Investigation of Solid Plume Simulation Criteria To Produce Flight Plume Effects on Multibody Configuration in Wind Tunnel Tests

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DEFINITION OF SYMBOLS

\( A_{ORB} \) Orbiter base area
\( A_{ET} \) External tank base area
\( A_{SRB} \) SRB base area (one SRB)
\( A_{BF} \) Body flap planform area
\( C_{AT} \) Total axial force coefficient
\( C_N \) Normal force coefficient (uncorrected)
\( C_M \) Pitching moment coefficient (uncorrected)
\( C_{AF} \) Forebody axial force coefficient
\( C_{NF} \) Forebody normal force coefficient
\( C_{MF} \) Forebody pitching moment coefficient
\( C_{NW} \) Wing normal force coefficient
\( C_{BW} \) Wing bending moment coefficient
\( C_{TW} \) Wing torsion moment coefficient
\( C_{Heo} \) Outboard elevon hinge moment coefficient
\( C_{Hei} \) Inboard elevon hinge moment coefficient
\( C_{NB\ ORB} \) Orbiter base normal force coefficient correction
\( C_{NB\ BF} \) Body flap normal force coefficient correction
\( C_{MB\ ORB} \) Orbiter base pitching moment coefficient correction
\( C_{MB\ BF} \) Body flap pitching moment coefficient correction
\( C_{AB\ ORB} \) Orbiter base axial force coefficient correction
\( C_{AB\ ET} \) External tank base axial force coefficient correction
\( C_{AB\ SRB} \) SRB base axial force coefficient correction
\(C_{pB\ ORB,\ ET,\ SRB}\)  Element base pressure coefficient
\(C\)  Mean aerodynamic chord
\(C_e\)  Elevon reference length
\(D\)  Solid plume cone base diameter
\(D_{ORB}\)  Orbiter fuselage width
\(D_{SRB}\)  SRB aft skirt base diameter
\(F_A\)  Total axial force
\(F_N\)  Total normal force
\(F_{NW}\)  Wing normal force
\(H_{Mei}\)  Inboard elevon hinge moment
\(H_{Mco}\)  Outboard elevon hinge moment
\(L_{REF}\)  Reference length
\(q\)  Tunnel freestream dynamic pressure
\(S_{REF}\)  Reference area
\(S_{eREF}\)  Elevon reference area
\(X_1\)  Horizontal distance from centroid of orbiter base to MRP
\(X_{TO}\)  Horizontal distance from balance center to MRP
\(Z_1\)  Vertical distance from centroid of orbiter base to MRP
\(Z_{TO}\)  Vertical distance from balance center to MRP
\(\alpha\)  Angle of attack
\(\theta\)  Solid plume cone angle
\(X\)  Distance from SRB/ORB base to SRB/SSME cone base
\(M_{BW}\)  Wing bending moment
\(M_{TW}\)  Wing torsion moment
TECHNICAL PAPER

INVESTIGATION OF SOLID PLUME SIMULATION CRITERIA TO PRODUCE FLIGHT PLUME EFFECTS ON MULTIBODY CONFIGURATION IN WIND TUNNEL TESTS

INTRODUCTION

The Space Shuttle flight test program revealed that the propulsion system exhaust plume effect on vehicle base pressure had been considerably underestimated by ground testing. Flight base pressures were much higher on all of the vehicle elements than was predicted. The results of the ascent aerodynamic extraction process seemed to indicate that forebody forces, most significantly normal force and pitching moment, were also inconsistent with experimental results. One hypothesis was that the differences between flight and predicted forebody aerodynamics was a direct result of the higher base pressures feeding forward on the vehicle. To test this hypothesis, a wind tunnel test was conducted by MSFC to determine propulsion system plume effects on Space Shuttle Launch Vehicle (SSLV) aerodynamic force and moment coefficients when test model element base pressure coefficients were made equivalent to flight values. The test, designated TWT 675, was conducted in May 1982 in the Marshall Space Flight Center 14-in. Trisonic Wind Tunnel with a 0.004-scale model. Several solid body sting attachments simulating Space Shuttle Main Engine (SSME) and Solid Rocket Booster (SRB) plumes were used to produce the orbiter, SRB, and External Tank (ET) base pressures and orbiter elevon hinge moments observed in flight data. The test data yielded base pressures on the orbiter, ET, and SRBs that were within the flight data band for all Mach numbers. The best match of base pressures and inboard elevon hinge moments with flight data yielded forebody normal force changes of approximately 50 to 80 percent of flight deltas for both mated vehicle and orbiter. From these results, two important conclusions were drawn. Solid body plume simulation can be used to produce observed flight base pressures, and the flight extracted-preflight predicted differences may be attributed to plume effects. Solid plume simulators may therefore be an inexpensive, quick method of approximating the effect of engine exhaust plumes on the base and forebody aerodynamics of future, complex multibody launch vehicles.

