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ROCKET EXHAUST PLUME
COMPUTER PROGRAM
IMPROVEMENT

Volume I — Final Report

January 1972

Lockheed

HUNTSVILLE RESEARCH & ENGINEERING CENTER

LOCKHEED MISSILES & SPACE COMPANY

A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

HUNTSVILLE, ALABAMA

LOCKHEED MISSILES & SPACE COMPANY

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ROCKET EXHAUST PLUME
COMPUTER PROGRAM
IMPROVEMENT

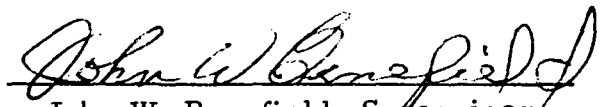Volume I — Final Report

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SUMMARY VOLUME

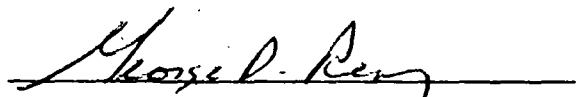METHOD-OF-CHARACTERISTICS
NOZZLE AND PLUME
PROGRAMS

Contract NAS7-761

by

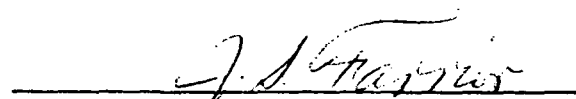Alan W. Ratliff
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FOREWORD

This document presents the results of work performed by the Fluid Mechanics Section of the Aeromechanics Department of Lockheed's Huntsville Research & Engineering Center. This report is Volume I of a four-part final report, as required to fulfill Contract NAS7-761. This work was partially sponsored by the Liquid Propulsion Section of Jet Propulsion Laboratories; Mr. Wolfgang Simon, Technical Manager. Other portions of the work reported herein were sponsored by the Aero-Astrodynamics Laboratory of Marshall Space Flight Center under the cognizance of Mr. Homer B. Wilson, Dr. Terry F. Greenwood and Mr. David C. Seymour.

This document constitutes Volume I of a four-part final report. The other three volumes, printed separately are:

Volume II — "User's Manual — Method of Characteristics Plot Program," LMSC-HREC D162220-II.

Volume III — "Solution of Non-Isoenergetic Supersonic Flows by the Method of Characteristics," LMSC-HREC D162220-III

Volume IV — "User's Manual — Variable O/F Ratio Method of Characteristics Program for Nozzle and Plume Analysis," LMSC-HREC D162220-IV.

In addition, the ancillary programs concerning plume impingement calculations and thermochemical computations are summarized in this report. These programs are more fully documented in Refs. 2, 4, and 6.

SUMMARY

This report is a summary of the various documents that discuss and describe the computer programs and analysis techniques which are available for rocket nozzle and exhaust plume calculations. The basic method of characteristics program is discussed, along with such auxiliary programs as the plume impingement program, the plot program and the thermochemical properties program. As a summary document, this report is written to supply a general idea of the programs and techniques available. For detailed information the other volumes listed in the Foreword should be consulted.

In addition to the description of current techniques and programs, a discussion is also included of areas of the computational schemes which can and should be improved. Finally, an appendix is supplied which is intended to give some insight into the anticipated accuracy that might be expected in plume calculation based on the various assumptions used.

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CONTENTS

Section 1

INTRODUCTION

The importance of accurate computations of rocket exhaust plumes and plume impingement cannot be overemphasized because of their direct impact on many facets of space vehicle design. In some cases impingement characteristics may dominate the design and operation of vehicles. A prime example is the separation problem of stages which must be protected from exhaust plume blasts in order to ensure re-usability of the stages.

At Lockheed-Huntsville, considerable capability for predicting plumes and plume impingement has been developed over the years. This document is intended to summarize the techniques and computer programs which have been developed and are available for such analyses. Included in this report are descriptions of the basic computer programs for both plume predictions and impingement calculations. Several auxiliary programs, used with the basic programs, are also described and discussed. This is a summary document to give the reader a general idea of the programs and techniques. For detailed information, the other volumes listed in the Foreword should be consulted.

Although the programs and techniques described are quite general and comprehensive, there remain several areas in the overall plume prediction state-of-the-art which should be improved. These programs and techniques are limited to the consideration of either equilibrium or frozen flowfield chemistry. Although a technique is available to approximate the finite rate effects, they should be included as an integral part of the flow field calculation. When engines are operated in a space environment, the plumes can, of course, expand without bound, and as the flow becomes highly rarefied the continuum techniques become questionable and should be supplemented by techniques which can account for non-continuum effects and eventually free

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molecular effects. At the low temperatures sometimes encountered in plume problems, the possibility of condensation of some of the species should be considered. Thus, the programs and techniques should be extended to treat condensing species and two-phase flow effects. At lower altitudes the possibility exists of encountering multiple shockwaves. Presently the programs handle such problems by a reflecting technique which is adequate for single shock problems but does not accommodate the general case. Methods should be developed to incorporate a general technique for accommodating multiple shockwaves.

Considering the comprehensive shockwave problem the possibility also exists for encountering subsonic regions in the flow field. This problem is usually referred to as the Mach disc or triple point problem and has been attacked analytically in various ways without much success. A new method should be developed which would handle simultaneously both the supersonic and subsonic portions of the flow. This, of course, would require some type of a finite difference or finite element numerical technique. Finally, the programs described here are for inviscid flows only and many problem areas are encountered where portions of the flow should be treated as viscous regions. Presently, this problem can be treated in an uncoupled fashion, but techniques should be incorporated to accommodate viscous effects simultaneously.

Thus, it can be seen that although the present set of computer programs will provide solutions to many plume and impingement problems, there is ample room for improvement.

In addition to the description of the computer programs and analysis techniques, an appendix is included which discusses the accuracy associated with various assumptions employed in plume analyses. This information indicates that there are wide variations in predicted plume properties, depending on the assumptions used.

Section 2
SUMMARY TABLE OF PROGRAMS

Table 2-1 summarizes the computer programs available for rocket engine exhaust studies. The computer system utilized, as well as the operational status of each program, is included along with appropriate comments concerning the utility of the program. These programs are operational at Lockheed-Huntsville although some were developed by other companies as indicated in the table.

Table 2-1

SUMMARY OF COMPUTER PROGRAMS AVAILABLE
FOR ROCKET ENGINE EXHAUST STUDIES

Program	Computer	Status	Comments (References)
1. Variable O/F Method-of-Characteristics (VOFMOC)	1108/7094 CDC6600	Operational	Performs nozzle and plume flowfield calculations. (5)
2. MOC/Free Molecular (FM)	1108	Not operational: Needs further programming and checkout.	Nozzle and plume flowfield calculations with capability to perform high altitude free molecular calculations. (None)
3. Viscous Method-of-Characteristics Program (MOCV) (from GASL)	1108	Operational	Basic MOC calculations with viscous terms used as forcing functions.(11)
4. Streamline Normal (STRNOR)	1108	Basic program is operational	Nozzle and plume calculations using MOC theory but with a different mesh construction technique. (12)
5. Two-Phase STRNOR	1108	Not operational	Coupled particle and gaseous flow. (Needs checkout work.) (13)
6. Two-Dimensional Kinetics Program (TDK) (from JANNAF)	1108/7094	Operational	Basically nozzle performance program. Handles variable O/F ratio by slipline technique. (14)
7. Automated Aerochem Streamline Program (from Aerochem)	1108/7094	Operational	A finite-rate streamline program to determine the chemical freezing.(15)
8. Method-of-Characteristics Plot Program	1108	Operational	Plots iso-value contours of flowfield properties generated by the VOFMOC program. (10)
9. Method-of-Characteristics Radial Plot Program	1108	Operational	Plots radial distributions of flowfield properties at constant axial distances. (3)
10. Chemical Equilibrium Composition (CEC) Program	1108/7094	Operational	Generates equilibrium and frozen thermochem data for use with the VOFMOC program. (2)
11. Master Tape Generator	1108/7094 CDC6600	Operational	Uses the output tape from the CEC program to prepare a thermochem input tape for the VOFMOC. (16)
12. Streamtube	1108/7094	Operational	Defines post combustion gas properties using several streamtubes treated as an equilibrium one-dimensional flow problem. (17)
13. Aerochem Finite Rate Mixing (from AeroChem)	1108/7094 CDC6600	Operational	Computes parallel viscous mixing of two or more concentric streams by finite difference solutions of parabolic differential equations. (18)
14. Mass Addition Boundary Layer (MABL)(from JANNAF)	1108	Operational	Solution of nozzle boundary layers by finite difference technique using equilibrium chemistry. (19)
15. LMSC/HREC Boundary Layer Program	1108/7094	Operational	Solves nozzle boundary layers by similarity technique. (20)
16. Transonic (unsteady)	1108/7094	Operational	A time-dependent finite difference program to calculate transonic flowfield. (21)
17. Transonic (Error Minimization Technique)	1108/7094	Operational	A finite difference program which uses the error minimization technique to solve the flowfield's transonic region. (22)
18. Transonic (Error Minimization with Fuel Striations)	1108/7094	Operational	Same as 17 except handles variable O/F problems. (23)
19. Plume Impingement Program (PLIMP)	1108	Operational	Calculates forces, moments and heating rate distributions on objects immersed in flowfields. (4)

Section 3
THE METHOD-OF-CHARACTERISTICS PROGRAM

A precise knowledge of local flow properties in nozzles and exhaust plumes is necessary for performance, radiation, attenuation, heat transfer and impingement analyses. All of these analyses are dependent on an accurate knowledge of the environment.

Lockheed Missiles & Space Company, Huntsville Research & Engineering Center has developed, under the sponsorship of several governmental agencies, a two-dimensional or axisymmetric method-of-characteristics program. The program is applicable for problems involving supersonic flow of an inviscid, adiabatic reacting gas in thermal equilibrium.

Areas of particular interest are modifications to the existing program to expand the capabilities and flexibility of the program. In particular the capability to handle O/F gradients within the flow field has been incorporated.

As a preliminary step in the plume analysis, an accurate knowledge of the nozzle flow field is required. Both nozzle and plume calculations are performed with the same program. This program is a versatile, user-oriented, analytical tool which is capable of producing all of the gas dynamic nozzle or plume data required for an impingement analysis. The user may choose a solution for a (1) nozzle only, (2) plume only, (3) combination nozzle and plume, depending on the options and starting data selected. This program has been in use for several years and experience has led to a continual refinement of the calculational procedure.

Answers to questions pertaining to the operation of the program should be found in this document or in the program listing. Questions involving initial assumptions made in applying the general theory can be answered by referring to Volumes I and III (Refs. 5 and 9) of this document.

3.1 CAPABILITIES

The nozzle and plume computer program described in this document can be used to solve a wide variety of problems in real gas, supersonic, compressible flow. Capabilities were previously discussed in Ref. 1; however, as improvements continue to be made to the basic program, new capabilities evolve. Some of the more important, basic capabilities of the existing program are outlined below:

- The gas may be ideal or real. If real, frozen or equilibrium assumptions can be made. Oxidizer/fuel gradients may be considered.

- Two-dimensional or axisymmetric problem geometry can be used.

- Both upper and lower boundaries can be solid or free. (A solid boundary can be approximated by either a conic or polynomial equation.)

- A nozzle wall may be curve fit with discrete points.

- One compression corner on the upper wall can be calculated. (Any number may be considered if the problem is re-started each time.)

- The number of Prandtl-Meyer rays to be computed around expansion corner discontinuities may be input.

- Any number of expansion corners can be considered on either the upper or lower wall.

