure of shock points and possible back-flow into the duct could be gained in a relatively limited program. This report gives the results and conclusions of this flow visualization study.

II. SUMMARY

The program objectives were to conduct a flow visualization study using a two-dimensional scale model of a Test Cell "D" duct, first, to determine qualitatively shock-wave and flow separation phenomena using spark and motion-picture shadowgraphs; second, to measure static pressures along the duct walls for correlation with the three-dimensional model tests; and third, to observe the tendency of backflow into the duct.

Cold-flow testing was conducted in a two-dimensional, glass-walled model of the -7c configuration (Figures 5 and 6 of Ref. 1) ejector duct considered for testing the NERVA engine in Test Cell "D". The objectives of this study were to obtain, for chamber pressures from 400 to 1100 psia, still and motion-picture shadowgraphs of the shock structure characterizing the flow in the ejector duct and the exit-flow characteristics of the duct. These data were then to be correlated with those obtained for the circular duct. At the time the experiments were started, however, only a lightweight version of the nozzle was at hand, limiting the maximum chamber pressure to 900 psia. Vibrational damage to the duct had become apparent at the time the heavier nozzle became available and it was decided not to risk testing at the higher pressures.

Shock waves were observed in the vertical section of the duct downstream of the transition section for $P_c/P_a \geq 40.1$. A strong shock occurred at the right-angle bend with highly turbulent flow existing immediately downstream, indicating

a region of a high heat transfer to the duct wall. No strong shock waves were noted at the duct exit, and no backflow was indicated.

Pressure data were obtained for the chamber, the nozzle exit, the environmental cell, and at four locations in the duct. The data correlate reasonably well with corresponding data obtained previously for the equivalent circular NERVA ejector model (Ref. 1). The starting pressure ratio, P_c/P_a , for the glass-walled duct was about 36, as compared to 37.5 (Table 1, Ref. 1) for the circular duct, indicating that no significant variation was introduced in making the transition from a circular to a rectangular cross section.

III. EXPERIMENTAL APPARATUS

A. DUCT-FLOW VISUALIZATION SYSTEM

The experimental approach utilized in the earlier cold-flow program (Ref. 1) was employed with minor modifications in the duct-flow visualization study. Regulated high-pressure nitrogen at ambient temperature was passed through a scale-model nozzle and thence through a glass-walled ejector duct. An air-tight environmental cell, with an internal volume of 1.22 cu ft, enclosed the nozzle and was connected to the ejector duct by a short transition section. This cell could thus be pumped down by the exhaust jet to give a low back-pressure which resulted in the nozzle flowing full. A schematic of the system is shown in Figure 1, and views of the test-cell duct installation are shown in Figures 2 and 3.

The test philosophy in this program was to utilize to the fullest possible extent hardware and test apparatus developed in the cold-flow test program. This requirement made mandatory the location of the flow visualization apparatus immediately adjacent to the cold-flow test stand in order to utilize existing nitrogen supply lines and control systems as well as the instrumentation channels developed on that program. A metal-roofed, canvas-walled structure enclosed the apparatus, providing some protection from the weather and reducing the problems of light fogging of photographic film.

B. TWO-DIMENSIONAL GLASS-WALLED DUCT

As initially conceived, the transparent-walled duct was to have been fabricated of metal with windows located at the inlet to the duct, at the elbow,

and at the duct exit. The gas passage was to be 1/2 in. thick, minimizing possible three-dimensional effects. This concept would thus have required the design and fabrication of a scaled-down two-dimensional model of the nozzle-cell assembly. In view of limited time and funds, however, it was decided to utilize a three-dimensional nozzle and cell used in the cold-flow tests and to incorporate a short transition section to vary the cross-sectional configuration from a circular shape to a square section of equal flow area (Figure 4).

The use of a metal duct with windows was judged to be unnecessarily restrictive, in that viewing would be limited to three preselected positions. In a design review conference, H. T. Knight of the Los Alamos Scientific Laboratory suggested cementing selected optical plate glass to plastic sections forming the duct channel, giving completely open viewing. LASL had previously used this technique with excellent results. The method appeared feasible if two requirements were met: (1) the glass-epoxy-plastic bond would withstand vibration, and (2) plate glass of satisfactory optical quality could be obtained.