The objective of this present investigation was to determine the sensitivity of the Shuttle base and forebody aerodynamics to the size and shape of various solid plume simulators. To support this task, a parametric evaluation of solid plume simulators was made in the MSFC 14-in. TWT using the 0.004-scale model of the SSLV. Families of cones of varying angle and base diameter at various axial positions behind the SSLV model were studied during this test, designated TWT 700.

FACILITY DESCRIPTION

The MSFC 14 x 14-in. Trisonic Wind Tunnel is an intermittent blowdown tunnel which operates by high pressure air flowing from storage to either vacuum or atmospheric conditions. The transonic section used for this test provides a Mach number range from 0.2 to 2.5. Mach numbers between 0.2 and 0.9 are obtained by using a controllable diffuser. The range from 0.95 to 1.3 is achieved through the use of plenum suction and perforated walls. A hydraulically controlled pitch sector located downstream of the test section provides the capability of testing up to 20 angles of attack from -10 to +10 deg during each run. On-line data is reduced to coefficient form by a solid-state data acquisition and computing system.
MODEL DESCRIPTION

The 0.004-scale model is a replica of the Space Shuttle launch vehicle consisting of the Orbiter (ORB), ET, and two SRBs. The total SSLV model was supported by a single sting and six-component balance in the orbiter. Two SRB dummy stings were also mounted in proximity to each SRB base. These stings in no way contacted the model, but served only to support the SRB plume simulators.

A typical plume simulation configuration is shown with the model in Figure 1. Plume geometry and position parameters are defined by Figure 2, and the test configuration geometries are given in Table 1. The SSME plume effects were simulated by mounting one of the cones with the CS designation to the main supporting sting, which was specially constructed so that the segment just aft of the orbiter is angled 16 deg from horizontal to simulate engine cant. Each CS cone was accompanied by a cylindrical extension of the same diameter to accommodate plume interference effects. The SRB plume effects were produced by mounting C designated cones to the dummy SRB stings, yet the SRB cones did not have extensions. The distances of the cones from the base of the respective vehicle element were variable as desired.

INSTRUMENTATION AND DATA REDUCTION

The SSLV model was mounted on a six-component balance which measured total mated-vehicle forces and moments. Model base pressures were measured using external tubes placed next to the base of each element as shown in Figure 3 and were sampled by transducers mounted outside the test section. The right-hand wing was supported on a single-beam, three-component balance in all degrees of freedom. The left-hand elevons were instrumented to measure hinge moment directly via gaged beams which supported each individual control surface.

Six-component force and moment coefficients were computed for the main balance using the axis system and reference point in Figure 4. Elevon hinge moments and wing forces and moments were computed in coefficient form about the reference locations given in Figures 5 and 6. Angles of attack were calculated from the sector reading, taking into account the sting and balance deflections as determined by pretest calibrations. The reference dimensions and constants used in data reduction are given in Table 2.

The following equations were used to reduce the force and moment data for wing, elevon, and mated vehicle coefficients.

