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SPACE SHUTTLE AERODYNAMIC DEVELOPMENT STUDIES

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ABSTRACT

Aerodynamic studies have been directed to investigating the design requirements associated with the unique operational flight profile of the space shuttle system. The flight regimes include launch, stage separation, orbital operations, entry, transition, cruise and landing. Aerodynamic configurations have been developed by interpreting the mission requirements in terms of required or desired aerodynamic characteristics. Analyses of configuration effects have been performed to obtain these characteristics. In many cases, experimental data has been obtained to either substantiate analytic trends or to provide basic data where the problem is not amenable to analysis.

INTRODUCTION

During the past year, the Convair division of General Dynamics has been actively engaged in conceptual design studies of reusable space transportation systems. These activities have necessitated an extensive technology effort to explore and study concepts and configurations. In particular, aerodynamic analytic and experimental investigations have been performed in support of these activities.

The aerodynamic studies have been directed to investigating the design requirements associated with the unique operational flight profile of the space shuttle system. The flight regimes, illustrated in Figure 1, include launch, stage separation, orbital operations, entry, transition, cruise and landing. The design studies to date have established approaches to the operational requirements of a space shuttle system. These approaches are reflected in the aerodynamic configurations shown in Figure 2. The launch configurations have included two-element and three-element (two-booster) arrangements. The application of deployable wings and engines for subsonic flight creates identifiably different configurations for entry and for cruise and landing. In the entry configuration, the body shape is established by mission requirements in terms of lateral range, by heating considerations, and by stability and control considerations. Surfaces are designed to provide aerodynamic stability during all phases of entry through the sensible atmosphere, to provide three-axis control and trim over a large angle of attack range. In the cruise and landing configuration, wing geometry and size are established by cruise or landing considerations. Wing location is established to provide stability and control characteristics comparable to conventional aircraft.

The aerodynamic configurations presented have been developed by interpreting the mission requirements in terms of required or desired aerodynamic characteristics. Analyses of configuration effects have been performed to obtain these characteristics. In many cases, experimental data has been obtained to either substantiate analytic trends or to provide basic data where the problem is not amenable to analysis. The following paragraphs summarize the aerodynamic studies which have been performed to date in support of the vehicle design studies.

LAUNCH AERODYNAMIC STUDIES

The launch phase of the operational flight profile has a significant influence on vehicle design. Of particular importance are the loads and control requirements established at the conditions of maximum dynamic pressure and angle of attack due to horizontal wind shears. The forces and moments acting on the vehicle during launch must be established for structural and control system design studies. The complex nature of the flow field associated with the launch configuration makes analytic prediction of the pressures, forces and moments acting on the vehicle difficult at best. For the design studies being performed at Convair, this data has been obtained experimentally.

Launch configuration wind tunnel tests were performed in the Cornell Aeronautical Laboratory's eight-foot transonic wind tunnel. Tests were conducted in July 1969 on two-element and three-element launch configurations over a range of Mach numbers from 0.7 to 1.2. Angles of attack in both pitch and yaw from -10 to +10 degrees were investigated. Force, moment and pressure data was obtained over the full range of test conditions. Interference effects, including the effect of gap spacing between elements, were also obtained. Figure 3 presents a photograph of one of the launch configuration models installed in the tunnel for testing. Additional tests were performed in the Marshall Space Flight Center 14 x 14 inch trisonic wind tunnel in October 1969. Two-stage launch configurations were tested over a range of Mach numbers from 0.7 to 5.0. Angles of attack from -4 to +12° in pitch and -10 to +10° in yaw were investigated. Force and moment data was obtained. The effect of orbiter location relative to the booster was investigated.