It was not possible to check readily the effects of vibration on the epoxy bond. However, a few preliminary tests were made while the duct was being designed to estimate the strength of this glass-epoxy-plastic bond. The average shear stress at the point of failure was 800 psia. Each sample failed in delamination of the plastic, a pressure-molded, paper-reinforced phenolic, rather than in the bond.

The final design of the glass-walled duct is shown in Figure 4. This consisted basically of phenolic sections cemented together to form the two opaque walls of the flow channel; these forms were then sandwiched between specially selected sheets of 1/2-in. plate glass. The glass was bonded to the phenolic with an epoxy-based adhesive^{*}; the area of glass cemented to the phenolic was at least 50% of the unsupported area at any one station. The phenolic sections were also bonded with an epoxy-based adhesive.^{**} For ease in fabricating and handling, and to reduce the total weight of the glass and the resulting shear stresses on the glass-to-phenolic bond, the glass sheet on each side was composed of two pieces with a sealant compound^{***} between the sections. This duct was equivalent to

-
- (1) Type EC-1838 B/A, Minnesota Mining & Mfg. Co., St. Paul, Minn.
 - (2) Epon 828 catalyzed with 8-10% DTA, Shell Chemical Co., Los Angeles, Calif.
 - (3) Silicone sealant RTV 731, Dow Corning Co., Midland, Mich.

the -7 NERVA ejector duct as tested in the cold-flow program (Fig. 5), which was determined to be the best suited for further scale-model testing (Ref. 1). The duct area-to-nozzle throat-area ratio was 35.

One prerequisite to the use of large sheets of glass to form the transparent walls of the duct was that of obtaining plate glass of satisfactory optical quality which could be procured withing time and fund limitations. Fortunately, shadowgraph techniques are less demanding than those of schlieren systems, and minor imperfections of ream and seed can be tolerated. Moreover, since the objective of this program was to determine only the grosser shock structure, fine detail was important only at the duct exit, where the question of back flow was of importance. The duct was fabricated with glass walls^{****} specially selected by a local glass-specialty house which is equipped to examine glass in a schlieren apparatus.

Every effort was made to minimize the problem of vibration stressing of the adhesive bonds. The duct was designed so that the glass walls did not extend to the junction plane between the lower plastic section and the metal bottom support plate, but were recessed about 0.050 in. in order to prevent the glass from coming in contact with the aluminum plate. In addition, two layers of neoprene, each 0.015 in. thick, were placed between the plastic and the metal plate to further absorb stresses due to vibration and uneven loading.

The duct was mounted on an angle iron and I-beam steel frame bolted to the concrete pad. The base of the duct was separated from this rigid mounting by two layers of a special rubber product used for shock-mounting of heavy equipment. Clamping devices were welded to the metal support frame to permit compressive loading on the glass by vibration dampeners, 2-in. polyurethane pads backed with plywood and a stress bar. This assembly is clearly shown in Figure 2, which shows the duct as mounted on the metal support frame with the left vibration dampener removed. The right side of the duct is shown in Figure 3, with the lower vibration dampener in place.

C. EXPANSION NOZZLE AND CELL

The nozzle/test-cell assembly used in these tests is one which was developed for the cold-flow test program (Ref. 1). Tests were conducted in a

(4) Pittsburgh Plate Glass Co., Pittsburgh, Pa.

similar manner, in the sense that regulated high-pressure nitrogen was passed through the scale-model nozzle and glass-walled ejector. The airtight environmental cell enclosed the nozzle during testing.

The convergent-divergent nozzle contour was a scaled-down version of the NERVA design. The converging nozzle section had a half-angle of 45° , and the diverging section was contoured (Figure 6). A view looking up into the divergent section of the nozzle as installed in the test cell is shown in Figure 7. This nozzle had an expansion ratio of 40.

D. OPTICAL-PHOTOGRAPHIC SYSTEMS

Of the numerous methods available for visualizing the flow of a compressible fluid past a model or through a duct, optical methods are most frequently used. These techniques are based on observations of changes in refractive index in the gas stream which accompany changes in density resulting from the formation of shock waves at sufficiently high Mach number. These optical methods enable a large field to be examined without the introduction of probes that may disturb the flow field. In addition, instantaneous recording of transient phenomena may be obtained, as compared to the relatively long response times of other observational methods. The mathematics relating the speed of light, the refractive index, and the fluid density may be found in many texts on such optical techniques and will not be further elaborated upon in this report. Refs. 3 and 4 are typical.

