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Produced by the NASA Center for Aerospace Information (CASI)
SPACE SHUTTLE ORBITER REACTION CONTROL SYSTEM JET INTERACTION STUDY

FINAL REPORT

GENERAL DYNAMICS
Convair Division
FOREWORD

The present study was undertaken by the Convair Division of General Dynamics under NASA contract NAS9-14095 and this report covers work undertaken from 15 June 1974 through 15 June 1975. The contract monitor was Mr. Barney Roberts of the NASA Johnson Space Center, Houston, Texas and the author wishes to acknowledge his very valuable assistance, direction and contributions to the successful completion of this study. The OA82 test data used in this program was generated in the NASA Langley Research Center CFHT hypersonic tunnel under the capable direction of Mr. Tom Blackstock to whom we wish to express our appreciation for his interest in and thorough efforts toward obtaining precise data required in this study.
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<td>body axis pitching moment coefficient = (pitching moment) / q Sref c</td>
</tr>
<tr>
<td>CN</td>
<td>body axis normal force coefficient = (normal force) / q Sref</td>
</tr>
<tr>
<td>Cn</td>
<td>body axis yaw moment coefficient = (yawing moment) / q Sref b</td>
</tr>
<tr>
<td>Cp</td>
<td>pressure coefficient = (P - P∞) / q</td>
</tr>
<tr>
<td>Ct</td>
<td>thrust coefficient = T / q Sref</td>
</tr>
<tr>
<td>Cy</td>
<td>body axis side force coefficient = (side force) / q Sref</td>
</tr>
<tr>
<td>d</td>
<td>diameter (ft)</td>
</tr>
<tr>
<td>h</td>
<td>kinetic energy parameter (ft²/sec²)</td>
</tr>
<tr>
<td>K</td>
<td>force or moment amplification factor</td>
</tr>
<tr>
<td>lref</td>
<td>longitudinal reference length (ft)</td>
</tr>
<tr>
<td>lB</td>
<td>body length (ft)</td>
</tr>
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</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>n</td>
<td>number of jets in cluster</td>
</tr>
<tr>
<td>P</td>
<td>pressure (lbf/ft²)</td>
</tr>
<tr>
<td>q</td>
<td>dynamic pressure (lbf/ft²)</td>
</tr>
<tr>
<td>R</td>
<td>gas constant (ft²/sec² lbf/°R)</td>
</tr>
<tr>
<td>r</td>
<td>radius (ft)</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>Sref</td>
<td>wing reference area (ft²)</td>
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<td>time (sec)</td>
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NOMENCLATURE (cont'd)

<table>
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<td>$T$</td>
<td>thrust (lb)</td>
</tr>
<tr>
<td>$T'$</td>
<td>temperature (°R)</td>
</tr>
<tr>
<td>$V$</td>
<td>velocity (ft/sec)</td>
</tr>
<tr>
<td>$x$</td>
<td>radial distance (ft)</td>
</tr>
<tr>
<td>$a$</td>
<td>angle of attack (deg)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>angle of yaw (deg); also $\sqrt{M^2 - 1}$</td>
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<tr>
<td>$\theta_N$</td>
<td>nozzle angle (deg)</td>
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<tr>
<td>$\theta$</td>
<td>angular orientation in jet (deg)</td>
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<tr>
<td>$\rho$</td>
<td>density (Ibm/ft$^3$)</td>
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<tr>
<td>$\gamma$</td>
<td>ratio of specific heat</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>momentum parameter (lbf) $= \gamma P M^2 A$</td>
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</table>

Subscripts
- **amb**: ambient conditions
- **c**: rocket chamber condition
- **i**: initial condition or conditions at point $i$
- **j**: jet exit conditions
- **$l$**: local condition or rolling moment
- **MAC**: mean aerodynamic chord
- **M**: any force or moment coefficient
- **m**: pitching moment
- **n**: yawing moment
- **N**: normal force
- **o**: total conditions
- **y**: side force
- **p**: peak
- **$\infty$**: free stream condition
- **interaction**: increment due to plume interaction
### NOMENCLATURE (cont'd)

<table>
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<td>impingement</td>
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<td>increment due to combined jets interacting</td>
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<td>sum of all terms</td>
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<tr>
<td>_</td>
<td>mean value or averaged value</td>
</tr>
<tr>
<td>*</td>
<td>throat condition</td>
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SUMMARY

This report is the final technical report and documents the work performed through 15 June 1975 under NASA Contract NAS9-14095.

The space shuttle orbiter has forward mounted and rear mounted Reaction Control Systems (RCS) which are used for orbital maneuvering and also provide control during entry and abort maneuvers in the atmosphere. RCS control effectiveness is critical to orbiter flight performance and safety. The effects of interaction between the RCS jets and the flow over the vehicle in the atmosphere is the subject of this study. This report presents the analysis of test data obtained in the NASA Langley Research Center 31 inch continuous flow hypersonic tunnel at a nominal Mach number of 10.3. The data was obtained with a 0.01 scale force model with aft mounted RCS nozzles mounted on the sting off of the force model balance. The plume simulations were accomplished primarily using air in a cold gas simulation through scaled nozzles, however, various cold gas mixtures of Helium and Argon were also tested to obtain (RT) ratio effects. The effect of number of nozzles was tested as were limited tests of combined controls.

The data shows that RCS nozzle exit momentum ratio is the primary correlating parameter for effects where the plume impinges on an adjacent surface and mass flow ratio is the parameter where the plume interaction is primarily with the external stream. An analytic model of aft mounted RCS units was developed in which the total reaction control moments are the sum of thrust, impingement, interaction, and cross-coupling terms.
INTRODUCTION

The space shuttle orbiter has two reaction control systems (RCS), as shown in Figure 1-1, which are used for orbital maneuvering. The rear RCS provides control during entry until the aerodynamic surfaces have sufficient effectiveness to assume full control of the vehicle as shown in Figure 1-2. Both the front and rear RCS units are also used during abort maneuvers to separate the orbiter from the tank, to pitch it to entry attitude, and to control it until aerodynamic control is established. Thus RCS control effectiveness is critical to the space shuttle orbiter flight performance and safety.

The study performed in reference 1 and wind tunnel data on the present baseline orbiter have shown that the control effectiveness of the RCS system is appreciably changed by the presence of air flow over and around the vehicle. These RCS - flow interactions have acted in directions such that the net RCS system effectiveness is much lower than the thrust moments alone and it is critical to flight safety and performance to know what the induced RCS - flow interaction moments are caused by and to develop methods to predict them. These are the basic purposes of this study conducted under NASA contract NAS9-14095. This report is the final report of this contract and documents the data analysis and analytic model development for RCS flow interference prediction. The data used for these analyses came principally from the space shuttle orbiter test designated OA82 which was documented in the interim technical report (reference 2) of this contract. These data were obtained from tests conducted by Rockwell International personnel within NASA test facilities, primarily the NASA-LRC 31 inch continuous flow hypersonic tunnel (CFHT) at a nominal Mach number of 10.3. The data was obtained primarily with a 0.010 scale force model with the RCS nozzles mounted on the sting of the force model balance. The plume simulations were accomplished primarily using air in a cold gas simulation through scaled nozzles, however, various cold gas mixtures of Helium and Argon were also tested to obtain (RT) ratio effects. The effect of number of nozzles was tested as were limited tests of combined controls.

The thermal analysis task was also documented in the interim report (reference 2) and will not be presented in this report.

This report will concentrate primarily on the data analyses and analytic model development and contains 5 parts:

a) Test Data Summary
b) Data Analysis
c) Analytic Model Development
d) Representative Full Scale Results
e) Study Conclusions

The data presented in this report is data for the aft RCS unit only. No test data has been obtained on forward RCS unit effectiveness at the time of preparation of this report.
Figure 1-1. Reaction Control Systems on Space Shuttle Orbiter
Figure 1-2. Aft RCS Operation During Entry
TEST SUMMARY

2.1 REAR MOUNTED RCS DATA BASE

Data from all rear mounted RCS tests was provided to Convair by NASA-JSC for compilation and analysis under this contract. This rear mounted RCS data base represents 10 tests as summarized in table 1. The PRR configuration data was obtained by General Dynamics/Convair in the test program reported in reference 1 and all of the remaining test data has been obtained in tests conducted by Rockwell International as part of the space shuttle orbiter development and the data for each test has been or will be reported in the DATAMAN reporting system for the shuttle. The OA82 test data documented in reference 2 is the principal source of data used in this study.

2.2 TEST MODEL AND RCS NOZZLES

Figure 2-1 presents the 139B orbiter configuration used in these tests. The model was a 0.010 scale model constructed from aluminum. The model was attached to a force balance mounted on a sting up through the base of the model as shown in Figure 2-2. The plenum chamber and nozzle block assembly was also mounted on the sting close to the base of the model but not attached to it. Thus the force balance measured model forces and moments and the loads induced by RCS operation but not the RCS jet moments. Grounding strips were mounted in the gap between the plenum and the model to insure that the model did not ground on the nozzles during the tests.

A number of different nozzles were used throughout the tests and tables 2 to 4 present the nozzle code numbers and a brief summary of the nozzle characteristics. All nozzles were tested using cold gas supplies located external to the tunnel and piped in through a pressure regulation system which was used to control the pressure in the plenum chamber manually during a tunnel data run. The pressure in the plenum chamber was measured by a pressure tap in the chamber connected to a pressure transducer mounted externally to the tunnel in most tests. The test gas used was air for all tests except for 12 runs on test OA82 where helium and Argon mixtures were used to vary the gas constant (R) of the test gas.

2.3 REFERENCE DIMENSIONS

All data used in the analysis was reduced to common reference dimensions using the orbiter wing area as the reference area, the wing mean aerodynamics chord (c) as the longitudinal reference length, and the wing span (b) as the lateral-directional reference length. The model scale for all tests but OA73 was 0.010 and the scale dimensions are:

\[
S_{\text{ref}} = S_{\text{wing}} = 0.02499 \text{ Meters}^2 (0.269 \text{ Ft}^2)
\]

\[
l_{\text{ref}} = \bar{c} = 12.06 \text{ cm (4.748 in)}
\]

\[
b_{\text{ref}} = b = 23.79 \text{ cm (9.367 in)}
\]
The moment reference center used for all model data reduction is located at 65% of the body length aft of the nose (full scale station 1076.7) on the fuselage reference line (full scale waterline 400). In .010 model scale

\[
\begin{align*}
X_{\text{CG}} & = 21.303 \text{ cm (8.387 in)} \text{ from nose} \\
Y_{\text{CG}} & = 0 \\
Z_{\text{CG}} & = 10.160 \text{ cm (4.0 in)} \text{ from bottom reference plane}
\end{align*}
\]

2.4 OA82 TEST PROGRAM SUMMARY

The aft RCS test designated OA82 was performed at the NASA Langley Research Center Continuous Flow Hypersonic Tunnel (CFHT) where it carried the test number CFHT113. The test was performed at a nominal Mach number of 10.3 using a .01 scale model of 139B orbiter to obtain 6 component force and moment data using a cold gas simulation of the RCS exhaust flow. The major test variables included:

- tunnel dynamic pressure \( (q = 75, 100, 125, 150, 200 \text{ PSIA}) \)
- RCS chamber pressure \( (P_{\text{OJ}} = 0 \text{ to 700 PSIA}) \)
- test gas \( \text{(air, He, Argon, .85 He,15A, .90 He,10A)} \)
- RCS control direction \( \text{pitch down N49, pitch up N52, yaw N84)} \)
- number of RCS nozzles
  
  | I   | Pitch down | 1,2,3 |
  | II  | Pitch up   | 1,2,3 |
  | III | Yaw        | 2,4   |

All aerodynamic control surfaces were kept at zero degree deflection throughout the test.

Reference 3 presents the error analysis performed on the PRR configuration data generated in the Unitary Plan Wind Tunnel at NASA-Langley Research Center. This data showed the advantages of obtaining repeat runs for the RCS off data in order to obtain a mean value for computing induced jet effects. A similar approach was taken during test OA82 where 6 repeat jet-off runs were obtained at a tunnel dynamic pressure \( (q_{\text{w}}) \) of 150 PSF and 4 repeat runs were obtained at \( q_{\text{w}} \) of 125 PSF. These data were used to generate mean value jet-off coefficients for the two dynamic pressures by selecting a base run and interpolating the 6 component data from all the other jet-off repeat runs to the base run angle of attack. The mean values were then computed for each force and moment component at each angle of attack.
Reference 2 documents the error analysis based on the OA82 test data which showed that there were systematic errors in the pitch axis jet off data at higher angles of attack as well as the statistical random errors in all data. This systematic error was interpreted as being caused by differences in upper surface pressures acting on the wing due to differences in the way the wing flow separates (reference 2). These data also show that the total error in amplification factor (Figure 2-3) is less than 20% for all moments except at the very lowest thrust coefficient tested and for normal force amplification where it is never better than 20%.

2.5 OA82 DATA SUMMARY

2.5.1 DATA REDUCTION PROCEDURE - The measured balance data from test OA82 included the basic vehicle aerodynamic forces and moments plus an induced loads resulting either from RCS jet impingement or from changes to the vehicle flow caused by the RCS jet plumes. The RCS jets were mounted on the non-metric sting so direct thrust forces were not measured on the balance. Therefore, the incremental induced effects are computed by removing the basic vehicle characteristics from the jet-on data:

\[ \Delta C_M = C_M^j - C_M^o \]  

where

- \( \Delta C_M \) = induced force or moment increment
- \( C_M^j \) = measured force or moment coefficient with jet on
- \( C_M^o \) = measured force or moment coefficient with jet off

Because the incremental values can be very small and thus sensitive to data scatter, the mean values of the jet off coefficient data were used as the best estimates of the data.

\[ \Delta C_M^i = C_M^j - \bar{C}_M^o \]  

where

- \( \bar{C}_M^o \) = mean value of jet off force or moment coefficient

Angle of attack differences between the jet-on data and the mean jet-off data were accounted for by passing a 3rd degree polynomial through the jet-off mean data with the nearest mean value angle of attack data as the midpoint of the curve fit and the interpolation is made to the jet-on angle of attack. The interpolation of the mean
value jet-off curves was done because it was assumed that these mean curves are less likely to have scatter to fit the curve through and better difference curves would result. Difference data was generated for all six aerodynamic components but axial force difference data was not analyzed.

During the data analysis the induced data increment was broken into an impingement component and a flow interaction component where the interaction component was obtained by

\[
\Delta C_M^{\text{interaction}} = C_{M}^{^\circ} - C_{M}^{\text{impingement}} - C_{M}^{\text{impingement}}
\]

where

\[
\Delta C_{M}^{\text{interaction}} = \text{induced force or moment resulting from RCS flow/flow field interactions}
\]

\[
C_{M}^{\text{impingement}} = \text{predicted force or moment due to plume impingement}
\]

and where the plume impingement of the model nozzles was predicted using the model to be discussed in Section 4.

Nozzle thrust was computed using the calibration data on the model nozzles while the other nozzle flow parameters were computed using ideal nozzle equations.

2.5.2 PITCH DOWN JET INDUCED DATA - The pitch down jet data was generated primarily with the nozzle set designated N49 whose principal characteristics are defined in table 2. This nozzle was mounted on the left side of the model as were all the other pitch nozzles used in this test except for one run of symmetric pitch down jets. The thrust moments thus would be nose down pitch (-) and right wing down roll (+) in the body axis data sign convention. The nominal values of the RCS thrust moments are tabulated with the run symbols on each plot.

Figure 2-4 presents the effect of supply pressure for nozzle N49 for freestream dynamic pressures of 125 PSF. These data show that the induced pitch and roll oppose the thrust moment and they are large compared to the control moment; therefore, the total control amplification factor will be low. The lowest pressure data on Figure 2-4 cluster very close together indicating a non-linearity in the induced effects and the data shows very little sensitivity or change with angle of attack. These data are typical of the pitch down jet incremental data shown in reference 2.

Figure 2-5 shows that symmetric firing of the pitch down jets results in an induced moment which is greater than twice the value for one side by a significant amount indicating plume/plume flow interaction in the base region of the model around the sting mount.
These data indicate that a better representation of the base region is needed for the pitch down RCS simulation. The roll jet data Figure 2-6, shows that the normal force and pitching moment effects are derived primarily from the pitch down jet, the side force and yawing moment are derived from the pitch up jet, and the induced roll increment as the sum of the single jet induced effects.

2.5.3 PITCH UP JET INDUCED DATA - The pitch-up RCS data was generated primarily with the nozzle designated as N52 whose principal characteristics are defined in Table 3. This nozzle block was mounted on the right side of the model and contains a two nozzle set exhausting vertically upward past the vertical fin which is approximately 9 nozzle diameters laterally from the nozzle centerlines. Figure 2-7 presents typical data of the induced forces and moments resulting from RCS jets firing upward. The pitch axis data shows some jet interaction effects at negative angle of attack where the upper surface is completely exposed to the flow but very little at higher angles of attack. The trends are much clearer in the lateral-directional data which shows strong interactions at negative angles decreasing as the angle of attack increases to approximately 10 degrees. Above this angle the induced effects become relatively insensitive to angle of attack. This data could be interpreted to show that a jet interaction type of flow occurs as long as the free stream flow is attached to the fin and when this is no longer true the interaction is primarily plume impingement on the fin where the plume shape is modified by freestream flow over the vehicle.

The only run of symmetric pitch up data obtained in the RCS test program to this time is presented in Figure 2-8. No difference can be seen in the induced pitching moment between the single side and the symmetric RCS cases in this figure.

2.5.4 YAW JET INDUCED DATA - The yaw jet data obtained in test OA82 was obtained with the nozzle set designated N85 whose characteristics are defined in Table 4. These nozzles were mounted on the left side of the model and exhausted perpendicular to the fuselage centerline in a plane parallel to the wing and approximately 13 nozzle diameters above it. This test concentrated on RCS pitch problems so that fewer yaw runs were obtained. Figure 2-9 presents yaw RCS data at two supply pressures and these data show little flow interaction at angles of attack below 5 degrees except in yaw where there appears to be some amplification of the thrust moment due to jet interaction. At higher angles of attack, pitch up and wing down moments are induced by the yaw jet but the effect appears to be non-linear in that the initial thrust created a larger change in moments than that caused by increasing thrust.

2.5.5 PITCH UP PLUS YAW JET COMBINED CONTROL - One nozzle set designated N84 was tested which contained both pitch-up and yaw nozzles. The nozzle characteristics are similar to those of nozzles N52 and N85. This nozzle set was mounted on the right side of the model firing upward and over the right wing. Figure 2-10 shows the effect
of supply pressure on induced forces and moments. At angles of attack below 10 degrees only the highest supply pressure shows any induced pitching moment but it is greater than the comparable data for the pitch up jet alone while at angles of attack above 10 degrees the pitching moment data looks quite close to the nearest comparable yaw jet case. The rolling moment at high angles appears to be due primarily to the yaw jet while at low angles it appears to be due to the pitch up/roll jet. Thus it appears for this combination of RCS controls that the pitch up/roll nozzles effects dominate at low angles of attack and yaw nozzle effects at high angles of attack.
### TABLE 1
RCS TESTS

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<th>Test Number</th>
<th>Test Type</th>
<th>Model</th>
<th>Scale</th>
<th>Facility</th>
<th>Date Received</th>
<th>Other</th>
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<td>Force + PRR Heat Transfer</td>
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</tr>
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<tr>
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</tbody>
</table>
### TABLE 3

**PITCH UP NOZZLES**

<table>
<thead>
<tr>
<th>Test</th>
<th>Nozzle</th>
<th>Expansion Ratio</th>
<th>Exit Diam.</th>
<th>Number in Aft Set</th>
<th>Aft Angle</th>
<th>Outboard Angle</th>
<th>Side</th>
<th>Exit Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA73</td>
<td>N\textsubscript{23}</td>
<td>1.159</td>
<td>.144 in</td>
<td>2</td>
<td>0\textdegree</td>
<td>0\textdegree</td>
<td>Right</td>
<td>5\textdegree</td>
</tr>
<tr>
<td>IA60</td>
<td>N\textsubscript{52}</td>
<td>4.43</td>
<td>.141</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>Right</td>
<td>34.25</td>
</tr>
<tr>
<td>OA105</td>
<td>Same as IA 60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LA25</td>
<td>N\textsubscript{32}</td>
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<td>Right</td>
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<tr>
<td></td>
<td>N\textsubscript{36}</td>
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<td>&quot;</td>
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<td>9</td>
</tr>
<tr>
<td>OA85</td>
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<td>.141</td>
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<td>Right</td>
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<tr>
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<td>N\textsubscript{81}</td>
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</tr>
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<td></td>
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<tr>
<td></td>
<td>N\textsubscript{84}</td>
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<td>&quot;</td>
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### TABLE 4

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<th>Test</th>
<th>Nozzle</th>
<th>Expansion Ratio</th>
<th>Exit Diam.</th>
<th>Number in Set</th>
<th>Aft Angle</th>
<th>Outboard Angle</th>
<th>Side</th>
<th>Exit Angle</th>
</tr>
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<tr>
<td>OA73</td>
<td>N19</td>
<td>10.81</td>
<td>.144</td>
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<td>0</td>
<td>Left</td>
<td>5</td>
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<td></td>
<td>N20</td>
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<td>(\ldots)</td>
<td>(\ldots)</td>
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<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
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<td>.141</td>
<td>4</td>
<td>0</td>
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<td>Left</td>
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<td>(\ldots)</td>
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<td>N51</td>
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<td>.141</td>
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<td>0</td>
<td>Left</td>
<td>34.25</td>
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<tr>
<td></td>
<td>N85</td>
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<td>2</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
</tr>
<tr>
<td></td>
<td>N84</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>2+2 Pitch</td>
<td>(\ldots)</td>
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Figure 2-1. 139B Orbiter Configuration
Figure 2-2. Model Base with Sting Mount
Figure 2-3: Expected Error in Amplification Factor
Figure 2-4a. N = 49 Effect of Supply Pressure at Q = 125 PSF
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>RUN</th>
<th>Pdj</th>
<th>Cm</th>
<th>Cl</th>
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</thead>
<tbody>
<tr>
<td>O</td>
<td>59</td>
<td>78</td>
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<td>X</td>
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<td>98</td>
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<td>□</td>
<td>61</td>
<td>129</td>
<td>-0.03117</td>
<td>0.00404</td>
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<tr>
<td>Y</td>
<td>62</td>
<td>261</td>
<td>-0.06307</td>
<td>0.00817</td>
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<tr>
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<td>-0.1143</td>
<td>0.01481</td>
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<td>64</td>
<td>702</td>
<td>-0.1696</td>
<td>0.02199</td>
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Figure 2-4b. N₄₉ Effect of Supply Pressure at Q=125 PSF
Figure 2-5. N49°50' Symmetric Pitch Down, Q=150 PSF
<table>
<thead>
<tr>
<th>SYMBOL</th>
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<th>P_{adj}</th>
<th>C_m</th>
<th>C_l</th>
<th>NOZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>6</td>
<td>155</td>
<td>-0.03121</td>
<td>0.00404</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>14</td>
<td>157</td>
<td>+0.03385</td>
<td>0.00440</td>
<td>Down</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>155</td>
<td>0</td>
<td>0.00845</td>
<td>Up</td>
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</tbody>
</table>

Figure 2-6a. N_{49} N_{52} Asymmetric Roll Jet at Q=150 PSF
### Table

<table>
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<tr>
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<th>$C_m$</th>
<th>$C_j$</th>
<th>NOZ</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-0.03121</td>
<td>0.00404</td>
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<td>14</td>
<td>157</td>
<td>+0.03395</td>
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<td>Up Roll</td>
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<tr>
<td>□</td>
<td>10</td>
<td>155</td>
<td>0</td>
<td>0.00845</td>
<td></td>
</tr>
</tbody>
</table>

### Diagram

#### Yawing Moment Increment ($C_y$)

-9.15 to 9.15

#### Rolling Moment Increment ($C_z$)

-9.15 to 9.15

#### Side Force Increment ($C_l$)

-9.15 to 9.15

### Figure 2-6b

Figure 2-6b. $N_49 N_{52}$ Asymmetric Roll Jet at $Q=150$ PSF
Figure 2-7a. \( N_{52} \) Effect of Supply Pressure at \( q=125 \) PSF
### SYMBOL RUN $P_0$ $C_m$ $C_1$

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>RUN</th>
<th>$P_0$</th>
<th>$C_m$</th>
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<tr>
<td>Y</td>
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<td>0.00889</td>
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<td>57</td>
<td>702</td>
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</table>

#### Figure 2-7b. $N_{52}$ Effect of Supply Pressure at $Q=125$ PSF
<table>
<thead>
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<th>SYMBOL</th>
<th>RUN</th>
<th>$P_{01}$</th>
<th>$C_m$</th>
<th>$C_f$</th>
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</thead>
<tbody>
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<td>.00440</td>
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<tr>
<td>X</td>
<td>12</td>
<td>157</td>
<td>.0679</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2-8. $N_{52}^{N_{81}}$ Symmetric Pitch Up at $Q=150$ PSF
Figure 2-9a. $N_{85}$ Effect of Supply Pressure at $Q=125$ PSF
Figure 2-9b.  Ns Effect of Supply Pressure at Q=125 PSF
### Table

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>RUN</th>
<th>$P_{o_j}$</th>
<th>$C_m$</th>
<th>$C_d$</th>
<th>$C_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
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<td>110</td>
<td>0.02785</td>
<td>0.00361</td>
<td>+0.01420</td>
</tr>
<tr>
<td>X</td>
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<td>131</td>
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<td>0</td>
<td>-0.01725</td>
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<tr>
<td>□</td>
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<td>124</td>
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<td>0.00439</td>
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</tbody>
</table>

### Diagram

- **NORMAL FORCE INCREMENT ($\Delta C_N$)**
- **PITCHING MOMENT INCREMENT ($\Delta C_m$)**

**Figure 2-10a.** Comparison of control additivity at $Q=125$ PSF

**Angle of Attack ($\alpha$) ~ DEG**
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>RUN</th>
<th>$P_0$</th>
<th>$C_m$</th>
<th>$C_\delta$</th>
<th>$C_n$</th>
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</thead>
<tbody>
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<tr>
<td></td>
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<td>131</td>
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<td>0.00439</td>
<td>0.01725</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>124</td>
<td>0.03391</td>
<td>0.00439</td>
<td>0.01725</td>
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</tbody>
</table>

Figure 2-10b. $N_{84}$ Comparison of Control Additivity at $Q = 125$ PSF
3. DATA ANALYSIS

3.1 SUMMARY OF PREVIOUS RESULTS

Reference 1 presents the final report analyzing the RCS data on the PRR configuration. That analysis showed that any nozzle parameter which was directly related to nozzle exit momentum ratio

\[ \frac{\delta_j}{\delta_{\infty}} = \frac{\gamma_j P_i M_j^2 A_j}{\gamma_{\infty} P_{\infty} M_{\infty}^2 A_{\infty}} \]  

(1)

was a good parameter with which to correlate the total induced effects of the RCS controls. That study could not show which of all the nozzle parameters was the best since only one nozzle shape was used to generate the data. In addition, data could not answer questions concerning the effects of number of nozzles firing in a given direction combining controls in other two directions, and the importance of gas temperature ratio as a parameter. Thus the purpose of this study was to obtain data on a more current orbiter base configuration and to update the analytic models to this configuration. In addition, data on the effects of temperature ratio, numbers of nozzles, and combined control were to be obtained and added to the models.