Typical data obtained from these tests is presented in Figure 4. Shown are the variations of axial force coefficient, longitudinal center of pressure and normal force coefficient gradient with Mach number. The launch configuration data is compared to the sum of the contributions of the isolated elements. A substantial interference increment is seen. The significant result presented is that both configurations are inherently stable during launch. This natural stability can be used to reduce the launch loads, since the vehicle will "weather-cock" during ascent through the wind shear, and the angle of attack can be held low. The other consequence is that control requirements, especially engine gimbal limits, can be reduced, since the engines do not have to control large angle-of-attack excursions.

STAGING AERODYNAMIC STUDIES

The complex arrangement of elements in the launch configuration of a space shuttle system makes the stage separation phase of the operational profile an important design consideration. The primary objective is to develop separation techniques which will ensure safe separation of the elements during normal staging or under abort conditions. The aerodynamic stability characteristics of each element, influenced by the interference effects between the elements during staging, must be predicted before analyses of relative stage motion can be made. These characteristics, along with the weight and inertia properties of the stages, may impose specific control requirements which must be provided in the vehicle design.

Staging studies have been performed at Convair through use of a unique experimental tool: the captive trajectory system in operation in the General Dynamics high-speed wind tunnel. Figure 5 shows the installation for the staging tests. In this test the element representing the orbiter stage was rigidly mounted. The other element, representing the booster stage, was mounted to a six-degree-of-freedom support. A strain gage balance mounted within the element feeds force and moment data continuously to an analog computer which uses the data, along with body mass characteristics, to compute the resultant trajectory. The trajectory is simulated by the six-degree-of-freedom support. The simulation includes the aerodynamic characteristics of the separating element during and just after separation and the dynamic and propulsion characteristics of the body itself. In this way, the effects of body release and flight conditions can be studied.

Captive trajectory tests were performed at tunnel Mach numbers of 1.63 and 4.0. At the low Mach number, flight conditions used to compute the trajectory corresponded to abort at ascent conditions at that Mach number; simulated dynamic pressure was 473 psf. At the high Mach number, the trajectory was simulated using nominal staging conditions of Mach 8 and dynamic pressure of 50 psf. In addition to the captive trajectory tests, traverse data was obtained to provide interference data over a wide range of positions and angles of attack to allow generalization of the results to other conditions. Single-element tests were performed to provide basic single-element data which could be compared with the traverse data to derive incremental interference effects.

Typical results from the captive trajectory stage separation tests are presented in Figure 6. In the simulation of staging during abort conditions, ($M = 1.6$, $q = 473$ psf), with release conditions of 20 degrees angle of attack and 20 degrees per second pitch rate, separation is clean and the vehicle attitude quickly begins to stabilize. With conditions simulating normal staging ($M = 8$, $q = 50$ psf), with initial angle of attack of 10 degrees and pitch rate of 20 degrees per second, aerodynamic forces and moments are insufficient to counteract the initial motion, and angle of attack increases monotonically. Figure 7 presents results of the traverse runs at Mach 4. Shown are normal force and pitching moment coefficients as functions of angle of attack and relative position of the two stages. The data indicates a significant interference effect and that as the stages separate, the element representing the booster develops an initial nose-up pitching moment.

The results of these tests have been used to develop staging techniques and to define control requirements during staging. As an example, the amount of restoring moment required to counteract the initial motion of the booster during staging at low dynamic pressure has been defined. This can be provided either by aerodynamic control or by an attitude control system.

ENTRY AERODYNAMIC STUDIES

The entry phase of the mission profile sets aerodynamic design criteria primarily through the mission requirements in terms of maneuvering capability. For the orbiter the lateral range requirement establishes the hypersonic lift-drag ratio which must be provided. Maneuver capability in pitch and roll is required to achieve a proper entry corridor and acquisition of the landing site. For the booster, the entry maneuver is one of minimizing downrange flight. This is accomplished with a high angle-of-attack entry, in combination with a banked turn to prepare for cruise-back to the launch site.