- Various methods for obtaining an initial start line are utilized.
  1. The program will calculate a one-dimensional start line anywhere in the nozzle.
  2. The program will calculate a start line at points within the nozzle necessary to conserve mass.
  3. Characteristic data can be input at points across the flow field within the nozzle or in the plume.
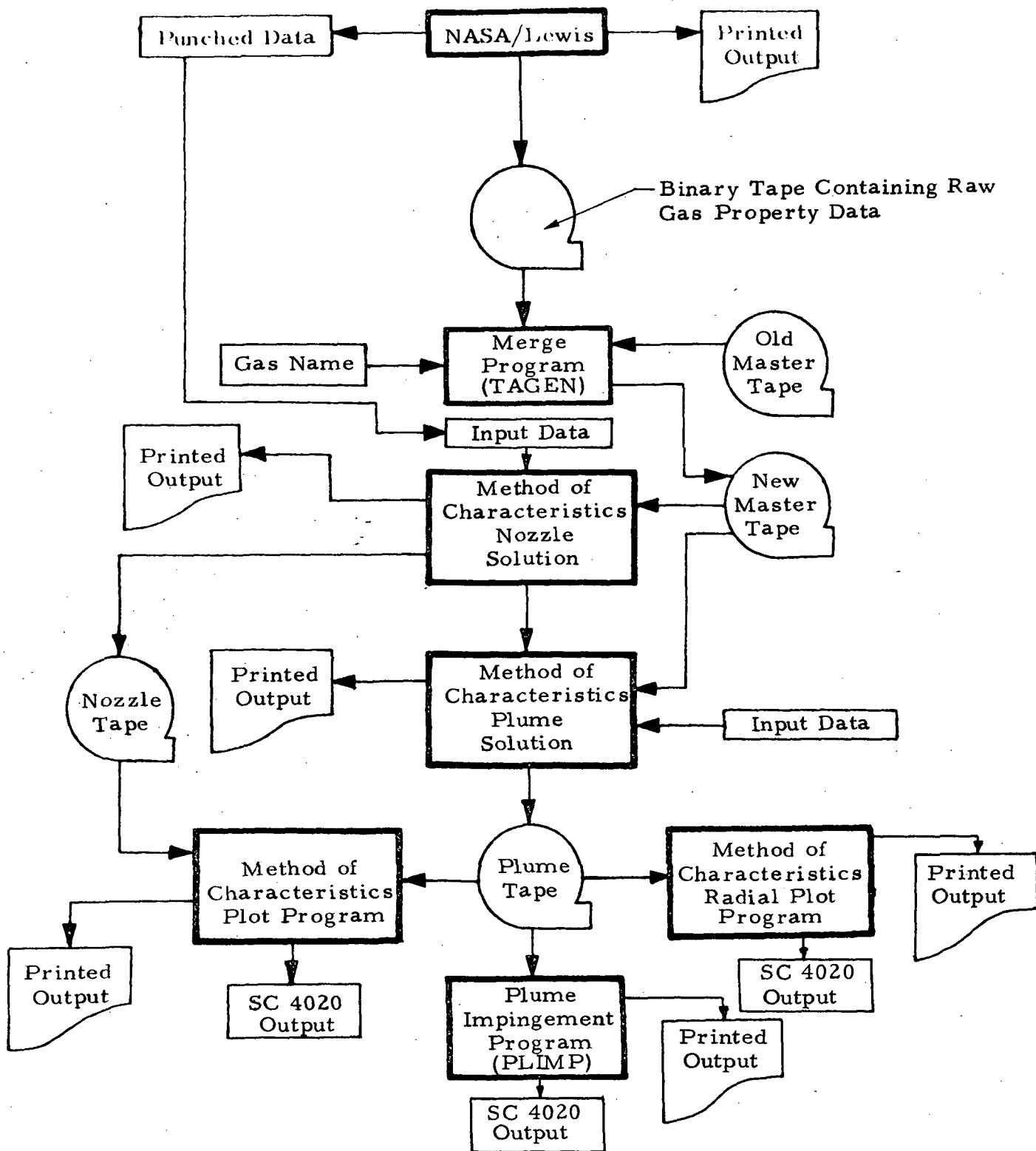
4. Any right running characteristic line can be used for a start line. (See page 3-11.)

5. Any left running characteristic line can be used (may be in combination with a normal start line). (See page 3-11.)

6. Any left running line may be input with a right running shock crossing it. (See page 3-25.)

● Hypersonic or quiescent approach flow options may be used.

● Exit to ambient pressure ratios from over expanded to highly under expanded are possible.

● Viscous boundary layer approximations at the nozzle lip are available. (See page 3-35 and Ref. 5.)

● Displacement of the axis of symmetry from the center of flow (i. e., the plug nozzle flow field) is possible.

Reacting gas solutions have been facilitated by modifying the Chemical Equilibrium Composition Program (CEC)(Ref. 2) to provide binary tape and punched output of its equilibrium or frozen real gas calculations at any desired O/F ratio(s). The Method-of-Characteristics program has the capability for selecting the proper case from a large set of real gas properties cases stored on a master tape. Lockheed-Huntsville's master tape presently consists of approximately 70 cases and is continually being expanded. The method of generating this master tape is outlined in the diagram on the following page. Cases stored are uniquely identified by some characteristic of the particular gas under consideration. For example, a LOX/LH_2 system may be identified by the following:

Gas Type	Mixture Ratio	Chamber Pressure
O2/H2	O/F = 1.5 - 8.0	PC = 546.0

New cases of general interest may be added to the master tape; however, ad hoc cases should be prepared on a separate tape. Tape preparation sequence and communication with the Method-of-Characteristics program is diagrammed on the following page.

Once the method-of-characteristics solution has been obtained, the output tape may be used to map the flowfield using the method of characteristics

Punched Data

NASA/Lewis

Printed Output

Binary Tape Containing Raw Gas Property Data

Gas Name

Merge Program (TAGEN)

Old Master Tape

Input Data

Printed Output

Method of Characteristics Nozzle Solution

New Master Tape

Nozzle Tape

Printed Output

Method of Characteristics Plume Solution

Input Data

Method of Characteristics Plot Program

Plume Tape

Method of Characteristics Radial Plot Program

Printed Output

Printed Output

SC 4020 Output

Plume Impingement Program (PLIMP)

Printed Output

SC 4020 Output

SC 4020 Output

Plot Program described in Volume III. The output tape may be used by the Method-of-Characteristics Radial Plot Program (Ref. 3) which determines the radial variations of flowfield properties across the nozzle and plume flow-fields at constant axial stations. The Plume Impingement Program (PLIMP) (Ref. 4) may also be run to determine the effects of the rocket exhaust plume on objects immersed in the plume. Sequencing and communication of auxiliary pro-grams with the Method-of-Characteristics program is shown on the preceding page.

Two-dimensional or axisymmetric solutions are selected by simply load-ing a control word in the program input data. This integer (0 or 1) is then multiplied by the term containing (1/r) in the governing differential equation. By appropriate description of the flow boundaries, it is possible to change from a solid to free boundary on either the upper or lower walls. Conversely, it is not possible to change from a free to a solid boundary on either wall.

Compression corners are allowed only on the upper wall. Because the program is restricted to a single shock within the flow field, the number of compression corners is limited to one. Also, right-running shocks only can be handled, thus no provision exists for compression corners on the lower wall. Remembering that a mirror image solution is possible, the problem can be inverted for this type of solution. Note that the program will fortuitously handle two shocks if the first shock terminates by intersecting a lower free boundary before the second shock begins.

By choosing an input option, it is possible for the program to automati-cally reflect a shock which intersects the horizontal axis. The method is illustrated on page 3-10 and explained in Ref. 5.

When a shock intersects the horizontal axis and the automatic reflection option has not been flagged, the solution may be restarted by inverting the prob-lem and "regularly" reflecting the shock. A shock is "regularly" reflected by inverting the problem and using start line options to initiate the reflected shocks (pages 3-9 and 3-25). When a restart is required for a shock which has terminated at a "Mach Disc," a boundary equation simulating a cylin-drical "pipe" must be used to approximate the subsonic region (page 3-9).

Problem solid boundaries can be described by a set of discrete points. The set of points is spline fit with individual polynomials for each pair of points, consistent with the polynomial boundary specification option of the program. Specific usage instructions for this option are included in the input Section (3.3.1).

Shock wave calculations may be discontinued when the shock strength decreases to an insignificant value. The shock will continue to be calculated in its usual manner until the change in stagnation pressure becomes less than a given input percentage. After the criterion is satisfied, the shock will no longer be iterated. If a value for the percentage change is not provided in the input, the shock will be computed in its usual manner until the percentage change drops below 0.1. (See Section 3.3.1 for description of input for this option.)

The program computes nozzle thrust by integrating the pressure distribution along the nozzle wall, including the thrust increment between the last characteristic line inside the nozzle and the Prandtl-Meyer expansion at the nozzle lip. The vacuum specific impulse and nozzle thrust coefficient at each nozzle wall point is also calculated.

A mesh control option exists whereby the maximum and minimum characteristic mesh size can be controlled by input to the program. Mesh control increases program accuracy in large vacuum plume calculations. A description of mesh control is contained in the Appendix of Ref. 5.

The streamline at each characteristic data point is calculated and stored on the output tape.

3.2   APPLICATIONS

The most common applications of this program are in the areas of standard rocket nozzles and axisymmetric plumes. Many other complex flow fields can be treated, however, if the user is familiar with the flexibility of

the problem and its options. Several problems are discussed in the remaining paragraphs of this section to illustrate the versatility of the program.

Consider the boundary conditions given below. This problem was run two-dimensionally (although it could just as well have been asixymmetric) for the purpose of program demonstration.
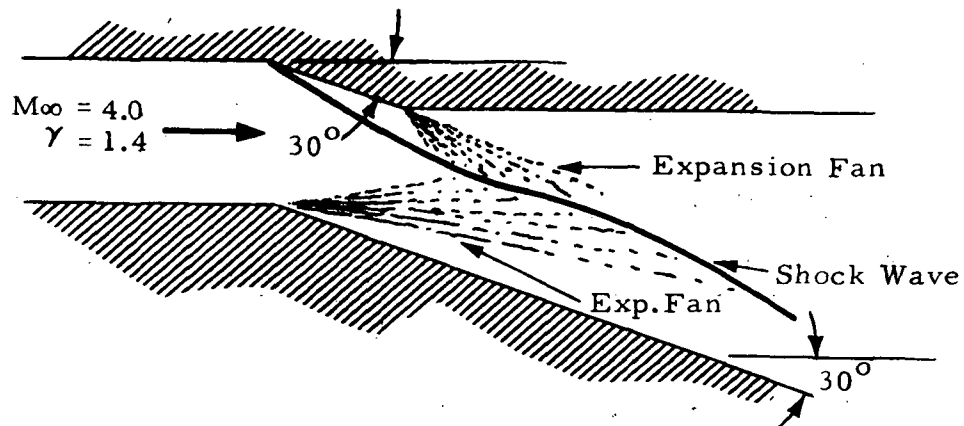
The problem above, while being restricted to one compression corner, could have had more expansion corners illustrating a more complex case.

