DESIGN, TESTS, AND VERIFICATION OF A DIFFUSER SYSTEM FOR A MACH 4 SCRAMJET TEST FACILITY

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Abstract

A fixed-geometry diffuser system was designed for use in Mach 4 free-jet tests of a hydrogen-burning modular scramjet engine. The scramjet engine has a rectangular cross section that blocks up to 33 percent of the existing tunnel nozzle exit area and swept leading edges of the scramjet produce an asymmetric downward flow that sharply increases when the scramjet inlet unstarts. Effects of these conditions on the operation of the diffuser system are not accurately predictable. An experimental investigation was therefore conducted in unheated air using a subscale model of the tunnel-scramjet-diffuser system to substantiate the design. Test results for this subscale model showed that the preliminary design could be modified to obtain an acceptable configuration of the nozzle exit, test cabin, and diffuser that would provide shock-free flow at the scramjet inlet for simulated Mach 4 flight at altitudes from 16,764 to 20,422 meters. These results were subsequently verified by full-scale engine combustion tests in a facility utilizing a similar diffuser design.

Nomenclature

D_j	tunnel nozzle exit diameter
D_{st}	diffuser straight duct diameter
L_{fj}	free-jet length
L_{st}	diffuser straight duct length
M_j	tunnel nozzle exit Mach number
M_∞	flight Mach number
$\dot{m}$	mass flow
p_j	nozzle exit static pressure
p_{cab}	test cabin static pressure
$p_{t,j}$	nozzle exit total pressure
$p_{t,d}$	subsonic diffuser exit pitot pressure
q_∞	flight dynamic pressure, atm.
$T_{t,j}$	nozzle exit total temperature, K
$T_{t,\infty}$	flight free stream total temperature, K
δ	vehicle angle-of-attack plus vehicle forebody surface angle, deg.
ϕ_T	total fuel equivalence ratio (ϕ = 1, stoichiometric combustion)

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Introduction

Research on an airframe-integrated scramjet modular engine concept[1] (figure 1), currently being conducted at NASA Langley, involves experimental investigations of hydrogen-burning component-integration (inlet-combustor-nozzle) scramjet models at simulated Mach 4 and 7 flight conditions. Experimental results obtained at Mach 4 and 7 should give sufficient definition within the interested Mach number range of 3 to 10. The facilities used for this research must duplicate Mach 4 and 7 flight enthalpies with tunnel flow Mach numbers somewhat less than the flight Mach numbers. Such tunnel conditions, shown in figure 2 for Mach 4 flight, simulate the compressed flow behind the bow shock of a flight vehicle.

An electric-arc-heated facility,[2] which duplicates Mach 7 flight enthalpy while simulating flight at an altitude of 36,600 meters, is currently in operation. Tests are being conducted in this facility on a heat-sink, hydrogen-burning scramjet modular engine.[3] To meet the requirements for Mach 4 tests, an existing engine test cell is being modified. Existing hydrogen, oxygen, nitrogen, air and cooling water systems, as well as some surplus hardware, are being used. Mach 4 enthalpy is obtained by burning hydrogen with oxygen-enriched air to produce a vitiated-air test stream; the heater design relies upon experience obtained from a similar heater[4] at Langley. This facility, as shown in figure 3 exhausting to the atmosphere, will be a free-jet blowdown tunnel with a nozzle exit Mach number of 3.15 or 3.42, and will simulate flight conditions indicated in figure 2. Such an arrangement requires a diffuser system to provide shock-free flow entering the component-integration scramjet engine. A preliminary diffuser design was defined based on published experimental results.[5,6] However, most of the literature results are not directly applicable to conditions where the model blockage is as high as 33 percent of the tunnel nozzle exit area, and where the model design causes asymmetry by creating a downward flow that increases when the model inlet unstarts.

An experimental investigation was therefore undertaken using unheated air and a subscale model of the tunnel-scramjet-diffuser system. The objective of these tests was to determine an acceptable nozzle exit, test cabin, and diffuser configuration. This configuration was to provide shock-free flow at the scramjet inlet for scramjet model blockages of 20 and 33 percent over a tunnel stagnation pressure range that simulates altitudes from 16,764 to 20,422 meters. A further requirement was that there be no drastic effect of a scramjet inlet unstart on the tunnel nozzle flow.