Development of an entry aerodynamic configuration which can satisfy the mission requirements described above has been accomplished primarily by analytic predictions of lift, drag, stability, and control characteristics. Figure 8 presents predicted characteristics of the entry configuration. Shown are normal force and pitching moment coefficients as functions of angle of attack and control deflection, as well as trimmed lift-drag ratio and directional stability as a function of angle of attack. This data reflects characteristics designed into the entry configuration, namely, trim capability over a wide range of angles of attack, lift-drag characteristics to provide a potentially high lateral range, and inherent stability in both pitch and yaw.

The entry characteristics presented in Figure 8 were predicted using a digital computer program based on Newtonian hypersonic theory. This computer program provides a valuable preliminary design tool. The effects of configuration modifications, such as body shape or surface size can be readily assessed.

Experimental investigation of the aerodynamic characteristics of the entry configuration at hypersonic and supersonic Mach numbers has been accomplished to provide verification of the predicted trends and to provide empirical data for modification of the theoretical results for Mach number and flowfield interference effects. Wind tunnel tests were conducted at the Marshall Space Flight Center tri-sonic tunnel. The entry configuration was tested over a range of Mach numbers from 0.9 to 5.0 and angles of attack from 0 to 20 degrees. Test parameters included the effects of stabilizing and control surfaces. Additional data at a Mach number of 10 was obtained during a test conducted at the Arnold Engineering Development Center's tunnel C. The entry configuration was tested over a range of angles of attack from 0 to 45 degrees. Figure 9 shows the entry model installed in the AEDC tunnel.

Typical data obtained from the supersonic and hypersonic tests is presented in Figure 10, compared with the theoretical predictions. Normal force and pitching moment coefficients as a function of angle of attack are presented for Mach numbers of 2, 4, 5, and 10. The pronounced Mach number effect on the stability characteristics of the entry configuration is evident. This trend is primarily the result of reduced effectiveness or contribution of the tail with increasing Mach number. The correlation of the Mach 10 data with the theoretical prediction is generally good. Excellent correlation of the normal force characteristics is seen. The difference in predicted and measured pitching moment is attributed to the forebody contribution and reduced tail effectiveness.

One result established by the experimental data is the natural trim to lower angles of attack as the Mach number is reduced from hypersonic to low supersonic. This occurs during the entry glide into the lower atmosphere. This tendency can be used to produce a gradual transition to powered cruise and/or landing.

Design of the thermal protection system and control system for the entry phase of flight for the orbiter and booster stages requires definition of the flight trajectories of each stage. Trajectory analyses have been performed in support of these studies using the theoretical and experimental aerodynamic characteristics of the entry configurations, discussed previously. Figure 11 presents typical entry trajectories predicted for the booster and orbiter stages. The fundamental difference between the two entries is obvious. The booster enters from staging conditions at moderate altitudes with near-orbital velocities. The primary consequences of the differing entry conditions are longer entry time and aerodynamic heating which requires thermal protection. Maneuver requirements and control system design are also established by these considerations. As an example, the orbiter performs a constant-altitude maneuver following initial pullout during entry. This maneuver, which requires lift modulation, can be performed by controlled banking or angle-of-attack modulation. Studies at Convair have been and are being conducted to define the aerodynamic control requirements based on the entry trajectories.

TRANSITION AERODYNAMICS

The entry phase of flight for either the orbiter or the booster is followed by a transition to the powered cruise and/or landing mode for the terminal phases of the mission operation. Included in this transition period is passage through transonic conditions. Although this is a transient condition, the aerodynamic requirements are for stability and control throughout the transitional phase.

The configurations studied by Convair use deployable wings and engines for powered subsonic flight. The transitional maneuver, for this approach, is to fly through the transonic regime in the entry configuration, using the inherent stability and trim discussed in the previous section. After subsonic conditions have been reached, the wing is gradually deployed to the cruise or landing position. This is followed by deployment of the engines, and if desired, an air start maneuver can be performed.