For the mated vehicle total forces and moment:

\[ C_N = \frac{F_N}{qS_{REF}} \]  

\[ C_M = \frac{M_Y}{qS_{REF}L_{REF}} + \frac{F_N \cdot X_T}{qS_{REF}L_{REF}} - \frac{F_A \cdot Z_T}{qS_{REF}L_{REF}} \]
Base force and moment coefficients were calculated as follows:

\[
C_{AT} = \frac{F_A}{q S_{REF}}
\]  \hspace{1cm} (3)

\[
C_{NBORB} = \frac{C_{PBORB \ ORB \ AORB \ \tan \ (14.75^\circ)}}{S_{REF}}
\]  \hspace{1cm} (4)

\[
C_{NBF} = -\frac{C_{PB \ BF \ A_{BF}}}{S_{REF}}
\]  \hspace{1cm} (5)

\[
C_{MBORB} = C_{NBORB} \left(\frac{X_1}{L_{REF}}\right) - C_{ABORB} \left(\frac{Z_1}{L_{REF}}\right)
\]  \hspace{1cm} (6)

\[
C_{MBF} = C_{NBF} \left(\frac{X_2}{L_{REF}}\right)
\]  \hspace{1cm} (7)

\[
C_{ABORB} = -\frac{C_{PBORB \ ORB}}{S_{REF}}
\]  \hspace{1cm} (8)

\[
C_{ABET} = -\frac{C_{PBET \ A_{ET}}}{S_{REF}}
\]

\[
C_{ABSRB} = -\frac{C_{PBSRB \ A_{SRB}}}{S_{REF}}
\]

Now, adjusting for base coefficients, forebody coefficients are:

\[
C_{NF} = C_N - C_{NBORB} - C_{NBF}
\]  \hspace{1cm} (9)

\[
C_{MF} = C_M - C_{MBORB} - C_{MBF}
\]  \hspace{1cm} (10)
\[ C_A = C_A - C_{AB_{ORB}} - C_{AB_{ET}} - 2C_{AB_{SRB}} \] (11)

Wing-normal force-bending and torsion moments and elevon hinge moments are calculated as follows:

\[ C_{NW} = \frac{F_{NW}}{q \, S_{REF}} \] (12)

\[ C_{BW} = \frac{M_{BW}}{q \, S_{REF} \, L_{REF}} \] (13)

\[ C_{TW} = \frac{M_{TW}}{q \, S_{REF} \, \bar{c}} \] (14)

\[ C_{Heo} = \frac{H_{Meo}}{q \, S_{eREF} \, \bar{c} \, e} \] (15)

\[ C_{Hei} = \frac{H_{Mei}}{q \, S_{eREF} \, \bar{c} \, e} \] (16)

**TEST PROCEDURE**

The test schedule followed a systematic variation of the solid plume parameters previously defined. The SRB plumes were varied with two different fixed SSME plume configurations. This procedure was then followed for the SSME plume variation, using two different fixed SRB plume configurations. After completing a set of baseline plume-off runs, one run was made for each configuration at four Mach numbers, \( M = 0.8, 0.95, 1.10, \) and 1.25. During each run, the sector was stepped through five angles of attack: \(-6, -4, -2, 0, \) and \(+2 \) deg. For all runs, the angle of sideslip remained at 0 deg. Complete test conditions are given in Table 3.

**ANALYSIS AND RESULTS**

The test run schedule was successful in providing a parametric matrix of data. As shown in Figure 7, the resultant test base pressures encompassed the measured flight pressure data band observed during Space Shuttle flights STS 1-5. The complete data matrix indicates that any data point within this flight band can be achieved with the hardware used in this test. Since matching base pressures is one of
the most important criteria for plume simulation design, this could be considered the most significant result of this study.