Thayer's dimensional analysis model (Ref. 1) for jet interaction problems shows that energy ratio

\[ \frac{h_{oj}}{h_{\infty}} = \frac{R_j T_{oj}}{R_{\infty} T_{\infty}} \]  

(2)

is a parameter for these types of flow interaction although he showed little effect if the ratio is below 9. The applicability of cold gas simulation techniques to simulate RCS effects and the extrapolation to full scale results depends on knowledge of how strong a parameter the energy ratio is and helium/argon gas mixtures were tested during test OA82 to vary the gas constant (R) in order to answer this question.

The data of Reference 1 were generated with two RCS nozzles being used in all control planes and the model was developed on a unit area ratio basis

\[ A_{\infty} = A_j \]  

(3)

However, the Shuttle control system determines the control requirements and uses varying numbers of nozzles to obtain the desired control moment. Thus a major test
parameter on test OA82 was to vary the number of nozzles in each control plane to determine the additivity of numbers of nozzles. Also a limited amount of combined control testing was performed to determine the cross-coupling effects on RCS flow-interaction.

The analytic model developed in Reference 1 assumes that the total control force or moment of a RCS control is the linear sum of the jet force or moment and an induced force or moment which is itself the sum of a term contributed by the direct impingement of the RCS plumes on adjacent surfaces and an interaction term which is the plume flow interacting with the external flow over the vehicle.

\[ C_{M_{\text{total}}} = C_{M_{\text{jet}}} + C_{M_{\text{impingement}}} + C_{M_{\text{interaction}}} \]  

where

- \( C_{M_{\text{total}}} \) = total control force or moment coefficient
- \( C_{M_{\text{jet}}} \) = RCS force or moment coefficient
- \( C_{M_{\text{impingement}}} \) = force or moment coefficient due to plume impingement on adjacent surfaces
- \( C_{M_{\text{interaction}}} \) = force or moment coefficient caused by plume interactions with the flow over the vehicle

The reasons for dividing the RCS induced effects into an impingement and an interaction component are that the vehicle geometry is such that the RCS jets exhaust toward many surfaces such as the wing upper surface, the body flap, the main propulsion engines, and vertical fin. The vacuum test data (Ref. 3) shows that there is plume impingement on these surfaces; but, the total induced forces and moments are larger than that which is predicted by plume impingement alone (Ref. 1), and this shows that there is a plume interaction with the flow field around the shuttle orbiter. In order to derive this interaction term, however, it is necessary to know or assume the impingement term and to subtract it from the total induced term. This was done in these analyses by using the analytic plume impingement model presented in Section 4 to predict the plume impingement for the model nozzle, test gas, and wind tunnel conditions and to remove it from the induced data as shown in Equation 3 of Section 2.

The analysis of the data will be presented by the direction of the control thrust and includes the following topics:

- 3.2 Pitch Down/Roll RCS
- 3.3 Pitch Up/Roll RCS
- 3.4 Yaw RCS
- 3.5 Combined Control
- 3.6 Possible Sting Interference
- 3.7 Time Dependent Effects
3.2 PITCH DOWN/ROLL RCS

Section 2.5.2 presents a summary of the left side, pitch down/roll jet data obtained during test OA82 and Figure 3-1 presents typical pitching moment increments obtained from these data. This figure shows that there appears to be little angle of attack effects in the data and that it may be possible to treat the incremental data as a function of nozzle flow parameters only. Figure 3-2 to 3-4 present comparisons of data averaged at all angles of attack with the data averaged in a high angle and a low angle of attack range. These figures show that there is a difference in data particularly at the lower momentum ratios and as a result a high/low range breakdown was selected for the pitch down data correlations in which 15 degrees angle of attack is the crossover point between models.

3.2.1 HIGH ANGLE OF ATTACK CORRELATIONS. Having divided the data into two groups above and below 15 degrees angle of attack, the data correlations for the high angle of attack represent approximately 5 points per data run taken at 5 degree intervals from 15 degrees to 35 degrees angle of attack. These data were treated as a set containing no angle of attack effects.

These data showed some correlation with all nozzle parameters which are directly related to nozzle momentum ratio (for a fixed nozzle geometry) such as jet exit pressure ratio in Figure 3-5. This figure shows, however, that the number of nozzles is a parameter which must be accounted for in some way. It was found that by redefining momentum ratio (Equation 1) with wing area as $A_w$ and the sum of the nozzle exit areas as the equivalent nozzle area $A_j$ was the best method for accounting for numbers of nozzles: Thus, momentum ratio is defined as:

$$
\frac{\dot{\gamma}_j}{\dot{\gamma}_\infty} = \frac{\gamma_j P_j M_j^2 \sum A_j}{\gamma_\infty P_\infty M_\infty^2 S_{wing}}
$$

The breakdown of the total induced moments into an impingement component and an interaction component still remains the best model of accounting for the differences between the flow in the base region of the model where the primary interactions should be impingement and that part of the plume which impinges on and interacts with wing flow. The plume impingement component of the pitch down data was generated using the model presented in Section 4 and the data was analyzed to determine the interaction term. Figure 3-6 presents the interaction pitching moment and rolling moment increments for the left side only pitch down jet ratioed to total jet moment. This data is very interesting because it shows that the interaction components are initially very large relative to the jet moments but becomes a smaller effect compared to the jet moment as jet moments increase. This is a new result compared to the PRR data (Ref. 1) due in part to higher jet momentum ratios achieved in these tests compared to the earlier results.
Figure 3-7 through 3-12 present the interaction increments for the pitch down jets firing on the left side only and these data show that the interaction terms increase very rapidly at low momentum ratios but tend to reach a constant level at higher momentum ratios. It was decided to develop the interaction model in terms of the interaction increments shown in these figures by curve fitting the data on these figures. The figures present average data for each run but the curve fits were generated as least square polynomial fits through all of the data.

The question of the need to simulate the exhaust gas energy ratio in addition to momentum ratio for the pitch down jets is answered by comparing Figure 3-9 with 3-8 where, for a fixed nozzle mass flow ratio is proportional to momentum ratio times energy ratio.

\[
\frac{\dot{m}_j}{\dot{m}_\infty} = \left[ \frac{\dot{E}_j}{\dot{E}_\infty} \cdot \frac{A_j P_j}{A_\infty P_\infty} \left( \frac{R_\infty T_\infty}{R_j T_j} \right) \right]^{1/2}
\]

(6)

In Figure 3-8 the gas mixture data from helium (R = 386) to Argon (R = 38.6) agree well with the air data based on momentum ratio whereas in Figure 3-9 the data form a line which crosses the air data correlation. Thus, cold air simulations appear to be adequate and momentum ratio is the parameter for pitch down RCS.

The normal force data whose averages are shown on Figure 3-7 were fit with a 2nd order least squares curve fit whose equation is

\[
\Delta C_{N_{\text{Interaction}}} = -0.0021945 - 0.811385 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right) + 4.51527 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right)^2
\]

(7)

This curve has a minimum value at a momentum ratio of 0.08985 and the minimum value of incremental normal force is -0.0386.

The incremental pitching moment (Figure 3-8) due to interaction curve fit is given by the equation

\[
\Delta C_{m_{\text{Interaction}}} = 0.004384 + 0.52205 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right) - 3.37717 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right)^2
\]

(8)

and has a maximum value of 0.024562 at a momentum ratio of 0.07729. The rolling moment data of Figure 3-10 curve fit is given by Equation 9

\[
\Delta C_{\ell_{\text{Interaction}}} = -0.0017358 - 0.1628144 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right) + 0.802611 \left( \frac{\dot{E}_j}{\dot{E}_\infty} \right)^2
\]

(9)

and this curve has a minimum value of -0.009993 at a momentum ratio of 0.1014.

The side force data (Figure 3-12) and yawing moment data (Figure 3-11) have different shapes than the previous curves and fourth order curve fits were made
through these data to get better representations of curve shape. The incremental yawing moment due to interaction is given by Equation 10 while the side force data was fit by Equation 11.

\[
\Delta C_n \text{Interaction} = 0.00034372 - 0.221604 \left( \frac{\Phi_j}{\Phi_\infty} \right) + 8.022016 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2 - 79.03936 \left( \frac{\Phi_j}{\Phi_\infty} \right)^3 + 246.3438 \left( \frac{\Phi_j}{\Phi_\infty} \right)^4
\]  

(10)

\[
\Delta C_y \text{Interaction} = 0.0067507 + 0.6925 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2 - 17.07348 \left( \frac{\Phi_j}{\Phi_\infty} \right)^3 + 477.2934 \left( \frac{\Phi_j}{\Phi_\infty} \right)^4
\]  

(11)

3.2.2 LOW ANGLE OF ATTACK CORRELATIONS. The low angle of attack data was analyzed in the same manner as the high angle data and the correlations are presented in Figure 3-13 to 3-17. The normal force due to interaction curve fit is given by Equation 12.

\[
\Delta C_n \text{Interaction} = 0.000406927 - 0.795865 \left( \frac{\Phi_j}{\Phi_\infty} \right) + 4.1104 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2
\]

(12)

which has a minimum value of -0.03812 at a momentum ratio of 0.096811. The pitching moment due to interaction equation is

\[
\Delta C_m \text{Interaction} = 0.000999527 + 0.501729 \left( \frac{\Phi_j}{\Phi_\infty} \right) - 3.0783998 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2
\]

(13)

and this curve has a maximum value of 0.02144292 at a momentum ratio of 0.08149. Equation 14 defines the rolling moment due to interaction as

\[
\Delta C_\phi \text{Interaction} = -0.000033456 - 0.132110 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2 + 0.5691798 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2
\]

(14)

and this equation has a minimum value of -0.007699 at a momentum ratio of 0.11605. These maximum or minimum values show close agreement with the results of the high angle of attack curve fits as was expected from Figure 3-3 and 3-4.

The side force and yawing moment increments due to pitch down jet RCS interaction at low angles of attack are given by Equations 15 and 16.

\[
\Delta C_n \text{Interaction} = 0.000057745 - 0.259978 \left( \frac{\Phi_j}{\Phi_\infty} \right) + 9.05189 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2 - 86.79901 \left( \frac{\Phi_j}{\Phi_\infty} \right)^3 + 265.0127 \left( \frac{\Phi_j}{\Phi_\infty} \right)^4
\]

(15)

\[
\Delta C_y \text{Interaction} = -0.000174433 + 0.754012 \left( \frac{\Phi_j}{\Phi_\infty} \right) - 18.2713 \left( \frac{\Phi_j}{\Phi_\infty} \right)^2 + 163.014 \left( \frac{\Phi_j}{\Phi_\infty} \right)^3 - 481.427 \left( \frac{\Phi_j}{\Phi_\infty} \right)^4
\]

(16)

Comparing these curves with the high angle of attack models at a momentum ratio of 0.1 shows
high $\alpha$ \[ \Delta C_n = 0.0039982, \quad \Delta C_Y = 0.0089138 \]

low $\alpha$ \[ \Delta C_n = 0.0042811, \quad \Delta C_Y = 0.0073851 \]

a good agreement between curve fits.

3.3 PITCH UP/ROLL RCS

Section 2.5.3 presents a summary of the right side pitch up/roll jet data obtained during test OA82 and Figure 3-18 presents the rolling moment increments obtained as a function of angle of attack. Above 15 degrees, the data appears much like the pitch down data in that angle of attack effects are small. As angle of attack decreases below 15 degrees angle of attack, all the data appears to follow one curve until a peak value is reached and the data decays along separate curves. The peak values and the angles of attack at which they occur appear to be functions of supply pressure or some other nozzle related parameters. The pitch up RCS data was broken into three parts for analysis based on these observations which are

a) high angle of attack
b) peak values
c) below peak values

3.3.1 HIGH ANGLE OF ATTACK CORRELATIONS. The division between the high angle of attack data and the other regions was arbitrarily chosen as 15 degrees. There are approximately five data points on each tunnel run between 15 and 35 degrees angle of attack which were analyzed as a set independent of angle of attack. These data were treated in the same way as the pitch down data in which it was assumed that the total induced force or moment was the sum of an impingement term and an interaction term. A theoretically predicted impingement term was then subtracted from the induced terms in order to define the interaction terms for correlation with nozzle parameters. Figure 3-19 shows that the interaction terms are large relative to the thrust at low values of momentum ratio (and thrust) but decline in much the same way as the pitch down data of Figure 3-4 did.

Figure 3-20 to 3-23 present the incremental normal force and pitching moment due to interaction correlated to mass flow ratio and momentum ratio respectively. The scatter in these data makes it difficult to choose a correlating parameter but the case is much clearer for the peak value which demonstrates what Figure 3-20 hints at, that is that the energy ratio cannot be ignored as a parameter for these data and as a result mass flow ratio is the better parameter. Least square polynomial curve fits were made through the mass flow data and Equations 17 and 18 were obtained

\[ \Delta C_{N_{\text{interaction}}} = 0.008828 - 0.156367 \left( \frac{m_j}{m_w} \right) + 0.051909 \left( \frac{m_j}{m_w} \right)^2 \] (17)
\[ \Delta C_{\text{m,interaction}} = -0.000421898 - 0.0168642 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right) + 0.026014 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right)^2 \]  

(18)

The normal force curve has a minimum value of -0.118 at a mass flow ratio of 1.506 while the pitching moment curve has a maximum value of 0.021443 at a mass flow ratio of 0.3241 which is much closer to the actual range of the data. The normal force and pitching moments due to interaction are not consistent with each other at low mass flow ratios (i.e., a positive normal force increment and a negative moment increment) and this must be laid to the relative inaccuracies of the data in this range. At low mass flow ratios the impingement predictions were zero and did not add scatter to the interaction data.

Figure 3-24 presents the rolling moment resulting from plume interaction correlated against momentum ratio. The moment due to interaction is small at high angles of attack and the correlation was weak with any parameter tried. The data was curve fitted using momentum ratio as the parameter because the lower angle peak values correlate better with this parameter and because plume impingement on the fin will induce rolling moments. Equation 19 is the resulting curve fitted through the data of Figure 3-24.

\[ \Delta C_{\text{\theta,interaction}} = -0.0010188 - 0.037801 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right) - 0.147119 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right)^2 \]  

(19)

The side force and yawing moment correlations are presented in Figure 3-25 and 3-26. These data were found to correlate but with momentum ratio and Equations 20 and 21 present the least square curve fit polynomials fitted through the data.

\[ \Delta C_{\text{\nu,interaction}} = 0.0013671 + 0.079588 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right) + 0.26561 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right)^2 \]  

(20)

\[ \Delta C_{\text{\gamma,interaction}} = -0.0030983 - 0.16962 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right) - 0.639818 \left( \frac{\dot{m}_j}{\dot{m}_\infty} \right)^2 \]  

(21)

Equations 19 to 21 do not have maximum or minimum values for positive momentum ratios unlike the pitch down data correlations and caution must be used in extending these curves too far from the range of the fit.

3.3.2 PEAK VALUE CORRELATIONS. Figure 3-18 showed that the interaction data exhibited a range of peak values at lower angles of attack which are dependent on nozzle conditions as is the angle of attack at which the peak value occurred. Figure 3-27 and 3-28 present peak values of interaction rolling moment and yawing moment plotted against the angles of attack at which they occur to show that there is a range of angles of attack where the peak values of interaction moments occur and that the data at angles of attack above the peak value lies on the same curve. No curve fitting nor interpolating of data was used to determine peak values of the data and some scatter must result because of the fixed angles of attack tested over this region of angles of attack. The model for predicting the effects in the peak value region consists of the following steps:
a. predict peak value as a function of nozzle parameters,
b. predict peak angle of attack from peak value,
c. if the angle of attack is above that for the peak value, predict interaction
value from angle of attack vs peak value curve

and the discussion will proceed in this stepwise fashion.

Figure 3-29 to 3-32 present correlations of peak value data as functions of momentum
ratio. These data in general show very good correlation with momentum ratio with
the exception of the longitudinal data whereas Figure 3-33 shows the gas mixture data
shows better agreement when it is correlated on the basis of mass flow ratio. The
peak interaction data for the lateral/directional increments was curve fitted with
momentum ratio as the parameter and Equations 22 to 24 present the results.

\[
\Delta C_{\text{L}}^{\text{peak}} = -0.0005544 - 0.2908833 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right) + 0.4219384 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right)^2
\]

(22)

\[
\Delta C_{\text{N}}^{\text{peak}} = 0.0006995 + 0.5021707 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right) - 0.718513 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right)^2
\]

(23)

\[
\Delta C_{\text{Y}}^{\text{peak}} = 0.00113266 - 1.1443836 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right) + 1.868108 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right)^2
\]

(24)

These curves all have a maximum or minimum value reasonably close to the data
range; the rolling moment has a minimum value of -0.05068797 at a momentum ratio
of 0.344699; the yawing moment peak has a maximum value of 0.08844 at a momentum
ratio of 0.34945; and the side force has a minimum value of -0.174127 at a momentum
ratio of 0.306295. The agreement between the values of momentum ratio at the curve
maxima would indicate that the peak value curves are good fits of the data.

The normal force peak value data of Figure 3-32 and 3-33 clearly indicate that the energy
ratio is an important parameter and must be accounted for by using mass flow ratio
rather than momentum ratio as the curve fit parameter given in Equation 25.

\[
\Delta C_{\text{N}}^{\text{peak}} = 0.008828114 - 0.1563674 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right) + 0.0519091 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right)^2
\]

(25)

and this curve has a minimum value of -0.11817 at a mass flow ratio of 1.506. The
pitching moment peak values data was very erratic at low values of momentum ratio
or mass flow ratio and while not an important term a curve fit (Equation 26) was made
through it for completeness of the model.

\[
\Delta C_{\text{m}}^{\text{peak}} = 0.00116665 + 0.0073166 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right) + 0.114445 \left( \frac{\dot{m}_J}{\dot{m}_\infty} \right)^2
\]

(26)

Equations 22 to 26 present curve fits which allow computation of the peak value of the
coefficients as a function of nozzle parameters. The next step is to compute the angles
of attack at which these peak values occur and the shape of the peak value versus angle
of attack curve. Equations 27 to 31 were obtained by curve fitting the data of Figure
3-27, 3-28 and similar data for the remaining peak increments.

\[
\Delta C_{T,\text{peak}} = -0.0435488 \left( \alpha + 13.273 \right)^{-1} + 0.00081505 \left( \alpha \right) - 0.0082231 \quad (27)
\]
\[
\Delta C_{n,\text{peak}} = 0.588341 \left( \alpha + 18.9366 \right)^{-1} + 0.000111737 \left( \alpha \right) + 0.0140611 \quad (28)
\]
\[
\Delta C_{Y,\text{peak}} = -6.06039 \left( \alpha + 31.8419 \right)^{-1} - 0.0017003 \left( \alpha \right) + 0.154756 \quad (29)
\]
\[
\Delta C_{N,\text{peak}} = 42.9197 \left( \alpha - 91.8437 \right)^{-1} + 0.00822308 \left( \alpha \right) + 0.435187 \quad (30)
\]
\[
\Delta C_{m,\text{peak}} = 0.0590783 \left( \alpha + 16.9382 \right)^{-1} + 0.00055711 \left( \alpha \right) - 0.00208543 \quad (31)
\]

Equations 27 to 31 can be solved for the angle of attack of peak increments determined from Equations 22 to 26 and if the vehicle angle of attack is higher than the peak angle the value of the induced increment is computed from Equations 27 to 31 directly as a function of vehicle angle of attack.

3.3.3 DATA AT ANGLES OF ATTACK BELOW PEAK VALUES. Figure 3-18 shows that the data below the angle of attack where the peak value occurred decays to a reduced level. A limited amount of analysis has been performed in this region because the number of data points is very small particularly for the higher jet pressures where the peak value was reached at or very near the lowest value of angle of attack tested and the curves depend on the lowest pressure data where error effects become significant. Figures 3-34 to 3-36 present typical results of these correlations. The data is presented as ratios of the peak value plotted against angle of attack measured from the peak value. These figures show the decline in the data below the peak value very clearly, however the scatter in the data is large and is introduced by all of the terms \( \left( \alpha, \alpha_{\text{peak}}, C_Y, C_{Y,\text{peak}} \right) \), for example. A model has been tentatively selected for this region which uses the peak value and assumes that the interaction increment goes to zero at 20 degrees below the peak. Equation 32 presents the model

\[
C_M = C_{M,\text{peak}} \left\{ \sin \left[ \frac{\pi}{2} \left( \frac{\alpha - \alpha_{\text{peak}} + 20}{20} \right) \right] \right\}^2
\]

where

\[
C_M = \text{pitch up force or moment coefficient}
\]
\[
C_{M,\text{peak}} = \text{peak pitch up force or moment coefficient}
\]

The value of 20 degrees below the peak was chosen because of the rolling moment data (Figure 3-34) and is below the range of angles of attack of practical interest.
3.4 YAW RCS

Figure 3-37 presents the induced yaw and roll data from the left side mounted yaw jets of test OA82. The data shows differences between the values at high angles of attack and those at low angles but within each range the variation with angle of attack is small and a high angle/low angle model similar to the pitch down model of Section 3.2 was used to correlate this data. There was fewer yaw data runs on test OA82 than pitch runs so that the models have fewer conditions to correlate against.

3.4.1 HIGH ANGLE OF ATTACK DATA. The high angle of attack range was defined as angles of attack above 15 degrees and the data presented in Figure 3-38 to 3-44 are averages of all the data above this angle of attack. Figures 3-39 and 3-41 present the longitudinal data correlated to momentum ratio while Figures 3-38 and 3-40 show that RT ratio is important and mass flow ratio is the better correlating parameter. This result was true for all of the yaw RCS increments.

The least squares curve fits through the normal force and pitching moment are given in Equations 33 and 34.

\[
\Delta C_{N_{\text{interaction}}} = 0.012030 - 0.443928 \left( \frac{m_j}{m_\infty} \right) + 0.423644 \left( \frac{m_j}{m_\infty} \right)^2 \tag{33}
\]

\[
\Delta C_{m_{\text{interaction}}} = 0.00153551 + 0.1525983 \left( \frac{m_j}{m_\infty} \right) - 0.9910115 \left( \frac{m_j}{m_\infty} \right)^2 \tag{34}
\]

The normal force curve fit has a minimum value of -0.1042558 at a mass flow ratio of 0.5239 while the pitching moment has a maximum value of 0.0074098 at a mass flow of 0.07699.