This phase of the mission has been studied to establish vehicle control and system requirements. Figure 12 presents a terminal entry trajectory using aerodynamics based on the experimental data previously presented. An air start corridor is shown and start-of-cruise conditions defined. It is indicated that deployment of the wings and engines can be performed over a wide corridor; definition of this maneuver is currently under study.

BOOSTER CRUISE AERODYNAMIC STUDIES

In the operational flight spectrum of the booster stage, the subsonic cruise back to the launch site has profound influence on the system design. Cruise propulsion system design, flyback fuel allotment, and even the geometry of the wings are established by this phase of the mission. These design studies require definition of the cruise configuration aerodynamic characteristics, primarily lift and drag. Stability and control characteristics must also be established.

Aerodynamic studies to define the booster cruise configuration have been accomplished primarily with the aid of data obtained from low-speed wind tunnel tests. An exploratory test was performed early in 1969 in the Princeton University two-by-three foot subsonic wind tunnel. Thirty-seven configurations involving changes in body shape and tail geometry were tested. These tests established a preliminary low-speed configuration. In June 1969, tests were performed in the General Dynamics eight-by-twelve-foot low-speed wind tunnel. Test conditions were Mach 0.31 and a Reynolds number of 2.1 x 10^6 per foot. Configuration parameters included wing geometry (sweep, area, aspect ratio, and incidence), tail geometry (incidence and rollout), body geometry (fineness ratio and boattailing), and control effectiveness. Six-component force and moment data was obtained. Figure 13 shows the cruise configuration model installed in the GDLSWT test section. In August 1969, a cruise configuration defined from the previous tests was tested in the Langley Research Center two-dimensional, low-turbulence pressure tunnel. The primary purpose of the tests was to provide data on the effect of the Reynolds number, of extreme importance in correcting wind tunnel results to full scale. Tests were conducted at Mach numbers from 0.23 to 0.35 and a Reynolds number from 2.3 to 14.6 x 10^6 per foot. Model buildup, wing position and sweep, and control effectiveness data was obtained.

Cruise configuration experimental data obtained both in the General Dynamics and Langley wind tunnels is presented in Figure 14. Lift coefficient, pitching moment coefficient, and lift-drag ratio are presented as a function of angle of attack. Of interest is the change in stability obtained by fore and aft movement of the wing. This demonstrates a design degree of freedom in the deployable wing approach since the desired low-speed stability can be obtained without compromise to the entry configuration. Good correlation of lift and lift-drag ratio is seen between the two sets of data. The effect of the Reynolds number on the maximum lift/drag ratio is seen for the cruise configuration (shown with and without boattailing). The maximum lift-drag is highest at the low Reynolds number, due to laminar flow effects on the wing. As the Reynolds number increases, the flow on the wing becomes fully turbulent and the lift-drag ratio reaches a minimum. As the Reynolds number is further increased, lift-drag ratio increases due primarily to the reduction of skin friction drag. The experimental trend is shown analytically extrapolated to the full-scale Reynolds number.

An important cruise configuration design consideration is wing sizing. The direct influence of wing size is on the cruise lift-drag ratio and, of course, wing weight. As the cruise L/D increases, engine size and weight and fuel quantity are reduced. The optimum, naturally, is the wing size which produces minimum system weight (essentially the minimum sum of wing,propulsion, fuel tank, and fuel weight). However, landing considerations may establish the minimum wing size.

Wing sizing studies have been performed at Convair as a part of conceptual design activities. Figure 15 presents typical results for a booster having a landing weight of approximately 320,000 pounds. These results were obtained using the experimental data previously presented. The direct effect of wing size on cruise L/D is presented. Also presented is the effect of flyback range on the wing size, which results in minimum system weight. It is indicated that as the required range is reduced, a landing speed limit becomes the wing sizing criteria. For the design presented, a landing speed requirement of 165 knots at touchdown sizes the wing until the range requirement exceeds 300 nautical miles.