Apparatus and Tests

An analysis using pipe-flow theory indicated that the flow in a 1/5-scale diffuser model would properly simulate that of a full-scale diffuser.

(Throughout the text, full scale refers to the size of scramjet test facilities at NASA-Langley and not to flight hardware.) A photograph of the 1/5-scale apparatus that was constructed based on this theory is shown in figure 4; the insert depicts the subscale scramjet model employed from a previous investigation.[7]

Tests were conducted with unheated air at nozzle stagnation pressures from 5 to 11.6 atmospheres. Figure 5 presents the various test configurations; the basic arrangement is represented in figure 5(a). Results of initial tests indicated that the straight-duct length had very little affect upon the diffuser performance; therefore, a straight-duct length of 8 D_j, figure 5(b), was used in all remaining tests. The tunnel nozzle had an exit diameter of 9.144 cm and an exit Mach number of 3.15 to simulate an existing full-scale nozzle. For this case, the scramjet model cross-sectional area equaled 20 percent of the nozzle exit area (20 percent blockage model). Another existing full-scale nozzle has an exit Mach number of 3.42 and a smaller exit area; therefore, using the Mach 3.15 nozzle, the scramjet model size was increased (33 percent blockage) (fig. 5(e)) to simulate the model blockage that would result with the Mach 3.42 nozzle. The rationale of the various modifications to the diffuser catch cone as shown in figures 5(c) and 5(d) was based on results of a previous investigation.[8] The two different test cabin sizes represent the sizes of two available full-size cabins. During tests with the smaller test cabin, figures 5(e) and 5(f), a plug could be remotely inserted into and withdrawn from the model internal passage to, respectively, unstart and restart the scramjet model inlet. This simulated an inlet unstart/restart situation that may occur in an operational scramjet caused by the burning of the fuel within the engine and subsequent reduced fuel flow (combustor/inlet interaction).

The data obtained during these subscale tests were in the form of continuously measured pressures and schlieren and shadowgraph photographs. An image was observed during the tests with the large test cabin, figures 5(a) - (d); shadowgraphs had to be employed with the smaller test cabin, figures 5(e) and 5(f), and could not be observed during the tests. The pressure measurements consisted of nozzle stagnation and exit wall static pressures, test cabin pressure, longitudinal wall static pressures in the diffuser duct, a pitot pressure on the centerline at the subsonic diffuser exit, and a pitot pressure profile at the nozzle exit.

Results

Starting Pressures

In the design of the diffuser system with a model in the stream, several assumptions had to be made. A total pressure recovery of 70 percent was assumed from the nozzle exit, through and around the scramjet model, to the entrance of the catch cone. The Mach number entering the straight duct was estimated to be 2.5 - 3.0; a pressure recovery of 25 percent, based on documented results,[9] was assumed through the straight-duct supersonic diffuser and the conical subsonic diffuser. Calculations using these assumptions indicated that a nozzle total pressure of approximately 11.5 atmospheres was required to insure that the straight duct would have supersonic flow throughout, and that the flow would shock down to atmospheric pressure in the expanding subsonic diffuser. During the tests the nozzle flow became fully expanded and the flow within the test cabin established at total pressures as low as 5.5 atmospheres with the test cabin empty and at about 7 atmospheres with the scramjet model installed as shown in figure 6. The diffuser system was considered started when the nozzle flow became started (nominally, $p_j/p_{t,j}$ = 0.022) and when the test cabin pressure became equal to or less than the nozzle exit static pressure. As can be seen in figure 6, in order to obtain a started condition with the smaller scramjet model (20 percent blockage area) a total pressure about 24 percent greater than that required for no model was required; an additional increase of about 8 percent was required for the larger model (33 percent blockage area).

Observation of a schlieren image along with the pressure measurement data aided in the determination of a started condition. Figure 7 presents some schlieren photographs that were obtained for the various configurations tested; the scramjet model shown in the photographs was the smaller size model (20 percent blockage). Tests without the model installed allowed the system to easily start at a nozzle total pressure of about 5.5 atmospheres with a free-jet length of 3.0 D_j; the system would not start at a free-jet length $\geq$ 3.5 D_j.