In general, optical techniques may be subdivided into schlieren, interferometer, and shadowgraph methods. These techniques give observations which depend on the density and on different derivatives of the density and are thus complementary rather than alternative. Each shows features of the flow which are not as well demonstrated by the others.

Direct-shadow or shadowgraph is the simplest of these methods. It can be shown that the effects observed with this method are a function of the second derivative of the density. If the density gradient normal to the light path is nonuniform, because of such mechanisms as the formation of shock waves at high Mach numbers or thermal turbulence, adjacent light rays will be deflected to different degrees and will converge or diverge on leaving the working section.

Thus still or motion-picture coverage shows not only the shadow of opaque bodies in the field but also shadows due to density changes in the compressible fluid. Excellent discussions on the method are given in Refs.3 and 4.

1. Spark Shadowgraph Techniques Employed

In the simplest case, an image is formed as a shadow on a photographic plate or screen held behind the working section. The light source must be small and of sufficient brilliance to form a sharp image. In this direct-shadow system, the magnification of the image is unity and the photographic plate must be held close to the working section. Since the technique is essentially open-shutter photography, its application requires a well darkened room to prevent fogging of the film. Although all testing in this program was carried out at night, there was sufficient light in the working area to fog the film. Most of this light entered the enclosure through the opening in the canvas wall which was required to permit the nitrogen to escape.

Rather than build a light-trap gas-exit opening and minimize other light leakage, the initial plan was to use the focused direct-shadow system in which a parallel beam of light formed by the spark and collected by a parabolic mirror is passed through the working section, collected by a second parabolic mirror, and focused on the lens of a camera. The light source, mirrors, and camera for this preliminary set-up can be seen in Figures 2 and 3. A plan view of this method is shown in Figure 8.

Checkout of this system, however, indicated that under the conditions peculiar to these tests, the results obtained were not satisfactory. Considerable time and effort were required to position the various components to optimize the results. In addition, air turbulence created by the high-velocity exhaust jet entering the curtained room caused the camera to vibrate sufficiently to obscure photographic detail. Test photos so obtained were not so sharp and clear as sample photos taken later using the direct-shadow system in which the film-holder was positioned directly behind the working section, with a lightproof tunnel of opaque cloth shrouding the light path between the duct and the spark

source and the light-collecting parabolic mirror. Use of this light tunnel thus permitted open-shutter photography, eliminating the second mirror and the camera.

2. Spark-Shadowgraph Apparatus

The most important component in a spark-shadowgraph system is the light source. This consisted of an electrical capacitor, a high-voltage supply for charging it, a device to form the spark gap which provides the high-intensity point-source light, and a method of triggering the discharge of the capacitor. The circuit diagram for the system used in this program is shown in Figure 9. The output energy of the power supply was controllable, for any particular storage capacitor, by regulating the input voltage with a Variac. Normally the capacitor was charged to a potential of 5,000 to 6,000 volts. The 0.1-microfarad capacitor was triggered by a 5C22 thyratron to discharge across the spark gap. This was a confined-air spark gap of the Libessart type in which the light-emitting spark occurs in a small chamber between two metallic electrodes, one of which contains an opening through which the light emerges. This unit is shown assembled in Figure 10, in an exploded view in Figure 11.

The spark gap was located at the focal point of a 12-in.-dia parabolic mirror. Worm-drive gearing gave fine adjustment in positioning the mirror in three dimensions. The light collected by the mirror (focal length of 72 in.) was thus collimated into a parallel beam when passed through the working section. The mirror and stand assembly are shown in Figure 12.

Photographs of flow phenomena in the working section were obtained using a 8-by-10-in. film holder fastened to the rear wall of the duct. Eastman Royal Panchromatic sheet film with an ASA speed rating of 400 was used. Negatives were developed in DK60A for 5 minutes at 68°F. Printing paper of varying degrees of contrast, together with variations in exposure and developing, were used to bring out details of the flow structure.