Another problem depicting the program's versatility is the following:
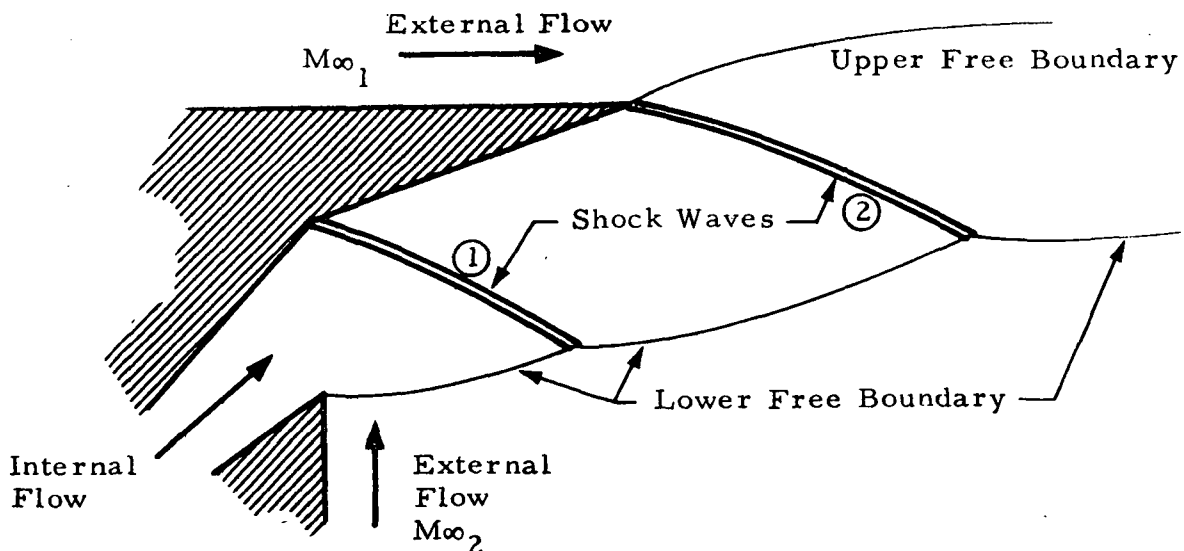
The restriction that the flow remain supersonic (inherent in the method-of-characteristics solution) must be observed through the flow field.

External flow can be simulated by specifying the necessary stagnation conditions and inserting a two-dimensional or axisymmetric object in the flow field.
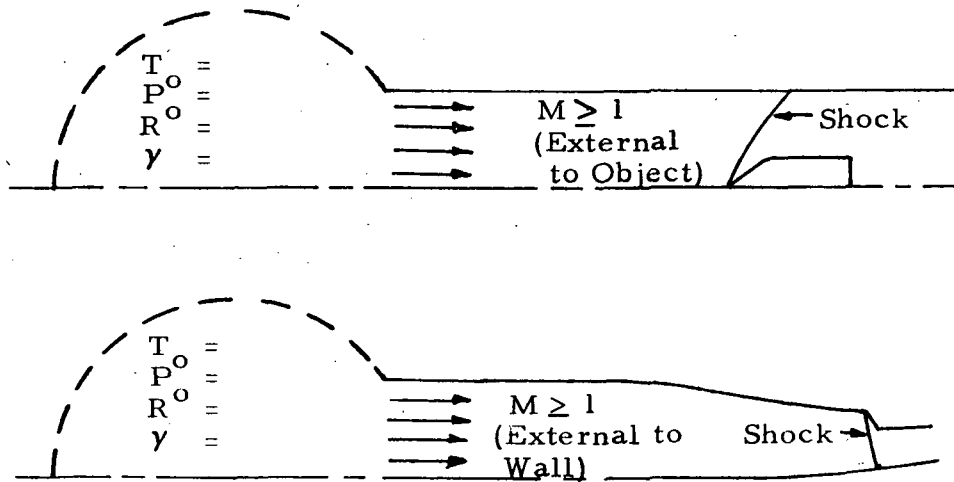
The method of manually reflecting a shock "regularly" or through a "Mach reflection" is outlined below.

(1) Initial Run (right side up)
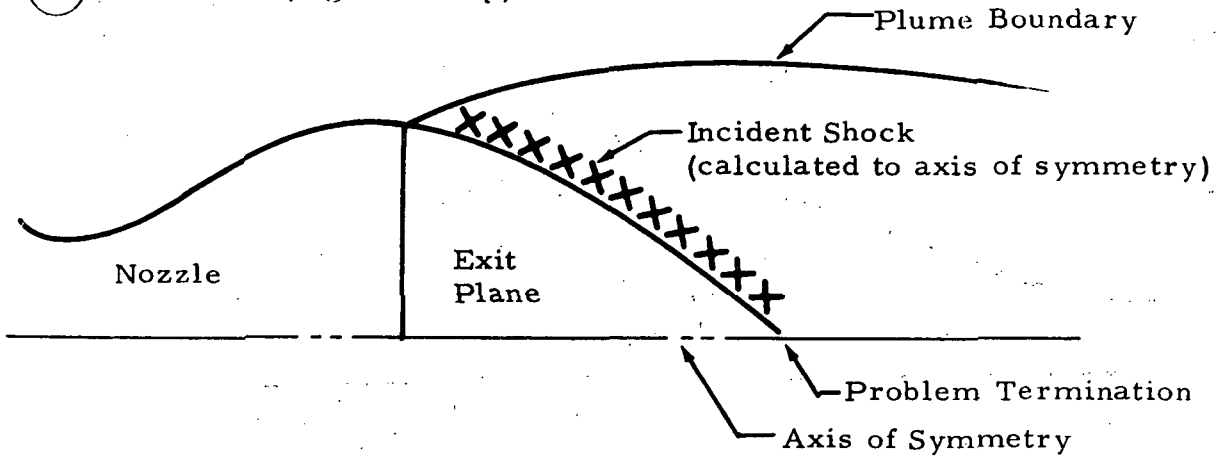
(2) Restart (regular reflection)
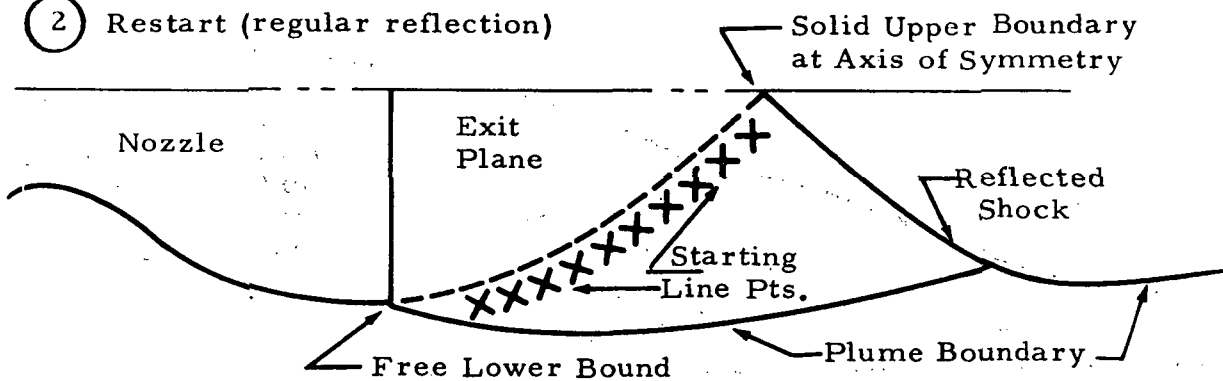
(3) Restart (Mach reflection)

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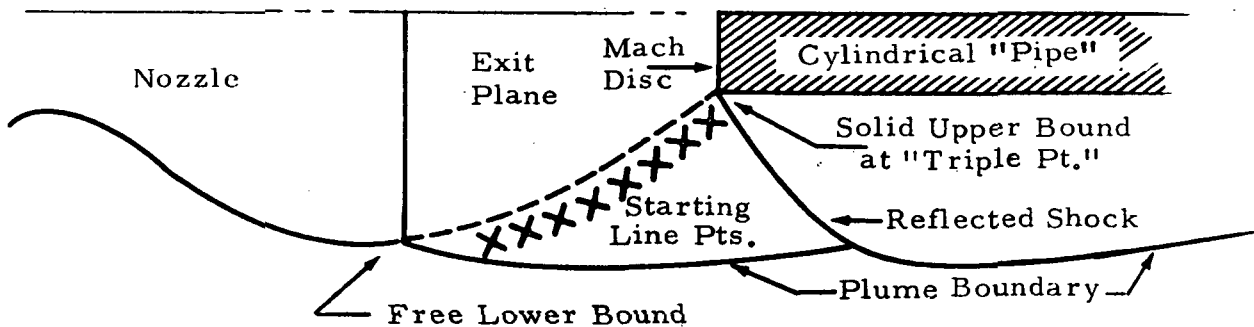
When the automatic reflection option is selected and a shock terminates at the lower boundary the program will automatically reflect the shock as outlined in the diagrams below.

Example of Automatic Restart

Plume Boundary

Shock Points

Incident Shock

Nozzle

Axis of Symmetry

Initial Problem Termination

New Start Line is Determined from Flow Field Data Up to the Shock Intersection with Lower Boundary