The lateral-directional interaction increments are shown in Figure 3-42 to 3-44. The rolling moment increments showed the poorest correlation to any of the nozzle parameters and more data is needed to refine this curve. Curves fitted through these increments are given in Equations 35 to 37.

\[
\Delta C_{l_{\text{interaction}}} = -0.0017298 - 0.079945 \left( \frac{m_j}{m_\infty} \right) + 0.575868 \left( \frac{m_j}{m_\infty} \right)^2 \tag{35}
\]

\[
\Delta C_{n_{\text{interaction}}} = -0.00034818 - 0.0193889 \left( \frac{m_j}{m_\infty} \right) + 0.0929347 \left( \frac{m_j}{m_\infty} \right)^2 \tag{36}
\]

\[
\Delta C_{y_{\text{interaction}}} = 0.00273838 + 0.157324 \left( \frac{m_j}{m_\infty} \right) - 0.920077 \left( \frac{m_j}{m_\infty} \right)^2 \tag{37}
\]

Each of these curves has a maximum within the range of the test data. The rolling moment curve has a minimum value of -0.004504 at a mass flow ratio of 0.069413; the yawing moment has a minimum value of -0.001359 at a mass flow ratio of 0.1043; and the side force curve has a maximum value of 0.009464 at a mass flow ratio of 0.85495.
3.4.2 LOW ANGLE OF ATTACK YAW DATA. Figure 3-45 to 3-49 present similar data to that presented above with the exception that it is low angle of attack yaw data. The trends are very similar to the high angle of attack data and mass flow ratio was found to be the better parameter thus RT ratio simulation is important in the interaction. Equations 38 to 42 present the curve fits for these data:

\[
\Delta C_N\text{interaction} = 0.00340516 - 0.4768133 \left( \frac{m_j}{m_\infty} \right) + 3.8111191 \left( \frac{m_j}{m_\infty} \right)^2
\]

\[
\Delta C_m\text{interaction} = 0.000219195389 + 0.0251417 \left( \frac{m_j}{m_\infty} \right) - 0.0637262 \left( \frac{m_j}{m_\infty} \right)^2
\]

\[
\Delta C_\ell\text{interaction} = -0.00049126 - 0.00860359 \left( \frac{m_j}{m_\infty} \right) + 0.0470322 \left( \frac{m_j}{m_\infty} \right)^2
\]

\[
\Delta C_n\text{interaction} = -0.00017444 - 0.07711317 \left( \frac{m_j}{m_\infty} \right) + 0.5407319 \left( \frac{m_j}{m_\infty} \right)^2
\]

\[
\Delta C_Y\text{interaction} = 0.00111215 + 0.3044469 \left( \frac{m_j}{m_\infty} \right) - 2.233286 \left( \frac{m_j}{m_\infty} \right)
\]

and the table presented below compares the peak values which result from these curves with those of the high angle of attack models of Section 3.4.1

<table>
<thead>
<tr>
<th>Increment</th>
<th>Low (\alpha) Curve</th>
<th>High (\alpha) Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta C_N)</td>
<td>-0.0111507, 0.06255</td>
<td>-0.1042558, 0.5239</td>
</tr>
<tr>
<td>(\Delta C_m)</td>
<td>0.002772, 0.19726</td>
<td>0.0074098, 0.0769911</td>
</tr>
<tr>
<td>(\Delta C_\ell)</td>
<td>-0.0008847, 0.09146</td>
<td>-0.004504, 0.069413</td>
</tr>
<tr>
<td>(\Delta C_n)</td>
<td>-0.002924, 0.07130</td>
<td>-0.0013595, 0.10431</td>
</tr>
<tr>
<td>(\Delta C_Y)</td>
<td>0.011488, 0.06816</td>
<td>0.0094636, 0.0855</td>
</tr>
</tbody>
</table>

These peak values show that the high angle of attack yaw RCS data showed much greater effects on the wing resulting in higher values of \(\Delta C_N\), \(\Delta C_m\), \(\Delta C_\ell\) while the lower angle data shows greater effects on the side of the fuselage and possibly the fin.

3.5 COMBINED CONTROL

All of the data presented in Section 3 have been devoted to RCS controls operating on a single side of the vehicle and not in combination with other controls. The possibility of combined control interference was shown in References 1 and 2, and these effects...
must be accounted for in any model of RCS effects. A limited set of data was obtained during test OA82 on certain control combinations which include:

a. Symmetric pitch down RCS
b. Symmetric pitch up RCS
c. Roll RCS
d. Combined right side pitch up and yaw RCS

Because the data set is limited the measured effects must be considered preliminary only.

3.5.1 SYMMETRIC PITCH DOWN. Figure 2-5 presents the symmetric pitch down data obtained in test OA82 and Figure 3-50 presents the ratio of the symmetric jet data to that of a single side set. These data show that the symmetric pitch down RCS effects are significantly greater than twice that of a single side firing and although there is some scatter it does not appear to be related to angle of attack. The interaction between the plumes must occur in the base region of the model between the body flap and main propulsion engines and must be related primarily to the plume impingement component rather than the interaction component. The effect of the sting is unknown (see Section 3.6) in this plume/plume interaction but a preliminary model has been made by averaging the data of Figure 3-50.

\[ \Delta C_N^{\text{cross coupling}} = 0.3(\Delta C_{N_{\text{impingement}}} + \Delta C_{N_{\text{interaction}}}) \] 

\[ \Delta C_m^{\text{cross coupling}} = 0.32(\Delta C_{m_{\text{impingement}}} + \Delta C_{m_{\text{interaction}}}) \]

where Equations 43 and 44 are additional terms to be added to the basic Equation 1.

3.5.2 SYMMETRIC PITCH UP RCS. Figure 2-8 presented the symmetric pitch up data obtained in test OA82 and this figure showed no difference in pitching moment between the single side and symmetric firing data. The normal force increment shows a very large difference in the range from zero angle of attack to 15° but a reversal occurs at higher angles of attack. While more data is needed to better define these effects, the pitching moment data should be more accurate and no effect of symmetric pitch up cross-coupling has been modeled.

3.5.3 ROLL RCS CROSS-COUPLING. Figure 2-6 presented a comparison of the roll jet increments with the two single side components which make up the roll jet combination. Figure 3-51 presents the roll combined control ratioed to the sum of
the individual components. There is large scatter in the normal force results at higher angles of attack but an average value taken through the data below 15° shows that there is a small increment

$$\Delta C_N \text{cross coupling} = 0.124 \left( \Sigma \Delta C_N \right) \text{components}$$ (45)

while the pitch data shows a slightly greater effect which is

$$\Delta C_m \text{cross coupling} = 0.211 \left( \Sigma \Delta C_m \right) \text{components}$$ (46)

The rolling moment data shows that it is very close to the sum of the two components (1.057 $\Sigma \Delta C_\alpha$) and no cross coupling term is used.

In the data presented above the components from the left and right sides act in the same direction and add together. The nozzles on opposite sides of the vehicle cause induced effects which oppose each other in the case of side force and yawing moment. Figure 3-51 shows that the resulting yawing moment is less than the difference of the two values and the average cross coupling term is

$$\Delta C_n \text{cross coupling} = -0.206 \left( \Sigma \Delta C_n \right) \text{components}$$ (47)

The side force components from both sides almost completely cancel each other except at the higher angles. Thus an average was taken for the data above 15° which relates the cross coupling to the pitch up force only

$$\Delta C_Y \text{cross coupling} = -0.431 \left( \Delta C_Y^{\text{pitch up}} \right)$$ (48)

3.5.4 RIGHT SIDE PITCH UP COMBINED WITH RIGHT SIDE YAW. Figure 2-10 presents a comparison of the combined right side pitch-up and yaw RCS incremental data compared with right side pitch up data and left side yaw data. There was no right side yaw RCS data generated to make the comparison and thus the signs of the yaw lateral-directional increments are reversed on this plot. The longitudinal data (Figure 2-10a) shows that the normal force is close to the sum of the pitch up and yaw components at angles of attack below 15° while the pitching moment shows very close agreement with the yaw induced component. Thus the present cross coupling model assumes no normal force effect and that the pitching moment cross coupling cancels the pitch-up RCS increment.

$$\Delta C_m \text{cross coupling} = -\Delta C_m^{\text{pitch up}}$$ (49)

The side force and yawing moment increments should add to each other to obtain the combined pitch up/yaw data, however, the data shows that these increments from the
combined control follows the roll jet value at high angles and lies between the curves at the lowest angles. Thus the yaw cross coupling models were taken to be

\[ \Delta C_{n_{\text{cross coupling}}} = -\Delta C_{n_{\text{yaw}}} \text{ for } \alpha > 0^\circ \] (50)

\[ \Delta C_{n_{\text{cross coupling}}} = -0.6785 \Sigma (\Delta C_n) \text{ components for } \alpha < 0^\circ \] (51)

and the side force models are

\[ \Delta C_{Y_{\text{cross coupling}}} = -\Delta C_{Y_{\text{yaw}}} \alpha > 0^\circ \] (52)

\[ \Delta C_{Y_{\text{cross coupling}}} = 0 \alpha \leq 0^\circ \] (53)

The rolling moment induced effects should oppose each other, however, the data shows that the combined control tends to follow the yaw jet induced increment at high angles of attack and the pitch up jet increment at low angles. The models chosen give

\[ \Delta C_{\phi_{\text{cross coupling}}} = -\Delta C_{\phi_{\text{pitch up}}} \alpha > 15^\circ \] (54)

\[ \Delta C_{\phi_{\text{cross coupling}}} = 0 \alpha < 15^\circ \] (55)

3.6 POSSIBLE STING INTERFERENCE EFFECTS

All of the data presently available on rear RCS interference effects have been generated using a sting mounted model. The sting passes up through the base region of the model as is shown in Figure 2–2 with the nozzle block assembly used to simulate the RCS mounted to it. The net result is that only part of two MPS engines and the body flap were simulated and the sting and plenum act to restrict the plume flow across the model to the area between the sting and flap. Very highly underexpanded plumes, such as are needed for RCS simulation will expand to impinge on the sting and this impingement could be a significant factor in the RCS data obtained to date. Figure 3–50 showed that the RCS induced effects for the symmetric pitch down case are greater than twice the induced effect for a single side pitch down. This shows that there is plume-plume interaction occurring in the base region of the model and the sting's presence must influence this interaction. Other data presented in Reference 2 shows that the symmetric firing of pitch down jets causes a high pressure across the body flap under the sting. These data plus data on the effects of changing base geometry also given in Reference 2 present a good case for possible sting interference effects and for the need for a blade mounted model test.
3.7 TIME DEPENDENT EFFECTS

All of the data presented in this report were obtained from steady-state RCS jet testing, however, the RCS jets are not necessarily fired in this manner. The full scale vehicle jets are fired in a pulsed fashion where the duration of a pulse is determined by the vehicle response to the pulse and the minimum length pulse can be very short. The question then can be asked whether these induced effects could be time dependent and thus completely different for a rapidly pulsing control.

The answer to this question can only be obtained indirectly since no data is presently available to verify it. The interaction induced effects which use mass flow ratio as the correlating parameter have had little or no impingement correction taken from them so that it appears that they are caused by the plume acting on the external flow over the vehicle. This being the case there will be essentially no time delay between the rocket coming on and the interaction occurring. The forces and moments which were correlated to mass flow ratio included all of the yaw RCS interaction effects and the pitch up/roll RCS normal force and pitching moment. In addition, the other pitch up/roll RCS data had plume impingement corrections only at the highest nozzle pressure ratios. This coupled with the non-linearity of the incremental interaction data which shows a rapid increase in interaction at low values of jet momentum would argue for interaction occurring during the start of the RCS engine.

At high momentum ratios, the data shows that impingement dominates the pitch down data. The transit time of the RCS plume impinging on structure will be very short and thus the impingement terms will follow the thrust rise with essentially no delay.

In conclusion, it is not expected that there will be any difference between the pulsing control effectiveness and a steady state control.
### Table 3-1

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<tr>
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<th>$P_{oj}$ (PSI)</th>
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<td>△</td>
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<td>4.840119</td>
<td>702</td>
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$\Delta C_m = C_{m_{jet on}} - C_{m_{jet off}}$

![Diagram](image)

Figure 3-1. Typical Left Side Pitch Down RCS Pitching Moment
Figure 3-2. Left Side Down Data Averaged at All Angles of Attack
Figure 3-3. Left Side Down Data Averaged at Low Angles of Attack.
Figure 3-4. Left Side Down Data Averaged at High Angle of Attack
Figure 3-5. Pitch Down RCS at High Angles of Attack Correlated to Exit Pressure Ratio
Figure 3-6. Left Side Pitch Down RCS Interaction Data Ratioed to Jet Moment
<table>
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<td>V</td>
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<td>Helium mixtures</td>
<td>66, 74, 77</td>
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<tr>
<td>f</td>
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\(\alpha > 15^\circ\)

AVERAGED DATA

![Graph](image_url)

**Figure 3-7.** Left Side Pitch Down RCS Normal Force Interaction at High Angles of Attack
Figure 3-8. Left Side Pitch Down RCS Pitching Moment Interaction at High Angles of Attack
<table>
<thead>
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AVERAGED DATA

![Graph]

Figure 3-9. Left Side Pitch Down RCS Pitch Interaction Increment Correlated to Mass Flow Ratio
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<td>Helium mixtures</td>
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\(\alpha > 15^\circ\)

**AVERAGED DATA**

**MOMENTUM RATIO**

Figure 3-10. Left Side Pitch Down RCS Rolling Moment Interaction at High Angles of Attack
Figure 3-11. Left Side Pitch Down RCS Yawing Moment Interaction at High Angles of Attack
<table>
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**Figure 3-12.** Left Side Pitch Down RCS Side Force Interaction at High Angles of Attack
Figure 3-13. Left: Side Down RCS Interaction Normal Force at Low Angle of Attack
<table>
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</thead>
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<td>Air</td>
<td>23, 89, 90, 91, 92</td>
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AVERAGED DATA

Figure 3-14. Left Side Down RCS Interaction Pitching Moment at Low Angles of Attack
### Symbol Table

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<td>66, 74, 77</td>
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<td>Argon</td>
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</table>

### Plot

- **Figure 3-15.** Left Side Pitch Down RCS Interaction Rolling Moment at Low Angles of Attack

- **AVERAGED DATA**

- **α < 15°**
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<th>Run</th>
</tr>
</thead>
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$\alpha < 15^\circ$

AVERRAGED DATA

**Figure 3-16. Left Side Pitch Down RCS Interaction Yawing Moment at Low Angles of Attack**
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\( \alpha < 15^\circ \)

### Figure 3-17

Left Side Pitch Down RCS Interaction Side Force at Low Angles of Attack

**AVERAGED DATA**

**MOMENTUM RATIO**
Figure 3-18. Typical Pitch Up RCS Data
Figure 3-19a. Right Side Pitch Up RCS Interaction Moments Ratioed to Thrust Moments
Figure 3-19b. Right Side Pitch Up RCS Interaction Moments Ratioed to Thrust Moments
### Table

<table>
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<td>Air</td>
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<td>+</td>
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<td>$N_{82}$</td>
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AVERAGED DATA

$15^\circ < \alpha$

### Figure 3-20

**Right Side Pitch Up RCS Interaction Normal Force at High Angles of Attack**

**MASS FLOW RATIO**
<table>
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<td>55, 56, 57, 58</td>
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<tr>
<td>U</td>
<td>N_{82}</td>
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<td>24</td>
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<tr>
<td>+</td>
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<td>Air</td>
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<td>Z</td>
<td>N_{52}</td>
<td>Helium mixtures</td>
<td>67, 73, 79</td>
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<tr>
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<td>N_{52}</td>
<td>Argon</td>
<td>72</td>
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</table>

AVERAGED DATA

$15^\circ < \alpha$

![Graph](image)

**Figure 3-21.** Right Side Pitch up RCS Interaction Normal Force Correlated to Momentum Ratio
Figure 3-22. Right Side Pitch Up RCS Interaction Pitching Moment at High Angles of Attack
<table>
<thead>
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<th>Symbol</th>
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<th>Gas</th>
<th>Run</th>
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</thead>
<tbody>
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<td>Air</td>
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</tr>
<tr>
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<td>N₂</td>
<td>Air</td>
<td>24</td>
</tr>
<tr>
<td>+</td>
<td>N₂</td>
<td>Air</td>
<td>25</td>
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<td>Z</td>
<td>N₂</td>
<td>Helium mixtures</td>
<td>67, 73, 74</td>
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<td>N₂</td>
<td>Argon</td>
<td>72</td>
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</table>

AVERAGED DATA

$15^\circ < \alpha$

Figure 3-23. Right Side Pitch Up RCS Interaction Pitching Moment Correlated With Momentum Ratio
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nozzle</th>
<th>Gas</th>
<th>Run</th>
<th>AVERAGED DATA</th>
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</thead>
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<td>Air</td>
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<td>N$_{2}$</td>
<td>Air</td>
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<td>Helium mixtures</td>
<td>67,73,79</td>
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<td>N$_{52}$</td>
<td>Argon</td>
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**MOMENTUM RATIO**

Figure 3-24. Right Side Pitch Up RCS Interaction Rolling Moment at High Angles of Attack
### Table 3-25

<table>
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<th>Nozzle</th>
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**AVERAGED DATA**

$15^\circ < \alpha$

---

**Figure 3-25.** Right Side Pitch up RCS Interaction Yawing Moment at High Angles of Attack
AVERAGED DATA

15° < α

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<th>Run</th>
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<td>N₂₂</td>
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<tr>
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<td>N₂₂</td>
<td>Argon</td>
<td>72</td>
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**Figure 3-26.** Right Side Pitch Up RCS Interaction Side Force at High Angles of Attack
Figure 3-27. Right Side Pitch Up RCS Peak Rolling Moment Correlation
Figure 3-28. Right Side Pitch Up RCS Peak Yawing Moment Correlation
Table 3-29: Right Side Pitch Up RCS Peak Rolling Moment Due to Interaction

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<td>+</td>
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Figure 3-29. Right Side Pitch Up RCS Peak Rolling Moment Due to Interaction
Figure 3-30. Right Side Pitch Up RCS Peak Yawing Moment Due to Interaction
### Figure 3-31. Right Side Pitch Up RCS Peak Side Force Due to Interaction

<table>
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<td>N₅₂</td>
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<td>+</td>
<td>N₇₈</td>
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**MOMENTUM RATIO**
Figure 3-32. Right Side Pitch Up RCS Peak Normal Force Correlated With Momentum Ratio
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<tr>
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<td>Argon</td>
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Figure 3-33. Right Side Pitch Up RCS Peak Normal Force Due to Interaction
<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Gas</th>
<th>Refs</th>
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<tr>
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<td>14, 28, 29, 48, 49, 50, 51, 53, 54, 55, 56, 57, 58</td>
</tr>
<tr>
<td>U</td>
<td>N\textsubscript{22}</td>
<td>Air</td>
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</tr>
<tr>
<td>+</td>
<td>N\textsubscript{28}</td>
<td>Air</td>
<td>25</td>
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<td>Z</td>
<td>N\textsubscript{22}</td>
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<td>67, 73, 79</td>
</tr>
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<td>O</td>
<td>N\textsubscript{22}</td>
<td>Argon</td>
<td>72</td>
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</tbody>
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Figure 3-34. Right Side Pitch Up RCS Rolling Moment Correlation Below Peak Values
Figure 3-35. Right Side Pitch Up RCS Yawing Moment Correlation Below Peak Values
<table>
<thead>
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<th>Run</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>U</td>
<td>$N_{22}$</td>
<td>Air</td>
<td>24</td>
</tr>
<tr>
<td>+</td>
<td>$N_{78}$</td>
<td>Air</td>
<td>25</td>
</tr>
<tr>
<td>Z</td>
<td>$N_{22}$</td>
<td>Helium mixtures</td>
<td>67,73,79</td>
</tr>
<tr>
<td>O</td>
<td>$N_{22}$</td>
<td>Argon</td>
<td>72</td>
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</tbody>
</table>

Figure 3-36. Right Side Pitch Up RCS Side Force Correlation Below Peak Values
Figure 3-37. Typical Yaw RCS Data
### Table

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Gas</th>
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<tbody>
<tr>
<td>E</td>
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<tr>
<td>ζ</td>
<td>N51</td>
<td>Air</td>
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<td>Helium Mixtures</td>
<td>68, 75, 78</td>
</tr>
<tr>
<td>O</td>
<td>N51</td>
<td>Argon</td>
<td>70</td>
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**AVERAGED DATA**

$15^\circ < \alpha$

**Figure 3-38.** Left Side Yaw RCS Interaction Normal Force Correlation at High Angles of Attack
Figure 3-39. Left Side Yaw RCS Interaction Normal Force Correlation With Momentum Ratio
Figure 3-40. Left Side Yaw RCS Interaction Pitching Moment Correlation at High Angles of Attack
## Table

<table>
<thead>
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<th>Gas</th>
<th>Run</th>
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</thead>
<tbody>
<tr>
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<td>N₅₁</td>
<td>Air</td>
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</tr>
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<td>☐</td>
<td>N₉₅</td>
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<td>Helium Mixtures</td>
<td>68, 75, 78</td>
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<tr>
<td>☐</td>
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<td>Argon</td>
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## Averaged Data

$15^\circ < \alpha$

### Figure 3-41

Left Side Yaw RCS Interaction Pitching Moment Correlated With Momentum Ratio
Figure 3-42. Left Side Yaw RCS Interaction Rolling Moment at High Angles of Attack
Figure 3-43. Left Side Yaw RCS Interaction Yawing Moment at High Angles of Attack
<table>
<thead>
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</thead>
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<tr>
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<td>N₅₁</td>
<td>Air</td>
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<td>C</td>
<td>N₈₅</td>
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<tr>
<td>D</td>
<td>N₅₁</td>
<td>Helium Mixtures</td>
<td>68, 75, 78</td>
</tr>
<tr>
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<td>N₅₁</td>
<td>Argon</td>
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</table>

AVERAGED DATA

$15^\circ < \alpha$

Figure 3-44. Left Side Yaw RCS Interaction Side Force at High Angles of Attack
Figure 3-45. Left Side Yaw RCS Interaction, Normal Force at Low Angles of Attack
Figure 3-46. Left Side Yaw RCS Interaction, Pitching Moment at Low Angles of Attack
Figure 3-47. Left Side Yaw RCS Interaction Rolling Moment at Low Angles of Attack
Figure 3-48. Left Side Yaw RCS Interaction Yawing Moment at Low Angles of Attack
### Table 3-49

<table>
<thead>
<tr>
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<th>Gas</th>
<th>Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>§</td>
<td>N$_{51}$</td>
<td>Air</td>
<td>22</td>
</tr>
<tr>
<td>צ</td>
<td>N$_{85}$</td>
<td>Air</td>
<td>16, 26, 28, 33, 37, 58</td>
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<tr>
<td>☼</td>
<td>N$_{61}$</td>
<td>Helium Mixtures</td>
<td>68, 75, 78</td>
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<tr>
<td>○</td>
<td>N$_{51}$</td>
<td>Argon</td>
<td>70</td>
</tr>
</tbody>
</table>

**AVERAGED DATA**

\[ \alpha < 15^\circ \]

---

**Figure 3-49.** Left Side Yaw RCS Interaction Side Force at Low Angles of Attack
\[ \Delta C_N = C_{N_{\text{jet on}}} - C_{N_{\text{jet off}}} \]
\[ \Delta C_m = C_{m_{\text{jet on}}} - C_{m_{\text{jet off}}} \]

Figure 3-50. Symmetric Pitch Down Amplification
Figure 3-51a. Coupled Roll RCS Effects
Figure 3-51b. Coupled Roll RCS Effects
Figure 3-51c. Coupled Rolled RCS Effects
ANALYTIC MODEL DEVELOPMENT

4.1 GENERAL DESCRIPTION

The analysis presented in Section 3 provides the basis of the analytic model developed in this study. In general the total control effectiveness of a given control is defined as the sum of a number of parts as shown in Equation 1.

\[ C_M = C_{M_{\text{thrust}}} + C_{M_{\text{impingement}}} + C_{M_{\text{interaction}}} + C_{M_{\text{cross coupling}}} \]  

(1)

where

\[ C_M = \text{RCS force or moment component} \]

and the resulting control effectiveness called control amplification is defined as an amplification factor which is the total control moment divided by the thrust moment

\[ K_M = \frac{C_{M_{\text{total}}}}{C_{M_{\text{thrust}}}} \]  

(2)

where

\[ K_M = \text{RCS force or moment amplification factor} \]

In addition to the effects in the thrust direction, the RCS controls induce out of plane forces and moments which are the sum of some terms given in Equation 1. The data of Section 3 showed that each control generated measurable data of the five vehicle forces and moments correlated in this study and these components must be added together on each axis to determine the total value of the induced moments. It is desirable to relate these out of plane forces and moments to a thrust term in order to generate an amplification factor which is a measure of RCS effectiveness. This is done by relating the out of plane induced data to the control moment required to compensate for it. For example, rolling moment caused by yaw jets

\[ K_{yaw} = \frac{(\Delta C_y)}{C_{roll jet thrust}} \]  

(3)

which is the same definition as Reference 3. Since we wish to define amplifications for arbitrary numbers and combinations of controls, however, another definition must be used for the thrust moment term. When an arbitrary combination of RCS controls is
being used and one of combination generates a control moment in the same plane as the induced moments, then that thrust moment is used in Equation 3. If none of the control combinations has a thrust term in the plane of the interaction then a two jet in plane control is used in Equation 3. For example for a single pitch up/roll nozzle being fired, the rolling moment will be related to the jet thrust roll component whereas for the rolling moment from a yaw jet firing will be related to a two jet roll nozzle combination.

The thrust moments required in Equations 1 to 3 are easily solved knowing the RCS nozzle characteristics, its location relative to the vehicle moment reference center and the mounting angle of the nozzle relative to the vehicle axis system. The interaction and cross-coupling terms were derived in Section 3 and their application in the analytic model will be described in Section 4.5. The sole remaining term which needs to be defined then is the plume impingement term.