3. Motion-Picture Apparatus

A 100-watt concentrated arc lamp was used to continuously illuminate the working section for the motion-picture coverage of flow at the duct exit.

(This lamp was also used for system adjustment for the still shadowgraphs.) Light was collected by a condensing lens and focused on a 0.1-in. pinhole located at the focal point of the 12-in. parabolic mirror, thus effectively providing a point source of illumination. The parallel rays of light from the mirror passed through the working section and illuminated a rear-projection screen positioned behind and normal to the duct exit plane. The camera, a Fotosonic 16mm Model 1-B camera using Tri-X reversal (ASA 250) film, was located approximately 20 in. from the rear-projection screen. Film speed was 100 frames/sec, the equivalent shutter speed was 1/500 sec at an f-stop of 2.3. The film was developed in undiluted 53D for 5 minutes at 68°F. A schematic of the motion-picture setup is shown in Figure 13.

IV. TEST PROCEDURE

Photographic coverage of shock structure and flow phenomena, together with duct pressure data, were obtained for a rectangular cross-section model of the -7c (Ref. 1) configuration of the ejector duct. It was necessary to use a lightweight version of the NERVA-contoured nozzle (see Figures 6 and 7) in which chamber pressure was limited to a maximum of 900 psia, as the heavier-walled nozzle was not available when testing was commenced. Later in the program, when the other nozzle could have been installed, vibration damage to the duct was evident, and it was decided to postpone higher-pressure runs until all the lower-pressure test conditions were met. The destruction of the duct cancelled these plans. The gimbal angle was 0°. Fifty-five tests (including check-out runs) were conducted by varying P_c in steps of about 100 psi, starting around 400 psia and terminating at 900 psia.

Pressure data obtained were the nozzle-chamber pressure (P_c), nozzle-exit pressure (P_e), cell pressure (P_v), three static pressures along the ejector walls (P_4 , P_5 , and P_6 - see Figure 1), the total ejector-exit pressure (P_{7T}), and the ambient atmospheric pressure (P_a). The only temperature recorded was the ambient.

A. SPARK-SHADOWGRAPHS

Spark-shadowgraphs were taken of flow in the duct inlet, elbow, and at the outlet, as well as in the zone between the inlet and elbow locations. These runs, although made at night, necessitated the installation of a dark tunnel to prevent light-fogging of film while using open-shutter photography.

In general, the sequence of operations was as follows: the duct was prepared by arranging the vibration absorption pads so that only the working section was not externally supported. The spark gap and mirror were then adjusted, using the continuous light source, to give a parallel beam of light through the working section. The film-holder was then affixed in position, the light-tunnel adjusted, all lights in the immediate area turned off, and all instrumentation, including the precalibrated pressure pickups, actuated. The film-holder slide was then manually removed, and the test enclosure evacuated by all personnel. Cold nitrogen was then allowed to expand from the pre-set chamber pressure through the duct. As soon as steady-state was achieved (less than about 1.0 sec), the thyatron was manually triggered to discharge the capacitor across the spark gap. Flow was then terminated and the film-holder slide replaced. A new film holder was then affixed in position and the run repeated at a higher chamber pressure. After the highest-pressure test, the duct support pads and optical system were repositioned to permit a repetition of this procedure at a new working section.

B. MOTION-PICTURE SHADOWGRAPHS

Motion picture coverage (shadowgraphs) was obtained of flow phenomena at the duct exit during the start transient, steady-state, and the shutdown transient periods. In these tests the camera was remotely operated, being actuated immediately prior to initiation of gas flow and remaining in operation until after the flow had ceased. Three chamber pressures were investigated - 400, 500 and 700 psia.

To supplement the shadowgraphic visualization of flow turbulence for evaluation of the possibility of back-flow from the atmosphere into the duct, small tufts of thread were taped to the glass near the duct exit at various points to show direction of the gas flow. This installation is shown in Figure 14.

V. TEST RESULTS AND DISCUSSION

A. GENERAL DISCUSSION

In interpreting the results of this experimental program, it must be noted that the glass-walled duct used in these tests was a three-dimensional duct of rectangular cross section (4.76 by 3.738 in.) rather than either a true two-dimensional duct or a unit with a circular cross section. Further, the requirement

for the transition section between the circular exit of the environmental cell and the rectangular entrance of the duct proper undoubtedly introduced unknown effects. Study of the shock structure in the duct inlet section indicates that the transition section may have been the source of additional shock waves in addition to those normally present in the flow. The opaque transition section also prevented photographing the shock structure immediately below the nozzle exit.