New Start Line

Nozzle

Shock Points

Problem Inverted and Restarted

Nozzle

Reflected Shock

Start Line

Plume Boundary

3-10
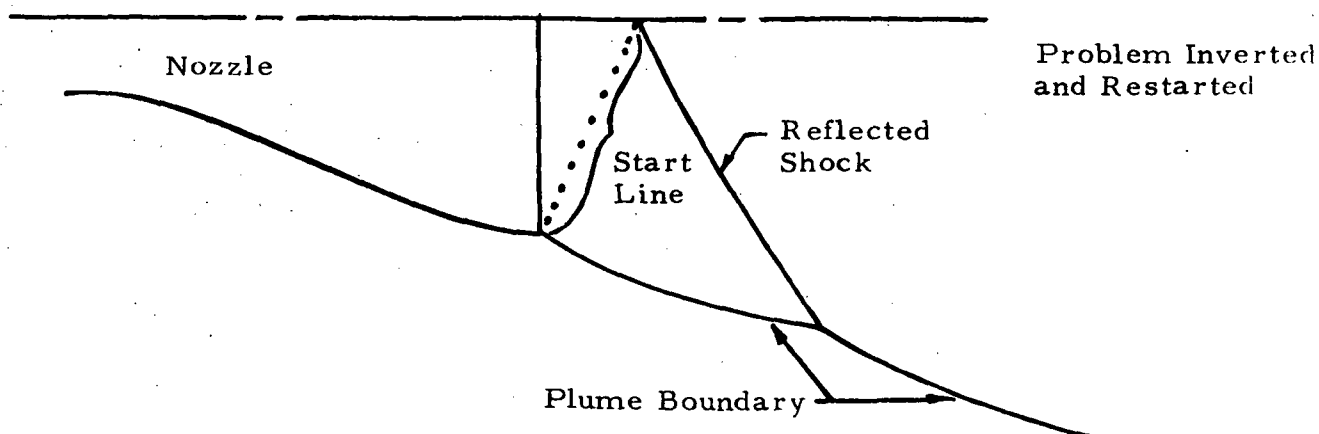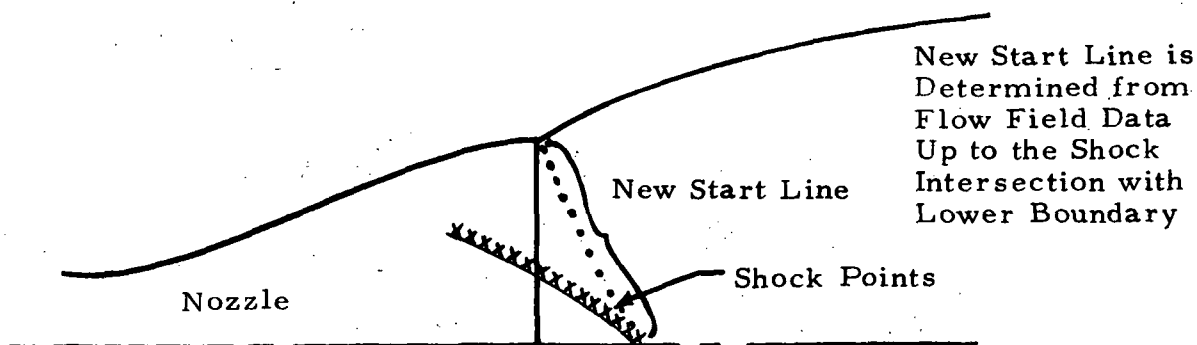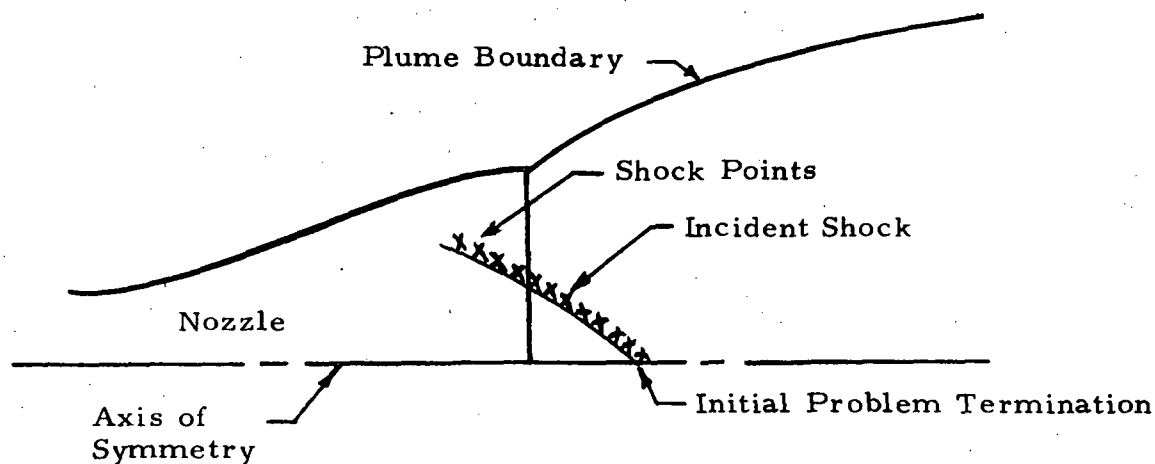
The sketches below illustrate the start line options available to the user to begin the method of characteristics solution. Lines a, b and c are normal start lines obtained by specifying the same axial location of the upper and lower limits of the start line. Lines d, e and f are right-running start lines obtained by specifying different locations of the upper and lower limits of the start line. Lines g, h and i are left-running start lines. All three types of start lines may be input or calculated by specifying the Mach number along the start line, the area ratio (A/A^*) at the start line, or by using conservation of mass and the Mach number at the upper wall. Lines a, d and g may not be calculated by area ratio since they initiate from the nozzle throat.
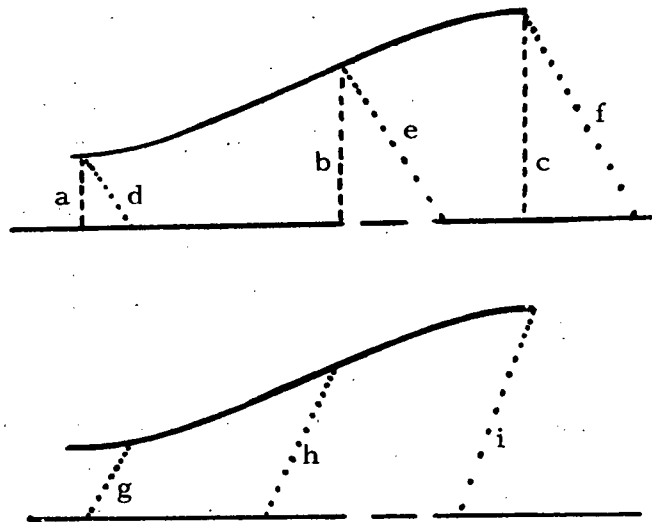
The options available to manually input a start line for a reflected shock case are explained and illustrated in Section 3.3.2 (ICON(9)).

3.3 INPUT INSTRUCTIONS

This subsection contains a detailed description of the program input instructions as follows:

- Detailed input guide
- Detailed description of the input FORTRAN symbols

3.3.1   Detailed Guide for Input Data to MOC-O/F Program
        (Section 3.3.2 contains a detailed description of each of the input variables)

<u>CARD NO. 1</u>   <u>Problem Title or Identification</u>

Format: 12A6

Cols. 1-72   ·HEADER(I)   Comment card, header information such as
                                   problem title may go on this card. It is
                                   printed at the top of each page of output.

<u>CARD NO. 2</u>   Run Control Card

Format: 16I5 (right adjusted)

Col 5   ICON(1)   1 Read cards for gas properties
                                   2 Read tape 10 (A6) for gas properties
Col 9   ICON(2)   0 Regular start line (A start line other
                                      than right or left running)
                                   1 Right-running characteristic start line
                                   2 Left-running characteristics start line
Col 10   ICON(2)   0 .Straight start line M given
                                   1 Source start line A/A* given
                                   2 Starting line input
                                   3 Starting line calculated by conservation of
                                      mass using a linear Mach number distribution
Cols 14, 15   ICON(3)   Number of starting line points (50 max)
Cols 18-20   ICON(4)   Number of upper boundary equations including
                                   free boundary equation (100 max)

Option for ICON(4) when upper boundary is to be curve fit

Cols 17-20   ICON(4)   1000 + number of discrete points specifying
                                   upper boundary + 2, where the 2 represents
                                   the nozzle throat equation and the free
                                   boundary equation
Cols 23-25   ICON(5)   Number of lower boundary equations
                                   (100 max)

Option for ICON(5) when lower boundary is to be curve fit

Cols 22-25   ICON(5)   1000 + number of discrete points specifying
                                   lower boundary + 2, where the 2 represents
                                   the nozzle throat equation and the free
                                   boundary equation.
Col 27   ICON(6)   0 The start line will not be output on
                                      punched cards
                                   1 The start line will be punched on cards
                                      in the form of Card 9. (This start line
                                      can be used to manually restart an
                                      "automatic" shock reflection if the pro-
                                      blem terminates incorrectly after the
                                      shock is reflected by the program.)

(Card No. 2 Continued)

Col 28-29   ICON(6)   N The boundary equation at which it is desired to begin the characteristic solution to automatically restart a reflected shock. This must be an upper solid wall equation (see Section 3.3.2)

Col 30   ICON(6)   0 Only the flowfield data generated after a shock is automatically reflected will be saved on the output tape.

1 The data generated before a shock is automatically reflected will be saved on the first file of the output tape and the flowfield data generated after the shock is reflected will be written on the second file of the flowfield tape.(This option requires the use of computer system routines which space past records on data tapes.)

NOTE: ICON(6) is the controlling flag for the "automatic" shock reflection. Cards 13, 14 and 15 are also required for "automatic" reflection.

Col 35   ICON(7)   0 Two-dimensional solution
1 Axisymmetric solution

Cols 37-38   ICON(8)   This option controls the type of output obtained after the problem has reached a free boundary equation. The same scheme is used in cols 37-38 as in 39 and 40. If blanks are used in Cols 37-38 then Cols 39 and 40 will control the printout for the entire run. (Ref. Section 3.3.2.)

Col 39   ICON(8)   0 Full output
1 Limited output (boundary, shock, input, and P-M points)

Col 40   ICON(8)   1 One line output
(R, X, M, THETA, S, Shock Angle)
2 Two lines, above plus
(Mach Angle, P, Density, T, V)
3 Three lines, above plus
(MWT, GAMMA, TO*, PO*, S*)

Cols 41-43   ICON(9)   No. of left-running points up to and including upstream shock point. Used when ICON(2) ≥ 20 and shock crosses starting line. (See Section 3.3.2, p. 3-25.)

Cols 44, 45   ICON(9)   Number of regular start line points if ICON(2) ≥ 20

Col 50   ICON(10)   0 Not presently used

Cols 51-55   ICON(11)   Case number (prints at top of each page)

Col 60   ICON(12)   0 Calculate shock wave
1 No rotation option

3-13

(Card No. 2 Continued)

Col 65	ICON(13)	0	Do not use the viscous option to set up the start line
		1	Use the viscous option to set up a start line at a nozzle exit plane. (See Card 12, Section 3.3.2 and Ref. 5).[**]
Cols 69-70	ICON(14)	N	Number of Prandtl-Meyer rays to be used in expansions
		O	Program will determine number of rays to be used.
Col 74	ISTOP	0	Single case is being run
		1	Multiple cases are being run
Cols 75	ICON(15)	0	Mesh control is not desired
		1	Mesh control is desired (Ref. Section 3.3.2 and Ref. 5).
Col 80	ICON(16)	0	No printout
		1	Printout intermediate data[*]

[*] NOTE: This option causes intermediate calculations to be printed out during shock and pitot pressure calculations. This option was used during program checkout and is not generally required except for debugging purposes.

[**] Entire start line must be a regular start line at exit plane.

| CARD NO. 3 | | Describes physical boundaries of the flow field. For use when ICON(4) and/or ICON(5) $\leq$ 100. |

Format: II, 3X, II, 5X, 6E10.6

Col 1   IWALL   1, Conic equation
$$R = A^* (SQRT (B + C^* X + D^* X^{**}2) + E)$$
(See Section 3.3.2 pg. 3-27 for an example and description)

Col 1   IWALL   2, Polynomial equation
$$R = A*X^{**}4 + B*X^{**}3 + C*X^{**}2 + D*X + E$$

Col 1   IWALL   3, Free boundary equation
$$P = PINF^* (1+E*X)*(1+GAMMAINF*(MINF*SIN*(THETAB - THETAINF))^{**}2$$
(See Section 3.3.2 pg. 3-27 for an example and description)

Col 1   IWALL   6, Free boundary equation of same form as IWALL=3, except oblique shock solution is used to generate plume boundary. Use number 6 for free stream approach flow in range of Mach 1.5 to 5.5.

NOTE: The problem uses air with a molecular weight of 28.966 for these oblique shock calculations.

Col 5	ITRANS	0 No discontinuity follows this equation
	ITRANS	1 Expansion corner follows this equation
	ITRANS	2 Compression corner follows this equation
Cols 11-20	WALLCO(I,1,J)	A(If IWALL = 1 or 2), PINF (If IWALL=3)(PSFA)
21-30	WALLCO(I,2,J)	B(If IWALL = 1 or 2), GAMMAINF (If IWALL=3)
31-40	WALLCO(I,3,J)	C(If IWALL = 1 or 2), MINF (If IWALL=3)
41-50	WALLCO(I,4,J)	D(If IWALL = 1 or 2), THETAINF (If IWALL=3)
51-60	WALLCO(I,5,J)	E(If IWALL = 1 or 2), E(If IWALL=3)
61-70	XMAX	Maximum X value for which this equation applies.

NOTE: The coefficients of each equation are contained on a single card. As many cards, i.e., equations, as necessary to describe the boundaries are input. The units of physical dimensions affect only the thrust calculations in which units of feet are assumed. Upper boundary information is given first. Program assumes that starting line is bounded by solid walls and that the equations are ordered with XMAX monotonically increasing.

CARD NO. 3A   Optional, physical flowfield boundary condition for use when ICON(4) and/or ICON(5) ≥ 1000.