Pressure Distributions

The effect that the free-jet length has upon the diffuser duct pressure distribution with the test cabin empty can be readily seen by comparing the circle and square open symbols in figure 8(a) for free-jet lengths of 3.5 D_j and 3.0 D_j, respectively; further reduction in the free-jet length had little affect on the pressure distributions downstream of the catch cone. Symbols to the far left represent the nozzle exit static and test cabin pressures and those to the far right are the pitot pressure measurements at the subsonic diffuser exit. The nozzle static-to-total pressure ratio for the L_{fj} = 3.5 D_j case is well above the nominal ratio of about 0.022 for the Mach 3.15 nozzle and indicates that the nozzle flow never became started. Also the pressure distribution through the straight duct is decreasing slightly (indicative of subsonic flow) instead of an increasing trend (supersonic flow) as evidenced for the other distributions. Pressure trends in the conical subsonic diffuser, calculations using the continuity equations, and the pitot pressure measurement at the diffuser exit indicate for this case that: (1) the flow is separated just downstream of the end of the straight duct supersonic diffuser and (2) a series of oblique shocks exists through the subsonic diffuser.

Installation of the scramjet model required the free-jet length to be reduced to 1.75 D_j or less before the system became completely started. The schlieren photographs of figure 7 show an incomplete start (nozzle flow started and $\frac{p_{cab}}{p_j} \geq 2.0$) at L_{fj} = 2.0 D_j (fig. 7 (b)), and completely started cases for L_{fj} = 1.75 D_j (figs. 7(c) and 7(d)). However, the tunnel flow pulsated (fig. 7(c)) with the scramjet model installed and no changes made to the nozzle exit - catch cone arrangement (fig. 5(b)). The installation of a ring on the front of the catch cone eliminated most of the flow pulsation, but complete pulsation-free flow was not obtained until an oblique nozzle exten-

sion was installed along with the catch cone entrance ring (fig. 5(d)). Use of the nozzle extension only (cone ring removed) again resulted in flow pulsation. Diffuser pressure distributions with the smaller scramjet model installed are shown as the solid symbols in figure 8(a). The pressure distribution for the case with a catch cone entrance ring and the nozzle oblique extension (the solid diamonds, fig. 8(a)) closely match the distributions for the test cabin empty cases with the free-jet lengths of 3.0 D_j and 1.0 D_j. This indicates that very small effects to the diffuser performance occurred with the installation of the small scramjet model (20 percent blockage). As previously mentioned (fig. 6), the nozzle and test cabin flows were established at about 7 atmospheres with the model installed; however, at this nozzle total pressure, the flow was not completely established (pressure measurement traces continued to be erratic) throughout the diffuser duct. At about 10 atmospheres the diffuser pressure distributions became established (all pressure traces were steady) and matched closely those shown in figure 8 for 11.6 atmospheres.

Cylindrical catch-cone extensions of various lengths, with and without entrance rings installed (fig. 5(c)), were installed and tested in an attempt to have the entrance to the straight duct further downstream from the scramjet model exit. This was desired to prevent the possibility of shock waves in the catch cone from influencing the scramjet model exit flow. When the free-jet length with the catch cone extensions was smaller than the free-jet length without extensions, started flow within the diffuser systems occurred. A common factor, when the started flow was obtained for each of the different cylindrical lengths, was that the distance from the tunnel nozzle exit to the straight duct entrance was nearly equal; this agreed with a similar finding noted in a previous investigation where the nozzle flow impingement point upon the catch cone was referred to as the effective free-jet length.[6] The use of an oblique cone extension (fig. 5(f)) showed similar results to those of the cyclindrical extensions. None of these configurations allowed increases in the nozzle exit-to-straight duct entrance dimension. Therefore, the "best" nozzle exit-scramjet-catch cone arrangement was concluded, based on the diffuser pressure measurements, to be the one utilizing the oblique nozzle extension and a catch cone with an entrance ring of either internal diameter size (figs. 5(c) and 5(d)).