B. SPARK SHADOWGRAPHS

1. Duct Inlet and Bend Section

The effects of variation in chamber pressure on the gas-flow structure in the vertical and elbow sections of the glass-walled duct are shown in Figures 15 through 20. These shadowgraphs show essentially the entire length of the duct from the plane between the transition section and the duct to a point past the right-angle elbow. These composite figures were prepared from individual working-section photographs taken for different runs for nominally identical chamber pressures. Actual pressure data applicable to each portion of the composite are tabulated on each figure. Also shown are the locations of the P_4 and P_5 pressure taps.

For nominal chamber pressures of 400 and 500 psia, no shock waves were present in the flow (subsonic). Some evidence of turbulence can be noted in views B and C in Figure 15 for a P_c of 500 psia. Shock waves were present in the flow for all chamber pressures equal to or greater than 578 psia. The shock waves appear as a dark line immediately followed by a bright line and are all oblique in character. The shock thickness appears to be relatively thin with respect to the duct width. It should be noted, of course, that the shock thickness as it appears on these shadowgraphs is, to a degree, a function of the particular optical and photographic set-up used.

There also appears to be a series of shock waves across the thickness of the duct. This most probably results from the fact that the duct cross section was nearly square, and thus in some respects the flow was more three-dimensional than two-dimensional. The formation of the dark, irregularly shaped core in the vertical section of the duct (Figures 17 through 20) is attributed to a

condensation mechanism. As the nitrogen gas used was obtained from evaporation of liquid nitrogen, no condensation of water vapor was possible. However, if an isentropic expansion from the chamber pressure to the cell pressure is assumed, the final-state point lies in the two-phase region. Although the actual expansion process was not isentropic, as shown by the presence of shock waves, the net result appears to give a fog of nitrogen droplets.

For chamber pressures equal to or greater than approximately 600 psia, a weak oblique shock originates at the point where the inside radius of the 90° elbow begins its curvature (see Figure 20). This shock wave terminates on the opposite wall of the duct, where it strikes the strong wave (dark curved line). After the flow passes this oblique shock front, the fog of condensed nitrogen vaporizes. This weak oblique shock wave (actually a series of waves across the duct thickness) is caused by a low-velocity region which acts like a wedge and separates the flow from the wall, resulting in the shock. Postulated gas-flow streamlines are illustrated in Figure 20.

This low-velocity region is caused by the 90° elbow. The momentum of the gas entering the 90° turn is such that there is a resistance to the change in flow direction, resulting in the strong compression shock wave along the outer radius of the elbow. After passing through the strong shock, the gas rapidly expands upwards towards the inner elbow radius. This expansion tends to form the lower boundary of the low-velocity region, forcing the gas flowing along the inner wall of the curve also upward. This process results in the formation of a recirculation eddy along the inner curve, a region of relatively low velocity and somewhat greater static pressure. This hypothesis is supported by static pressure measurements obtained at this point in hot-flow tests of nitrogen in the -7 circular duct (Ref. 2). For example, at a P_c of 900 psia in these hot-flow tests, the static pressure at this point was about 17 psia as contrasted to the free-stream static pressure in the vertical section of the duct, which ranged up to 6 psia.

The flow separation at the inner radius of this 90° bend can be likened to flow separation in the diverging section of a highly overexpanded supersonic nozzle. For a given nozzle configuration, jet separation occurs when the pressure ratio P_e/P_a (where P_e is the static pressure of the exhaust-gas stream and P_a is the ambient pressure) falls below a certain critical value.

The zone between the strong shock wave (the outside wave) and the wall itself is a highly turbulent region in which much of the kinetic energy of the gas is transformed into static pressure. Heat-transfer problems will be maximized in this region.

2. Duct Exit

Shadowgraphs of flow at the duct exit are presented in Figures 21 through 26 for nominal chamber pressures of 400 to 900 psia. These shadowgraphs have been photographically developed in such a manner as to show most clearly the gas flow both in the duct and as it leaves the exit. The dark region just upstream of the duct exit plane results from a light reflection and has no physical meaning.