Format: 6E10.6

Cols		
1-10	RC	Radius of curvature of nozzle throat
11-20	RT	Radius of nozzle throat
21-30	THETA	Nozzle throat divergence angle
31-40	XO	Axial coordinate shift (Axial distance from the origin of the coordinate system to the throat)

Cols		
1-10	XIN(I)	Each pair of XIN(I) and YIN(I) represents
11-20	YIN(I)	a discrete point for spline-fitting of the
21-30	XIN(I+1)	nozzle solid boundary. As many of these
31-40	YIN(I+1)	points as necessary can be input to a
41-50	XIN(I+2)	maximum of 100. Points must be input
51-60	YIN(I+2)	with XIN(I) monotonically increasing.

NOTE: The first point describing the wall must be downstream of the throat equation.

Cols 1-10   XIN(I+3)
    YIN(I+3)
    etc
    .
    .
    .

Format: I1, 3X, I1, 5X, 6E10.6

Col 1	IWALL	3 Free boundary equation
Col 5	ITRANS	0 No discontinuity follows this equation.

Col		
11-20	WALLCO	PINF
21-30	"	GAMMAINF
31-40	"	MINF
41-50	"	THETAINF
51-60	"	E
61-70	"	XMAX

NOTE: Optional boundary description, Card Type 3A, is set up specifically for a rocket nozzle. The first card describes the nozzle throat, which is followed by cards containing sets of discrete points, three per card, describing the nozzle contour. The points will be automatically spline-fit to form equations for the contour. It is assumed that a free boundary equation follows the last nozzle point. Card types 3 and 3A may be mixed, i.e., the upper boundary may be described by type 3A while the lower boundary is described by type 3, or vice versa. Card type 3 and 3A may not be used simultaneously for a given boundary.

CARD NO. 4   Gas Identification and Gas Property Input Control

Format:	4A6, 5X, A3, 6X, I2, 3X, I2	
Cols 1-24	ALPHA	Gas name, identification for real gas properties on tape. May be any name when gas properties are input via cards.
Cols 30-32	UNITS	ENG English units are to be input (cards only) MKS Metric units (cards or tape)
Cols 39-40	IOF	Number of O/F cuts, 1 min., 10 max.
Cols 44-45	IS	Number of entropy cuts (ignored for tape, 1 for ideal gas, 2 max for real gas via cards).

CARD NO. 5   O/F value of each table (must be input even if constant O/F case is run). O/F tables must be input with O/F values monotonically increasing.

Format:	E10.6	
Cols 1-10	OFRAT	

CARD NO. 6   Entropy value and number of velocity cuts. (Not input if ICON(1) = 2, i.e., gas properties via tape; 0.0 if ideal.)

Format:	E10.6, 8X, I2	
Col 1-10	STAB	Entropy value
Col 19, 20	IVTAB	Number of Mach numbers for this entropy value 13 max, (1 if ideal gas)

CARD NO. 7   This card(s) gives the Mach number and associated gas properties at that Mach number and entropy.

Format:	5E10.6	
Cols 1-10	TAB (I, J, K, 1)	Mach number
Cols 11-20	TAB (I, J, K, 2)	Gas constant (R) if UNITS = ENG, Molecular weight (MWT) If UNITS = MKS.
Cols 21-30	TAB (I, J, K, 3)	GAMMA
Cols 31-40	TAB (I, J, K, 4)	Temperature at this Mach number
Cols 41-50	TAB (I, J, K, 5)	Pressure at this Mach number

Units	MKS	ENG
Temperature	$^{\circ}K$	$^{\circ}R$
Pressure	Atmospheres	psfa
Gas Constant (R)	(Molecular Weight)	1545.2x 32.2/Mwt

(Card 7 continued)

NOTE: If two O/F tables were input with 2 entropy tables and 10 velocity "cuts" for each entropy the cards would be arranged as follows:

Card 5
Card 6
Cards 7 (10 ea)
Card 6
Card 7 (10 ea)
Card 5
Card 6
Card 7 (10 ea)
Card 6
Card 7 (10 ea)

NOTE: Cards number 5, 6, and 7 are omitted if gas properties are input via tape.

CARD NO. 8   This card specifies the necessary infor-
                                            mation for the starting line. (If ICON(2)
                                            ≠ 2, 12 or 22) (Ref. Section 3.3.2)

Format: 8E10.6

Cols 1-10   CORLIP(1)   Axial coordinate of upper limit of start
                                  line.
Cols 11-20   CORLIP(2)   Axial coordinate of lower limit of start
                                  line.
Cols 21-30   CORLIP(3)   Mach number or A/A* for start line.
Cols 31-40   CORLIP(4)   Entropy level of start line.
Cols 41-50   STEP(5)   Area of nozzle throat (units consistent
                                  with boundary equations) (Must be input
                                  for thrust coefficient calculation). This
                                  must also be input if the start line is
                                  generated by conservation of mass.
Cols 51-60   CORLIP(5)   Constant O/F value
Cols 61-70   STEP(6)   Minimum ΔP for discontinuing shock calc.
                                  If zero is used the program assumes
                                  .001 (Ref. 3.3.2)

CARD NO. 9   These cards are used to read in a known
                                            starting line (ICON(2) = 2, 12 or 22).
                                            Omit when Card no. 8 is used. As many
                                            of these cards are input as specified by
                                            ICON(3) on the run control card. Used
                                            only if ICON(2) = 2, 12, or 22. (Ref. Section
                                            3.3.2)

Format: 8E10.6

Cols 1-10   PSI(K, 1)   Radial coordinate of this point
Cols 11-20   PSI(K, 2)   Axial coordinate of this point
Cols 21-30   PSI(K, 3)   Mach number of this point
Cols 31-40   PSI(K, 4)   Flow angle of this point
Cols 41-50   PSI(K, 5)   Entropy level of this point
Cols 51-60   PSI(K, 6)   Shock angle of downstream shock point.
Cols 51-60   STEP(5)   For last card only STEP(5) where STEP(5)
                                  is the area of nozzle throat (units consistent
                                  with boundary equations, must be input for
                                  thrust calculation).
Cols 61-70   STEP(6)   For last card only STEP(6) where STEP(6)
                                  is the minimum ΔP for discontinuing shock
                                  calculation.
Cols 71-80   PSI(K, 8)   Value of O/F at each starting line point.

NOTE: To use the variable O/F capability, supply a value of O/F for each
       input point. Option 2 for ICON(2), must be selected for starting line
       input. For constant O/F operation supply one O/F table and set O/F
       constant on card 8.

3-19

CARD NO. 10

This card contains the necessary information to limit the calculations to those areas of interest. An unusual scheme is employed in order to make these limits efficient for the many problem orientations which are possible. Units should be consistent with those used on card 3. (Ref. Section 3.3.2)

Format: 8E10.6

Cols 1-10	CUTDAT(1)	Radial coordinate defining upper cutoff.
Cols 11-20	CUTDAT(2)	Axial coordinate defining upper cutoff.
Cols 21-30	CUTDAT(3)	Angle cutoff line makes with horizontal.
Cols 31-40	CUTDAT(4)	Radial coordinate defining downstream cutoff.
Cols 41-50	CUTDAT(5)	Axial coordinate defining downstream cutoff.
Cols 51-60	CUTDAT(6)	Angle cutoff line makes with horizontal.
Cols 61-70	STEP(3)	Point Insert Criteria. If the change in axial distance between two characteristic lines along the axis exceeds Step (3) a new characteristic point will be inserted. If nothing is input the program will use 10,000.
Cols 71-80	TINF	Free stream temperature ($^{\circ}R$). Use only if IWALL=6 on card 3.

CARD NO. 11

Mesh control parameters, controls mesh size by inserting or deleting points. Use this only if ICON(15) on Card 2 is greater than zero. (Ref. Section 3.3.2 and Appendix of Ref. 5)

Format: 6E10.6

Cols 1-10	DIV(1)	Length control abs. $\Delta\ell$ insert
Cols 11-20	DIV(2)	Length control abs. $\Delta\ell$ delete
Cols 21-30	DIV(3)	Mach No. control abs. ΔM insert
Cols 31-40	DIV(4)	Mach No. control abs. ΔM delete
Cols 41-50	DIV(5)	Flow angle control abs. $\Delta\theta$ insert
Cols 51-60	DIV(6)	Flow angle control abs. $\Delta\theta$ delete

CARD NO. 12

This card contains the input information for the viscous boundary layer option. Use this card only if ICON(13) on Card 2 is greater than zero. (Ref. Section 3.3.2)

Format: I1, 2X, I2, 5X, 2E10.6

Col 1	NPOWER	Reciprocal of exponent of the velocity profile in the boundary layer
Cols 4, 5	NBLPTS	Number of boundary layer points specified
Cols 11-20	XL	A characteristic length (usually nozzle wall length)
Cols 21-30	CU	Conversion factor for mixed units of length.

3-20

Automatic Shock Reflection (Cards 13, 14, and 15)

If the automatic shock reflection option is used a namelist must be used to change some of the original input data. It is possible to change any of the ICON variables of Card 2, cutoff data of Card 10, mesh control criteria of Card 11 and point insert criteria of Card 10. The cutoff data must be changed to indicate a reflected or inverted case. Angle cutoff parameters of Card 10 are input in radians on the namelist.

CARD NO. 13 (For reflected shock cases only)

Col 2-7 $INPT2   Control card for namelist

CARD NO. 14

Format: Free Field

Col 2 - 72   Changes to data consisting of, for example
                                     *Cutoff data array - CUTDAT(6)
                                     *Mesh control array - DIV(6)
                                     *Control array - ICON(16)
                                     *Point insert - STEP(3)

A typical example of the NAMELIST card is:

    CUTDAT(1) = 100., CUTDAT(2) = 0.0, CUTDAT(3) = 0.0,
    CUTDAT(4) = -100., CUTDAT(5) = 100., CUTDAT(6) = 1.57,
    DIV(1) = 40., ICON(6) = 1000

CARD NO. 15

Col 2-5 $END   End of data card.

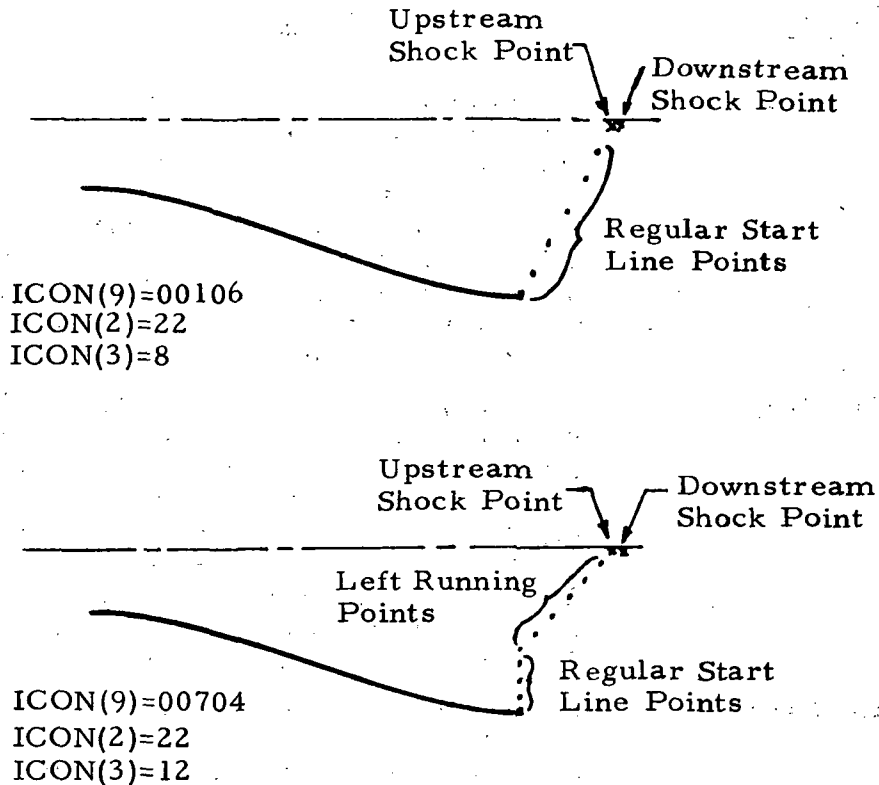*Cutoff data array is mandatory change to reset the problem limits. All other NAMELIST changes are optional.