4.2 PLUME IMPINGEMENT INCREMENTS

Figure 2-1 shows a view of the space shuttle orbiter which emphasizes the closeness of the rear RCS package to the base area of the vehicle. It is evident that the aft RCS engines will impinge heavily on the vehicle wing, vertical tail, body flap, main propulsion engine nozzles, and possible fuselage sides, depending on the nozzle set fired and on the altitude and other flight conditions affecting plume size. Reference 1 showed that plume impingement was a sizeable term for the PRR configuration while Reference 3 shows the same for the present configuration based on a vacuum chamber test (Rockwell Test OA99) and impingement predictions for the vacuum case.

Two models of plume impingement effects were developed for this prediction method and are included in the prediction computer program. The first is a vacuum data model while the second is an analytical plume prediction model.

4.3 VACUUM TEST DATA MODEL

The first model developed is based on the assumption that the range of interest of flight conditions for full scale RCS estimation is sufficiently close to the vacuum case that the test data amplification factors from test OA99 reported in Reference 3 can be used directly from the thrust and thrust moments. Converting the data into coefficient form, the impingement increments from the pitch up jets are given in Equations 4 to 10 in body axis form:

\[
\Delta C_{N_{\text{impingement}}} = -0.00086 \, C_{T_{\text{PU}}} 
\]

\[
\Delta C_{X_{\text{impingement}}} = 0.00246 \, C_{T_{\text{PU}}} 
\]

\[
\Delta C_{Y_{\text{impingement}}} = -0.06238 \, C_{T_{\text{PU}}}
\]

4-2
\[ \Delta C_{\text{impingement}} = -0.130 \, C_{\text{PU}} \]  
\[ \Delta C_{\text{m,impingement}} = 0.00078 \, C_{\text{m,PU}} \]  
\[ \Delta C_{\text{n,impingement}} = 0.0593 \, C_{\text{n,Y}} \]  

where

\[ C_{\text{T,PU}} = \frac{\text{total thrust of pitch up engines}}{(q \, S_{\text{ref}})} \]  
\[ C_{\text{PU}} = \text{pitch up thrust rolling moment coefficient} \]  
\[ C_{\text{n,Y}} = \text{yaw thrust yawing moment coefficient} \]  
\[ C_{\text{m,PU}} = \text{pitch up thrust pitching moment coefficient} \]

The pitch down jet impingement increments are given in Equations 11 to 16:

\[ \Delta C_{\text{z,impingement}} = -0.27389 \, C_{\text{T,PD}} \]  
\[ \Delta C_{\text{x,impingement}} = 0.10709 \, C_{\text{T,PD}} \]  
\[ \Delta C_{\text{y,impingement}} = 0.01837 \, C_{\text{T,PD}} \]  
\[ \Delta C_{\text{t,impingement}} = -0.2312 \, C_{\text{t,PD}} \]  
\[ \Delta C_{\text{m,impingement}} = -0.3018 \, C_{\text{m,PD}} \]  
\[ \Delta C_{\text{n,impingement}} = 0.01657 \, C_{\text{n,Y}} \]  

where

\[ C_{\text{T,PD}} = \text{total pitch down thrust coefficient} \]  
\[ C_{\text{t,PD}} = \text{pitch down thrust rolling moment coefficient} \]  
\[ C_{\text{m,PD}} = \text{pitch down thrust pitching moment coefficient} \]
and the yaw impingement equations are:

\[
\Delta C_{Z_{\text{impingement}}} = 0.01634 C_{T_Y} \tag{17}
\]

\[
\Delta C_{X_{\text{impingement}}} = 0.00288 C_{T_Y} \tag{18}
\]

\[
\Delta C_{Y_{\text{impingement}}} = 0.00077 C_{T_Y} \tag{19}
\]

\[
\Delta C_{f_{\text{impingement}}} = 0.03477 C_{f_{\text{PU}}} C_{T_Y}/C_{T_U} \tag{20}
\]

\[
\Delta C_{m_{\text{impingement}}} = 0.00873 C_{m_{\text{PU}}} C_{T_Y}/C_{T_U} \tag{21}
\]

\[
\Delta C_{n_{\text{impingement}}} = 0.0013 C_{n_Y} \tag{22}
\]

where

- \( C_{T_Y} \) = total yaw RCS thrust coefficient
- \( C_{T_U} \) = total pitch up RCS thrust coefficient
- \( C_{f_{\text{PU}}} \) = pitch up thrust rolling moment coefficient
- \( C_{m_{\text{PU}}} \) = pitch up thrust pitching moment coefficient
- \( C_{n_Y} \) = yaw thrust yawing moment

This model has its limitations in that it assumes that there will always be impingement, that the amount of impingement is related only to thrust, and it cannot account for nozzle or geometry variations. This last limitation was a large one because of the need to generate plume impingement corrections for the OA82 wind tunnel data which used much different nozzles and test gases than the vacuum chamber test.

This model is available in the prediction program to use if desired.

4.4 ANALYTIC PLUME IMPINGEMENT MODEL

The analytic plume impingement model of Reference 1 was compared against the OA99 vacuum chamber results and other test data and was found to underpredict the plume impingement by a significant margin and was discarded early in the data analysis and another method was sought which provided a better representation of the plume characteristics.
Simon's, Reference 4, modeled the flow field of the RCS engines as

\[ \dot{m} = 217 \frac{f(\theta)}{r^2} \frac{g_{sec}}{cm^2} \]  

(23)

where

\[ r = \text{radial distance from nozzle in inches} \]

\[ f(\theta) = \cos^{10} \left( \frac{\pi \theta}{250} \right); 0 < \theta < 60^\circ \]  

(24)

\[ f(\theta) = 0.0438 \left( e^{-0.064(\theta-60^\circ)} \right); 60^\circ < \theta \]  

(25)

where

\( \theta \) is angle from nozzle centerline in degrees

and a similar approach to the plume shape was sought for this analysis based on the assumptions that at the flight conditions of highest importance and the RCS plumes exhausting into the leeward flow over the wing at angle of attack or into the vehicle base region that the external pressure will be close to vacuum. A modified vacuum plume model would be the best representation of the RCS plume where the primary modification is to limit the plume boundary to the limit turning angle of plume flow.

Computation of plumes expanding into a vacuum by methods of characteristics (Reference 5) show that at large distances from the nozzle that the streamlines appear to emanate as radial flow from a common source point at the nozzle exit. Since the rate of mass flow through the nozzle is a constant, the mass flux \( \rho u \) in the far field should vary inversely as \( x^2 \). And, since the velocity in the far field approaches the limiting velocity \( \bar{u} = \sqrt{2 \bar{h}_0} \), the density variation should approach \( \rho \sim x^{-2} \) as seen in Figure 4-1. Thus, one should be able to express the density distribution along the centerline \( f(\theta) = 1 \) in terms of the supply density as

\[ \frac{\rho}{\rho_0} = B (x/d^*)^{-2} f(\theta) \]  

(26)

where \( B \) depends on the nozzle shape and the properties of the gas. Equation 23 has this form for the centerline decay of the flow properties of the RCS engine plume but a more generalized expression was sought so that the plumes from test OA82 could also be treated in the same model. Thus Equation 26 was used where the value of \( B \) was solved in Reference 5 by using characteristics calculations of density variation along various nozzle centerlines and gas specific heats from 1.2 to 1.67.

A jet expanding into a vacuum (Figure 4-2) is bounded by a straight streamline at zero pressure and \( M = \infty \). The location of this boundary, denoted as \( \theta_w \) in Figure 4-2, will depend upon the nozzle exit lip angle \( \theta_e \), the area ratio of the nozzle \( A_o/A^* \), and the \( \gamma \) of the exhausting gas. This angle \( \theta_w \) may be determined from the Prandtl-Meyer
Figure 4-1. Density Distribution Along the Plume Axis
Figure 4-2. Schematic Drawing of a Jet Expanding Into a Vacuum
expansion relationship and \( \theta_e \) as a function of area ratio. For other values of \( \theta_e \), the value of \( \theta_\infty \) may be determined from the relationship

\[
\theta_\infty = (\theta_\infty)_{e=0} + \theta_e \tag{27}
\]

The solid angle \( \psi_\infty \) corresponding to \( \theta_\infty \) is given by

\[
\psi_\infty = 2\pi (1 - \cos \theta_\infty) \tag{28}
\]

The flow boundary \( \theta_\infty \), and thus the limiting solid angle \( \psi_\infty \) with increasing area ratio at a constant \( \gamma \), while at a given area ratio, \( \theta_\infty \) increases for decreasing value of \( \gamma \).

Reference 5 showed that for a family of nozzles having the same mass flow rate the density decay along the nozzle axis is dependent upon the limiting flow angle \( \theta_\infty \) as shown in Figure 4-3. The variation of \( B \) with \( \theta_\infty \) for both the theoretical curves of Reference 6 and the characteristics calculations shown as symbols appear on this figure.

\[
B = \frac{\text{constant}}{\psi_\infty} = \frac{0.4\pi}{\psi_\infty} \tag{29}
\]

where the value of the constant has been chosen to fit the data of Figure 4-3. This expression assumed that the dependence of \( B \) upon specific heat ratio is small and the characteristic solution data of Figure 4-3 was recomputed to derive a new expression for \( B \) which is

\[
B = \frac{K\pi}{\gamma^2 \psi_\infty} \tag{30}
\]

and where \( K \) was defined from Figure 4-4 as

\[
K = 1.24 - 0.0040894 \theta_\infty \tag{31}
\]

In these expressions \( \theta_\infty \) is defined by expanding the nozzle flow to the ambient pressure of free stream or wind tunnel rather than to a vacuum angle. This approximation has been shown to cause only small errors since most of the mass and momentum within a plume are contained near the central core of the plume and truncating the vacuum plume at the angle defined by ambient pressure results in very little loss of plume mass (Ref. 7) in the conservation equations particularly where ambient pressures are low.

Figure 4-1 showed that the square power decay law does not work at distances of less than 10 to 15 throat diameters away from the nozzle exit and empirical fits were generated to cover this region using the nozzle exit density ratio as a parameter:
Figure 4-3. A Comparison of Density Decay and Limit-Turning Angle
Figure 4-4. Plume Density Decay Factor Correction With Limit Turning Angle
If \((X/d^*)\) was greater than \(B/(\rho_j/\rho_{Oj})\) Equations 26 to 31 were used. If \((X/d^*)\) was less than the square root of \(B/(\rho_j/\rho_{Oj})\) then
\[
\frac{\rho_j}{\rho_{Oj}} = \left[ 1 + \frac{\gamma - 1}{2} \frac{M_j^2}{\gamma j - 1} \right]^{-1} f(\theta) \tag{32}
\]

and in between these two ends; two other expressions were used if \((X/d^*)\) were less (Equation 34) or greater (Equation 35) than \([B/(\rho_j/\rho_{Oj})]\)\(^{67}\).

\[
\frac{\rho_j}{\rho_{Oj}} = \frac{\rho_j}{2 \rho_{Oj}} \left[ \left( \frac{X}{d^*} \right)^{-0.5} + \left( \frac{X}{d^*} \right)^{-1} \right] f(\theta) \tag{34}
\]

\[
\frac{\rho_j}{\rho_{Oj}} = \frac{1}{2} \left[ \frac{\rho_j}{\rho_{Oj}} \left( \frac{X}{d^*} \right)^{-1} + B \left( \frac{X}{d^*} \right)^{-2} \right] f(\theta) \tag{35}
\]

In all these expressions, the variation \([f(\theta)]\) away from the plume centerline was taken from Simon's model (Equations 24 and 25). The plume Mach number, local static pressure and local dynamic pressure at a point are defined from the density ratio based on isentropic flow relations.

In the cases of the plumes firing upward past the fin (pitch up) and outward over the wing (yaw) where the plume is likely to be interacting with the flow over the vehicle, the plume is assumed to stop when the plume local dynamic pressure is less than the free stream dynamic pressure. A further limitation is placed on the plume to terminate the plume if the free stream impingement pressure coefficients are less than zero.

Multiple sets of nozzles are handled by defining a single equivalent nozzle which has the same geometric shape as the other nozzles but which has an exit area equal to the sum of the exit areas of the nozzles in the cluster. Its location is chosen as the center of the cluster. This representation of the plume from multiple sets of nozzles has been found to be a good approximation (Reference 8) and changes plume characteristics through the larger value of throat diameter in Equations 26 to 35.

4.4.1 PLUME IMPINGEMENT FORCES. The highly underexpanded flow from the nozzle expands very quickly to high Mach numbers at small distances from the exit and this supersonic flow will be undisturbed by a surface it may impinge until it is close to the surface. A detached shock wave would be formed by the high Mach number flow impinging on a surface with a region of subsonic flow between the strong...
shock and the surface where the flow is turned to a direction paralleling the plate. The pressure on the surface of the vehicle was assumed to be related only to the plume conditions at the point in question and to the local slope between the surface at that point and the plume flow vector emanating from the point source at the nozzle exit (radial flow approximation). It was also assumed that the surface pressure could be predicted by a modified Newtonian pressure law because of the high plume Mach numbers and large turning angles.

\[
P_{w_1} = 1.85 \frac{1}{2} P_{j_1} M_{j_1}^2 \cos^2 \theta_i + P_{j_1}
\]

(36)

where

- \( P_{w_1} \) = plume impingement pressure at \( i^{th} \) point on body
- \( P_{j_1} \) = plume ambient pressure at point \( i \)
- \( M_{j_1} \) = plume Mach number at point \( i \)
- \( \theta_i \) = local slope between plume flow and surface at point \( i \)

The local plume impingement pressure is then converted into a pressure coefficient related to ambient flight conditions to put it into the same reference as the vehicle aerodynamic coefficients and is integrated to obtain vehicle force and moment coefficients resulting from impingement.

The integration of impingement pressures was approximated in the analytic model by breaking elements of the vehicle into flat plates of known centroid location, area, and local slope, the plume impingement pressures at each point were computed, the local force and moment coefficients computed by applying the impingement pressure across the area, and the total vehicle values obtained by summing the local values. Figures 4-5 to 4-7 present the points representing the centroids of the areas used in the determination of the plume impingement corrections to the wind tunnel data. Only one side of the vehicle is represented to increase the accuracy by having a larger number of plates which will have impingement but to reduce the computation time for plates not affected.

Figures 4-8 presents a comparison of the computed impingement force and the interaction increments for the left side pitch down jets which shows that the impingement term does not become larger than the interaction term until well past the peak interaction. Figure 4-9 presents a comparison of the impingement and interaction increments of rolling moment caused by the right side jets exhausting up past the vertical fin at high angles of attack. In this case the impingement correction never exceeds the interaction increment but they tend to parallel each other as thrust moment increases.
Figure 4-5. Side View of Vehicle Showing Centroids of Plates Used for Impingement
Figure 4-6. Top View of Vehicle Showing Centroids of Plates Used for Impingement
Figure 4-7. Rear End View of Vehicle Showing Centroids of Plates Used for Impingement
Figure 4-8. OA82 Left Side Pitch Down RCS Impingement Correction on Pitching Moment
Figure 4-9. OA82 Right Side Pitch Up RCS Impingement Correction on Rolling Moment
This impingement model was checked against the method of characteristics vacuum case solution as well as the vacuum chamber test (OA99) results of Reference 3 and close agreement was obtained as shown in the table below.

<table>
<thead>
<tr>
<th>Case</th>
<th>( P_{0j} )</th>
<th>A/A*</th>
<th>( \theta )</th>
<th>( \gamma )</th>
<th>( K_{m\text{down}} ) Ref.</th>
<th>( K_{m\text{down}} ) Computed</th>
<th>( K_{A\text{down}} ) Ref.</th>
<th>( K_{A\text{down}} ) Computed</th>
</tr>
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<tbody>
<tr>
<td>OA99 Model</td>
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<td>10°</td>
<td>1.4</td>
<td>0.6982</td>
<td>0.6479</td>
<td>0.6596</td>
<td>0.6671</td>
</tr>
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<td>9</td>
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<td>0.6713</td>
<td>0.6888</td>
<td>0.7085</td>
<td>0.7035</td>
</tr>
</tbody>
</table>

4.5 INTERACTION AND CROSS COUPLING MODELS

Section 3 which presents the data analysis contains within it the curve fits derived from that data analysis. These curve fits were used as the analytic model of interaction and cross coupling terms with some limitations. The limitations were generally applied in defining the upper limits of the curves. In general if a curve has a maximum or minimum value (defined in Section 3) it was only used up to the maximum (minimum) value and was assumed as a constant value beyond this mass flow or momentum ratio. When a curve fit shape is such that it has no maximum or minimum value, an arbitrary limit was applied and the data was assumed constant beyond this limit. This limit was usually taken at or near the upper value of mass flow or momentum ratio tested in test OA82.
5

ANALYTIC COMPUTER PROGRAM

5.1 GENERAL DESCRIPTION

The model of RCS control effectiveness presented in sections 3 and 4 of this report were programmed into a digital computer program named PRED which will predict reaction control system effectiveness on a space shuttle type vehicle for any combination of Rear RCS engines firing at any angle of attack and flight condition up to the vacuum case. Numbers of RCS Engine, engine size, engine operating conditions, exhaust gas properties, and nozzle geometry can be varied as input parameters. Engine location on the rear of the vehicle and cant angles can also be varied, however, the analytic models were developed from one configuration (figure 2-1) and large departures from these RCS locations will probably invalidate some of the models of interaction and cross coupling terms.

Figure 5-1 presents a flow diagram of the program which consists of a main program and 17 subroutines. The program was divided into this large number of subroutines so that modification of any part could be more easily accomplished without disrupting the whole program. The names of the subroutines are:

1. INPUTT 7. MACH 13. QUAD
2. JET 8. THR 14. KABD
3. PARCEO 9. IMPINGE 15. AKABD
4. ATMOS 10. VACPLU 16. CCOUPL
5. EXPAN 11. INTER 17. AMPL
6. SCAL 12. QUART

The name of the main program is PRED and FORTRAN listings of all parts of the program are contained in Appendix A. Each subroutine will be briefly discussed in the sections below with the input subroutine and input key presented last.

5.2 MAIN PROGRAM PRED

Figure 5-1 shows that the function of the main program is to drive the subroutines in an orderly fashion first to obtain the input to start the problem, to define the equivalent nozzles firing upward, downward, and side ways, to define the flight conditions and resulting nozzle flow parameters for a single nozzle and then
Figure 5-1. Program PRED Flow Diagram
proceed to define the various components of total RCS effectiveness for each set of equivalent nozzles fixing up, down, and sideways. These components must be corrected for the symmetric firing sets and for the side that non-symmetric sets are firing on. The cross coupling terms are then determined and all of the components of data are summed into the 6 total RCS aerodynamic force and moment coefficients and the amplification factors determined. When this occurs the program returns to the beginning to start the next case.

All input comes into the program through the INPUTT subroutine, but the main program handles most of the output printing at various stages throughout its length.

The program is set up to assume all RCS nozzles are on the left side of the vehicle when viewed from the rear looking forward in order to standardize the data for the impingement calculation and to set the signs of the interaction models. The data is corrected to the proper side of the vehicle or to symmetric firing by two input parameters for each RCS direction. The RCS directions are upward firing designated by a U as the last letter of a variable name in the listing, downward firing designated by a D as the last letter, and side firing designated by a Y as the last letter. The program always assumes that there are some upward, downward, and side firing nozzles in each problem so that all of the components are computed for all three sets before the summation of terms is made. If the number of nozzles (NONOZU, NONOZD, NONOZY) is zero those components are equal to zero. The axis system used is a body axis system shown in Figure 5-2 and the component data has these designations CX, CY, CZ, CL, CM, CN as the first two letters of the variable name where CN refers to yawing moment. Finally where the component force or moment is derived from is specified by the two middle letters of the variable names and IM is an impingement force or moment component, IN is an interaction component, and CC is a cross-coupling component. The thrust terms have no component designation and thus are 3 letter variable names while the others are 5 letter names. A typical example of a variable name is CMIMU which is the pitching moment induced by plume impingement of the upward firing nozzles.

Figure 5-3 shows that the program assumes that a downward firing set, an upward firing set, and a side firing set exist for a given problem. A set of nozzles is defined in this program as the actual number firing in a given cluster on one side of the vehicle. It is not the total number available to fire on one side nor the total number firing on both sides in a symmetric firing case.

The input data required for a first case is all of the data defining the vehicle, RCS units, and flight conditions, however, once this has been defined only the parameters which are to be changed need be input for additional cases.

5.3 COMPUTE JET EXIT MACH NUMBER(SUBROUTINES JET AND PARCEO)

After the program has received input defining the reaction control system engine in 5-3
$C_N = -C_z$

$C_A = -C_x$

Figure 5-2. Body Axis Sign Convention
NONOZD = Actual Number of Downward firing nozzles operating in one cluster on one side.

NONOZU = Actual number of upward firing nozzles, etc.

NONOZY = Actual number of side firing nozzles, etc.

Figure 5-3. Nozzle Set Convention
terms of nozzle expansion ratio \((A/A^*)\), chamber pressure \((P_{oj})\), chamber temperature \((T_{oj})\), and exhaust gas specific heat ratio \((\gamma)\), the subroutine JET is called to determine the nozzle exit conditions for this engine. The exit conditions are exit Mach number \((M_j)\), static pressure \((P_j)\) and static temperature \((T_j)\).

Exit Mach number is computed by solving the Prandtl Meyer expansion ratio Mach number relationship (Ref. 9).

\[
A/A^* = \left(\frac{\gamma_j + 1}{2(\gamma_j - 1)}\right)^{\frac{\gamma_j + 1}{2(\gamma_j - 1)}}
\]

\[
M_j = \left(1 + \frac{\gamma_j - 1}{2} M_j^2\right)
\]

JET solves this expression by computing expansion ratio for increasing jet Mach numbers until the correct expansion ratio has been passed saving the last 3 values of each. When the correct expansion ratio is passed, JET calls the subroutine PARCEO to put a quadratic curve fit through the expansion ratio-jet Mach points and PARCEO returns the coefficients of the equation which JET then solves for jet Mach number. With jet exit Mach number determined the jet exit static pressure and temperature are computed from isentropic flow relations. In addition JET computes some constants which are related to specific heat ratio, pressure ratio, and thrust from the flow through the nozzle throat for use in later routines.

PARCEO is a standard quadratic curve jet routine which will give the coefficients for a curve through any 3 sets of points defined in the call statement. The main program defines the throat diameters of the single equivalent nozzles for each cluster of upward (DSTARU) downward, (DSTARD), and side (DSTARY) firing sets before proceeding to the definition of flight conditions.

5.4 COMPUTE FLIGHT PARAMETERS (SUBROUTINE ATMOS).

The input subroutine provides data required by the program at this point to define the flight conditions in one of four allowable ways defined by an input parameter (IOPT):

a) \( IOPT = 1 \) altitude, Mach, and angle of attack specified
b) \( IOPT = 2 \) altitude, velocity, and angle of attack specified
c) \( IOPT = 3 \) altitude, freestream dynamic pressure, and angle of attack specified
d) \( IOPT = 4 \) Mach, ambient pressure, ambient temperature, and angle of attack specified
The first 3 options require an atmosphere model to define ambient pressure and ambient temperature and the program currently contains a subroutine ATMOS which provides these data from the 1962 US Standard atmosphere model. The fourth option is a means of expressing an arbitrary flight condition from some other atmosphere model or for a wind tunnel test.

Subroutine ATMOS can provide a number of flight parameters not currently used in this program including local gravity for an oblate earth model, atmosphere density, local speed of sound, dynamic pressure, absolute viscosity, kinematic viscosity, and stagnation temperature on a reference sphere. The program consists of curve fits of atmospheric properties from sea level to 230,000 meters (754,600 ft) and all conditions are set to zero above this altitude.

The vacuum case \((P = q = 0)\) is treated in a special way in the program to avoid divisions by zero. A special note will be printed in the output and dynamic pressure \((q)\) is set equal to 1 PSF. The interaction terms are not computed for the vacuum case nor are cross coupling terms which are not related to impingement. The force and moment coefficients printed are based on a \(q\) of 1 PSF while the amplification factors are independent of \(q\).

With the flight conditions defined, all the required data is in the program and the RCS effectiveness computed. In order to do this the RCS nozzle parameters must be computed.

5.5 COMPUTE SINGLE NOZZLE PARAMETERS (SUBROUTINES EXPAN, SCAL MACH).

The nozzle parameters necessary to compute the RCS effectiveness include RCS engine thrust coefficient \((TCOEF)\), jet exit momentum ratio \((RMFS)\), and jet mass flow ratio \((FMR)\). These are all computed for a single nozzle and then multiplied by the number of nozzles in each set to obtain the parameters for the three directions of firing.

Plume limit turning angle \((TURN)\) is also required to define the plume decay characteristics as well as the extent of the plume for impingement calculations, it however is not related to the number of nozzles but rather to jet exit and freestream conditions. The limit turning angle is computed in subroutine EXPAN based on Prandtl-Meyer expansion of the flow from RCS chamber conditions to freestream ambient pressure minus the expansion in the nozzle plus the nozzle exit angle.