A reduction in the test cabin size appeared to have little affect upon the performance of the diffuser system. The installation of the larger scramjet model (33 percent blockage) required a slightly higher total pressure to obtain started flow as previously mentioned (fig. 6). Also, the test cabin pressure was equal to or slightly greater than the nozzle exit pressure (never lower), and the pressure distribution throughout the diffuser duct was at a higher level than that for the smaller model as shown in figure 8(b). The pressure level for the large scramjet model (solid right triangle, fig. 8(b)) is noted to be slightly higher than that for the unstable flow case (solid triangle, fig. 8(a)) for the smaller scramjet model.

Inlet Unstart Interaction

Results utilizing the plug inside the scramjet models to examine the effects of inlet unstart indicated that the unstarted inlet greatly disturbed the test cabin/diffuser flow field, and the diffuser flow became subsonic. However, the test cabin pressure increased only slightly for both model sizes, and the nozzle exit static pressure was unaffected at the free-jet lengths of 1.5 D_j and 1.75 D_j. Removal of the plug (simulated the termination of engine fuel flow) resulted in an immediate restart of the diffuser system flow to the same condition prior to the inlet unstart.

Pressure Recovery

The various configurations for which started flows were obtained in the diffuser duct resulted in different pitot measurements (shown at the far right in fig. 8) at the exit of the subsonic conical diffuser. The configuration with the oblique nozzle extension and the catch cone entrance ring resulted in higher pitot pressure measurements (better recovery) than the other cases tested. These measurements expressed as a ratio of the nozzle total pressure to the pitot pressures are compared in figure 9 to results of many previously documented investigations.[6] It is readily evident that the present results are within the acceptable band of 50 - 100 percent normal-shock recovery.

Acceptability

The "best" configuration of the subscale system tested (oblique nozzle extension and catch cone with an entrance ring) appears to be acceptable to the full-scale system. This "best arrangement" yielded acceptable diffuser pressure recovery and starting characteristics, stable diffuser pressure distributions, and unaffected tunnel nozzle flow when the scramjet model inlet was unstarted. A disadvantage, however, with this arrangement is that the free-jet length had to be equal to 1.75 D_j or less. This length results in the scramjet engine aft section protruding into the catch cone, thus, observation of the scramjet exhaust flow for composition measurements is somewhat hindered.

An additional concern is the applicability of the unheated tunnel results to the case where hydrogen fuel burned in the scramjet engine will substantially increase the temperature (about 80 percent increase) of the diffuser duct flow. In such a case, continuity requires that the Mach number in the duct must be lower than it would be for a no-fuel-burned case. This decrease in Mach number is detrimental to diffuser performance. For the small scramjet model (20 percent blockage), the subscale tests indicated that the subsonic diffuser entrance Mach number was approximatel 1.55, which appears to be high enough to assure $M \geq 1.0$ at the same location for the scramjet hydrogen-fuel-burning case. For the 33 percent model blockage, the subscale test results indicated that the subsonic diffuser entrance Mach number was only 1.13 and this may not be sufficient to assure $M \geq 1.0$ at the diffuser entrance for the hydrogen-fuel-burning case. The acceptability of the design for a scramjet engine blockage as high as 33 percent is therefore somewhat questionable. However, with an ejector system or a vacuum system (as discussed in the next section), even higher blockage models may be used.

Application to On-going Engine Tests

The opportunity to determine the applicability of the subscale test results to full scale has already occurred. As the subscale investigation was near completion, tests with a 20.3 cm high scramjet engine module were underway at a contractor's facility (General Applied Science Laboratories, Westbury, NY). The nozzle-scramjet-test cabin initially had been connected by piping to a vacuum-sphere system as represented by the solid lines in figure 10(a). The square cross-section test cabin was connected to the vacuum sphere pipe by a transition section which did not incorporate a catch cone-diffuser system. During early hydrogen-burning scramjet tests, scramjet-facility interactions were experienced. Specifically, the test cabin and nozzle exit pressures increased with time from the no-fuel level (at time zero) to some significantly higher level as the total fuel equivalence ratio (ϕ_T) was incrementally increased to its final value for the run. This is illustrated for a ϕ_T range of 0 to 0.44 by the dashed curves in figure 11. The test cabin and nozzle pressure trends were indicative of an engine-facility interaction; that is, almost immediately after fuel injection commenced, these pressures were affected and an engine unstart occurred. Since an engine unstart could also be caused by combustor-inlet interactions independent of the test cabin pressure, interpretation of the data was therefore impossible.