Now, given that a particular data point could be obtained during testing, trying to match a set of desired data points including the various pressure and force coefficients becomes the challenge. Understanding the effects of solid plume geometry on these pressures and forces is necessary to solving the problem. Therefore, the data are presented in such a way that parametric effects become more obvious. An example plot is shown in Figure 8 and includes one orbiter base pressure data point for each of nine different parametric plume configurations at one Mach number. This data is plotted versus two different plume geometry parameters. The larger scale represents the dimensionless position \( \frac{X}{D_{SRB}} \) of the SRB cone behind the model as defined earlier. \( D_{SRB} \) is defined as the diameter of the base of the model SRB aft skirt. For SSME plume variations, the “diameter” of the orbiter, taken to be the width of the fuselage, will determine SSME cone position as \( \frac{X}{D_{ORB}} \). The smaller scale represents the dimensionless diameters of the cones and applies to all three different positions. Complete data from the test for one sector reading (\( \alpha = 0 \text{ deg} \)) are included in the appendices. The data are not interpolated to constant values of angle of attack. Therefore, there are slight variations of \( \alpha \) versus Mach number. But the deflections are less than 1 deg for all Mach numbers and the spread is only 0.25 deg. An analysis for angle of attack effects appears later in this section.

**Base Pressure Effects**

**Orbiter**

Orbiter base pressure coefficient data are given in Appendix A. In general, for SRB plume variations (Figs. A-1 through A-6) the data are more sensitive to diameter than position. As would be expected, the closer the plumes are to the vehicle model, the steeper the slope of \( C_{PB\ ORB} \) versus \( \frac{D}{D_{SRB}} \) becomes. The greatest data spread and sensitivity occur in the near Mach number equal to one range. Overall, the resulting trends are fairly predictable. For SSME plume variations (Figs. A-7 through A-10) the data display less sensitivity to variation in both position and diameter. However, very distinguishable trends do exist.

**External Tank**

External tank base pressures presented in Appendix B also displayed predictable behavior in that the effect of SRB cone diameter decreases somewhat proportionately with increase in \( \frac{X}{D_{SRB}} \). The SRB plume variation (Figs. B-1 through B-6) resulted in very few “irregular” data points and shows the high sensitivity of ET base pressure to SRB plumes. Both the orbiter and ET data showed more sensitivity to parametric variation for \( M = 0.95 \text{ and } 1.10 \). It appears that ET base pressures are as sensitive to SSME plume variations (Figs. B-7 through B-10) as the orbiter, and even more sensitive in some cases with larger diameters.

**Solid Rocket Boosters**

The SRB base pressure data are given in Appendix C. For SRB plume variations (Figs. C-1 through C-6), at the subsonic Mach numbers, the SRB base pressure data responds as expected, but
supersonically the sensitivity of $C_{P_{SRB}}$ to diameter is not diminished, as it was for the orbiter and ET, by increasing $X/D_{SRB}$. SSME plume variations (Figs. C-7 through C-10) caused very little effect on SRB base pressure at $M = 0.8$ and only diameter effects can be observed at other Mach numbers. As with the orbiter and ET, the effect of diameter did not taper off until $X/D_{ORB}$ was greater than 4.

Overall, several general observations can be made. The orbiter base pressure is very sensitive to both SSME and SRB plume variation. The ET is very sensitive to the SRB plumes and less sensitive to the SSME plume changes. The SRB base is highly affected by variation in SRB plume geometry, but shows little effect due to SSME plume variation. Finally, flight base pressure values can be obtained in scale model wind tunnel testing utilizing solid plumes.

**Body Force and Moment Effects**

Forebody axial force (CAF) coefficient data can be found in Appendix D. For both SRB and SSME plume variations, the data reveals very little or no change at $M = 0.8$. There occurred a slight reduction in $C_{AF}$ at all other Mach numbers. This was probably due to reduced interference drag through the aft attach structures. The almost negligible parametric effects of SSME variation were somewhat enhanced by the addition of the larger fixed SRB plume 2.

The observed trends for forebody normal force (CNF) given in Appendix E were similar to those displayed by ET base pressure. This cause and effect is obvious because the pressure distribution on the lower orbiter wing and fuselage surfaces are greatly affected by pressure in the ET base area. Also, as for ET base pressure, the orbiter normal force shows more sensitivity to SRB plumes than orbiter plumes. The forebody pitching moment (CMF) trends, shown in Appendix F, are primarily the result of the changes in $C_{NF}$. By observing the $C_{NF}$ and $C_{MF}$ trends with plume changes, it is obvious that the plume effects are occurring on the aft region of the vehicle.