The Subroutine SCAL computes the nozzle exhaust scaling parameters of Pindzola (reference 10) and Herron (reference 11) for the single nozzle while the Subroutine Mach computes the Mach number of the fully expanded flow for SCAL. The program prints the flight conditions as well as a large number of nozzle parameters for the single RCS unit at this point in the main program winding up with the important nozzle interaction parameters in the three RCS directions.
5.6 COMPUTE THRUST TERMS (SUBROUTINE THR)

The thrust for a single nozzle was computed as the theoretical thrust when the other nozzle parameters were computed and the aerodynamic coefficients of thrust moment for the three RCS directions are now computed using the subroutine THR. The values of all coefficients are first set to zero to remove the data from previous cases prior to the call for THR. Subroutine THR computes the thrust coefficients for the three RCS firing directions and multiplies these by the direction cosines of the thrust vectors to obtain the thrust force coefficients. The program assumes that the nozzle clusters are all on the left side of the vehicle in determining the direction cosines of the thrust vectors and appropriate sign corrections will be made further on in the program. The nozzles are allowed an outboard and an aft cant angle in the computation of direction cosines. These are defined in figure 5-4. The direction cosines are the angles of a unit vector along the centerline of the plume in the body axis system. The thrust moments are then computed about the body reference moment center accounting for cant angles and vertical position.

5.7 COMPUTE IMPINGEMENT INCREMENTS (SUBROUTINES IMPING AND VACPLU)

The program now computes the plume impingement force and moment components from three choices based on an input parameter (IIMP):

a) No impingement
b) Vacuum data from OA99
c) Predict plume impingement

The first option simply sets the impingement terms to zero and proceeds to the interaction computation. The second choice is a computation still in the main program which uses equations 4 to 22 in section 4 and computes the impingement increments as a function of thrust coefficient.

The third choice causes the program to make its own prediction of plume impingement by computing the pressures on the vehicle from the three direction plumes separately and integrating each pressure distribution to obtain the 6 component impingement increments. No plume/plume interaction is accounted for the three directions of RCS firing. The subroutine IMPING is called three times to integrate the pressures from each direction separately.

IMPING depends on subroutine VACPLU for its definition of plume characteristics at a given point on the vehicle by sending VACPLU the location of the point in a nozzle based ordinate system by in terms of distance from the nozzle exit plane and the angle from the centerline as well as the equivalent nozzle thrust size and the engine operating characteristics. VACPLU then computes the plume local ambient pressure, dynamic pressure, and Mach number from equations 24 to 35 of section...
Left Side RCS Pod

Figure 5-4. Nozzle Cant Angles
4.4.1 and by assuming isentropic flow relations. If the angle from the centerline of the plume is greater than the limit turning angle the plume pressures are set to zero.

IMPING selects the correct dimensions for the nozzle set being used, zeros the total coefficients and proceeds to use VACPLU to predict the plume pressures on a set of flat plates representing the left side of the vehicle. The plume local static and dynamic pressures are used to compute the local surface pressure through a modified Newtonian pressure law and the local pressure is converted to a pressure coefficient based on free stream conditions. The pressure coefficient is multiplied by the local area and the direction cosines of the plate to obtain incremental force coefficients. The local force coefficients are used to compute local plate moments about the moment reference center and all of the local values are summed up to obtain total vehicle values. Since this integration is accomplished by summing up local values for a series of plates, a large number of plates is desirable for good accuracy as well as to minimize the pressure change on a plate. This is one of the principal reasons for confining all predictions to one side of the plane of symmetry of the vehicle. The program presently allows a total of 300 plates to represent the vehicle. Figures 4-5 to 4-7 show the spacing of one series of approximately 280 plates representing the left side of the orbiter. Each plate is defined by 7 variables which are the location of the plate centroid from the moment reference center (X, Y, Z), the local area (SLOC), and the direction cosines of the outer unit normal vector from the plate with respect to the body axis system as is shown in Figure 5-5. The direction cosines define the local slope of the plate which combined with the angle of the plate to the nozzle determines the local slope of the surface to the flow and from equation 36 of section 4 the pressure at that point from the Newtonian pressure law.

The program assumes that the plume cannot extend beyond the point where its dynamic pressure is less than that of the free stream or where the plume induced pressure is less than ambient free stream pressure.

5.8 COMPUTE INTERACTION INCREMENTS (SUBROUTINES INTER, QUART, QUAD, KABD, ADABD).

As in the earlier terms, the program zeros the increments from a previous case and then calls the interaction subroutine INTER to compute the interaction increments for each RCS direction. The curve fit equations defined in section 3 (equations 5 through 41) are the basis of this model. The subroutine INTER contains all of the coefficients of these curves as subscripted variables defined in data statements and a namelist input option is available in the input subroutine to input changes to any or all equations. This was done to add flexibility to the program. There are three types of curves fitted to the data, a 4th power Polynomial, a 2nd power polynomial, and a hyperbolic curve. The subroutine QUART is called to evaluate the fourth
Figure 5-5. Direction Cosines of Plate on Vehicle Surface
power polynominal and the subroutine QUAD is called to evaluate the second power polynominal. These curves are fit through the interaction increments and are functions either of mass flow ratio or momentum ratio depending on the increment and RCS direction. The fourth coefficient and the sixth coefficients of the quadratic and quartic equations are upper limits beyond which a constant value of incremental force or moment is assumed. These constant values are specified as the last coefficients of a given curve fit name.

The hyperbolic curve fit is used for the pitch up RCS peak value versus angle of attack curves (section 3 equations 26 to 30) and these equations are solved by the KABD subroutine. In addition it is necessary to solve the inverse of the peak value curves and this is done by the AKABD routine.

The OA82 windtunnel data was computed in a normal force body axis system so that the sign of the normal force increment must be reversed for all RCS directions. The upward firing pitch nozzle data was generated on the right side of the vehicle in test OA82 and the lateral-directional increments must be reversed to the left side convention used in this program.

5.9 CORRECT FOR SYMMETRIC FIRING AND/OR RIGHT SIDE LOCATION.

The program has the thrust terms, the impingement increments, and the interaction increments for all nozzle sets based on one set of each on the left side of the vehicle and at this point in the main program these data are corrected to represent the actual nozzle locations. This is done by two input parameters, IBOTH and ISIDEA for each nozzle firing direction (A = U, D, Y), with values of 0 or 1. IBOTH is the higher order parameter of the two and if it has a value of 1 then the set firing in this direction has a symmetric set on the right side of the vehicle also. This being the case the lateral-directional turns are set to zero and the longitudinal turns are doubled. For example IBOTHU = 1 results in

\[
\begin{align*}
CLU &= 0 \\
CNU &= 0 \\
CYU &= 0 \\
CLIMU &= 0 \\
CNIMU &= 0 \\
CYIMU &= 0 \\
CLINU &= 0 \\
CNINU &= 0 \\
CYINU &= 0 \\
CMU &= 2 \cdot CMU \\
CXU &= 2 \cdot CXU \\
CZU &= 2 \cdot CZU
\end{align*}
\]
If IBOTHA is set to 1, ISIDEA is ignored, but, if IBOTHA is set to zero, then this is a non-symmetric set of nozzles and ISIDEA has meaning. If ISIDEA is set as zero then this set up of nozzles is on the left side of the vehicle and no sign changes are required. If ISIDEA is equal to 1 then this set of nozzles is on the right side of the vehicle and the signs of the lateral directional components must be reversed.

5.10 COMPUTE CROSS COUPLING INCREMENTS (SUBROUTINE CCOUPL)

The final incremental terms needed to complete the RCS effectiveness prediction are the cross coupling terms which are computed in the subroutine CCOUPL. This subroutine has only limited models because data is not available of all possible interactions between RCS units but the model is based on the models derived in section 3.5 and given in equations 42 to 54 of that section.

5.11 SUM COMPONENTS AND COMPUTE AMPLIFICATION FACTORS (SUBROUTINE AMPL)

The total RCS aerodynamic coefficients are computed as the sum of the increments from all sets of nozzles and printed out by the main program. Since it is also desirable to relate these total coefficients to RCS thrust the amplification factors as defined by equations 2 and 3 of section 4.1 are computed in the Subroutine AMPL.

Subroutine AMPL begins by computing the thrust moments for a two nozzle symmetric pitch up set, a two nozzle symmetric pitch down set, a two nozzle yaw set, and a two nozzle (one on each side) roll set by calling subroutine THR. These two nozzle thrust moments are the thrust terms which are used to compute the out of plane amplification factors. For this reason the nozzle coordinates for all directions must be specified even if no nozzles are being used in that direction. The program will terminate if a set of nozzle specifications is missing and amplification factors will not be computed. The subroutine then proceeds to determine which types of control are being used of the twelve possible combinations:

a) symmetric pitch up
b) symmetric pitch down
c) yaw
d) pure roll
e) pitch up + Yaw
f) pitch down + yaw
g) pitch up + roll
h) pitch down + roll
i) yaw + roll
j) pitch up + yaw + roll
k) pitch down + yaw + roll
l) symmetric yaw

and a decision is reached whether to use the actual thrust moment or the two jet thrust moment to compute amplification factor. For example a yaw only case uses actual thrust side force and yawing moment to compute side force amplification and yawing moment amplification. This case, however, uses 2 jet pitch down to compute normal force and pitching moment amplification and 2 jet roll to compute roll amplification. A set of comments is printed to help clarify the definition of thrust moments used. The thrust moments used to compute amplification are also printed out and can be compared to the actual thrust moment table printed out previously.

Axial force amplification is not computed because there are no interaction or cross coupling models of these effects.

The computations are now completed and the program returns to the place specified by input parameter INEXT either for another case or to terminate the program.

5.12 PROGRAM INPUT (SUBROUTINE INPUTT)

The preceding sections have given a summary of the program operation and given a brief outline of the data required for the program to execute. This data is loaded into the program through a subroutine called INPUTT which will be briefly described in this section while a detailed description of the input data will be given in the next section.

The input subroutine is called at three different places in the main program and provides different data at each point based on a parameter INEXT. Four types of data are required for a full loading of the program:

a) vehicle surface plates
b) analytic model coefficients (namelist INCOF)
c) nozzle definitions (namelist IN)
d) flight conditions (namelist FC)

When the program is first loaded or if INEXT = 1 all of the input is required. When INEXT = 2, nozzle definitions and flight conditions changes must be input, and if INEXT = 3 only flight condition changes can be made.
The vehicle flat plate data is input using formatted read statements while the remain­
ing data is entered through namelist. The use of namelist was made to minimize
the input required for multiple cases. No input for a given variable in a namelist
leaves that variable at its present value. No input should be provided for the analytic
model coefficients unless changes are desired since the basic model developed in
this report is already specified in data declarations in the subroutines where they
are used.

Provisions have been made in INPUTT to rescale the flat plate vehicle surface data
if for example model computations are to be made. The input routine also computes
the direction cosines of the RCS nozzles including nozzle cant angles.

5.13 INPUT DATA DEFINITIONS

A new problem starts with first loading the vehicle flat plate surface data as formated
data at a maximum of 8 words per card with an F10.3 format.

<table>
<thead>
<tr>
<th>Card</th>
<th>Column</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1    | 1-10   | SCALE    | Scale factor for flat plate surface data
|      |        |          | SCALE = 1. if SCALE = 0 card must be input |
| 2 to N-1 | flat plate surface cards one plate per card up to 300 allowed at least one must be input |
| 1-10 | DNX(I) | X direction cosine of flat plate I. plates are counted as input is used. See figure 5-5 for definition of direction cosine. |
| 11-20| DNY(I) | Y direction cosine of flat plate I |
| 21-30| DNZ(I) | Z direction cosine of flat plate I |
| 31-40| X(I)   | X distance of centroid of plate I from reference center. See figure 5-2 for definition of axis system. Units are feet |
| 41-50| Y(I)   | Y distance of centroid of plate I from moment reference center. Units are feet |
| 51-60| Z(I)   | Z distance of centroid of plate I from moment reference center. Units are feet |
| 61-70| SLOC(I)| area of plate I in square feet |
| N    | 1-10   | 2.0      | Last card of flat plate input is signified by DNX(N) being greater than 1.1. This ends flat plate input. |
The remaining input is by namelist rather than formatted read and so no card can be specified. A namelist specification is made by a $ in column 2 of the first card of the list followed by the namelist name. Each variable name to be loaded must appear followed by an equal sign and the value of the input with commas separately variable specifications. The list can extend over a number of cards and is closed by a $.

The order of names within a list is not important and names can be repeated if newer data becomes available. There are three namelists within INPUTT having the names INCOF, IN, and FC and they load in that order on a new job.

<table>
<thead>
<tr>
<th>Namelist</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCOF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unless changes to the analytic model are to be made, do not input any data in INCOF and one card $ INCOF $ is sufficient.</td>
<td></td>
</tr>
<tr>
<td>INCOF</td>
<td>*Quadratic curve fit coefficient arrays for downward firing jets (5 coefficients)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Y = C (1) + C (2) x + C (3) x^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C (4) = \text{limit } x$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C (5) = \text{y value above limit } x$</td>
<td></td>
</tr>
<tr>
<td>INCOF</td>
<td>CZIDL</td>
<td>Normal force coefficient as a function of momentum ratio at low angles of attack (below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CMIDL</td>
<td>Pitching moment coefficient as a function of momentum ratio at low angles of attack (below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CLIDL</td>
<td>Rolling moment coefficient as a function of momentum ratio at low angles of attack (below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CZIDH</td>
<td>Normal force coefficient as a function of momentum ratio at high angles of attack (above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CMIDH</td>
<td>Pitching moment coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CLIDH</td>
<td>Rolling moment coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CZIUP</td>
<td>Peak normal force coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>Namelist</td>
<td>Variable</td>
<td>Description</td>
</tr>
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<td>----------</td>
<td>-------------</td>
</tr>
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<td>Peak side force coefficient as a function of momentum ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
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<td>CMIUP</td>
<td>Peak pitching moment coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNIUP</td>
<td>Peak yawing moment coefficient as a function of momentum ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CLIUP</td>
<td>Peak rolling moment coefficient as a function of momentum</td>
</tr>
<tr>
<td>INCOF</td>
<td>CZIUH</td>
<td>Normal force coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYIUH</td>
<td>Side force coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CMIUH</td>
<td>Pitching moment coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNIUH</td>
<td>Yawing moment coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
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<td>Rolling moment coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
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<td>CZIYL</td>
<td>Normal force coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
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<tr>
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<td>CMIYL</td>
<td>Pitching moment coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
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<td>CLTYL</td>
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<td>CZIYH</td>
<td>Normal force coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CMIYH</td>
<td>Pitching moment coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CLIYH</td>
<td>Rolling moment coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>Namelist</td>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>INCOF</td>
<td><em>Quartic</em></td>
<td>curve fit coefficient arrays for downward firing jets (7 coefficients)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Y = C(1) + C(2)X + C(3)X^2 + C(4)X^3 + C(5)X^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C(6) = \text{limit } X$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$C(7) = \text{Y value above limit } X$</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYTDL</td>
<td>Side force coefficient as a function of momentum ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNTDL</td>
<td>Yawing moment coefficient as a function of momentum ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYIDH</td>
<td>Side force coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNIDH</td>
<td>Yawing moment coefficient as a function of momentum ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td><em>Quartic</em></td>
<td>curve fit coefficient arrays for sideway firing jets</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYIYL</td>
<td>Side force coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNIYL</td>
<td>Yawing moment coefficient as a function of mass flow ratio at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYIYH</td>
<td>Side force coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CNIYH</td>
<td>Yawing moment coefficient as a function of mass flow ratio at high angles of attack (Above ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td><em>KABD</em></td>
<td>curve fit coefficient arrays for upward firing jets (6 coefficients)</td>
</tr>
<tr>
<td></td>
<td>CZAUP</td>
<td>Peak normal force coefficient as a function of angle of attack at low angles of attack (Below ALPHBK)</td>
</tr>
<tr>
<td>INCOF</td>
<td>CYAUP</td>
<td>Peak side force coefficient as a function of angle of attack at low angles of attack (Below ALPHBK)</td>
</tr>
</tbody>
</table>
Namelist Variable | Description | Description
--- | --- | ---
INCOF CMAUP | Peak pitching moment coefficient as a function of angle of attack at low angles of attack (Below ALPHBK) | 
INCOF CNAUP | Peak yawing moment coefficient as a function of angle of attack at low angles of attack (Below ALPHBK) | 
INCOF CLAUP | Peak rolling moment coefficient as a function of angle of attack at low angles of attack (Below ALPHBK) | 

The namelist IN defines the RCS engine, the locations of the sets and the geometry of the firing arrangement.

<table>
<thead>
<tr>
<th>Namelist</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td>*</td>
<td>There are no default values built in for the variables and all input must be included in the first case of a run.</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>RCS Engine Characteristics</td>
</tr>
<tr>
<td>IN</td>
<td>XMJ</td>
<td>Jet Mach number (not required, internally calculated)</td>
</tr>
<tr>
<td>IN</td>
<td>GJ</td>
<td>Specific heat of jet</td>
</tr>
<tr>
<td>IN</td>
<td>ARJ</td>
<td>Expansion ratio of jet, exit area-to-throat area</td>
</tr>
<tr>
<td>IN</td>
<td>AJE</td>
<td>Jet exit area (sq. ft.)</td>
</tr>
<tr>
<td>IN</td>
<td>POJ</td>
<td>Chamber pressure of jet (PSIA)</td>
</tr>
<tr>
<td>IN</td>
<td>RJ</td>
<td>Jet gas constant (R Air = 53.35)</td>
</tr>
<tr>
<td>IN</td>
<td>TOJ</td>
<td>Jet chamber temperature (Deg F)</td>
</tr>
<tr>
<td>IN</td>
<td>DEXIT</td>
<td>Jet exit diameter (Ft)</td>
</tr>
<tr>
<td>IN</td>
<td>THETA</td>
<td>Nozzle exit angle (angle of bell mouth nozzle wall) (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Reference dimensions</td>
</tr>
<tr>
<td>IN</td>
<td>SREF</td>
<td>Reference area (Sq. Ft.) = wing area</td>
</tr>
<tr>
<td>IN</td>
<td>C</td>
<td>Mean aerodynamic chord (reference length) (ft)</td>
</tr>
<tr>
<td>IN</td>
<td>B</td>
<td>Wing span (reference length) (ft)</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Nozzle locations (all sets must be input and left side locations specified)</td>
</tr>
<tr>
<td>Namelists</td>
<td>Variables</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>IN</td>
<td>XREU</td>
<td>X coordinate of upward firing nozzles exit plane from moment reference center (ft)</td>
</tr>
<tr>
<td>IN</td>
<td>YREU</td>
<td>Y coordinate of upward firing nozzle exit from moment reference center (ft) (always negative)</td>
</tr>
<tr>
<td>IN</td>
<td>ZREU</td>
<td>Z coordinate of upward firing nozzle exit from moment reference center (ft)</td>
</tr>
<tr>
<td>IN</td>
<td>XRED, YRED, ZRED</td>
<td>Coordinates of downward firing jets from the moment reference center</td>
</tr>
<tr>
<td>IN</td>
<td>XREY, YREY, ZREY</td>
<td>Coordinates of sideway firing jets from the MRC (Ft)</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Input values of location even if the number of nozzles is zero, so that amplification factors can be calculated</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Nozzle angles see figure 5-4 for positive directions</td>
</tr>
<tr>
<td>IN</td>
<td>THAFTU</td>
<td>Aft cant angle of upward firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>THAFTD</td>
<td>Aft cant angle of downward firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>THAFTY</td>
<td>Aft cant angle of sideway firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>THOUTU</td>
<td>Outboard cant angle of upward firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>THOUTD</td>
<td>Outboard cant angle of downward firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>THOUTY</td>
<td>Upward cant angle of sideway firing nozzle (Deg)</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Input values of angles even if the number of nozzles is zero, so that amplification factors can be calculated</td>
</tr>
<tr>
<td>IN</td>
<td>*</td>
<td>Nozzle set definitions</td>
</tr>
<tr>
<td>IN</td>
<td>NONOZU</td>
<td>Number of upward firing nozzles (causing pitch up) operating in a set</td>
</tr>
<tr>
<td>IN</td>
<td>NONOZD</td>
<td>Number of downward firing nozzles (causing pitch down) operating in a set</td>
</tr>
<tr>
<td>IN</td>
<td>NONOZY</td>
<td>Number of sideway firing nozzles (causing yaw) operating in a set</td>
</tr>
<tr>
<td>IN</td>
<td>IBOOTHU</td>
<td>Defines whether upward firing nozzles are operating on one or both sides of the center of gravity,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 0, Nozzles operating on one side only (set ISIDEU),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1, Nozzles operating on both sides</td>
</tr>
<tr>
<td>Namelist</td>
<td>Variable</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| IN       | IBOTHD  | Defines whether downward firing nozzles are operating on one or both sides of the center of gravity,  
|          |          | \( = 0 \), Nozzles operating on one side only (set ISIDED),  
|          |          | \( = 1 \), Nozzles operating on both sides  
| IN       | IBOOTHY | Defines whether sideway firing nozzles are operating on one or both sides of the center of gravity,  
|          |          | \( = 0 \), Nozzles operating on one side only (set ISIDEY),  
|          |          | \( = 1 \), Nozzles operating on both sides  
| IN       | ISIDEU  | Defines side on which upward firing nozzles are operating,  
|          |          | \( = 0 \), Operating nozzles are on the left,  
|          |          | \( = 1 \), Operating nozzles are on the right  
| IN       | ISIDED  | Defines side on which downward firing nozzles are operating,  
|          |          | \( = 0 \), Operating nozzles are on the left,  
|          |          | \( = 1 \), Operating nozzles are on the right  
| IN       | ISIDEY  | Defines side on which sideway firing nozzles are operating  
|          |          | \( = 0 \), Operating nozzles are on the left,  
|          |          | \( = 1 \), Operating nozzles are on the right  
| IN       | *       | Impingement Selector  
| IN       | IMP     | Defines the type of mathematical model to be used,  
|          |          | \( = 1 \), Use the empirical impingement model,  
|          |          | \( = 2 \), No impingement model used,  
|          |          | \( = 3 \), Use the semi-empirical impingement model (Modified Newtonian pressures plus vacuum plume model) \ IM \( = 3 \) is the default value  

The final namelist in is called FC and contains the flight conditions as well as a indicator which determines the input options on multiple cases.
<table>
<thead>
<tr>
<th>Namelist</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
</table>
| FC       | IOPT     | Defines the flight conditions to be read  
= 1, Mach number, angle of attack (Deg) and altitude (Ft) must be input, all others are not used  
= 2, Velocity (FPS), altitude (Ft), and angle of attack (Deg) must be input  
= 3, Dynamic pressure (PSF), altitude (Ft), and angle of attack (Deg) must be input  
= 4, Ambient pressure (PSF), temperature (Deg F), Mach number and angle of attack (Deg) must be input. This is default value. |
| FC       | MINF     | Free stream Mach number |
| FC       | PINF     | Free stream ambient pressure (PSIA) |
| FC       | TINF     | Free stream ambient temperature (Deg F) |
| FC       | QI       | Free stream dynamic pressure (PSF) |
| FC       | ALPH     | Angle of Attack (Deg) |
| FC       | HI       | Altitude (Ft) |
| FC       | VINF     | Velocity (FPS) |
| FC       | INEXT    | Defines content of next set of data  
= 1, All data are to be read  
= 2, Nozzle definitions and flight conditions (namelists IN AN: FC) must be read  
= 3, Flight conditions only (namelist FC) are to be read  
= 4, No more data will be read in, program stops |
5.14 OUTPUT DATA DEFINITIONS

The data printed out from a sample run is shown in figure 5-6. Not shown in this figure is the listings of input which occur because of the use of the namelist input option and the names are defined in the preceding section. The output starts with a definition of the characteristics of a single RCS nozzle in lines 1 to 3.