Examination of the flow fields illustrated in the shadowgraphs indicates that the 45° bend in the flow path causes the flow near the duct exit not to be one-dimensional at the duct exit plane. The flow is densest at the lower section of the exit and becomes progressively less dense towards the top of the duct. The linear velocity profile thus varies asymmetrically across the duct vertical dimension.

For nominal chamber pressures of 400, 500, and 600 psia, the flow was subsonic and no shock waves were observed. The local Mach number was calculated just upstream of the duct exit (pressure tap P_6), assuming adiabatic flow. The calculation indicates that the flow is subsonic for $P_c = 600$ psia and supersonic for $P_c = 700$ (see Figure 27).

For nominal chamber pressures of 700, 800, and 900 psia, faint shock waves were observed in the lower part of the flow field both inside and outside of the duct exit, indicating that this portion of the flow was in the low supersonic or transonic regime. The flow towards the center of the duct was subsonic for all chamber pressures; this is clearly indicated by the lack of a bow shock in front of the total-pressure probe (see Figures 24, 25, and 26). Turbulence (as evidenced by variable-density patterns in the exit gas) becomes noticeable at a P_c of 600 psia and is readily apparent at a P_c of 700 psia. The level of turbulence then increases with increasing chamber pressure.

Tufts of silk thread of various lengths were attached to the edge of the duct-exit phenolic section, to the glass walls, and also on the face of the phenolic surface a short distance from the lower edge of the duct exit. All tufts along the duct edge, regardless of length, were blown out in the downstream direction except possibly the very shortest tufts positioned along the top edge of the duct exit. It appears that some of the shorter tufts ($3/8$ in.) located along the top edge may possibly have been sucked inward. This conclusion is tentative since it is extremely difficult to see the shorter tufts in the shadowgraphs. Tufts positioned 1.25 in. away from the lower duct edge were bent inward toward the duct opening. Short tufts (less than 1.25 in.) were bent inward only, while longer tufts were blown downstream in addition to being bent inward. The behavior of those tufts not directly contacted by nitrogen from the duct reflects the entrainment of ambient air by the jet of gas leaving the duct.

The turbulence of the flow leaving the duct appeared more marked along the lower wall of the exit. Density variations were greater in this region and were therefore more clearly shown by the shadowgraph technique.

C. MOTION-PICTURE COVERAGE

Motion-picture shadowgraphs (100 frames/sec) of flow at the duct exit were taken for the entire run duration, thus including the start transient, steady-state operation, and the shutdown transient, for nominal steady-state pressures of 400, 600, 700, and 900 psia. Pressure data were obtained for all but the highest-pressure run. The chamber pressure for this last run rose smoothly to a value just above the nominal pressure desired, then dropped abruptly. The glass walls of the duct were found to be severely and irreparably damaged, necessitating the termination of the test program. Two views of the damaged duct are shown in Figures 28 and 29.

The possibility of back flow into the duct was investigated by fastening tufts of various lengths on the inside of the glass wall near the duct exit. These were mounted so as to be perpendicular to the direction of flow of the gas (see Figure 14). Frame-by-frame examination of the motion-picture film showed that the threads were always bent downstream, indicating that backflow did not occur at any

time during the run. However, as mentioned above, a possibility exists that a slight amount of backflow could occur at the top of the duct exit. Destruction of the duct prevented tests in which (1) the actual Test Cell "D" start transient was to be approximately simulated and (2) the chamber pressure was to be varied so as to induce backflow.

D. PRESSURE DATA

Duct pressure data at pressure tap locations shown in Figure 1 are tabulated on the composite shadowgraphs (Figures 15 through 20). These data are presented graphically in ratio form in Figures 30 through 35. In general, these data are in good agreement with the experimental pressure data obtained for cold flow in the circular duct (Ref. 1) and for some hot-flow tests (Ref. 2).

The nozzle-exit pressure ratio (Figure 30) and the cell pressure ratio (Figure 31) compare very well with the circular duct data. A few points show wide divergence from the rest of the data; it is suspected that this difference resulted from a small air leak in the environmental cell. Static pressures at the location of the P_4 pressure tap were appreciably higher for the glass-walled duct for chamber pressures above the starting value (Figure 32). Again some scatter is evident. The static pressure ratio at the P_5 location shows good agreement with the circular duct data below the starting pressure, but exhibits a lower-pressure trend for P_5 data above the starting pressure.