3-21

3.3.2 Input FORTRAN Symbols

Symbol	Description	Units (if appl)
HEADER(I)	This array contains the problem description which is written at the top of every page of printed output. This header input with Card 1 of the input data.	N/A
ICON(1)	Used to tell the program if the gas properties are read in from cards (ICON(1) = 1) or read from tape 10 (A6)(ICON(1) = 2) which was generated by the NASA Lewis Thermochem Program and Tapegen Program. After the gas properties have been written on the output tape ICON(1) is used by subroutines TABLE and FABLE for communication.	N/A
ICON(2)	ICON(2) is the type of starting line the program is to calculate or read in from cards. ICON(2) consists of 2 digits. The first digit is a 0, 1 or 2 for a normal start line, a right-running start line or a left-running start line respectively. The second digit is a 0, 1, 2 or 3 for a straight start line Mach No. given, source start line A/A* given, starting line input or starting line calculated by conservation of mass respectively. The second digit is used in subroutine PLUMIN for a computed go to statement which calculates or reads in the starting line depending on the type desired. The first digit is used in PHASE 1 to initialize the starting line into a usable array for beginning the method-of-characteristics solution.	N/A
ICON(3)	The total number of starting line points input or desired to be calculated by the program. Used as a reference for determining when the starting line points are used up.	N/A

3-22

Symbol	Description	Units
ICON(4)	ICON(4) is a dual purpose input parameter. When it is not desired to input an upper boundary with points, ICON(4) is the number of upper boundary equations and ICON(4) is used to read in the desired number of upper boundary equations. When it is desired to curve-fit the upper boundary ICON(4) is 1000 plus the number of discrete points specifying the upper boundary plus 2 where 2 represents the nozzle throat equation and the free boundary equation. For the curve fit case ICON(4) is used to read in the information on the nozzle throat equation, the points representing the wall and the free boundary equation.	N/A
ICON(5)	Same as ICON(4) except ICON(5) applies to the lower boundary equations.	N/A
ICON(6)	This parameter supplies the program information necessary to automatically reflect a shock which intercepts the horizontal axis. ICON(6) is a four-digit number. The first digit is a 0 if it is not desired to have the start line punched and a 1 if it is desired that the start line be punched. The second and third digits are the number of the upper boundary equation which the program will use in restarting the problem. The program uses the last point on this upper boundary as the first point on the starting line. The fourth digit is either a one or a zero. If a one is used, an end of file mark is placed after the MOC data already on the output tape. If a zero is used, the MOC output created after the shock is reflected is written over the original output which was created before the reflection. This option requires system routines to space past end-of-file marks on flowfield tape which are not a part of the MOC program and must be a part of the individual computer system.	N/A

| Symbol	Description	Units
ICON(7)	The type of flowfield solution which is to be performed. A (0) for a two-dimensional solution and a (1) for an axisymmetric solution. ICON(7) is used in the mass flow calculations and in the axisymmetric term of the compatibility equation used for the solution of each characteristic point.	N/A
ICON(8)	ICON(8) indicates the type of printed output desired by the user. ICON(8) consists of two pairs of digits. The first pair controls the type of printout after the program begins using a free boundary equation for problem limits. The second pair indicates the type of output desired before the program begins using a free boundary equation or throughout the entire plume if nothing is input for the first two digits. The first digit of each pair controls the output at interior points on a characteristic line. If a zero is used the program will print out information at every characteristic point. If a one is used, printout will occur only at the boundary and shock points. The second digit is a 1, 2 or 3 for one, two or three line output at each point.	N/A
ICON(9)	ICON(9) is a dual purpose control for starting the characteristic solution of a reflected shock case. The first three digits are used for inputting the start line for a reflected shock case in which a left-running characteristic is crossed by the shock. These digits represent the total number of left-running points up to and including the upstream shock point. The last two digits are numbers of regular start line points. Two examples of this input are illustrated on the following page.	N/A

Upstream
Shock Point

Downstream
Shock Point

Regular Start
Line Points

ICON(9)=00106
ICON(2)=22
ICON(3)=8

Upstream
Shock Point

Downstream
Shock Point

Left Running
Points

Regular Start
Line Points

ICON(9)=00704
ICON(2)=22
ICON(3)=12

Symbol	Description	Units
ICON(10)	A flag which tells the program if a radiance tape is desired. A zero indicates no radiance tape and a 1, one tape, a 2, two tapes. The subroutines for generating the radiance tapes are called through ICON(10) but the routines are presently dummied out.	N/A
ICON(11)	The case number for the problem under consideration. This number is printed out at the top of each page of output.	N/A
ICON(12)	A 0 allows the program to calculate a shock wave while a 1 will cause the program to skip the shock calculation. ICROSS is set equal to ICON(12) and ICROSS is used as a test for shock calculations.	N/A

Symbol	Description	Units
ICON(13)	Flag which tells program to use a viscous calculation in setting up the starting line.* A zero does not read in viscous card and does not call subroutine VISCUS. A(1) reads in boundary layer information and calls subroutine VISCUS which calculates a boundary layer then merges the supersonic portion of the boundary layer into the starting line.	N/A
ICON(14)	ICON(14) is the number of Prandtl-Meyer rays to be used by the program in any expansions encountered in the solution. A zero will allow the program to calculate the number of rays. The program finds the limiting expansion angle then divides this angle into the number of rays to numerically integrate the Prandtl-Meyer expansion equation.	N/A
ICON(15)	ICON(15) is a two-digit number. The first digit is a flag which allows multiple cases to be run. When it is a 1 subroutine DRIVER reinitiates the program for the second case. A zero terminates the program after the first case has terminated. The second digit is used for reading in mesh control criteria. If it is a 1, the mesh control criteria are read in. If it is a zero, no mesh control is used in the solution.	N/A
ICON(16)	A flag which is set to a 1 will result in intermediate printout in the shock solution subroutines. There will be no intermediate printout if ICON(16) is a 0. This parameter is useful in program checkout.	N/A
IWALL	The type of boundary equation which is used in checking a characteristic point against problem boundaries. A 1 indicates a conic equation, a 2 a polynomial equation and a 3 a free boundary equation. (See following page for description and example.)	N/A

*At nozzle exit plane only.

A typical use of the conic equation is the throat of a nozzle. A sketch of a nozzle throat region shows the coefficients of circular throat.
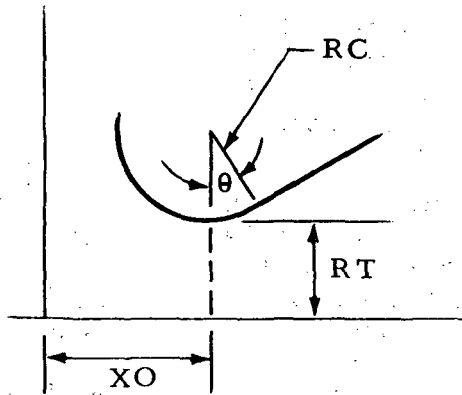
RC - radius of curvature of the circular arc of the throat
RT - Throat radius
XO - Axial distance from the origin of the coordinate system to the throat
θ - Throat divergence angle corresponding to the maximum axial value for which the throat conic equation applies

The conic equation for this case would have the following form

A = -1 for an upper equation, +1 for a lower equation
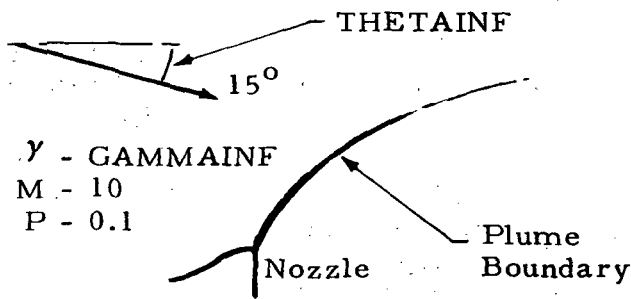(-1 for this case)

$B = RC^2 - XO^2$

C = 2XO

D = -1

E = -(RC + RT)

Xmax = RC sin θ + XO

An example of a free boundary is shown below.

The freestream approach flow is inclined at 15 deg to the plume with a gamma (γ) of 1.4, a Mach No. of 10., and a static pressure of 0.1 PSFA.

PINF = 0.1 (PSFA)
E = 0 (No pressure variation with axial distance)
GAMMAINF = 1.4
MINF = 10
THETAINF = -15°

Symbol	Description	Units
ITRANS	Indicates whether or not a discontinuity follows a particular boundary equation. ITRANS is used by the program in flaging calculations which will put a characteristic point at the exact location of the discontinuity (expansion or compression corner) so that a Prandtl-Meyer expansion or shock calculation may begin.	N/A
WALLCO(5)	The coefficients of the equations which describe the physical boundaries of the problems. These coefficients (A, B, C, D or E) and (PINF, GAMMAINF, MINF, THETINF or E) are used in either a conic or polynomial equation (A, B, C, D or E) or a free boundary equation (PINF, GAMMAINF, MINF, THETINF or E) depending on what was used for IWALL.	The radial and axial components of the equations should be consistent with units for the particular problem being run.
XMAX	XMAX is the maximum axial coordinate for which any one particular boundary equation is valid. XMAX is used by the program to test when the next boundary equation in the WALLCO(100, 6, 2) array should be used to check characteristic points against the physical boundaries of the problem. XMAX is stored in the 6th position of the WALLCO array.	Same as above.
RC	RC, RT, THETA, and XO are used when it is desired to curve fit an upper or lower wall equation. RC is the radius of curvature of the nozzle throat and is used in calculating the equation of the nozzle throat.	Consistent with the units in which XIN and YIN are input
RT	RT is the radius of the nozzle throat. RT is used in calculating the equation of the nozzle throat.	Consistent with the units in which XIN and YIN are input
THETA	The nozzle throat divergence angle. THETA is used to determine the maximum axial coordinate for which the nozzle throat equation will be applied.	Degrees

Symbol	Description	Units
XO	If the nozzle throat is not at the origin then XO is the distance from the origin to the nozzle throat.	Consistent with the units in which XIN and YIN are input.
XIN	The axial coordinate of a discrete point which is to be used in spline fitting the nozzle solid boundary.	The units of XIN and YIN should be the same as the units the program uses in the solution.
YIN	The radial coordinate of a wall point associated with a XIN coordinate.	
ALPHA	The gas name identifying the real gas properties on tape. This name is compared with the names of gas cases appearing on a master gas tape. When the program encounters the same case the gas data is read from the tape and stored for use by the program. If gas properties are to be read in from cards the only limit on the name is that it satisfy the format. This name is also written out at the top of the pages which contain the gas data written out.	N/A
UNITS	Either ENG or MKS. ENG can be used for cards only while MKS can be used for either cards or tape. If the gas properties are in MKS units, subroutine GASRD changes the gas properties to ENG units.	N/A

ENG and MKS units are as follows:

	ENG	MKS
Temperature	^{o}R	^{o}K
Entropy	$ft^2/sec^{2\,o}R$	$cal/gram\,^{o}K$
Pressure	psfa	ATM
Gas constant	$\dfrac{1545.5 \times 32.174}{MWT}$	MWT (molecular weight)

Note: These units are used only for inputting gas properties. Program uses ENG units internally.