<table>
<thead>
<tr>
<th>Output Line</th>
<th>Word</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nozzle Characteristics</td>
<td>single RCS nozzle data</td>
</tr>
<tr>
<td>2</td>
<td>EXIT DIA</td>
<td>RCS nozzle exit diameter in feet (input as DEXIT)</td>
</tr>
<tr>
<td>2</td>
<td>EXPANSION RATIO</td>
<td>RCS nozzle exit to throat area ratio (input as ARJ)</td>
</tr>
<tr>
<td>2</td>
<td>EXIT ANGLE</td>
<td>RCS nozzle exit lip angle in degrees (input as THETA)</td>
</tr>
<tr>
<td>2</td>
<td>NOZZLE MACH</td>
<td>Computed nozzle exit Mach number</td>
</tr>
<tr>
<td>3</td>
<td>THRUST</td>
<td>Computed RCS nozzle thrust in pounds</td>
</tr>
<tr>
<td>3</td>
<td>CHAMBER PRESSURE</td>
<td>RCS chamber pressure in PSIA (input as POJ)</td>
</tr>
<tr>
<td>3</td>
<td>EXIT PRESS</td>
<td>Computed static pressure at nozzle exit plane in PSIA</td>
</tr>
<tr>
<td>3</td>
<td>EXHAUST GAMMA</td>
<td>Specific heat ratio of nozzle gases (input as GJ)</td>
</tr>
</tbody>
</table>

The freestream flight conditions are briefly described in lines 4 and 5

<table>
<thead>
<tr>
<th>Line</th>
<th>Word</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>FREESTREAM CONDITIONS</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P/INFINITY</td>
<td>Ambient pressure at flight condition either input or defined by standard atmosphere in PSIA (limited printout resolution)</td>
</tr>
<tr>
<td>5</td>
<td>MACH INF</td>
<td>freestream Mach number</td>
</tr>
</tbody>
</table>
(1) NOZZLE CHARACTERISTICS

(2) EXIT DIA  

(3) THRUST  

(4) FREE STREAM CONDITIONS

(5) P INFINITY  

(6) PRESSURE RATIO  

(7) RT RATIO  

(8) (R*TOJ)/(R*TINF)  

(9) THRUST TERMS

(10) PITCH UP  

(11) PITCH DOWN  

(12) YAW

Figure 5-6. Sample Output
### Impingement Forces

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>-0.000000</td>
<td>0.000000</td>
<td>-0.000000</td>
<td>0.000000</td>
<td>-0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CM</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CN</td>
<td>3.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CX</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CY</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CZ</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
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</table>

### Interaction Terms

<table>
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<tr>
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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CM</td>
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<td>0.000000</td>
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</tr>
<tr>
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<td>0.300000</td>
<td>0.000000</td>
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</tr>
<tr>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CY</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CZ</td>
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</tbody>
</table>

### Cross Coupling Terms

<table>
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<th>F</th>
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<tbody>
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<td>0.360000</td>
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</tr>
<tr>
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<tr>
<td>CX</td>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CY</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
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<td>0.000000</td>
<td>0.000000</td>
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<td>0.000000</td>
</tr>
</tbody>
</table>

### Total Values

<table>
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<tr>
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<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
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<td>-0.007555</td>
<td>0.000000</td>
<td>0.005536</td>
<td>0.000000</td>
<td>-0.008462</td>
</tr>
<tr>
<td>CM</td>
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<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CN</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CX</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CY</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>CZ</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
</tbody>
</table>

Figure 5-6. Cont'd
(27) Thrust moments used for amplification factors are dependent on control used.

(28) Unless otherwise noted, amplification is based on 2 assumed nozzles in each control.

(29) Pitch amp based on pitch down jets.

(30) CZTH = -0.0264444 CYTH = 0.0141316 CLTH = 0.0019355 CNTH = -0.0256689 CNTH = -0.0059215

(31) Amplification factors

<table>
<thead>
<tr>
<th></th>
<th>KL</th>
<th>KM</th>
<th>KN</th>
<th>KX</th>
<th>KY</th>
<th>KZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(32) Amplification</td>
<td>0.0000000</td>
<td>0.292068</td>
<td>0.033000</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.3249256</td>
</tr>
</tbody>
</table>

Figure 5-6. Cont'd
Output Line | Word | Description
--- | --- | ---
5 | GAMMA | freestream specific heat ratio
5 | ANGLE OF ATTACK | Input angle of attack (ALPH) in degrees

Same single RCS nozzle scaling conditions are defined in lines 6 to 8.

<table>
<thead>
<tr>
<th>Line</th>
<th>Word</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>PRESSURE RATIO</td>
<td>Single RCS nozzle jet exit pressure ratioed to freestream pressure ( \frac{P_J}{P_\infty} )</td>
</tr>
<tr>
<td>6</td>
<td>MOMENTUM RATIO</td>
<td>Single RCS nozzle momentum ratio (equation 5) ratioed using wing area as reference. ( \frac{\Phi_j}{\Phi_\infty} )</td>
</tr>
<tr>
<td>6</td>
<td>THRUST COEFF</td>
<td>Single RCS nozzle thrust ratioed by dynamic pressure and wing area = ( \frac{F}{qS} )</td>
</tr>
<tr>
<td>7</td>
<td>RT RATIO</td>
<td>( \frac{R_J T_J}{R_\infty T_\infty} ); RCS ambient temperature at exit ratioed to freestream</td>
</tr>
<tr>
<td>7</td>
<td>POJ/PINF</td>
<td>RCS chamber pressure ( P_{\text{oj}} ) ratioed to freestream ambient pressure ( P_\infty )</td>
</tr>
<tr>
<td>7</td>
<td>FREESTREAM DYNAMIC PRESSURE</td>
<td>( q_\infty = 0.7 \frac{P_\infty M_\infty^2}{P_{\text{oj}}} ) in PSF</td>
</tr>
<tr>
<td>8</td>
<td>( \frac{R^*T_{\text{oj}}}{R^*T_{\text{inf}}} )</td>
<td>RCS chamber temperature ratioed to freestream ambient temperature - Thayer's parameter</td>
</tr>
</tbody>
</table>

The program now begins a printout of all terms which are combined into total control moments and amplification. This printout is in a systematic form in which any pitch up nozzle contributions are listed first (lines 10, 14, 18, and 22); then pitch down nozzles (lines 11, 15, 19, and 23) and finally yaw nozzle contributions (lines 12, 16, 20, and 24). The data is all presented in aerodynamic coefficient form so that the force terms are non-dimensionalized by dividing by dynamic pressure and wing area and additionally the moment terms by the appropriate reference length. Column A presents rolling moment \( (C_{r}) \), column B presents pitching moment \( (C_{M}) \), Column C presents yawing moment \( (C_{N}) \), Column D presents body axis axial force \( (C_{x}) \), Column E presents side force \( (C_{y}) \), and Column F presents vertical force \( (C_{z}) \) where figure 5-2 defines the sign convention of the force and moment coefficients.
The thrust terms are computed first and are presented first in lines 9 through 12. These thrust terms have all nozzle cant angles included in their computation. The plume impingement terms are presented in lines 13 through 16. If the input option is selected to ignore impingement a comment will be printed between lines 8 and 9. The Interaction terms are presented in lines 17 to 20 and the cross coupling terms in lines 21 to 24. The summation of all components (equation 1 of section 4) listed in lines 9 to 24 are then obtained and printed in lines 25 and 26.

The amplification factors are then computed as described in section 4.1 and lines 27 and 28 are always printed. If data does not exist to define all nozzle locations the program will terminate at this point with a note defining this problem because the amplification factors cannot be computed without the all nozzle locations. When all nozzle locations have been defined the program goes through some logic to determine the control moments to be used to define amplification factors (see Section 4.1) and the control forces and moments used are defined in line 30. Line 29 is printed to show that the pitch down jet thrust itself is being used to compute pitch amplification. Similar statements are printed if actual thrusts are used for pitch up, yaw and roll cases. Line 30 prints the actual thrust force and moment numbers used to compute the amplifications.

```
CZTH = control thrust vertical force coefficient
CYTH = control thrust side force coefficient
CLTH = control thrust roll moment coefficient
CMTH = control thrust pitch moment coefficient
CNTH = control thrust yaw moment coefficient
```

The amplification factors then are the total data from line 26 divided by the thrust terms defined in line 30. Note that where possible the actual thrust terms of lines 9 to 12 are used and only if no thrust term exists is the 2 jet assumed value used.
6

REPRESENTATIVE FLIGHT PREDICTIONS

6.1 GENERAL

The space shuttle orbiter rear RCS packages shown in Figure 1-1 have three engines for firing upward, three for firing downward, and four engines for yaw thrust on each side of the vehicle and considering that the number of RCS engines firing can be varied in addition to at least twelve combinations of combined control, the total number of predictions required becomes a very large task. The purpose of this section is rather to apply the analytic prediction method developed in this study to representative cases to illustrate the results obtained from the method. Reference 1 showed that the symmetric pitch down RCS thrust case and a pure roll thrust case were the most critical so they were chosen as representative cases. Two nozzles were assumed to be firing on each side of the vehicle in each of these cases.

6.2 ENTRY TRAJECTORY RESULTS

A representative set of flight conditions along a space shuttle orbiter entry trajectory were obtained and the flight conditions along a segment of it are shown in figure 6-1. The vehicle starts re-entry at a high angle of attack and maintains this attitude until a low Mach number transition is made. The segment shown here is at the start of reentry and the high angle of attack is maintained throughout it. The rear RCS control system starts as primary control in all axes at zero dynamic pressure and maintains control functions until dynamic pressure is high enough for the aerodynamic control surfaces to be used. Figure 1-2 shows a representative control schedule for this transfer. The area of highest interest in RCS effectiveness is the region from zero dynamic pressure to a q of 20 PSF. The single nozzle flow scaling parameters are shown in Figure 6-1 also. Predicted Control amplification factors during entry for pitch down control is shown in figures 6-2 to 6-3 while roll amplification is shown in figure 6-4. Figure 6-2 shows that the adverse effect of interaction grows with increasing dynamic pressure and causes a decreasing control amplification even if no impingement would be experienced. Figure 6-2 shows that the impingement term also causes a reduction in control amplification at the lower dynamic pressures and the total control moment at low q is very sensitive to the impingement model used. The analytic model developed in this report gives a minimum value of control amplification of about 0.21 at dynamic pressures from 2 to 4 PSF. At this low effectiveness, the question arises of how the inaccuracy in wind tunnel data will affect it. Figure 2-3 presented the error in amplification factor resulting from the wind tunnel error analysis plotted as a function of thrust coefficient. This data was applied to the pitch down and roll flight data by computing flight thrust coefficients and Figures 6-3 and 6-4 present the error envelopes on the flight predictions. Thrust coefficient increases with decreasing
Figure 6-1. Entry Trajectory Conditions
Figure 6-2. Pitch Down Control Amplification During Entry
Figure 6-3. Effect of Wind Tunnel Error on Pitch Amplification During Entry
Figure 6-4. Effect of Wind Tunnel Error on Pitch Amplification During Entry
dynamic pressure so that the wind tunnel errors are only a small part of the total amplification factor in the flight range below 20 PSF dynamic pressure.

6.3 RTLS Abort Trajectory Results

Under certain abort conditions during the Space Shuttle launch, a maneuver is performed in which the orbiter jettisons the external tank and returns to the Launch site (RTLS). One critical maneuver during this abort is to jettison the tank and assume reentry attitude. The vehicle is pitched to zero angle of attack and maintains this angle until the tank separates and a pitch maneuver is started to reentry angle. Figure 6-5 present some of the flight conditions which occur during this maneuver. The vehicle starts the maneuver at the highest dynamic pressure and pitches to entry attitude at the end of the maneuver. This maneuver occurs at much lower altitude than the same dynamic pressure range during entry shown in Figure 6-1 and the Mach numbers and angles of attack are much lower.

The lower altitude effects change the plume conditions sufficiently so that much lower control is available from either pitch down or roll RCS. Figure 6-6 shows that the roll control amplification is nearly zero during the zero angle of attack portion of the maneuver. This is because the peak value of the adverse roll interaction increment on the vertical fin occurs in this range of angles. The lower altitude results in a lower plume pressure ratio and a small plume turning angle and no plume impingement occurs on the vertical fin. This lower plume turning angle, however, results in higher plume pressures on the wing and more impingement than for the entry case. When the wind tunnel error increment is applied as in section 6.2, the range of possible roll amplifications goes through zero and the RCS roll control is non existent from a 2 upfiring, 2 down firing combination. Some roll control could be obtained by firing only the upward facing engines if the pitch up moment which also results could be canceled by some other method.

The same problem of lack of control is also seen in the symmetric pitch down RCS case shown in Figure 6-7. The wind tunnel error band gives a control amplification of zero. Two terms in the analytic model appear to dominate the adverse interaction in this figure. The first and largest is the plume impingement term. The effect of lower altitude is to reduce the plume turning angle and makes the area affected by plume impingement smaller, however, the same term enters the plume decay parameter and causes the plume to decay slower. The net result is high plume impingement pressures over the smaller area and increased impingement increments. The second term is related to plume impingement and that is the symmetric firing cross coupling increment which is a function of impingement. Figure 6-7 shows that control exists if there is no cross coupling and this term needs further definition particularly because of the sting in the base of the wind tunnel model.
Figure 6-5. RTLS Abort Trajectory Conditions
Figure 6-6. Roll Control Amplification on RTLS Abort Trajectory
Figure 6-7. Pitch Down Control Amplification on RTLS Abort Trajectory
CONCLUSIONS

The interaction between the aft mounted reaction control system plumes and flow over the space shuttle orbiter vehicle is a very complex interaction and the adverse forces and moments which result are large relative to the thrust terms. An analytic model has been generated which predicts the total RCS control moment as the sum of the thrust term, an impingement term, an interaction term, and a cross coupling term. A program which incorporates this model has been written and is documented in this report.

7.1 STUDY CONCLUSIONS

1. The wind tunnel data accuracy was found to be good for all moments and the error in resulting full scale amplification was small at low dynamic pressure.

2. The interaction increments resulting from plume flow toward a surface correlated best with jet exit momentum ratio as the parameter.

3. The interaction increments resulting from plumes not flowing toward a surface correlated best with jet mass flow as a parameter.

4. Temperature ratio (RT) effects are important for those terms correlating with mass flow.

5. Additional yaw RCS simulation is desirable to improve the analytic model.

6. Combined control cross coupling is an important term and additional data is desirable.

7. Possible sting interference effects need to be resolved in the pitch down data.

8. Symmetric pitch down cross coupling needs more data to refine the model.

9. The RTLS abort maneuver appears to provide the most adverse flight conditions for RCS effectiveness.

10. Steady state simulation results are adequate for pulsing RCS controls.
7.2 STUDY RECOMMENDATIONS

1. A blade mounted model be built with a better representation of base geometry to evaluate sting interference.

2. A vacuum chamber test of symmetric pitch down RCS be performed with a good base geometry representation (no sting) to evaluate symmetric pitch down cross-coupling in the base region.

3. More wind tunnel tests be made to obtain the following data.
   a) Yaw RCS
   b) symmetric pitch down cross coupling
   c) other nozzles to verify mass flow as a parameter
   d) combined nozzles
   e) control deflection effects
SECTION 8
REFERENCES


APPENDIX A PROGRAM LISTING

PROGRAM PRED( INPUT, OUTPUT, TAPE5 = INPUT, TAPE6 = OUTPUT, TAPE48 )

DIMENSION SF(15)

REAL NONOZU, NONOZD, NONOZY
REAL MINFO
COMMON/CONST/Pi, RADIAN, G1, Hi, G0
COMMON/GRP2/DX(300), DYN(300), DNOZ(300), X(300), Y(300), Z(300), SLOC(3)

COMMON/UP/NONOU, YREU, ZREU, DXNOZU, DYN0ZU, DZNOZU, DSTARU
1 ISIDEU, IBOTHE, RFMSU, AEXU, FMRU
COMMON/LN/NONOZD, XRED, YRED, ZRED, DXNOZD, DYN0ZD, DZNOZD, DSTARD
1 IISIDEU, IBOTHE, RFMSD, AEXD, FMRD
COMMON/SIDE/NONOZ, YREY, ZREY, DXNOZY, DYN0ZY, DZNOZY, DSTARY
1 IISIDEY, IBOTHE, RFSY, AEY, FMKY
COMMON/HLY/XINF, PINF, TINF, ALPH, 10PT, G1, Hi, INF, THRUST, INEXT
COMMON/KEF/SCALE, XRED, YRED, ZRED, DXNOZD, DYN0ZD, DZNOZD, DNOZZ,
1) YNOZD, DNOZ2
COMMON/N0Z/XN5, G5, ARJ, AUE, POJ, RJ, TOJ, TURN, DSTAR, AN, THETA, DEXIT,
1) INF
COMMON/A/POW, POW1, PR1, T1, PZT
COMMON/INCOF/ C20H(5), C10H(5), CYDL(7), CYIDH(7), CMIDL(5),
1 CMIDH(5), CMIH(7), CMIUH(7), CLID(5), CLIDH(5), ALPGBK,
2 CZIUH(5), CYIH(5), CMIH(5), CMIUH(5), CLIH(5),
3 CIUH(5), CAYUH(5), CMAUH(5), CLAUH(5),
4 CZAUP(5), CAYAUP(5), CMAUP(5), CLAUP(5),
5 CZYI(5), CYIY(5), CYIH(5), CYIYH(5), CMYI(5),
6 CMIYH(5), CNIYH(5), CNIYH(5), CLIY(5), CLIYH(5)
COMMON/I/INCOF/ CXIMU, C2IMU, C1IMU, CMMU, CUMU, CI2MU, CI2MU, CI2MD, CI2MN,
1 CMIMU, CMIMD, CMIND, CLIMU, CI2MU, CI2MN, CMYI, CMYI,
2 CNIMU, CNIMY, CLIY, CLIY
COMMON/I/INCOF/ CXIMU, C2IMU, C1IMU, CMMU, CUMU, CI2MU, CI2MU, CI2MD, CI2MN,
1 CMIMU, CMIMD, CMIND, CLIMU, CI2MU, CI2MN, CMYI, CMYI,
2 CNIMU, CNIMY, CLIY, CLIY
COMMON/I/INCOF/ CXU, C2U, CYU, C1MU, C2MU, CLU, C2MU, CZU, CYD, CMD, CNU, C2D,
1 CXY, C2XY, CYY, CNY, CNY, CLY
COMMON/I/INCOF/ CXT, C2XT, CYT, CMT, CNT, CLT

GIN = 5.4
RINF = 53.3
PIE = 3.1415926
N1 = 33.5
U1 = 1.4
RADIA = 5.72958
u0 = 2.14049
OHC = 0
TLAIS = 0
INS = 5
IN1 = 1
100 CONTINUE
CALL IPUT(1IN)
1 IN2
101 CONTINUE
CALL IPUT(1IN)

AN = 7.705*DEXT**2
CALL SET(4J, ARJ, POJ, PJJ, TOJ, TJ, XMJ, AN)
AEXU = AN*NONOU
AEXA = AN*NONOZD
AEXS = AN*NONOZY
DISTARZ = sqrt(4./PIE*AEXU/ARJ)
DISTAZ = sqrt(4./PIE*AEXA/ARJ)
DISTARY = sqrt(4./PIE*AEXY/ARJ)

ORIGINAL PAGE IN OF POOR QUALITY
C
    II=3
    1 CONTINUE
C
    PHM1 4000
+000 FORMAT (1H1)
    CALL INPUT(1H1)
C
    GO TO (507,67,68,69), 1007
500 CONTINUE
    CALL ATMOS(1IT,+,PINF,RH,SOS,A0,100,0,DUM1,AM,AA,G,G0,TS,TLAT,0BC)
    PINF=PHM1/144.,
    TINF=TI
    VINF=PINF*SUS
    GO TO 69
600 CONTINUE
    CALL ATMOS(1IT+,PINF,RH,SOS,A0*,VINF,MINF,AK,AN,G,G0,TS,TLAT,0BC)
    PINF=PHM1/144.,
    MINF=VINF*SUS
    TINF=T
    GO TO 69
69 CONTINUE
    CALL ATMOS(1IT+,PINF,RH,SOS,A0,100,0,DUM1,AK,AA,G,G0,TS,TLAT,0BC)
    PINF=PHM1/144.,
    UJ=U/144.,
    VINF=UJ/(UJ+PINF))
    TINF=T
  01 CONTINUE
    IE=0+**144.*+PINF*PINF**2
    IE=U
    IF(UJ,0.,0.) IE=1.
    IF(UJ,0.,0.) IE=1.
    CALL EAM1(00,PO2,PINF,XMU,THETA,TURB)
    PHM1=PHM1/144.
    PHM1=PHM1
C JET MACH RATIO
  RAP=SU+02+PJJAM+2*AM/GINF/PINF/MINF/MINF/SR1E
  RAP=SU+02+PJJAM+2*AM/PHM1/144.
  RAP=SU+02+PJJAM+2*AM/PHM1/144.
  RAFL=SU+02+PJJAM+2*AM/PHM1/144.
  THURST=T+A+U*(PO2-PINF)
  CDEF-THURST/UJ/SR1E
  Print 3000
  Print 3006
  Print 3009
  Print 4001
  Form 1H10,123H NOZZLE CHARACTERISTICS
  PHM1=4000+PLAT,ARU,THETA,XMU
  4002 FORMAT (1H10,12+12H EXIT UA+F12.4*16H EXPANSION RATIO,F12.4*11H EXIT AN
  HELIX,F12.4*13H NOZZLE MACH,F15.4)
  PHM1=4000+THURST+PO2*+JU+6J
  4003 Format (1H10,12+12H THRUST=F12.4*14H CHAMBER PRESS+F12.4*11H EXIT PRESS,+
  F12.4*14H EXHAUST GAMMA,F12.4)
  Print 3006
  Print 4004
  Print 4009
  Print 4004
  Format (1H10,12+12H FREE STREAM CONDITIONS)
  PHM1=4005+PINF+M1N+M1N+PINF+GAMM+ALPH
  4005 Format (1H10,12+12H P INFINITY,F13.5*9H MACH INF,F12.4*6H GAMMA,F12.4,+
  05H ANGLE OF ATTACK,F12.4)
  PHM1=4000+PM+KMF+S+CDEF
  4006 Format (1H10,12+12H PRESSURE RATIO+F12.4*15H MOMENTUM RATIO,F12.4*13H TH
  RUST COEFF,F12.4)
  RH=RR+JX/JU+11H INF)
  RTU=12+12H MACH+TJ/TH
  PO2+PINF+PINF
  PHM1=4000+RTKAT+PO2+PINF+QI
  4007 Format (1H10,12+12H R1 RATIO,F13.5*9H PO2/PINF,F13.5*25H FREE STREAM DYNAMI
  1C PRESS,F13.5)
C JET MASS FLOW RATIO

FMK = SF(3)
FMUK = NONOZ*FMK
FMUK = NONOZ*FMK
FMUK = NONOZ*FMK
PRINT 4009 IF = IF + 1
CALL SCAL(PJ,6J,XPJ,J,AN,THP,J,PRJ,FJ,MINF,SHF,TINF,RI,
LH,ANS)
SF(IF) = ANS
PRINT 4009 IF, SF(IF)
4009 FORMAT(140,15,5F20.0)
10 CONTINUE

C COMPUTE THRUST MOMENTS

CALL THK(IT,CXT,CYT,CLT,CLT,CMT,CMT)
CALL THK(IT,CXT,CYT,CLT,CLT,CMT,CMT)
GO TO (74,75,76), IT
74 CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
GO TO 77
75 CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
GO TO 77
76 CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
CLU=CLT
GO TO 77
77 CONTINUE

C COMPUTE PLUME IMPINGEMENT MOMENTS

CLU=0.
CLU=0.
CLU=0.
CLU=0.
CLU=0.
CLU=0.
CLU=0.