LANDING AERODYNAMIC STUDIES

One of the mission requirements of both the orbiter and the booster stage is that it be able to make an approach to the landing strip, flare, and land in the manner of a conventional aircraft. In addition, the vehicle should not have landing and handling qualities characteristics more demanding than those of a conventional aircraft. Visibility, landing gear design, propulsion system design, and structural design also have influence on the development of a landing configuration.

Landing aerodynamic studies have been performed primarily through the use of experimental data obtained from the low-speed wind tunnel tests previously discussed. Figure 16 presents results of landing configuration tests. Shown are the lift coefficients versus angle of attack for an unflapped wing and for simple unslotted trailing edge flaps with deflections of 25 and 45 degrees, respectively. The implications of this data are seen in the effect of maximum lift coefficient on touchdown speed for a typical design. If touchdown speeds comparable to current commercial aircraft are desired, high lift coefficients are required. The configuration under consideration would require a more sophisticated high lift system or larger wings. The argument might be posed for not having flaps at all, thereby making touchdown at higher velocities. This approach may compromise other considerations, including visibility and structural loads associated with touchdown at higher angles of attack.

Control studies to define the landing maneuver have been performed based on the experimental aerodynamic data. Figure 17 presents typical results of these studies. Shown are time histories of vehicle height, velocity, sink rate, vehicle attitude, and angle of attack during an approach, flare and landing maneuver. The results indicate characteristics comparable to conventional aircraft. Touchdown occurs at a speed of 162 knots, with the sink rate dropping to 4 fps. Vehicle attitude is nearly horizontal throughout the maneuver, providing good visibility.

FUTURE AERODYNAMIC STUDIES

As a result of the aerodynamic studies and other design activities associated with the formulation of a space shuttle concept, additional aerodynamic investigations are being defined. Future studies include several additional wind tunnel programs. The lift/drag, stability and control characteristics which result during the transitional flight phase prior to cruise are being investigated. The effects of cruise propulsion exhaust flow on the aerodynamic characteristics of the cruise configuration will be determined by a powered-model test to be performed early in 1970. Additional captive trajectory tests are being defined to further investigate staging phenomena, including the effects of the exhaust plume of the orbiter stage. Flight simulator studies are being pursued to investigate handling qualities of the space shuttle elements throughout the operational flight regimes.

The unique requirements of the space shuttle vehicles - that they be capable of surviving the aerodynamic heating and deceleration loads of entry and be capable of flying and landing like a conventional aircraft - pose formidable problems to be analyzed. Aerodynamic studies such as those discussed will continue as configurations are modified to reflect further development.

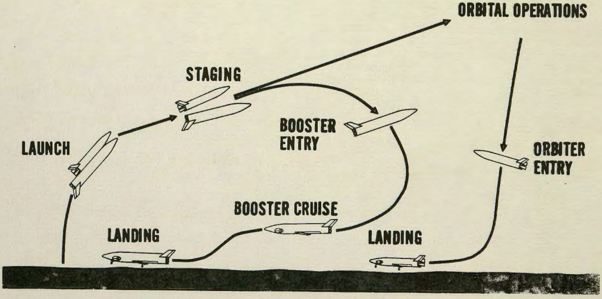


Figure 1. Operational Mission Profile

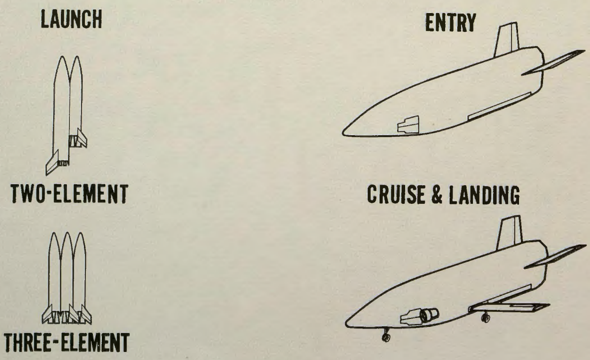
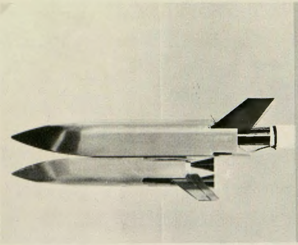