To eliminate the facility-engine interaction, a catch cone-diffuser arrangement, based on the "best arrangement" of the subscale tests, was designed and installed in the full-scale setup. Restrictions in the connecting pipe to the vacuum system and differences in the model lengths from subscale to full scale meant that the method of simply "scaling-up" from the diffuser subscale tests was not possible. A decision was therefore made to maintain approximately the same relative free-jet length and flow area around the aft end of the engine model and thereby produce approximately the same results. The dashed lines of figure 10(a) represent the full-scale diffuser modification; a sketch of the subscale test arrangement is shown for comparison in figure 10(b). Noticeable differences are: (1) the catch-cone half angle was reduced from 7° to 4.2°, (2) the straight-duct length was reduced from 7.2 to 4.0 pipe diameters, and (3) the straight duct diameter was increased to 45.7 centimeters from the "scaled-up" value of 41.4 centimeters. The larger straight duct diameter was incorporated to allow for the effect of heat addition in the engine fuel-burning tests. This diameter increase was simply based upon the ratio of free-stream temperatures (assumed fully-mixed flow at a station downstream of the engine) with and without stoichiometric heat addition in the engine model.

The modifications to the full-scale system resulted in the elimination of the scramjet-facility interaction as indicated by the nearly constant-level trend of the test cabin pressure as the ϕ_T was increased to a value of 0.77 represented in figure 11 by the solid-line curve. Pressure ratio distributions obtained from unheated and heated tunnel flow tests of the full-scale system are presented in figure 12 compared to those of the subscale tests. It can be seen that for the full-scale system the test cabin pressure is lower than the nozzle exit static pressure and the pressure distributions are similar to those for the subscale tests. With the heated tunnel flow and the engine fuel burning (injected for stoichiometric conditions), the trend is actually at a lower level even though a larger model blockage exists (41% as compared to 33%). These full-scale results were obtained with the vacuum system in use; however, the vacuum connecting pipe was choked for the tunnel mass flow being used. This choked condition resulted in a pressure in the connecting pipe just downstream of the straight-duct diffuser of about 0.5 atmospheres (mass flow dependent) even when the vacuum sphere pressure was 0.03 atmospheres.

Concluding Remarks

A subscale model of the nozzle exit-scramjet-diffuser system configuration of a Mach 4.0 flight simulation scramjet test facility has been successfully tested using unheated air over a nozzle total pressure range of 5 to 11.6 atmospheres. Although such a diffuser system cannot be accurately designed from existing literature alone, it was shown that a literature-based basic design can be made to operate adequately using modifications determined from subscale tests such as has been performed in the present investigation. The "best" nozzle exit-scramjet-catch cone arrangement appeared to be one that contained an oblique nozzle extension, a washer-type ring on the catch cone entrance, and a free-jet length of 1.5 to 1.75 nozzle exit diameters. The ratio of the nozzle total pressure to the diffuser exit pitot pressure for this arrangement fell within an acceptable band of 50 - 100 percent normal-shock pressure recovery. An analysis based on satisfying continuity indicated that the performance of the "best arrangement" should be sufficient for testing a hydrogen burning scramjet engine that blocks 20 percent of the nozzle exit flow. However, for an engine with a blockage as high as 33 percent, the performance of the "best arrangement" tested may not be sufficient to allow the engine to burn the hydrogen fuel stoichiometrically; for such a case an air injector may be required.

A full-scale nozzle-scramjet-test section connected to a vacuum system without a catch cone-diffuser system experienced scramjet-facility interactions. A catch cone-diffuser arrangement, based upon the present subscale "best arrangement", was employed within the piping to the vacuum system. Subsequent full-scale tests with heated tunnel flow and hydrogen fuel burning within the scramjet showed that the scramjet-facility interactions were eliminated and pressure distributions within the diffuser indicated very satisfactory performance of the arrangement.