ORIGINAL PAGE IS OF POOR QUALITY
170 CONTINUE
CN1MU=CN1MU+0.0593*CNY
CN1MU=CN1MU+0.00072*CMU
CL1MU=CL1MU+0.13*CLU
CZ1MU=CN1MU+0.0086*TCOEF*NONOZU
CX1MU=CN1MU+0.0026*TCOEF*NONOZU
CY1MU=CN1MU+0.00623*TCOEF*NONOZU
CN1MY=CN1MY+0.0157*CMY
CL1MY=CL1MY+0.3018*CMY
CZ1MY=CL1MY+0.2312*CMY
CX1MY=CN1MY+0.1079*TCOEF*NONOZY
CN1MY=CN1MY+0.0137*TCOEF*NONOZY
CN1MY=CN1MY+0.2734*TCOEF*NONOZY
CN1MY=CN1MY+0.0013*CMY
CN1MY=CN1MY+0.00073*TCOEF*NONOZY*XREU/C
CL1MY=CL1MY+0.03477*TCOEF*NONOZY*YREU/B
CX1MY=CN1MY+0.00268*TCOEF*NONOZY
CN1MY=CN1MY+0.00077*TCOEF*NONOZY
CN1MY=CN1MY+0.01634*TCOEF*NONOZY
GO TO 180

180 PRINT 4010
4010 FORMAT (2D12.0) (EDNO IMPINGEMENT FORCE IGNORED)
GO TO 190

180 CONTINUE
P0120=IT+1
CALL IMPINGE IT,CXT,CYT,CZT,CLT,CMT,CNT
GO TO (180,181,182,183) IT

180 CL1MU=CLT
CN1MU=CMT
CL1MU=CMT
CN1MU=CMT
CN1MY=CMT
CL1MY=CMT
CN1MY=CMT
CN1MU=CMT
CL1MU=CMT
CN1MY=CMT
CL1MY=CMT
CN1MY=CMT
CL1MY=CMT
GO TO 190

180 CL1MU=CLT
CN1MU=CMT
CL1MU=CMT
CN1MU=CMT
CN1MY=CMT
CL1MY=CMT
CN1MY=CMT
CL1MY=CMT
GO TO 190

180 CL1MY=CLT
CN1MY=CMT
CL1MY=CMT
CN1MY=CMT
CN1MY=CMT
CL1MY=CMT
CN1MY=CMT
CL1MY=CMT
GO TO 190

180 CONTINUE
190 CONTINUE
CL1MU=CN1MY=CM1MY=CM1MU=

A4
C  COMPUTE PLANE INTERACTION MOMENTS
IF(IW,EQ.1) GO TO 204
DO203 I=1,3
CALL INTER(IT,CX,B,CYB,CZB,CLH,CMH,CMH)
GO TO (200,201,202), IT
D200 CLIMU=CLD
CNIMU=CNB
CZIMU=CXB
CIMU=C1D
CZIMU=C1B
GO TO 200
D201 CLIMU=CLB
CNIMU=CNB
CZIMU=CXB
CIMU=CYB
CZIMU=C1B
GO TO 201
D202 CLIMU=CLB
CNIMU=CMH
CZIMU=CXB
CIMU=CYB
CZIMU=CMH
GO TO 202
D203 CONTINUE
D204 CONTINUE
IF(ISDTEU.EQ.1) GO TO 205
IF(ISDTEU.LT.1) GO TO 206
CLU=CLU
CNU=CNU
CYU=CYU
CLIMU=CLIMU
CNIMU=CNIMU
CYNAM=CYNAM
CLIMU=CLIMU
CNIMU=CNIMU
CYNAM=CYNAM
GO TO 204
D205 CONTINUE
CLU=0,
CNM=0,
CY=0,
CLIMU=0,
CNIMU=0,
CYNAM=0,
CLIMU=0,
CNIMU=0,
CYNAM=0,
CLM=2.*CMU
CNM=2.*CM
CZM=2.*CZM
CMIMU=2.*CMIMU
CASD-NSC-75-002

204 CONTINUE
IF(ISNLE.EQ.1)GO TO 207
IF(ISNLE.LT.1)GO TO 208
CLUE=CLU
CNUN=CNU
CYN=CYU
CLIM=CLIM
CNYM=CNMY
CMY=CLMY
CLIM=CLIM
CNYM=CNMY
CMY=CLMY
GO TO 208
207 CONTINUE
CLUE=.
CNUN=.
CYN=.
CLIM=.
CNYM=CNMY
CMY=.
CLIM=.
CNYM=CNMY
CMY=.
GO TO 208
208 CONTINUE
IF(ISNLE.EQ.1)GO TO 209
IF(ISNLE.LE.1)GO TO 210
CLUE=CLU
CYZ=CYU
LYZ=LYU
CLMY=CLMY
CNMY=CNMY
CLMY=CLMY
CNMY=CNMY
LYZ=LYZ
GO TO 210
209 CONTINUE
CLY=.
LY=.
CLY=.
LY=.
CNMY=.
CLMY=.
CNMY=.
CLMY=.
CLMY=.
CNMY=.
CMY=.
CMY=.
CMY=.
CMY=.
GO TO 210
210 CONTINUE
CLY=.
LY=.
CLY=.
LY=.
CNMY=.
CLMY=.
CNMY=.
CLMY=.
CLMY=.
CNMY=.
CMY=.
CMY=.
CMY=.
CMY=.
GO TO 210
Cained * CZINT

CALL COUPL (2, LACCDD, CZCD, CYCD, CMCD, CNCD, CLCD)

IF(ww = 1) THEN TO 311
CALL COUPL (1, LCU, CYCU, CACCU, CNCCU, CLCCU)
CALL COUPL (1, LCU, CYCU, CACCU, CNCCU, CLCCU)

3001 FORMAT (14H0 IMPRINT TERMS)
PRINT 3002

3002 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3003

3003 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3004

3004 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3005

3005 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3006

3006 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3007

3007 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3008

3008 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3009

3009 FORMAT (1DH0, 'HClOMMIT TERMS')
PRINT 3010

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SUBROUTINE PARCEJ(Y,U,COEF)
DIMENSION Y(3), D(3), COEF(3)
C--Gives COEFFICIENTS FOR A PARABOLIC FIT
X1 = Y(1)
X2 = Y(2)
X3 = Y(3)
D1 = U(1)
D2 = U(2)
D3 = U(3)
FACTOR = X2*X3*X3 - X2*X2*X3 - X1*X3*X3 + X1*X2*X2 + X1*X1*X3
* = X1*X1*X2
A1 = X2*X3*X3 - X2*X2*X3
A2 = X3*X1*X1 - X1*X3*X3
A3 = X1*X2*X2 - X2*X1*X1
T1 = X2*X2 - X3*X3
T2 = X3*X3 - X1*X1
T3 = X1*X1 - X2*X2
C1 = X3 - X2
C2 = X1 - X3
C3 = X2 - X1
COEF(1) = (D1*A1 + D2*A2 + D3*A3)/FACTOR
COEF(2) = (D1*B1 + D2*B2 + D3*B3)/FACTOR
COEF(3) = (D1*C1 + U2*C2 + D3*C3)/FACTOR
RETURN
END
SUBROUTINE ATMOS(Z,TT,PRHO,C,THET,V,AMU,ANU,G,GO,TS,THET,0BC)
C
C LAI{AL COMPI{LATION DATED 0-27-72
C
C U.S. STANDARD ATMOSPHERE, 1962
Z=2*9.1*W
A=3.285462E-04
I=7.54E-1
C=1.517E-17

C GRAVITATIONAL FORCE DETERMINED FROM SMITHSONIAN POLYNOMIAL

IF (THET>0.0) THEN
THET=THET/57.29579
C=2.2267370+COS(2.0*THET)*0.000069*(COS(2.0*THET)+1.0)

DBAK=2.27E-07
EBAKE=1.3
FBAR=2.0

Z=0.14*(U+DBAK*DBAK+COS(2.0*THET))*ZM+(BBAR+EBAR*COS(2.0*THET)+ZM)*ZM

C 10 U=U+0.30+48
```
AMU = 1 + 1.5 / (198.72 + TE) / G0

AM = AM / KHO

C = SQRT(1.4 * 1545.31 * G0 * TE / AM)

AM = W / C

TS = (4.36E+16 * SQRT(KHO / 0.00238) * (V / 26000) ** 3.15) ** 0.25

G = G / 3.048

G0 = G / 3.048

RETURN

230 IF (LM = 1000000) 240, 240, 250

240 TMU = 100.65

ALK = 3.0

ZUK = 90.0

PBM = 1.6436E-03

AMU = 20.9644

G = 20.5

G0 = 10.5

250 IF (LM = 1000000) 260, 260, 270

260 TMU = 100.65

ALK = 3.0

ZUK = 100.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

270 IF (LM = 1200000) 280, 280, 290

280 TMU = 200.65

ALK = 1.0

ZUK = 10.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

290 IF (LM = 1500000) 300, 300, 310

300 TMU = 300.65

ALK = 20.0

ZUK = 10.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

310 IF (LM = 1000000) 320, 320, 330

320 TMU = 400.65

ALK = 15.0

ZUK = 15.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

330 IF (LM = 1700000) 340, 340, 350

340 TMU = 500.65

ALK = 10.0

ZUK = 10.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

350 IF (LM = 1900000) 360, 360, 370

360 TMU = 600.65

ALK = 5.0

ZUK = 5.0

PBM = 3.075E-04

AMU = 20.96

G = 20.5

G0 = 10.5

RETURN

```

ORIGINAL PAGE IS OF POOR QUALITY.
370 IF (ZK<230000.0) 390, 390, 390
380 FM=1.35456
ALM=0.0
ZBH=190.0
PHM=1.0b52E-06
AMM=2b-65
GMM=1.0b75
GO TO 400
390 CONTINUE
U = 0.0
P = 0.0
G = 60.0, 48
RETURN
400 CONTINUE
C COMPUTE KINETIC TEMPERATURE
ZK=ZK/100.0
AMMA=1.0*(AMM+0.0*(ZK-ZBH))/2.9644
TMUL=TMU+AMM*(ZK-ZBH)
TT=TMUL+AMMA*1.0
410 CONTINUE
C COMPUTE STATIC PRESSURE
AP=(TMU/ALM)-23K
PART=1.0*(ZK-ZBH)*1.256E-06*1.0325*1.0818b)*100.0*(ZK+AP)/(ZBK+AP)

C=0.0b52E-06*PHM*EXP(PRLU)
420 CONTINUE
C COMPUTE DENSITY, SPEED OF SOUND, DYNAMIC PRESSURE
RHOD=P*AMMA2b.96441156.31*TT+60.0
C=ROOT(1.4*0/0.0)
430 CONTINUE
C COMPUTE ACH NUMBER, GRAVITATIONAL FORCE, VISCOSITY + KIN. VISC'Y
440 FUNCTION (2.0) UPPER ALTITUDE LIMIT EXCEEDED)
EVL
SUBROUTINE EXPIAN(6,PT,PIT,XM,THEANO,TURN)
IF (11.11.11.11) 6
G1=(6-1.)/6
G2=1./(6-1.)
G3=SWRT((6+1.)/(6-1.))
G4=SWRT((6+1.)/(6-1.))
IF (PIT=0.0) 60 TO 5
XME=SWRT(G2*((PT/PIT)**G1-1.1))
X1=SWRT(XME**2-1.1)
TURN=57.2956*(GATAN(G4*X1-ATAN(X1))
RETURN
5 TUKR=0.0*(G3-1.1)
6 CONTINUE
TJNH=TURN
XME=XP
GO TO (10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130) + 1
10 ANS = PJ/PI*GJ/GI*AJ/AI*XMJ/XMI*AI**2
RETURN
20 ANS = PJ/PI*GJ/GI*(1.64 + GJ*XMI**2-1)/(GJ*GJ**2)
RETURN
30 ANS = PJ/PI*GJ/GI*AJ/AI*(1.64 + GJ*XMI**2)/(GJ*GJ**2)
RETURN
40 ANS = PJ/PI*GJ/GI*AJ/AI*(1.64 + GJ*XMI**2)/(GJ*GJ**2)
RETURN
50 ANS = PJ/PI*GJ/GI*AJ/AI*XMJ/XMI**2
RETURN
60 CONTINUE
TMI = XMJ/XMI-1,
IF (TMI.LT.0.) TMI = -TMI
TMJ = XMJ/XMJ-1,
IF (TMJ.LT.0.) TMJ = -TMJ
ANS = PJ/PI*GJ/GI*(XMJ/XMI)**2*SQR(TMI)/SQR(TMJ))
RETURN
70 CONTINUE
TMJ = XMJ/XMJ-1,
IF (TMJ.LT.0.) TMJ = -TMJ
ANS = PJ/PI*GJ/GI*(XMJ/XMI)**2*SQR(TMJ)
RETURN
80 ANS = PJ*AJ*(GJ**2)*(XMJ**2)/(GJ*(GJ-1.))*(RI**2.5)
RETURN
90 ANS = PJ*PI
RETURN
100 ANS = PJ/PI*(GJ**2)*GJ/XMI**2
RETURN
110 ANS = PJ*PI*(1.64 + GJ**2)*GJ/GJ/(GJ-1.))
RETURN
120 PJJ = PJJ*(1.64 + GJ**2)*GJ/GJ/(GJ-1.))
CALL MACH(PJ, PI, GJ, ANS)
ANS = ANS/GJ
RETURN
END

SUBROUTINE MACH(P, PI, G, XM)
A = (G-1.)/G
XM = X**T((2./G-1.)*(P/PI)**A-1.))
IF (XM.LT.1) XM = -4000.
RETURN
END

ORIGINAL PAGE IS OF POOR QUALITY
SUBROUTINE THR(1, CX, CY, CZ, CL, CM, CN)
COMMON/INF, PINF, TINF, ALPH, IUP, UI, HI, VINF, THRUST, INEXT
COMMON/SCS, SREF, C, B, SCALE, XRE, YRE, ZRE, DXNOZ, DYNOZ, DZNOZ, DXNOZZ,
10 DYNQZ, D2NOQZ
COMMON/IP, NONZU, XREU, YREU, ZREU, DXNOZU, DYNOZU, DZNOZU, DSTARU
11 IUP, ITHU, RMFSU, AEXU
COMMON/INF, INFZ, NONZD, XRED, YRED, ZRED, DXNOZD, DYNOZD, DZNOZD, DSTAR
11 DTHU, ITHU, RMFSU, AEXD
COMMON/V, NONQY, XREY, YREY, ZREY, DXNOQY, DYNOQY, DZNOQY, DSTARY
11 ITHY, ITHU, RMFSY, AEXY
COMMON/V, NONQZ, XREZ, YREZ, ZREZ, DXNOQZ, DYNOQZ, DZNOQZ, DSTARZ
11 ITHZ, ITHU, RMFSZ, AEXZ
REAL NONZU, NONZD, NONQY
C1=1*THRU/WI/SREF
GO TO 10 (1,2,3), 1
1 IF(NONZU.EQ.0,Go To 5
C1=LI#NONZU
DX=DXNOQZ
DY=DYNQZ
DZ=DZNOQZ
X=XREU
Y=YREU
Z=ZREU
GO TO 4
2 IF(NONZD.EQ.0,Go To 5
C1=LI#NONZD
DX=DXNOQD
DY=DYNQD
DZ=DZNOQD
X=XRED
Y=YRED
Z=ZRED
GO TO 4
3 IF(NONQY.EQ.0,Go To 5
C1=LI#NONQY
DX=DXNOQY
DY=DYNQY
DZ=DZNOQY
X=XREY
Y=YREY
Z=ZREY
GO TO 4
4 CX=CL*UX
CY=CL*UY
CZ=CL*UZ
UX=(1.0*Y-2.0*X)/B
UY=(1.0*Z-2.0*X)/C
UZ=(1.0*X-2.0*Y)/B
RETURN
5 CX=0
CY=0
CZ=0
CL=U
CM=U
RETURN
END
BEGIN CALCULATIONS OF COEFFICIENTS AND DERIVATIVES
COLJULU=1
630 1 = 1
   YQ = Y(I)
   UNV = UNY(I)
660 XU = X(I) / b
   XC = X(I) / C
   YB = Y / b
   ZB = Z(I) / b
   ZC = Z(I) / C
   SNAME=SLOC(I)/SREF
   VX=X(I)-XRE
   DZ=Z(I)-ZRE
   DLIST=5UK1(0X**2+DY**2+DZ**2)
   IF(UO1<400)60 TO 1150
   IF(UO1>E7)60 TO 7
       IF(UO1<ZL)60 TO 1150
   7 CUNT=1
   DXFUT=DX/E1ST
   PTY1=1/1S1ST
   DELL=1/DIST
   CE1L=X(I)*1+XNUX+DYL1*U%Y1+DZT0U+UZNOZ
   THE1=XG(V1+CTA)*RADIAN
   IF(THE1=85.1)60 TO 1150
   UYF1=1-DXT01
   UY1=1-1YT01
   ZC1=1-Z1
   CE1L=X(I)*1+XNUX+DY1*U%Y1+DZT0U+UZNOZ
   CALL VAPULU(V1,DIST,XMPLUN,PLOC,QLOC)
   CPLUCG(UO1,UI)+UJ1)*1-2/(XMPLUM**2+GJ+3.1)CTA**2
   IF(DPLUCG.LT.UI)60 TO 1150
   IF(DPLUCG=PLOC+PLOC-PINF)/UI
   IF(DPLUCG+PLOC)60 TO 1150
   DELLL=1.0CLC+SNATI0
1000 1ELLX=KELCR=UX(I)
   1ELLX=KELC=U(I)
   1ELLX=KELC*U(I)
   1ELLX=KELC+ZCB=DELC*Z
   1ELLX=KELC+ZSY=DELC*Z
   1ELLX=KELC*UX=DELC*Y
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
   1ELLX=KELC
1150 CONTINUE
   PRINT
2000  CALLU,
       CIEU=U
       CIE=U
       CIEN=U
       CIEU=U
       CIEN=U
       RETURN
   END
SUBROUTINE VACPLU(THET, RAD, XMP, PLOC, GLOC)
COMMON /N02/XNO2, XJ, ARJ, AYE, POJ, RJ, TOJ, TURN, DSTAR, AN, THETA, DEXIT,
 IIMP
 IF (THET.GT.70.0) GO TO 100
 PUNC=POJ*144.
 PIE=3.14159
 DSTAR=SQR(AJE/ARJ*4./PIE)
 RHORHE=((1.+(GJ-1.)/2.*XMJJ**2)**(-1./(GJ-1.)))
 BGJF=1.24-0.00494*TURN/(2.*GJ**2)*1.-COS(TURN/57.2958))
 XDLIM2=SQR(XDLOM2)
 XDLOM2=XDLM**0.667
 FTHE=(COS(RAD*THET/250.))/10.
 IF (THET.LE.0.0) GO TO 5
 FTHE=0.042372*EXP(-0.064*(THET-60.))
 5 CONTINUE
 POW=2.
 DCLINE=RAD/DSTAR
 IF (DCLINE.LE.XDLM2) GO TO 10
 IF (DCLINE.LE.XDLM3) GO TO 6
 IF (DCLINE.LE.XDLM4) GO TO 7
 RHORHE=FTHET*0.5*(RHORHE/DCLINE+BGJF/DCLINE**2)
 GO TO 11
 6 CONTINUE
 POW=0.5
 BGJF=RHORHE
 GO TO 10
 7 RHORHE=FTHET*0.5*(1./SQR(DCLINE)+1./DCLINE)
 GO TO 11
 10 CONTINUE
 RHOKAT=BGJF*(DCLINE**(-POW))*FTHE
 11 IF (RHOKAT.GT.RHORHE) RHOKAT=RHORHE
 XMP=SQR((1.+((GJ-1.)/2.*XMJJ**2)**(-1./(GJ-1.))))
 PLOC=P0H*(1.+(GJ-1.)/2.*XMP**2)**((GJ-1.)/(1.-GJ))
 GLOC=GJ/2.*PLOC*XMP**2
 GO TO 11
 100 XMP=0.
 PLOC=0.
 QLOC=0.
 RHOKAT=0.
 101 CONTINUE
 RETURN
 200 FUNKMA (1H0*6F15.7)
 ENU
AX = 0.0
AY = 0.0
AZ = 0.0
AX = 0.0
AY = 0.0
AZ = 0.0
AKL = 0.0

C COMPUTE THRUST MOMENTS FOR ALL CONTROLS USING 2 NOZZLE FOR EACH SIDE
15 IF (AREU = EQ.0.0.0, AND, YREU = EQ.0.0.0, AND, ZREU = EQ.0.0.0) GO TO 100
SAVNOZ = NONOZU
NONOZU = 4
CALL MTH (1, CXTH, CYTH, CZTH, CLTH, CMTH, CNTH)
CLTH = CLTH
CLTH = CLTH
CLTH = CLTH/4,
NONOZU = SAVNOZ
25 IF (AREU = EQ.0.0.0, AND, YREU = EQ.0.0.0, AND, ZREU = EQ.0.0.0) GO TO 100
SAVNOZ = NONOZU
NONOZU = 4
CALL MTH (2, CXTH, CYTH, CZTH, CLTH, CMTH, CNTH)
CLTH = CLTH
CLTH = CLTH
CLTH = CLTH/4,
NONOZU = SAVNOZ
35 IF (AREU = EQ.0.0.0, AND, YREU = EQ.0.0.0, AND, ZREU = EQ.0.0.0) GO TO 100
SAVNOZ = NONOZU
NONOZU = 24
CALL MTH (3, CXTH, CYTH, CZTH, CLTH, CMTH, CNTH)
CLTH = CLTH/2,
CMTH = CMTH/2,
NONOZU = SAVNOZ
S1 = 0,
S2 = 0,
S3 = 0,
S4 = 0,
PRINT = 24
IF (CYTH > L.E.0.0) SIGN = CYTH / ABS(CYTH)
IF (CLTH > L.E.0.0) SIGN = CLTH / ABS(CLTH)
IF (CNTH > L.E.0.0) SIGN = CNTH / ABS(CNTH)
IF (CLTH > L.E.0.0) SIGN = CLTH / ABS(CLTH)
CLTH = CLTH
CMTH = CMTH
CNTH = CNTH
CYTH = CYTH

C IF REAL YAW NOZZLES EXIST USE YAW THRUST TERMS
IF (NOTTHY = NC.0.0) GO TO 18
IF (NONOZU = Y.E.0.0) GO TO 16
PRINT = 22
CMTH = CYTH
CYTH = CYTH
18 CONTINUE
IF (NONOZU = EQ.0.0) GO TO 20
IF (NONOZU = EQ.0.0) GO TO 30
C PITCH UP AND PITCH DOWN COMBINATIONS
CLTH = CLTH + CLU
IF (SINGL = L.0.0, ISIDEQ, AND, NONOZU = EQ, NONOZU = EQ) GO TO 40
PRINT = 23
CMTH = CMTH + CMU
CMTH = CMTH
GO TO 70
20 IF (NONOZU = EQ.0.0) GO TO 70
C PURE YAW BRANCHES TO 70

,A18
C PITCH UP JET ONLY COMBINATIONS

**PRINTED**
CJITTCU
CMITTCU
IF(J(I(1,NE.U,J)GO TO 70
CLMTTCU
PRINTED
GO TO 70
30 CJITTCU
C PITCH DOWN JET ONLY COMBINATIONS

**PRINTED**
CJITTCU
PRINTED
IF(J(I(1,NE.U,J)GO TO 70
CLMTTCU
PRINTED
GO TO 70
40 PRINTED
C PURE ROLL CASE
70 CONTINUE
PRINT 1 SUB AXE,YREU,ZREU,XRED,YRED,ZRED,XRCV,YREY,ZREY
105 FORMAT (54HIH ******* NOZZLE COORDINATES NOT INPUT, IMPOSSIBLE, 1 7HTU CALCULATE AMPLIFICATION FACTORS ******* 7X4HXRREU, 2 7XH9REU,7X4HRRE0,7X4ZRE0,7X4H2RE0,7X4H2REY, 3 7X4H2REY,7X4H2REY,9F11.47)
CALL LAIT
222 FORMAT (1H0*YAN AMPLIFICATION BASED ON ACTUAL NOZZLES*)
223 FORMAT (1H0* PITCH AND ROLL AMPLIFICATION BASED ON SUM OF PITCH UP 1 PLUO DOWN NOZZLES*)
224 FORMAT (1H0*UNLESS OTHERWISE NOTED AMPLIFICATION IS BASED ON 2 ASS 1UMED NOZZLES IN EACH CONTROL*)
225 FORMAT (1H0*PITCH AMPLIFICATION BASED ON PITCH UP NOZZLES*)
226 FORMAT (1H0*ROLL AMP BASED ON PITCH UP NOZZLES*)
227 FORMAT (1H0*PITCH AMP BASED ON PITCH DOWN NOZZLES*)
228 FORMAT (1H0*ROLL AMP BASED ON PITCH DOWN JET DATA*)
229 FORMAT (1H0*PURE ROLL PITCH AMP BASED ON 2 JETS PITCH DOWN*)
END

SUBROUTINE INTER(IX,CXB,CM,CZB,CLB,CMB,CNB)
COMPUTES PLUME INTERACTION COEFFICIENTS

REAL XNOZU,YNOZU,ZNOZU
COMMON/ONSI/PIERADIAN,GRI,RI,GO
COMMON/ARC,PW,P01,PT,SN,PZT
COMMON/NOZ/AMX,MJ,ARJ,AGE,POJ,RJ,TOJ,TURN,DSTAR,AN,THETA,DEXIT
1111 COMMON/UP/XNOZU,YREU,ZREU,XRED,YRED,ZRED,XRCV,YREY,ZREY
1,ISUBU,ISUBW,RFMT,SEX,Y,FMRY
COMMON/UP/XNOZU,YREU,ZREU,XRED,YRED,ZRED,XRCV,YREY,ZREY
1,ISUBD,ISUBW,RFMT,SEX,Y,FMRY
COMMON/IDE/NOZU,XREU,YREU,ZREU
1,ISUBL,ISUBG,RFMT,SEX,Y,FMRY
A19
CASP-NSC-75-002

CALCULATION OF ATTACK AT PEAK YAWING MOMENT COEFFICIENT FOR THE
CPR/KN/THrust/INT
CALCULATION OF ATTACK AT PEAK ROLLING MOMENT COEFFICIENT FOR THE
CPR/KN/THRUST/INT

MOMENT RATIO FOR DOWNWARD FIRING JETS
CPR/KN/MOMENT RATIO FOR UPWARD FIRING JETS
CPR/KN/MOMENT RATIO FOR SIDEWAY FIRING JETS

MASS FLOW RATIO FOR DOWNWARD FIRING JETS
MASS FLOW RATIO FOR UPWARD FIRING JETS
MASS FLOW RATIO FOR SIDEWAY FIRING JETS

CPR/KN/Angle OF ATTACK AT PEAK YAWING MOMENT COEFFICIENT FOR THE
CPR/KN/Angle OF ATTACK AT PEAK ROLLING MOMENT COEFFICIENT FOR THE