Figure 2. Aerodynamic Configurations



CORNELL AERO LAB TRANSONIC WIND TUNNEL
- **TEST CONDITIONS**
  - **MACH NUMBER ($0.7<M<1.2$)**
  - **ANGLE OF ATTACK ($-10° < \alpha < 10°$)**
- **PARAMETERS**
  - **LAUNCH ARRANGEMENT (THREE-BODY, TWO-BODY)**

MARSHALL SPACE FLIGHT CENTER TRISONIC TUNNEL
- **TEST CONDITIONS**
  - **MACH NUMBER ($0.7<M<5$)**
  - **ANGLE OF ATTACK ($-4° < \alpha < 12°$)**
- **PARAMETERS**
  - **LAUNCH ARRANGEMENT (ORBITER LOCATION)**

Figure 3. Launch Configuration Test Summary

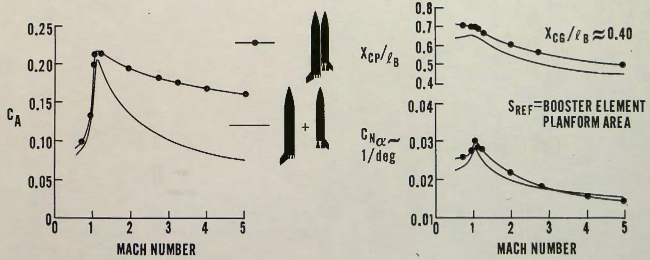
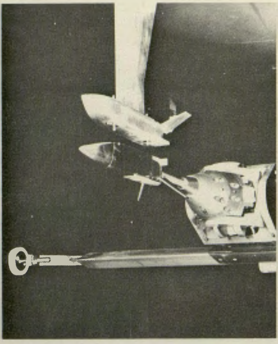