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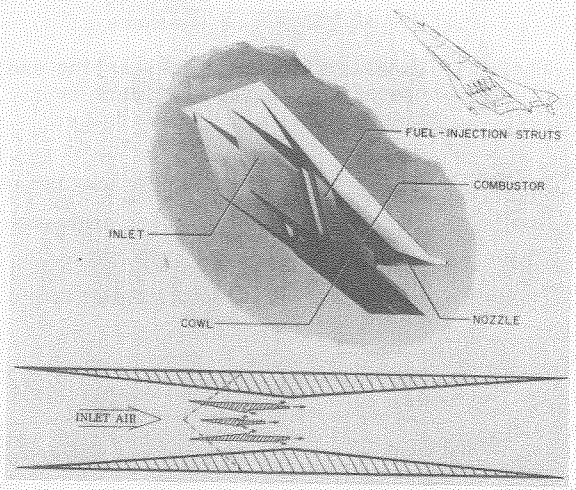


Fig. 1 Airframe-integrated modular supersonic combustion ramjet (SCRAMJET).

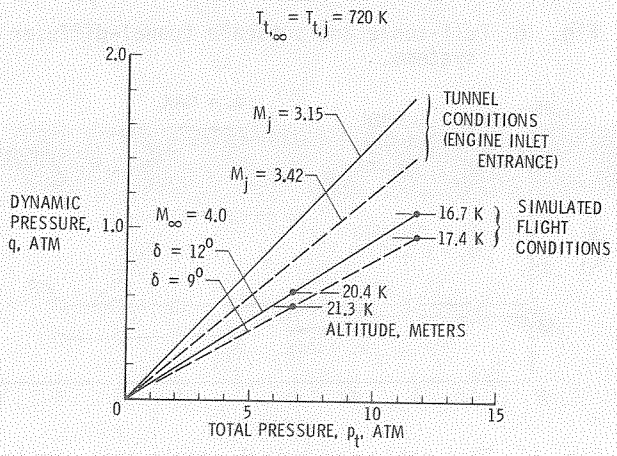
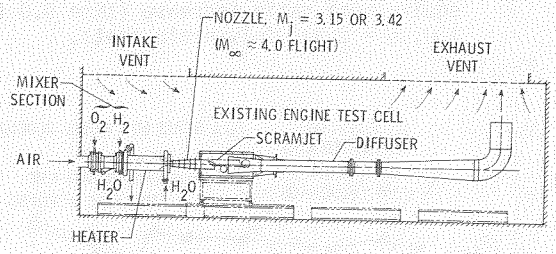


Fig. 2 Mach 4.0 flight condition simulation.



- VITIATED AIRSTREAM
- HYDROGEN-BURNING, HEAT-SINK ENGINE MODELS
- DUPLICATES MACH 4 FLIGHT ENTHALPY (T_t = 720 K)
- SIMULATES ALTITUDES FROM 16,764 TO 20,422 METERS
- SIMULATES AIRCRAFT BOW SHOCK PRECOMPRESSION
- SIMULATES FLIGHT ENGINE BOUNDARY LAYER INGESTION

Fig. 3 Mach 4.0 scramjet test facility.

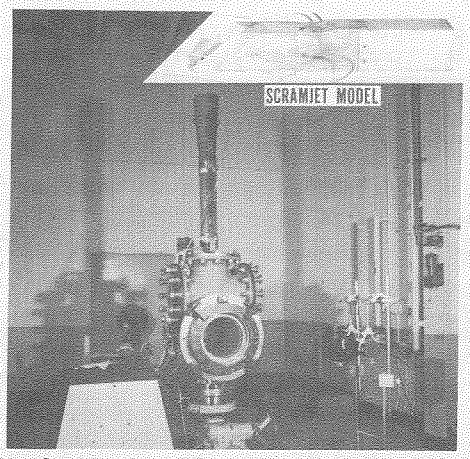


Fig. 4 Apparatus for 1/5-scale diffuser system investigation.