Symbol	Description	Units
IOF	The number of O/F ratio tables in the gas data. Used by the program for reading in gas properties from cards.	N/A
IS	The number of entropy cuts being considered for each O/F ratio table. Also used for setting limits on calculations and reading in gas properties from cards.	N/A
OFRAT	The O/F value for each O/F table. OFRAT is stored so that subroutine FABLE can locate the proper O/F tables to locate local gas properties in the flow field.	N/A
STAB	An entropy value associated with a table of velocity cuts at an O/F ratio. Used in table lookup for local gas properties.	ENG $-\dfrac{ft^2}{sec^2\,^oR}$ MKS $-\dfrac{cal}{gram\,^oK}$
IVTAB	The number of velocity cuts associated with a particular entropy cut.	N/A
TAB(I, J, K, ①)	The mach no. associated with a particular velocity cut and entropy for an O/F table.	N/A
TAB(I, J, K, ②)	The gas constant associated with the mach number and entropy for an O/F table.	$\dfrac{1545.4 \times 32.174}{MWT}$ -E MWT — MKS
TAB(I, J, K, ③)	GAMMA. The ratio of specific heats at a Mach no. and entropy for an O/F table.	N/A
TAB(I, J, K, ④)	The static temperature at the Mach no. and entropy for an O/F table.	^oR - ENG ^oK - MKS
TAB(I, J, K, ⑤)	The static pressure at the Mach no. and entropy for an O/F table	PSFA - ENG ATM - MKS
CORLIP(2)	The axial coordinate of the upper limit of the start line. CORLIP(2) is read in when it is desired for the program to set up the start line. CORLIP(2) is used to find the radial coordinate and flow angle at this axial coordinate. The resulting point is the first point on the start line.	Consistant with boundary equation. units.

Symbol	Description	Units
CORLIP (6)	The axial coordinate of the lower limit of the start line. Used for locating the lower point on the start line.	Consistent with boundary equation units.
CORLIP(4)	The Mach no. or A/A* for the start line location. If the starting line is set up using A/A*, subroutine AOASTR is called with A/A* and the Mach no. for the starting line is determined. The starting line Mach no. is used in subroutine MASCON for determining a Mach no. distribution at the starting line.	N/A
CORLIP(5)	The entropy level of the starting line. Only used if the program sets up the starting line.	$ft^2/sec^2 \, {}^{\circ}R$
CORLIP(8)	The area of the nozzle throat. This is used for thrust coefficient calculations.	Consistant with boundary equations.
CORLIP(9)	A constant O/F ratio across the starting line. This value is used only if the program is setting up the starting line. Note: The CORLIP values are used only if the program is to set up the starting line.	N/A
STEP(6)	The minimum percent change in pitot total pressure across a shock for discontinuing shock calculation. This is used to test shock strength. If the percent change from oblique shock theory is less than Step (6), then no iteration is performed by subroutine SHOCK, thereby keeping the shock strength the same. If nothing is read into the program, Step (6) is set to .001.	N/A
PSI(1, M)	For an input start line this is the radial coordinate for a particular starting line point.	Consistent with boundary equation.
PSI(2, M)	The axial coordinate of each start line point.	Consistent with boundary equations.
PSI(3, M)	The Mach no. at each start line point.	N/A
PSI(4, M)	The flow angle at each start line point.	Degrees
PSI(5, M)	The entropy level at each starting line point.	$ft^2/sec^2 \, {}^{\circ}R$
PSI(6, M)	The shock angle downstream of the shock point on the start line. This value is input on first card only for a reflected shock case.	Degrees

Symbol	Description	Units
PSI(8, M)	The value of the O/F ratio at each starting line point.	N/A
CUTDAT(1)	The radial coordinate defining upper cutoff of the characteristic solution.	Consistent with boundary equations.
CUTDAT(2)	The axial coordinate defining upper cutoff. If a characteristic point is calculated whose axial coordinate falls behind this coordinate the characteristic line is terminated and the next line started.	Consistent with boundary equations.
CUTDAT(3)	The angle the upper cutoff line makes with the horizontal. This line initiates from the point formed by CUTDAT(1) and CUTDAT(2). If a characteristic point is calculated which falls above this line the characteristic line is terminated and a new line begun.	Degrees
CUTDAT(4)	The radial coordinate defining downstream cutoff. If a characteristic point is calculated whose radial coordinate falls below this coordinate the line is terminated and a new characteristic line started.	Consistent with boundary equations
CUTDAT(5)	The axial coordinate defining downstream cutoff.	Consistent with boundary equations.
CUTDAT(6)	The angle the downstream cutoff line makes with the horizontal. The cutoff line initiates from the point formed by CUTDAT(4) and CUTDAT(5). If a characteristic point is calculated which falls beyond (and direct) this line the characteristic line is terminated and a new line begun. Note: The problem is terminated when a characteristic line is started beyond the limits set by CUTDAT's 1-6.	Degrees

Example of Cutoff Limits
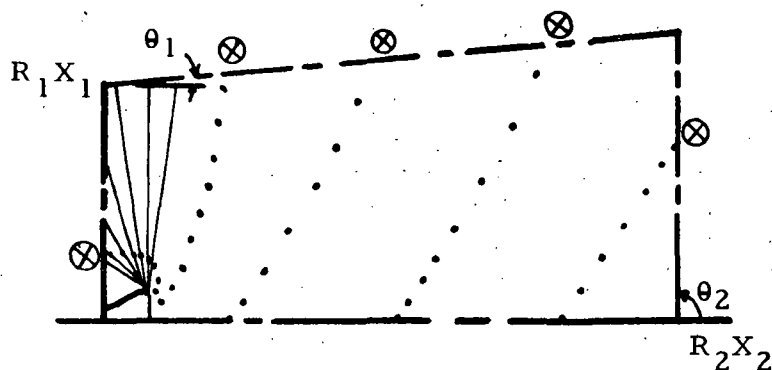
① Lines Terminated due to Cutoff Limits Alone

R_1 - CUTDAT(1)

X_1 - CUTDAT(2)

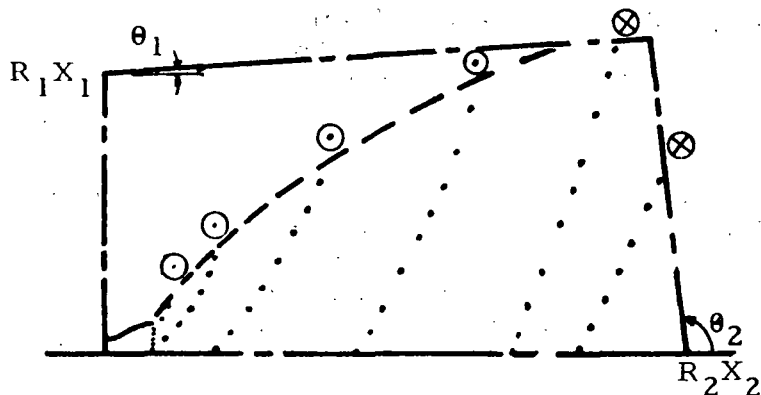θ_1 - CUTDAT(3)

R_2 - CUTDAT(4)

X_2 - CUTDAT(5)

θ_2 - CUTDAT(6)

⊗ - Line Terminated because of Cutoff Limits

⊙ - Line Terminated because of Free Boundary

• Characteristic Data Points along left-running characteristic lines

② Lines Terminated due to Cutoff Limits and Free (Pressure) Boundary

Symbol	Description	Units
DIV(1)	The maximum change in absolute length (axial or radial) between either of the two base points and a new characteristic point. If the change in distance is greater than this maximum a new point is added by the program.	Consistent with boundary equations.
DIV(2)	The minimum change in absolute length (axial or radial) between either of the two base points and a new characteristic point. If any change in length is less than this minimum the new characteristic point will be deleted.	Consistent with boundary equations.
DIV(3)	The maximum change in Mach no. between either of the two base points and a newly calculated base point. If the change in Mach no. exceeds this maximum a new point will be inserted which will satisfy the criteria.	N/A
DIV(4)	The minimum change in Mach no. between either of the two base points and a newly calculated base point. If the change in Mach no. is not greater than this value the point will be deleted.	N/A
DIV(5)	The maximum change in flow angle between either of the two base points and the newly calculated point. If the change in flow angle is greater than the maximum a new point is added which will satisfy the criteria.	Degrees
DIV(6)	The minimum change in flow angle between either of the two base points and the new characteristic point. If the change in flow angle is less than this minimum then the point is deleted.	Degrees

Note: Mesh control explained in detail in Appendix of Ref. 5.

Symbol	Description	Units
NPOWER	The reciprocal of exponent of the velocity profile in the boundary layer. This exponent is used only if the Reynolds no. calculated for the case at the exit condition at the wall indicates turbulent flow. If the flow is found to be laminar the NPOWER is set to 2 by the program.	N/A
XL	A characteristic length which will be used to calculate the Reynolds no. and the boundary layer thickness. This value is usually taken as the nozzle wall length.	Ft
NBLTS	The number of starting line points which are desired in the boundary layer.	N/A
CU	A conversion factor for mixed units of length. This conversion factor should be such that XL(ft) will be converted into the same units used in the boundary equation. If inches are used in boundary equations, then CU will be 12. If boundary equations are in ft., CU is 1. CU is used in calculating the boundary layer thickness.	inches/ft or as required by boundary equation units.

NOTE: A detailed description of the boundary layer option is explained in the Appendix of Ref. 5)

Symbol	Description	Units
STEP(3)	Point insert criteria. Step(3) is the maximum change in axial distance between two consecutive characteristic lines on a lower wall. If this value is exceeded then a new left running characteristic line is started at the lower wall.	consistent with flow-field units
TINF	Free stream static temperature. This temperature is used for the oblique shock calculation of the plume free boundary when IWALL on card 3 is set to a 6.	$^\circ$R

3.3.3   Problems Commonly Encountered

This section is intended to aid the user in utilizing the program and avoiding some common problems. The comments on mesh control and starting line points are only initial guidelines. A "feeling" for the starting line points and mesh control criteria will result as the user becomes familiar with the operation of the program.

The following is a list of hints to the user:

● If an automatic restart is not desired when a shock intersects the axis, set ICON(6) to zero in Cols 28, 29 and 30 on Card 2. (Refer to Section 3.3.2 and the Appendix of Ref. 5).

● If it is desired to keep the type of printed output the same throughout the entire plume use only Cols. 39 and 40 of Card 2 (ICON(8)).

● For inputting a start line for a highly expanded plume the start line points should be more highly concentrated near the nozzle wall.

● When setting up a nozzle wall with discrete points the first spline fit point must not be a part of the nozzle throat equation (i.e., the first input point should be beyond the maximum axial coordinate for which the throat equation applies).

● In general, the mesh control criteria can be relaxed as the number of start line points increases.

● For highly expanded nozzles where a very large plume is to be generated an approximate mesh control criteria for the maximum Mach quadrilateral size is 20 exit diameters. Corresponding values for Mach number and flow angle criteria would be about 10 and 20° respectively.

● If problems in the solution are encountered due to characteristic lines diverging, decrease the maximum mesh control criteria so that more lines may be added.