Figure 4. Launch Aerodynamic Data



CAPTIVE TRAJECTORY SYSTEM
GENERAL DYNAMICS HIGH-SPEED
WIND TUNNEL

TEST CONDITIONS
- **MACH NUMBER (M=1.6, 4)**
- **DYNAMIC PRESSURE (q=473, 50 PSF)**

PARAMETERS
- **VEHICLE WEIGHTS & INERTIAS**
- **INITIAL POSITION**
- **INITIAL RELEASE RATES**
- **THRUST**

Figure 5. Stage Separation Test Summary

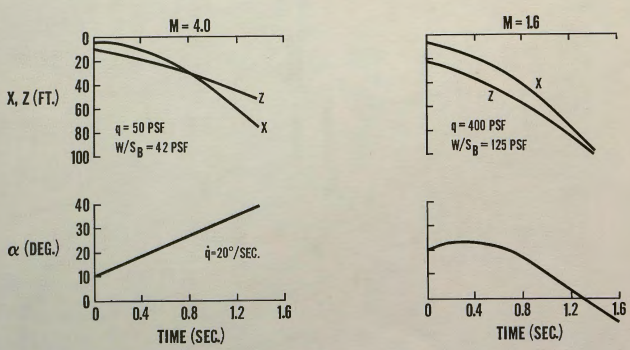


Figure 6. Captive Trajectory Stage Separation Data

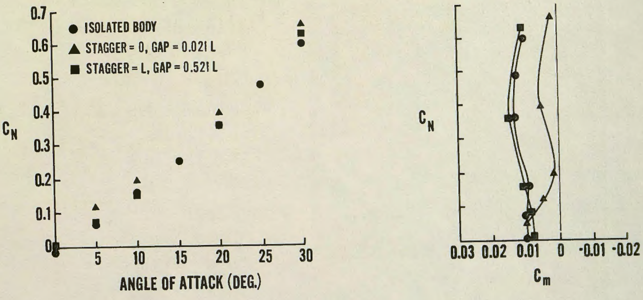


Figure 7. Staging Aerodynamic Interference Effects

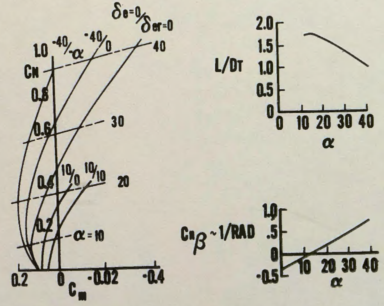
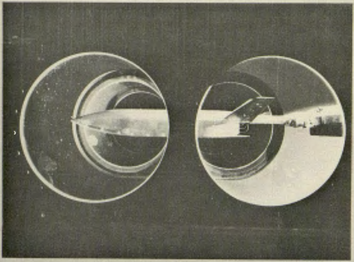


Figure 8. Predicted Entry Aerodynamics



MARSHALL SPACE FLIGHT CENTER
  TEST CONDITIONS
    MACH NUMBER $(0.9 < M < 5)$
    ANGLE OF ATTACK $(0° < \alpha < 20°)$
ARNOLD ENGINEERING DEVELOPMENT CENTER
  TEST CONDITIONS
    MACH NUMBER $(M = 10)$
    ANGLE OF ATTACK $(0° < \alpha < 45°)$
PARAMETERS
    CONTROL CONCEPTS
    STABILIZING SURFACES

Figure 9. Entry Vehicle Test Summary

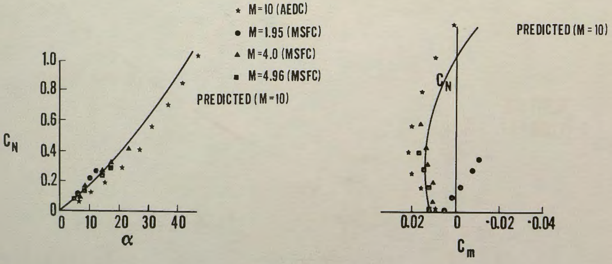


Figure 10. Experimental Entry Aerodynamic Data

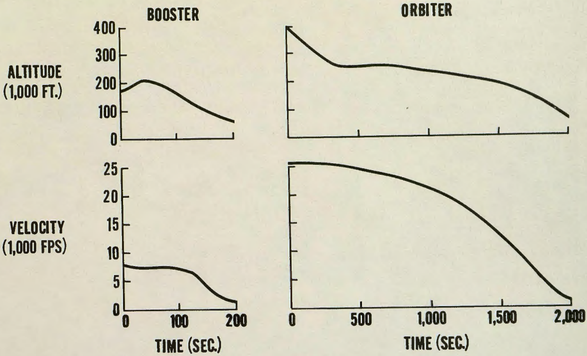


Figure 11. Predicted Entry Trajectories

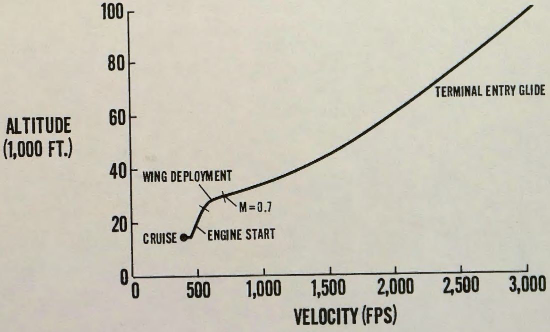
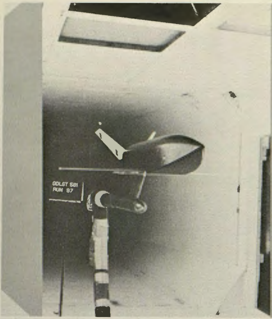