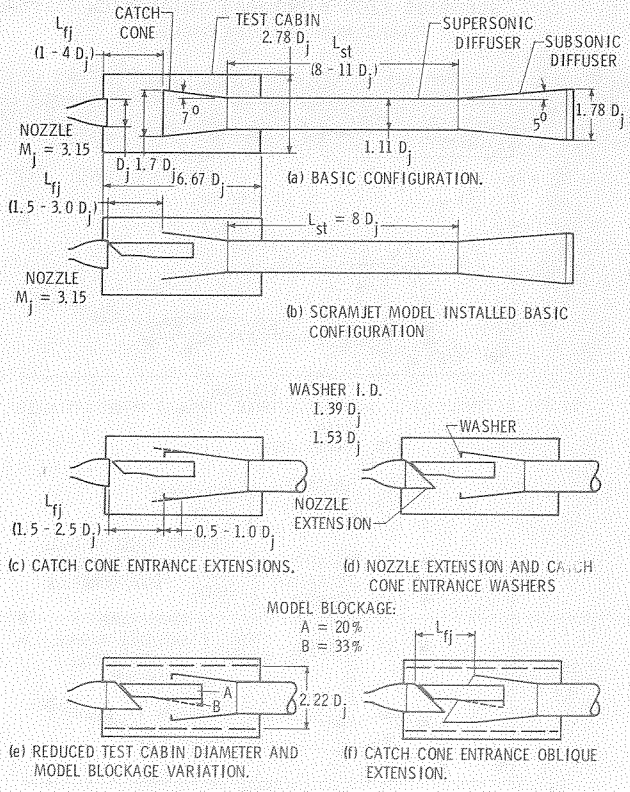


Fig. 5 Various test configurations; D_j = 9.144 cm.

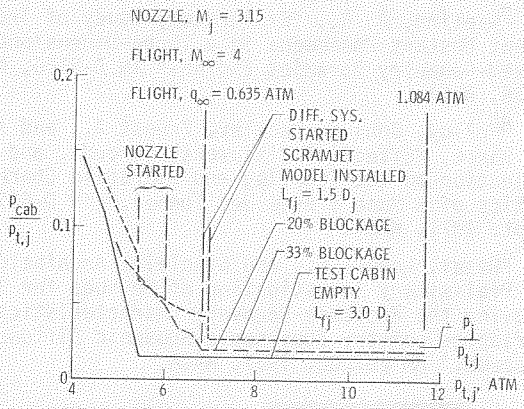


Fig. 6 Typical diffuser system starting pressures; scramjet model inlet flow started.

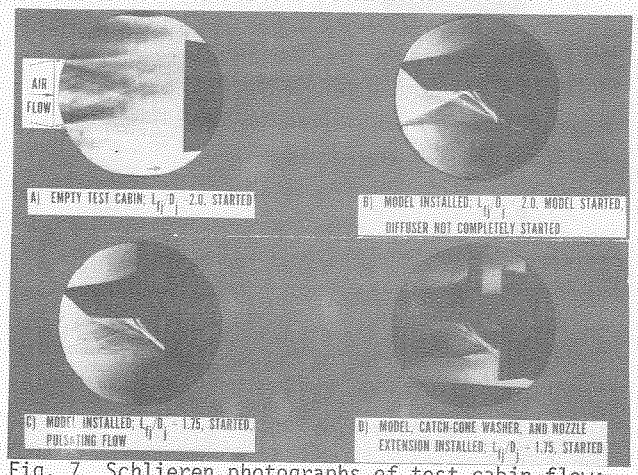


Fig. 7 Schlieren photographs of test-cabin flow; scramjet (20% blockage) inlet flow started.

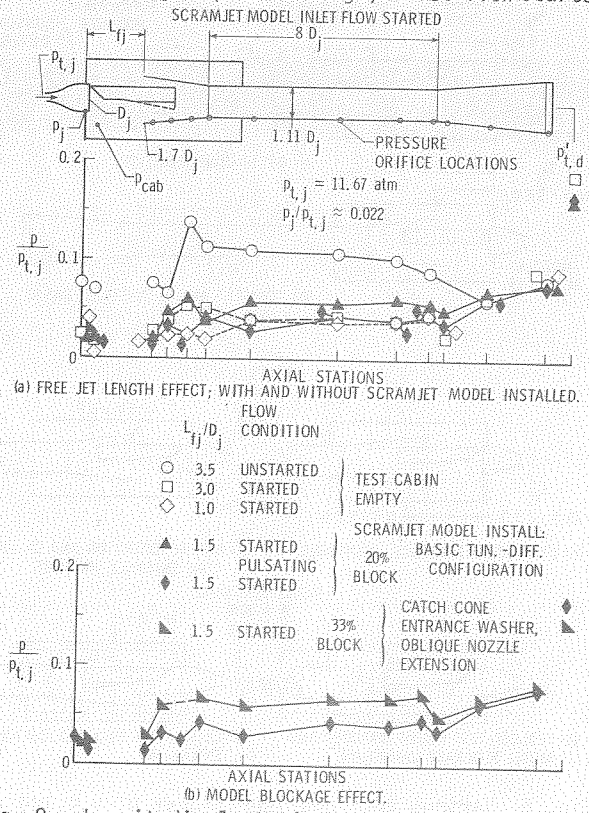


Fig. 8 Longitudinal static pressure distributions within the tunnel-diffuser system; scramjet model inlet flow started.