No cold-flow circular-duct data were available for comparison with the duct-pressure P_6 data (Figure 34). However, a few data points from the hot-flow test program (Ref. 2) indicate fair agreement with the present data. The sharp distinction between pressure data below and above the starting pressure ratio of about 36 is not nearly so evident at this point in the duct.

Because of a malfunction of the transducer, no usable total-pressure data, P_{7T} , were obtained during the test program. However, 18 apparently valid measurements were taken during the checkout period. These data are shown in Figure 35. Fair agreement with circular-duct data was obtained for chamber pressures below starting pressure; however, no increase in total pressure was noted at the

higher chamber-pressure ratios. Examination of Figures 21 through 25 indicates the probe was mounted at a slight angle from the normal to the duct exit. Since total-pressure probes are quite sensitive to position relative to the gas-flow streamlines, it is possible that this angular displacement of the probe tip resulted in erroneous readings. It is more likely, however, that the transducer malfunction was beginning to affect the results.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The results of this optical study indicate that for the expansion of cold nitrogen from a 40-to-1 nozzle into the -7c configuration ejector duct:

1. Oblique shock waves were observed in the flow in the vertical portion of the duct for $P_c/P_a = 40$ ($P_c \geq 578$ at Aerojet and $P_c \geq 512$ psia at NIS) and were not present at the next lower pressure tested, 519 psia.
2. A strong shock wave exists in the 90° bend along the outside wall of curve. The flow immediately downstream of this shock appears highly turbulent, indicating a region characterized by high heat-transfer rates.
3. The flow through the 90° elbow for $P_c/P_a = 40$ remains supersonic. Pressure data for the inside of the curve obtained from hot-flow tests (Ref. 2) with a circular duct support this conclusion.
4. Flow at the duct exit was subsonic at $P_c \leq 600$ psia; where $P_c \geq 700$ psia, flow appears to be in the transonic region.
5. No conclusive evidence of backflow was noted during transient and steady-state operation.
6. On the basis of relatively good agreement of pressure data, flow phenomena in the rectangular duct should be representative of flow in the circular duct.
7. Data obtained in the cold-flow program (Figure 29) indicates that the ejector "started" at a pressure ratio of about 36. No tests were conducted in the present study to pinpoint the exact starting pressure ratio for the glass-walled

duct. The data obtained, however, indicate approximately the same starting pressure ratio as previously determined for the similar circular duct.

B. RECOMMENDATIONS

The results of this study show that both qualitative and semiquantitative information of design value can be obtained with relative ease using shadow-graph techniques. Visualization of the shock structure is an aid in evaluating data obtained in conventional cold and hot flow tests in which static-pressure data are the primary information input.

If further similar work were to be contemplated, the following recommendations are suggested.

1. The extent of the relatively stagnant zone on the inside of the curve (see Figure 19) should be determined by closely spaced pressure taps along the wall. It would then be of interest to attempt to modify the characteristics of this gas "wedge" by both aspirating and pressurizing this region and observing changes, if any, on the shock structure at the bend.

2. Variations in the basic duct geometry, such as secondary injection, could well be evaluated using duct-flow visualization techniques.

3. Any future program employing glass-walled ducts of the size used herein should specify thicker plate glass ($5/8$ to $3/4$ in.) to delay stress cracking. The problem of reducing vibration and its effects should also be studied.

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SYMBOLS

A	Cross-sectional area, sq in.
d	diameter of nozzle
D	diameter
l	nozzle length at nozzle diameter d
L	nozzle length
M	Mach number
P	pressure, static or total
$\dot{w}$	weight flow rate, lbm/sec

SUBSCRIPTS

c	chamber	
e	nozzle-exit plane	
T	total pressure	
v	cell (environmental chamber)	
4	pressure tap location	} see Figure 1
5	pressure tap location	
6	pressure tap location	
7	pressure tap location