**Wing and Elevon Effects**

The wing normal force data in Appendix G indicates that only a small part of the increment in $C_{NF}$ is due to wing load change. These data, along with the wing bending and torsion coefficients in Appendices H and I, display some interesting trends.

The effect of varying plume configurations on the total wing aerodynamics is relatively small. Changes that did occur were primarily due to SRB plumes with changes due to SSME plume changes essentially indistinguishable from data scatter. The wing coefficient trends indicate that plume changes affect both upper and lower surfaces and tend to move aft as the Mach number increases.

The inboard and outboard elevon hinge moment data in Appendices J and K provide an indication of how parametric plume effects vary span-wise along the wing. The inboard elevon proved to be more sensitive at all Mach numbers except $M = 0.95$, and much more sensitive for $M > 1.0$, as the effects become more confined to the vehicle base regions. As might be expected for observing the mated vehicle and wing data, the inboard elevon is more sensitive to changes in SRB plumes than to SSME plumes. Note also, that changes in either SSME and/or SRB plumes results in trailing edge up (negative) moment changes. The effects of plume changes on outboard elevon hinge moments are much smaller than for the
inboard elevon. This is expected as the outboard elevons are further from the plumes. However, as for the inboard elevon, the outboard elevon is more sensitive to SRB plume changes than SSME changes.

Effects of Change in Angle-of-Attack

For both SRB and SSME plume variations the effects of angle-of-attack change appear fairly small. Appendix L presents comparisons of coefficient plots between two angles-of-attack at $M = 0.8$ and $M = 1.25$ for SRB 28 deg cone variations and Appendix M shows the same comparison for SSME 35 deg cone variations. The figures in Appendices L and M show that the various coefficient plots change very little for both SRB and SSME plume variation at both $M = 0.8$ and $M = 1.25$. In general though, significant shifts of baseline numbers occur with change in $\alpha$ for some coefficients, the changes in plume-on minus plume-off deltas remain relatively small. It is obvious that the basic trends with plume size and position are the same for a wide range of angle-of-attack and, therefore, it would be possible for a single plume configuration to cover an entire angle-of-attack range.

CONCLUSIONS

The results of this study show the sensitivity of the aerodynamic characteristics of a complex vehicle (Space Shuttle) to wind tunnel plume simulation consisting of simple, inexpensive solid bodies. These results indicate fairly linear aerodynamic trends for parametric plume geometry changes and that a wide range of plume effects are possible with simple plume designs. The data are very useful for determining the parametric effects of each plume shape and will aid the aerodynamicist in the configuration of a set of solid plume simulators to produce a known desired effect on future vehicle wind tunnel models during testing. Though Space Shuttle launch vehicle flight base pressures were produced on the model, along with considerable variations about the flight values, this study was not intended to derive any method of predicting flight base pressures beforehand, but to evaluate a method of producing predicted or known flight values during wind tunnel testing.
Figure 2. Plume parameters.

Figure 3. Base pressure tap locations.
Figure 4. Aerodynamic body-axis reference system.
Figure 5. Wing coordinate axes.