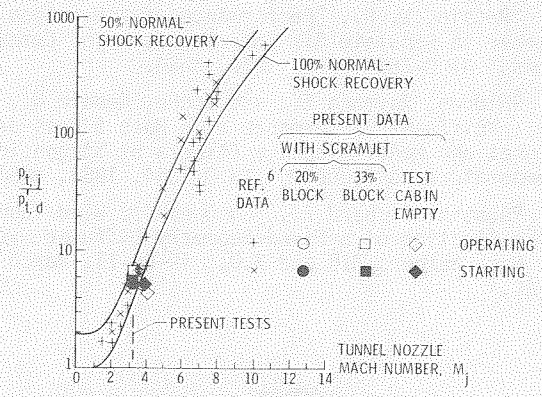


Fig. 9 Tunnel diffuser system starting and operating pressure ratios.

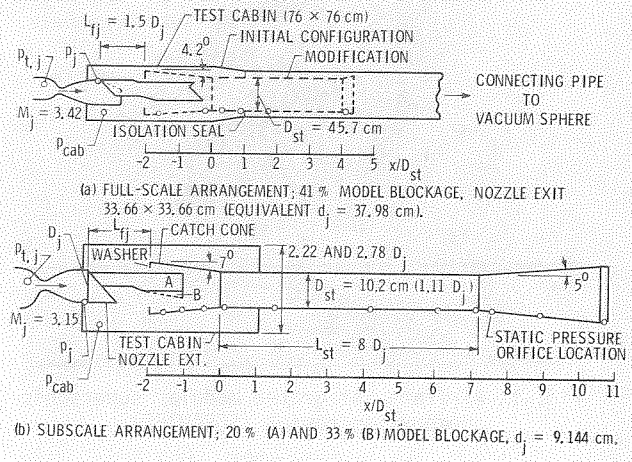


Fig. 10 Full-scale and subscale tunnel-diffuser systems.

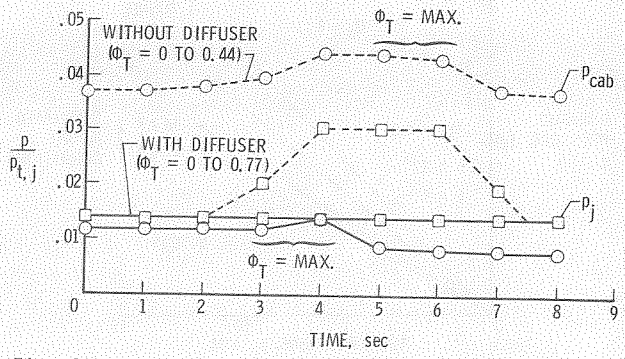


Fig. 11 Test cabin and tunnel nozzle exit static pressure variation with time and fuel equivalence ratio increase (time 0.0 to 1.0, ϕ = 0.0); full-scale tests.

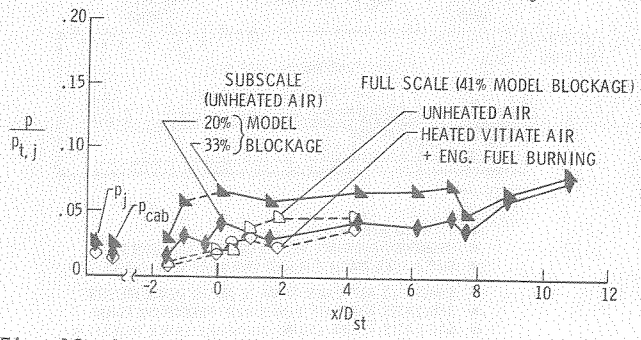


Fig. 12 Comparison of pressure distributions within full-scale and subscale tunnel-diffuser systems.