Figure 12. Transition Profile



GENERAL DYNAMICS LOW-SPEED WIND TUNNEL

TEST CONDITIONS
MACH NUMBER (M=0.3)

PARAMETERS
WING GEOMETRY (SWEEP, AREA, ASPECT RATIO, INCIDENCE)
TAIL GEOMETRY (INCIDENCE, ROLLOUT)
BODY GEOMETRY (BOATTAIL, LENGTH)
CONTROL EFFECTIVENESS

LANGLEY RESEARCH CENTER

TEST CONDITIONS
MACH NUMBER (M=0.25)
REYNOLDS NUMBER ($0.3\times10^6<R_N<2\times10^6$)

PARAMETERS
WING LOCATION, SWEEP
CONTROL EFFECTIVENESS

Figure 13. Low Speed Aerodynamic Test Summary

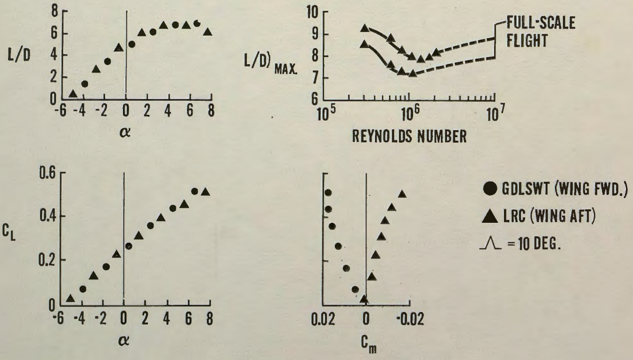


Figure 14. Experimental Low-Speed Aerodynamic Data

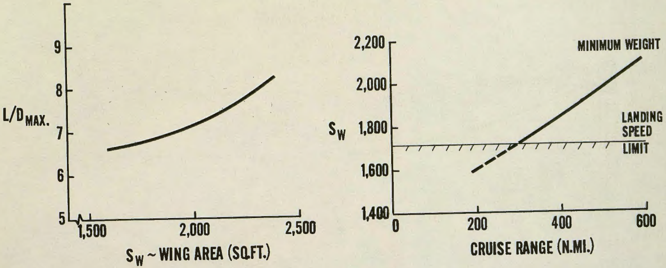


Figure 15. Booster Cruise Wing Sizing

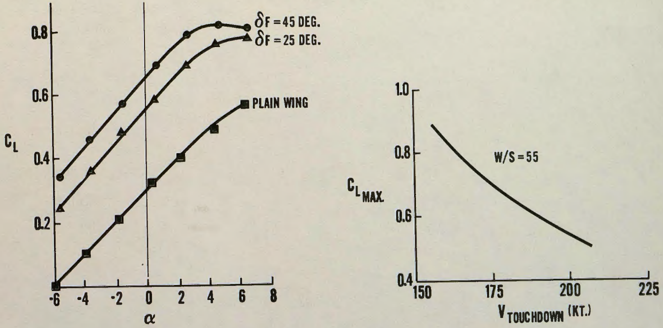


Figure 16. Landing Aerodynamic Characteristics

3° Glide Slope

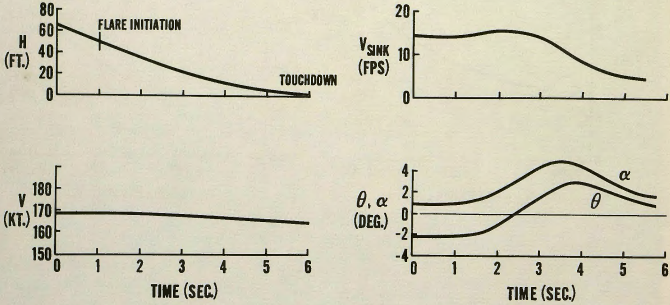


Figure 17. Landing Approach Control Studies