Figure 6. Elevon coordinate axes.
Figure 7. SSLV element base pressure.
Figure 8. Orbiter base pressure coefficient.
<table>
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<tr>
<th>Designation</th>
<th>Angle (θ) (deg)</th>
<th>Diameter(s) (in.)</th>
<th>Position(s) (in.)</th>
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<td>20</td>
<td>1.25, 1.50, 1.75</td>
<td>1.67, 2.50, 3.33</td>
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<td>C2</td>
<td>28</td>
<td>1.25, 1.50, 1.75</td>
<td>1.67, 2.50, 3.33</td>
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<td>C3</td>
<td>45</td>
<td>1.25, 1.50, 1.75</td>
<td>1.67, 2.50, 3.33</td>
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<td>Variable SSME Plumes</td>
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<td>2.57, 3.42, 4.28</td>
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<td>CS2</td>
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<td>AORB</td>
<td>Orbiter Base Area</td>
<td>6.878 cm² (1.066 in.²)</td>
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<td>AET</td>
<td>External Tank Base Area</td>
<td>8.885 cm² (1.377 in.²)</td>
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<td>ASRB</td>
<td>SRB Base Area (one SRB)</td>
<td>3.510 cm² (0.544 in.²)</td>
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<td>ABF</td>
<td>Body Flap Planform Area</td>
<td>2.123 cm² (0.329 in.²)</td>
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<td>C</td>
<td>Mean Aerodynamic Chord</td>
<td>4.8240 cm (1.8992 in.)</td>
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<td>Ce</td>
<td>Elevon Reference Length</td>
<td>0.9215 cm (0.3628 in.)</td>
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<td>DORB</td>
<td>Orbiter Fuselage Width</td>
<td>2.172 cm (0.855 in.)</td>
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<td>DSRB</td>
<td>SRB Aft Skirt Base</td>
<td>2.116 cm (0.833 in.)</td>
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<td>LREF</td>
<td>Reference Length</td>
<td>13.106 cm (5.160 in.)</td>
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<td>SREF</td>
<td>Reference Area</td>
<td>39.987 cm² (6.198 in.²)</td>
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<tr>
<td>SeREF</td>
<td>Elevon Reference Area</td>
<td>3.122 cm² (0.4838 in.²)</td>
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<tr>
<td>X1</td>
<td>Horizontal Distance from Centroid of Orbiter Base to MRP</td>
<td>-12.832 cm (-5.052 in.)</td>
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<td>XTO</td>
<td>Horizontal Distance from Balance Center to MRP</td>
<td>-9.253 cm (-3.643 in.)</td>
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<tr>
<td>Z1</td>
<td>Vertical Distance from Centroid</td>
<td>-3.380 cm (-1.306 in.)</td>
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<tr>
<td>ZTO</td>
<td>Vertical Distance from Balance Center to MRP</td>
<td>-3.470 cm (-1.366 in.)</td>
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### TABLE 3. TUNNEL OPERATING CONDITIONS

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<th>Mach Number</th>
<th>Reynolds Number (per ft)</th>
<th>Dynamic Pressure (psig)</th>
<th>Stagnation Temperature (°F)</th>
<th>Stagnation Pressure (psia)</th>
</tr>
</thead>
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<tr>
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<td>$6.6 \times 10^6$</td>
<td>9.29</td>
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<td>22</td>
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<tr>
<td>1.25</td>
<td>$6.8 \times 10^6$</td>
<td>11.38</td>
<td>120</td>
<td>22</td>
</tr>
</tbody>
</table>
Figure A-2.
Figure A-3.
Figure A.4.
Figure B-1.
Figure B-4.
Figure B-7.
Figure B-9.
Figure C-3.
Figure C-5.
Figure C-10.
Figure D-3.
Figure D-4.
Figure D-10.
Figure E-2.
Figure E-3.
Figure E-6.
Figure E-9.
Figure F-3.
Figure F-10.
APPENDIX G
Figure G-3.
Figure G-4.
Figure G-8.
APPENDIX H
Figure H-1.
Figure H-4.
Figure H-5.
APPENDIX I
Figure I-2.
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Figure J-2.
Figure J-4.
Figure J-7.
Figure J-9.
Figure K.9.
APPENDIX L
Figure L-1.
Figure L.3.
Figure L-8.
Figure L-11.
Figure M-3.
Figure M-4.
Figure M-7.
Figure M-8.
Figure M-11.
An investigation to determine the sensitivity of the Space Shuttle base and forebody aerodynamics to the size and shape of various solid plume simulators was conducted. Families of cones of varying angle and base diameter, at various axial positions behind a Space Shuttle launch vehicle model, were wind tunnel tested. This parametric evaluation yielded base pressure and force coefficient data which indicated that solid plume simulators are an inexpensive, quick method of approximating the effect of engine exhaust plumes on the base and forebody aerodynamics of future, complex multibody launch vehicles.