A20
10 IF (ALPH.GT.100) GO TO 65
   IF (ALPH.GT.100) GO TO 60
   CALL WUAJ (FAMU,CZIUP,CZP)
   CALL WUAJ (RMSU,FMUP,CYP)
   CALL WUAJ (RMSU,CMUP,CLP)
   CALL WUAJ (RMSU,CNUP,CNP)
   CALL WUAJ (RMSU,CLIP,CLP)
   CALL AKABD (CPZ,CZIUP,APKUZ)
   CALL AKABD (CPY,CYIUP,APKUY)
   CALL AKABD (CMU,CMIUP,APKU)
   CALL AKABD (CLP,CLIUP,APKUL)
   IF (ALPH.LT.APKUZ) GO TO 10 15
   CALL WADB (ALPH,CZIUP,ALPH)
   GO TO 10
   15 CZH = C2P*SIN(PIE/2.0*(ALPH-APKUZ+20.0)/20.0)**2.0
   20 IF (ALPH.LT.APKUY) GO TO 25
   CALL WADB (ALPH,CAUP,CYI)
   GO TO 20
   25 C1D = CYP*SIN(PIE/2.0*(ALPH-APKUY+20.0)/20.0)**2.0
   30 IF (ALPH.LT.APKUY) GO TO 35
   CALL WADB (ALPH,CAUP,CMU)
   GO TO 30
   35 C1D = CYN*SIN(PIE/2.0*(ALPH-APKUY+20.0)/20.0)**2.0
   40 IF (ALPH.LT.APKUL) GO TO 45
   CALL WADB (ALPH,CLIUP,CMU)
   GO TO 40
   45 C1D = CNP*SIN(PIE/2.0*(ALPH-APKUL+20.0)/20.0)**2.0
   50 IF (ALPH.LT.APKUL) GO TO 55
   CALL WADB (ALPH,CLIUP,CLP)
   GO TO 50
   55 CLD = CLP*SIN(PIE/2.0*(ALPH-APKUL+20.0)/20.0)**2.0
   GO TO 50
   60 CALL WUAJ (FAMU,CZIUP,CLP)
   CALL WUAJ (RMSU,FMUP,CYN)
   CALL WUAJ (RMSU,CMIUP,CLP)
   CALL WUAJ (RMSU,CNIU,CNP)
   CALL WUAJ (RMSU,CLIUP,CLP)
   GO TO 60
   65 IF (ALPH.LT.10) GO TO 70
   IF (ALPH.LT.10) GO TO 60
   CALL WUAJ (RMSFSD,CZIO,CZB)
   CALL WURT (RMSFSD,CYID,CYR)
   CALL WUAJ (RMSFSD,CNID,CNR)
   CALL WUAJ (RMSFSD,CLID,CLB)
   GO TO 60
   70 CALL WUAJ (RMSFSD,CZIO,CZB)
   CALL WURT (RMSFSD,CYID,CYR)
   CALL WUAJ (RMSFSD,CNID,CNR)
   CALL WUAJ (RMSFSD,CLID,CLB)
   GO TO 70
   75 IF (ALPH.LT.10) GO TO 80
   IF (ALPH.LT.10) GO TO 60
   CALL WUAJ (RMSFSCZIYL,CZB)
   CALL WUAJ (RMSFSCYIYL,CYB)
   CALL WUAJ (RMSFSCNIDL,CMB)
   CALL WUAJ (RMSFSCLIDL,CLB)
   GO TO 75
   80 IF (ALPH.LT.10) GO TO 70
   IF (ALPH.LT.10) GO TO 60
   CALL WUAJ (RMSFCLZIYL,CZB)
   CALL WUAJ (RMSFSCYIYL,CYB)
   CALL WUAJ (RMSFSCNIDL,CMB)
   CALL WUAJ (RMSFSCLIDL,CLB)
   GO TO 80
60 CALL WUAD (RMFSU,CZIYH,CZB)
   CALL WUAD (RMFSU,CZIYH,CYB)
   CALL WUAD (RMFSU,CZIYH,CMH)
   CALL WUAD (RMFSU,CZIYH,CYN)
   CALL WUAD (RMFSU,CLIYH,CLB)
GO TO 90
85 CYB = 0.0
   CMB = 0.0
   CYN = 0.0
   CLB = 0.0
   C = 0.0
90 CALL UAD (RMFSU,CZIYH,CZB)
THE FOLLOWING DATA MUST BE REVERSED IN SIGN SO AS TO CORRECTLY
CORRELATE THE BUILT-IN CURVE FIT COEFFICIENT DATA (BASED ON WIND
TUNNEL TEST DATA) WITH BODY AXES CONVENTION.
CZB = -CZB
IF (YZ.NE.1) RETURN
CYB = -CYB
CMB = -CMB
CLB = -CLB
RETURN
END

SUBROUTINE WUAD (X,C,Y)
EVALUATES AN ARRAY OF QUADRATIC CURVE FIT COEFFICIENTS AND
COMPUTES Y = C(1)+C(2)*X+C(3)*X*X+C(4)*X**2

DIMENSION C(1)

X = GIVEN INDEPENDENT PARAMETER
C = ARRAY OF QUADRATIC CURVE FIT COEFFICIENTS, THE FOURTH OF
   WHICH (C(4)) IS THE UPPER LIMIT OF X FOR WHICH THE
   COEFFICIENTS APPLY, THE FIFTH (C(5)) BEING THE Y VALUE AT
   GREATER X VALUES
Y = CALCULATED DEPENDENT PARAMETER

IF (X.GT.C(4)) GO TO 10
   Y = C(1)+C(2)*X+C(3)*X*X
   GO TO 20
10 Y = C(5)
20 RETURN
END

SUBROUTINE AKABD (Y,C,X)
EVALUATES AN ARRAY OF HYPERBOLIC CURVE FIT COEFFICIENTS AND
COMPUTES THE INVERSE SOLUTION, I.E.,
WHERE Y = C(1)/(X-C(2))+C(3)*X+C(4), CALCULATES THE VALUE OF X FOR
A GIVEN VALUE OF Y

DIMENSION C(1)

Y = GIVEN INDEPENDENT PARAMETER
C = ARRAY OF HYPERBOLIC CURVE FIT COEFFICIENTS, THE FIFTH OF
   WHICH (C(5)) IS THE FACTOR DEFINING THE PROPER ROOT TO
   BE USED
X = CALCULATED DEPENDENT PARAMETER

DISL = (Y-C(2)*C(4)-C(3))*2-4.0*C(4)*C(1)
IF (DISL.LT.0.0) GO TO 10
   A = C(5)-C(2)*C(4)-Y
   B = -2.0*C(4)
   X = (A+C5)*SQRT(DISL))/B
RETURN
SUBROUTINE KABD (X, C, Y)
C EVALUATES AN ARRAY OF HYPERBOLIC CURVE FIT COEFFICIENTS AND
C COMPUTES Y = C(1)/(X-C(2))+C(3)+X*C(4)

DIMENSION C(1)

C X GIVEN INDEPENDENT PARAMETER
C C ARRAY OF HYPERBOLIC CURVE FIT COEFFICIENTS
C Y CALCULATED DEPENDENT PARAMETER

Y = C(3)+X*C(4)
IF (X NE C(2)) Y = Y+C(1)/(X-C(2))
RETURN
END

SUBROUTINE QUART (X, C, Y)
C EVALUATES AN ARRAY OF QUARTIC CURVE FIT COEFFICIENTS, AND COMPUTES
C Y = C(1)+C(2)*X+C(3)*X**2+C(4)*X**3+C(5)*X**4

DIMENSION C(1)

C X GIVEN INDEPENDENT PARAMETER
C C ARRAY OF QUARTIC CURVE FIT COEFFICIENTS, THE SIXTH OF
C WHICH (C(6)) IS THE UPPER LIMIT OF X FOR WHICH THE
C COEFFICIENTS APPLY, THE SEVENTH (C(7)) BEING THE Y VALUE
C AT GREATER X VALUES
C Y CALCULATED DEPENDENT PARAMETER

IF (X LT C(6)) GO TO 10
Y = C(1)+C(2)*X+C(3)*X**2+C(4)*X**3+C(5)*X**4
GO TO 20
10 Y = C(7)
20 RETURN
END

SUBROUTINE CCOUPL (IT, CXC, CZC, CYC, CNXC, CNYC, CNZC, CNZC)
C CALCULATES CROSS COUPLING NOZZLE INTERACTION COEFFICIENTS

REAL NONOZU, NONOZD, HONOZU
COMMON/UP/NONOZU, XREU, YREU, ZREU, DXNOZU, DYNOZU, DZNOZU, CSTARU
1: ISIDEU, IBOTHU, RMFSU, AEXU, FMRU
COMMON/DWN/NONOZD, XRED, YRED, ZRED, DXNOZD, DYNOZD, DZNOZD, DSTAR
1: ISIDE, IBOTHD, RMFSD, AEXD, FMRD
COMMON/SIDE/NONOZU, XREY, YREY, ZREY, DXNOZY, DYNOZY, DZNOZY, DSTAR
1: ISIDEY, IBOTHY, RMFSY, AEXY, FMRY
COMMON/ANGLES/ APKUN, APKUL
COMMON/FLT/HINF, PINF, TINF, ALPH, IOPT, UI, VINF, THRUST, INEXT
COMMON/INCEFF/ CXIMU, CZIMU, CYMU, CMHU, CNIMU, CLIMU, CXIMD, CZIMD
1: CYIMD, CMIND, CNIND, CLIND, CXIMY, CZIMY, CYIMY, CMINY
2: CNIMY, CLIMY
COMMON/INCEFF/ CXINU, CZINU, CYINU, CMINU, CNINU, CLINU, CXIND, CZIND
1: CYIND, CMIND, CNIND, CLIND, CXINY, CZINY, CYINY, CMINY
2: CNINY, CLINY

1 PRINT 11, Y+C
11 FORMAT (/H49H********** ERROR---IMAGINARY ROOTS IN SUBROUTINE
1 I 13H KABD **************/10X3HY =E14.7/10X3HC = :4E15.7/) 
STOP
END
GO TO (10,50,60) IT
10 IF (NONOZU.LE.0.0 OR NONOZY.LE.0.0) GO TO 60
IF (ISIDEU.GT.0.0) GO TO 20
IF (ISIDEU.GT.0.0) GO TO 15
GO TO 20
15 IF (ISIDEY.GT.0.0) GO TO 20
GO TO 60
20 CXC = 0.0
CYC = 0.0
IF (ALPH.GT.0.0) CYC = -CYNY
CNC = -CNYNU
IF (ALPH.GT.15.0) GO TO 25
CNC = 0.3215*(CNYNU+CNYNY)
GO TO 35
25 IF (ALPH.GT.15.0) GO TO 30
CNC = -0.5*(CNYNU-CNYNY)
GO TO 35
30 CJC = -CNYNY
35 IF (ALPH.GE.APXKUL) GO TO 40
CLC = 0.32149*(CNYNU)
GO TO 45
40 CLC = 0.5*(CNYNU+CNYNY)
45 CONTINUE
GO TO 70
50 IF (NONOZD.LE.0.0) GO TO 60
IF (ISIDEU.GT.0.0) GO TO 60
CXC = 0.0
CYC = 0.0
CJC = 0.0
CNC = 0.0
CLC = 0.0
GO TO 70
60 CXC = 0.0
CYC = 0.0
CJC = 0.0
CNC = 0.0
CLC = 0.0
GO TO 70
70 RETURN
END

SUBROUTINE INPUTT IT
READS INPUT DATA

REAL NONOZU, NONOZD, NONOZY
REAL NIITF
COMMON/CONST/PIE, RADIAN, GI, HI, GO
COMMON/VRP2/ONX(300), ONY(300), ONZ(300), Y(300), Z(300), SLOC(3)
COMMON/UP/NONOZU, XREU, YREU, ZREU, DXNOZU, DYNZU, DZNOZU, DSTARU
COMMON/TV/ISIDEU, IDOTHU, RMFSU, AEXU, FMRU
COMMON/UP/NONOZD, XRED, YRED, ZRED, DXNOZD, DYNZD, DZNOZD, DSTARD
COMMON/SIDE/NONOZY, XREY, YREY, ZREY, DXNOZY, DYNZY, DZNOZY, DSTARY
COMMON/TV/ISIDEY, IDOTHY, RMFSY, AEXY, FMRY
COMMON/FLT/INF, PINF, TINF, TINF, ALPH, 10PT, HI, VINF, THRUST, INEXT
COMMON/REP/RREF, SCALE, XRE, YRE, ZRE, DXNOZ, DYNZ, DZNOZ, DNOZZ,
DSTARD, DNOZU, DNOZD
COMMON/PA, PO, PH, T1, TZ
COMMON/NZ/XMJ, GJ, ARJ, AJE, POJ, RU, TOJ, DSTAR, AN, THETA, DEXIT,
II, IMP
INPUT DEFINITIONS

***************

FORMATTED INPUT

SCALE FACTOR FOR THE FLAT PLATE SIMULATION DATA

DNX, DNY, DNZ

ARRAY OF DIRECTION COSINES OF THE FLAT PLATE

SIMULATION AREAS

X?, Y?, Z ARRAY OF CENTROIDS OF THE FLAT PLATE SIMULATION AREAS

FROM THE CENTER OF GRAVITY, X POSITIVE FORWARD,

Y POSITIVE TO THE RIGHT, Z POSITIVE DOWNWARD

SLOC

ARRAY OF LOCAL FLAT, PLATE SIMULATION AREAS (50 FT)

NAMELIST INCDF (PLUME INTERACTION COEFFICIENTS)

NOTE—CURVE FIT DATA IS CONTAINED IN DATA STATEMENTS IN

SUBROUTINE INTER, THAT DATA (BASED ON WIND TUNNEL TESTS)

PREDICTS COEFFICIENTS FOR CZ, CY, C2, AND CL OPPOSITE IN

SIGN TO THE BODY AXES CONVENTION USED HEREIN. THE

INTERACTION COEFFICIENTS ARE THEN CORRECTED (SEE

SUBROUTINE INTER). THUS, IF INPUTTING NEW DATA, ARRANGE

ACCORDINGLY.

QUADRIC CURVE FIT COEFFICIENT ARRAYS

(FOR DOWNWARD FIRING JETS)

CZIIL

NORMAL FORCE COEFFICIENT AS A FUNCTION OF MOMENTUM RATIO

AT LOW ANGLES OF ATTACK (Below ALPHBK)

CMIIL

PITCHING MOMENT COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)

CLIDL

ROLLING MOMENT COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)

CZIDH

NORMAL FORCE COEFFICIENT AS A FUNCTION OF MOMENTUM RATIO

AT HIGH ANGLES OF ATTACK, (Above ALPHBK)

CMIIDH

PITCHING MOMENT COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT HIGH ANGLES OF ATTACK (Above ALPHBK)

CLIDH

ROLLING MOMENT COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT HIGH ANGLES OF ATTACK (Above ALPHBK)

(COR UPWARD FIRING JETS)

CZIUP

PEAK NORMAL FORCE COEFFICIENT AS A FUNCTION OF MASS FLOW

RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)

CYIUP

PEAK SIDE FORCE COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)

CMIUP

PEAK PITCHING MOMENT COEFFICIENT AS A FUNCTION OF MASS

FLOW RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)

CNIUP

PEAK YAWING MOMENT COEFFICIENT AS A FUNCTION OF MOMENTUM

RATIO AT LOW ANGLES OF ATTACK (Below ALPHBK)
WHERE

C\cdots(4)\quad \text{is the maximum value of the momentum ratio for which the coefficients C\cdots(1) \text{ thru } C\cdots(3) \text{ apply}.

C\cdots(5)\quad \text{the value of the parameter (constant) at values of momentum ratio above } C\cdots(4).

C\quad \text{quartic curve fit coefficient arrays (for downward firing jets)}

C\quad \text{side force coefficient as a function of momentum ratio at low angles of attack (below } \alpha_{\text{phk}})

C\quad \text{yawing moment coefficient as a function of momentum ratio at low angles of attack (below } \alpha_{\text{phk}})

C\quad \text{side force coefficient as a function of momentum ratio at high angles of attack (above } \alpha_{\text{phk}})

C\quad \text{yawing moment coefficient as a function of momentum ratio at high angles of attack (above } \alpha_{\text{phk}})

C\quad \text{rolling moment coefficient as a function of momentum ratio at high angles of attack (above } \alpha_{\text{phk}})

C\quad \text{side force coefficient as a function of momentum ratio at low angles of attack (below } \alpha_{\text{phk}})

C\quad \text{yawing moment coefficient as a function of momentum ratio at low angles of attack (below } \alpha_{\text{phk}})

C\quad \text{side force coefficient as a function of momentum ratio at high angles of attack (above } \alpha_{\text{phk}})

C\quad \text{yawing moment coefficient as a function of momentum ratio at high angles of attack (above } \alpha_{\text{phk}})

C\quad \text{is the maximum value of the momentum ratio for which the coefficients } C\cdots(1) \text{ thru } C\cdots(5) \text{ apply}

C\quad \text{the value of the parameter (constant) at values of momentum ratio above } C\cdots(6).
**KABD CURVE FIT COEFFICIENT ARRAYS**

(For upward firing jets)

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak normal force coefficient as a function of angle of attack at low angles of attack</td>
<td>( C_{\text{norm}} )</td>
</tr>
<tr>
<td>Peak side force coefficient as a function of angle of attack at low angles of attack</td>
<td>( C_{\text{side}} )</td>
</tr>
<tr>
<td>Peak pitching moment coefficient as a function of angle of attack at low angles of attack</td>
<td>( C_{\text{pitch}} )</td>
</tr>
<tr>
<td>Peak yawing moment coefficient as a function of angle of attack at low angles of attack</td>
<td>( C_{\text{yaw}} )</td>
</tr>
<tr>
<td>Peak rolling moment coefficient as a function of angle of attack at low angles of attack</td>
<td>( C_{\text{roll}} )</td>
</tr>
</tbody>
</table>

Where:

- \( C_{\text{aoa}} \) is the factor defining the proper root when computing the inverse solution of the hyperbolic curve fit (call to subroutine KABD)

**NAMELIST IN (NOZZLE DESCRIPTIONS)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNOZU</td>
<td>Number of upward firing nozzles (causing pitch up) operating in a set</td>
</tr>
<tr>
<td>DNOZD</td>
<td>Number of downward firing nozzles (causing pitch down) operating in a set</td>
</tr>
<tr>
<td>SNOZT</td>
<td>Number of side-way firing nozzles (causing yaw) operating in a set</td>
</tr>
<tr>
<td>JREF</td>
<td>Jet Mach number (not required, internally calculated)</td>
</tr>
<tr>
<td>ES</td>
<td>Specific heat of jet</td>
</tr>
<tr>
<td>EX</td>
<td>Expansion ratio of jet, exit area-to-throat area</td>
</tr>
<tr>
<td>EIR</td>
<td>Jet exit area (sq ft)</td>
</tr>
<tr>
<td>PJO</td>
<td>Chamber pressure of jet (psia)</td>
</tr>
<tr>
<td>RJO</td>
<td>Jet gas constant (( k ) = 5.23)</td>
</tr>
<tr>
<td>TJO</td>
<td>Jet chamber temperature (deg F)</td>
</tr>
<tr>
<td>XKEU, YKEU, ZKEU</td>
<td>Coordinates of upward firing jets from the center of gravity (ft)</td>
</tr>
<tr>
<td>XRED, YRED, ZRED</td>
<td>Coordinates of downward firing jets from the center of gravity (ft)</td>
</tr>
<tr>
<td>XRET, YRET, ZRET</td>
<td>Coordinates of side-way firing jets from the center of gravity (ft)</td>
</tr>
<tr>
<td>DXET</td>
<td>Exit diameter (ft)</td>
</tr>
<tr>
<td>SREFA</td>
<td>Reference area (sq ft)</td>
</tr>
<tr>
<td>CMA</td>
<td>Mean aerodynamic chord (reference length) (ft)</td>
</tr>
<tr>
<td>BW</td>
<td>Wing span (reference length) (ft)</td>
</tr>
<tr>
<td>TNEU</td>
<td>Nozzle exit angle (angle of bell mouth nozzle wall) (deg)</td>
</tr>
<tr>
<td>TNEH</td>
<td>Defines the type of mathematical model to be used</td>
</tr>
</tbody>
</table>

- \( TNEH = 1 \), use the empirical impingement model, 
- \( TNEH = 2 \), no impingement model used, 
- \( TNEH = 3 \), use the semi-empirical impingement model (modified Newtonian pressures plus vacuum plume model)
POSITIVE NOZZLE CANTED TO THE LEFT
OUTWARD CANT ANGLE OF DOWNWARD FIRING NOZZLE (DEG)
POSITIVE NOZZLE CANTED TO THE LEFT
UPWARD CANT ANGLE OF SIDEWAY FIRING NOZZLE (DEG)
DEFINES WHETHER UPWARD FIRING NOZZLES ARE OPERATING ON
ONE OR BOTH SIDES OF THE CENTER OF GRAVITY,
= 0, NOZZLES OPERATING ON ONE SIDE ONLY (SET ISIDEUP);
= 1, NOZZLES OPERATING ON BOTH SIDES.
DEFINES WHETHER DOWNWARD FIRING NOZZLES ARE OPERATING ON
ONE OR BOTH SIDES OF THE CENTER OF GRAVITY,
= 0, NOZZLES OPERATING ON ONE SIDE ONLY (SET ISIDEUP);
= 1, NOZZLES OPERATING ON BOTH SIDES.
DEFINES WHETHER SIDEWAY FIRING NOZZLES ARE OPERATING ON
ONE OR BOTH SIDES OF THE CENTER OF GRAVITY,
= 0, NOZZLES OPERATING ON ONE SIDE ONLY (SET ISIDEUP);
= 1, NOZZLES OPERATING ON BOTH SIDES.
DEFINES SIDE ON WHICH UPWARD FIRING NOZZLES ARE
OPERATING;
= 0, OPERATING NOZZLES ARE ON THE LEFT;
= 1, OPERATING NOZZLES ARE ON THE RIGHT.
DEFINES SIDE ON WHICH DOWNWARD FIRING NOZZLES ARE
OPERATING;
= 0, OPERATING NOZZLES ARE ON THE LEFT;
= 1, OPERATING NOZZLES ARE ON THE RIGHT.
DEFINES SIDE ON WHICH SIDEWAY FIRING NOZZLES ARE
OPERATING;
= 0, OPERATING NOZZLES ARE ON THE LEFT;
= 1, OPERATING NOZZLES ARE ON THE RIGHT.
NAMELIST FC (FLIGHT CONDITIONS)
DEFINES THE FLIGHT CONDITIONS BEING INPUTTED;
= 1, MACH NUMBER, ANGLE OF ATTACK (DEG) AND ALTITUDE (FT)
ARE INPUTTED;
= 2, VELOCITY (FPS), ALTITUDE (FT) AND ANGLE OF ATTACK
(DEG) ARE INPUTTED;
= 3, DYNAMIC PRESSURE (PSF), ALTITUDE (FT) AND ANGLE OF
ATTACK (DEG) ARE INPUTTED;
= 4, MACH NUMBER AND ANGLE OF ATTACK (DEG) ARE INPUTTED
WIND:
FREE STREAM MACH NUMBER
PINF:
FREE STREAM AMBIENT PRESSURE (PSIA)
TINF:
FREE STREAM AMBIENT TEMPERATURE (DEG F)
U:
FREE STREAM DYNAMIC PRESSURE (PSF)
ALPHA:
ANGLE OF ATTACK (DEG)
H:
ALTITUDE (FT)
V:
VELOCITY (FPS)
INLAT:
DEFINES CONTENT OF NEXT SET OF DATA,
= 1, ALL TYPES OF DATA ARE TO BE INPUTTED;
= 2, NOZZLE DEFINITIONS AND FLIGHT CONDITIONS (NAMELISTS IN
AND FC) ARE TO BE INPUTTED;
= 3, FLIGHT CONDITIONS ONLY (NAMELIST FC) ARE TO BE
INPUTTED;
= 4, NO MORE DATA WILL BE READ IN, PROGRAM STOPS
GO TO (1,2,3,11)
1 CONTINUE
READ(5,2080)SCALE
2080 FORMAT(6(E10.3)) SCALE=1.
A28
J=0
120 J=J+1
   I=J
   READ (5,2080) DINX(I),DNY(I),DNZ(I),X(I),Y(I),Z(I),SLOC(I)
   X(I)=X(I)*SCALE
   Y(I)=Y(I)*SCALE
   Z(I)=Z(I)*SCALE
   SLOC(I)=SLOC(I)*SCALE*SCALE
   IF(DNX(I).LT.1.1)GO TO 120
   J=J-1
   READ (5,INCOF)
   WHITE (6,INCOF)
   RETURN
2 CONTINUE
   READ (5,IN)
   IF(I1MP.LE.0)IIMP=3
   IF(I1MP.GT.3)IIMP=3
   WHITE (6,IN)
   TATAF1=TAN(THAFT/DEG)
   TAT0UT=TAN(THOUT/DEG)
   DZNOZ=1.*COS(TATAN(SQRT(TATAFT**2+TATOUT**2)))
   DXN=1.*DZNOZ*TATAFT
   DYN=1.*DZNOZ*TATOUT
   DXO=DXNOZ
   DYN0=SYNOZ
   DZNOZ=1.*DZNOZ
   TATAF1=TAN(THAFT/DEG)
   TAT0UT=TAN(THOUT/DEG)
   DZNOZ=1.*COS(TATAN(SQRT(TATAFT**2+TATOUT**2)))
   DXN=1.*DZNOZ*TATAFT
   DYN=1.*DZNOZ*TATOUT
   DXO=DXNOZ
   DYN0=SYNOZ
   DZNOZ=1.*DZNOZ
   TATAF1=TAN(THAFT/DEG)
   TAT0UT=TAN(THOUT/DEG)
   DZNOZ=1.*COS(TATAN(SQRT(TATAFT**2+TATOUT**2)))
   DXN=1.*DZNOZ*TATAFT
   DYN=1.*DZNOZ*TATOUT
   DXO=DXNOZ
   DYN0=SYNOZ
   DZNOZ=1.*DZNOZ
   CONTINUE
   READ (5,PC)
   IF(INEXT.LE.0)INEXT=4
   IF(INEXT.GT.4)INEXT=4
   IF(IOPT.LE.0)IOPT=4
   IF(IOUT.GE.4)IOPT=4
   RETURN
   END