Figure 1
Ejector System

Figure 2

View of Left Side of Glass-Walled Duct as Installed

Figure 3
View of Right Side of Glass-Walled Duct as Installed

Figure 4
Duct Assembly - Ejector, 2 Dimensional, Glass-Walled

Figure 5

NERVA Ejector

Figure 6
Contour of Nozzles

Figure 7
Environmental Cell, Interior View

Figure 8
Plan View of Shadowgraph Optical System Setup
(Initial Method)

Figure 9
Circuit Diagram For Spark Light Source

Figure 10
Spark Light Source

Figure 11
Spark Light Source - Exploded View

Figure 12
Shadowgraph System - Mirror Assembly

Figure 13
Schematic Plan View of Motion
Picture System Setup

Figure 14

Tufts Used To Indicate Flow Direction

Figure 15

Figure 16

Figure 17

Figure 18

Figure 20

1267-699

PHOTO	NO	18
RUN	NO	42
	P_a	14.39
	P_c	393
	P_e	7987
	P_v	8330
	P_4	1500
	P_5	15.8
	P_6	12.25
	W	4.45
P IN psia		
W IN lb N_2 /sec		

Figure 21
Shadowgraph of Flow at Exit of Ejector Duct
Nitrogen Expanding From Nominal P_c of 400 psia

PHOTO	NO.	17
RUN	NO.	41
	P_d	14.39
	P_c	504
	P_e	1.274
	P_v	1.960
	P_4	15.34
	P_5	19.2
	P_6	10.93
	$\dot{W}$	5.71
	P IN psia	
	$\dot{W}$ IN lb N_2 /sec	

1261-101

Figure 22
Shadowgraph of Flow at Exit of Ejector Duct
Nitrogen Expanding From Nominal P_c of 500 psia

PHOTO	NO	16
RUN	NO	40
	P_a	14.39
	P_c	600
	P_e	5.635
	P_v	6.615
	P_4	15.78
	P_5	17.8
	P_6	9.85
	W	6.8
P IN psia		
W IN lb N_2 /sec		

1261-103

Figure 23
Shadowgraph of Flow at Exit of Ejector Duct
Nitrogen Expanding From Nominal P_c of 600 psia

1261-702

PHOTO	NO	15
RUN	NO	39
	P_a	14.39
	P_c	686
	P_e	1.646
	P_v	0.196
	P_4	8.08
	P_5	43.0
	P_6	975
	W	777
P IN psia		
W IN lb N_2 /sec		

Figure 24
 Shadowgraph of Flow at Exit of Ejector Duct
 Nitrogen Expanding From Nominal P_c of 700 psia

1261-704

PHOTO	NO	14
RUN	NO	38
	P_0	14.39
	P_c	821
	P_e	1.887
	P_v	0.196
	P_4	7.06
	P_5	48.7
	P_6	10.94
	W	9.3
	P IN psia	
	$\dot{W}$ IN lb N_2 /sec	

Figure 25
Shadowgraph of Flow at Exit of Ejector Duct
Nitrogen Expanding From Nominal P_c of 800 psia

1261-100

PHOTO NO	13
RUN NO	37
P_a	14.39
P_c	891
P_e	1.936
P_v	0.245
P_4	7.203
P_5	53.8
P_6	9.90
W	10.09
P IN psia	
W IN lb N_2 /sec	

Figure 26
Shadowgraph of Flow at Exit of Ejector Duct
Nitrogen Expanding From Nominal P_c of 900 psia

Figure 27

Mach Number as a Function of Chamber Pressure
Ratio at Plane of Pressure Tap -6

Figure 28
View of Left Side of Glass-Walled Duct
Showing Damage Sustained During Testing

1261-627

Figure 29
View of Right Side of Glass-Walled Duct
Showing Damage Sustained During Testing

Figure 30
Nozzle Exit Pressure Ratio as a
Function of Chamber Pressure Ratio

Figure 31
Cell Pressure Ratio as a Function
of Chamber Pressure Ratio

Figure 32
 P_4 Pressure Ratio as A Function
of Chamber Pressure Ratio

Figure 33
 P_5 Pressure Ratio as a Function
of Chamber Pressure Ratio

Figure 34
 P_6 Pressure Ratio as a Function
of Chamber Pressure Ratio

Figure 35
 P_{7T} Pressure Ratio as a Function
 of Chamber Pressure Ratio