● When the messages "negative velocities encountered" or "subsonic Mach number encountered," first check the input data. If no errors are noted in the input data decrease the mesh control criteria, or alter the number of start line points.

Section 4
THE PLUME IMPINGEMENT COMPUTER PROGRAM

The Plume Impingement program (Refs. 4 and 6) computes forces, moments, pressures and heating rates on surfaces immersed in or subjected to rocket exhaust plume environments. Program capabilities include the treatment of continuum, transitional*and "free molecular*" flow regimes for arbitrary body shapes. The impingement effects of fuel striations (oxidizer-to-fuel (O/F) ratio gradients) and internal shock waves in the exhaust plume and body shading effects can be calculated.

The body local impingement force data are obtained by numerically integrating the local impact pressure distributions over the body surfaces. Plume flowfield data to provide environmental data for the impact pressure and local heating calculations are obtained from a magnetic tape generated by the Variable O/F Method-of-Characteristics Computer Program (MOC), Ref. 5.

The vehicle composite shape and the particular motor are located with respect to the reference coordinate system (Fig. 4-1). The composite shape is then represented by a series of geometrically simple subshapes (each in its own local coordinate system; see Section 4.1). These subshapes are further divided into smaller incremental areas as determined from the input information (Section 4.1.1). Local flow conditions on a given body surface are obtained by locating the centroid of each elemental area in the free plume from a search of the plume flowfield data stored on magnetic tape. The flow properties thus obtained are assumed to act uniformly over the elemental area.

The plume data are generated along left-running characteristic lines (Ref. 5); where the data may have been generated using the mesh control option in either the first quadrant (Fig. 4-2a) or in the fourth quadrant

---

*Regardless of whether or not the plume flow is free molecular, transitional or continuum, the program checks on the body size and local Knudsen number to determine the proper flow regime with respect to the body.
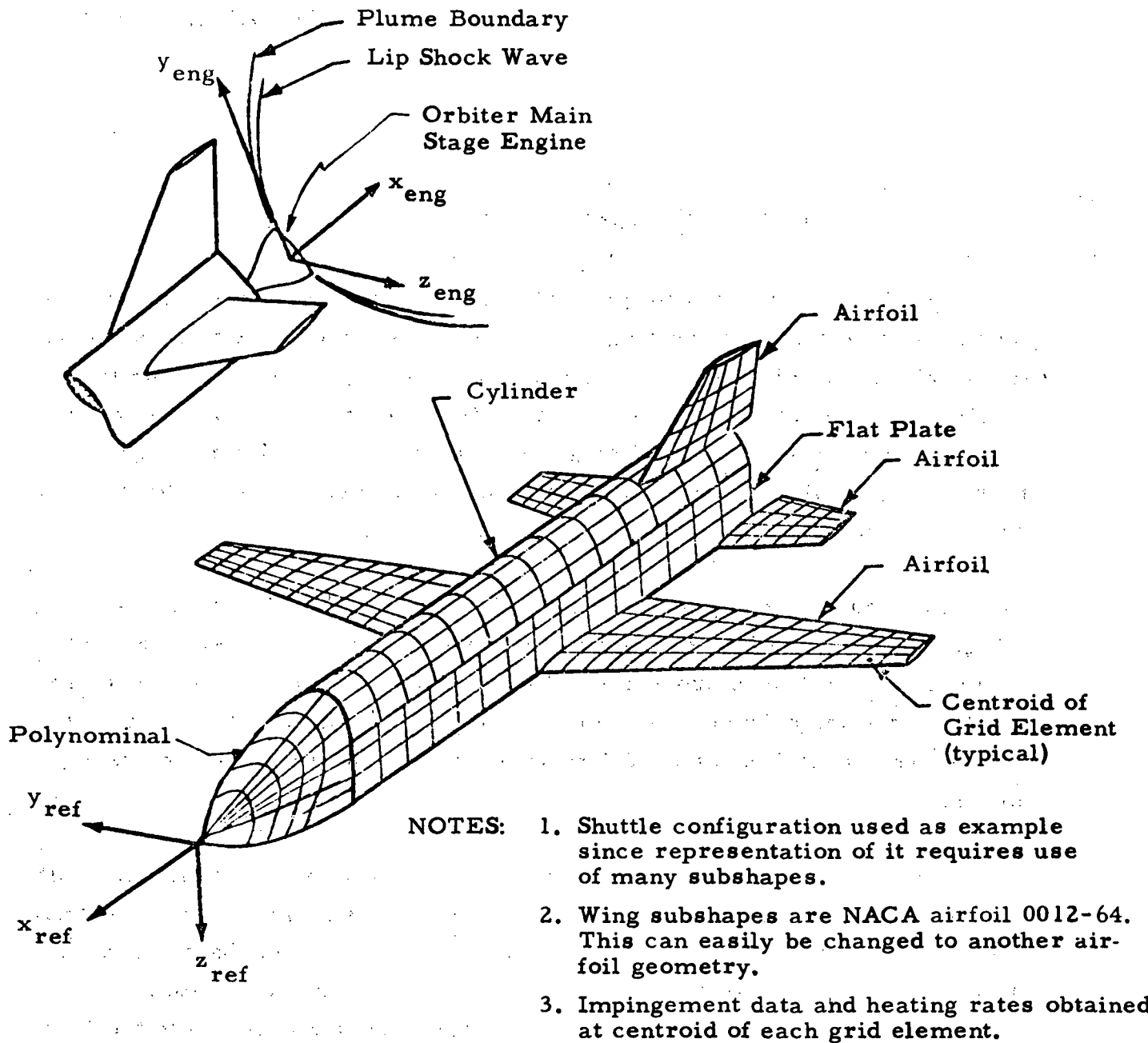
Plume Boundary

Lip Shock Wave

Orbiter Main
Stage Engine

y_{eng}

x_{eng}

z_{eng}

Airfoil

Cylinder

Flat Plate

Airfoil

Airfoil

Centroid of
Grid Element
(typical)

Polynominal

y_{ref}

x_{ref}

z_{ref}

NOTES: 1. Shuttle configuration used as example
since representation of it requires use
of many subshapes.

2. Wing subshapes are NACA airfoil 0012-64.
This can easily be changed to another air-
foil geometry.

3. Impingement data and heating rates obtained
at centroid of each grid element.

Fig. 4-1 - Sketch of a Subshape System and Grid Scheme Used
in the Force, Moment and Heating Analysis

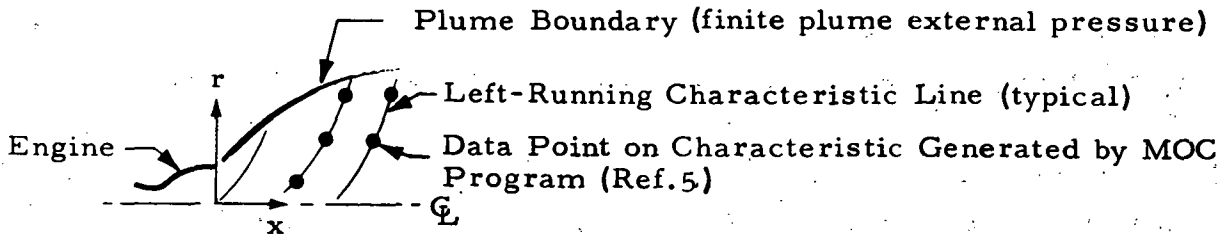(Fig. 4-2b) for the reflected shock case. The coordinate transformation

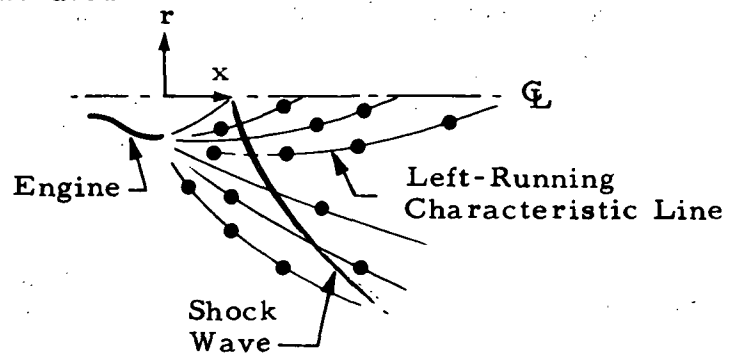Fig. 4-2a - Sketch of Plume Data Generated in First Quadrant

Fig. 4-2b - Sketch of Plume Data Generated in Fourth Quadrant

from the body local coordinate system to the plume coordinate system yields
the plume coordinates (r,x) of the local body station with respect to the plume
origin. The plume local flow properties are then obtained by a table lookup
for the properties. The independent plume variables describing each point
which are stored on the tape are the velocity, V, ft/sec; local flow deflection
angle, θ, radians; entropy level, S, $ft^2/sec^2/^{\circ}R$; O/F ratio; Mach number,
M; and the characteristic plume point identification flags, i.e., 0 = input point;
1 = interior point; 2 = wall point; 3 = free boundary point; and 4 = shock wave
point. The remaining gas properties are computed using the independent
variables and the gas thermochemistry data which are also stored on the
tape.

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All plume data points previously stored on magnetic tape by the MOC program (Ref. 5) for each plume flow field are rearranged by the "ordering" section of the Impingement program. The "ordered" flow field may be written on the magnetic tape as another data file and therefore may be referenced directly by the Impingement program for subsequent cases.

The ordering process involves first rearranging the data points by distance from a reference point (Fig. 4-3), generally the centerline of the engine exit plane. The ordered data are then divided into data blocks each containing a maximum of 300 data points. The maximum and minimum distances for each

$$D_i = \sqrt{x_i^2 + r_i^2}$$

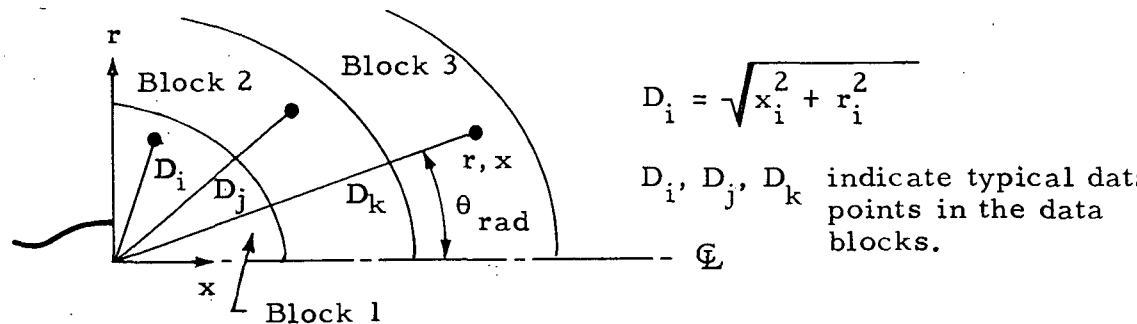D_i, D_j, D_k indicate typical data points in the data blocks.

Fig. 4-3 - Sketch of Plume Data Points Referenced to the Engine Exit Plane

data block are stored for later use in determining in which data block a particular point (r, x) will be located. The plume data points within each data block are then ordered by their angular location, θ_{rad}, from the plume centerline, where

$$\theta_{rad} = \tan^{-1}(r/x), \text{ see Fig. 4-3.} \tag{4-1}$$

When all manipulations involved in ordering the plume data are complete, the data will be stored on magnetic tape in a specific order which significantly simplifies the data lookup for a plume point. An end-of-file mark

is written at the end of the ordered data. The data block limits are then written on the second file.

The plume data as used by the impingement program is in a one-dimensional tabular array in terms of the radial distance from the plume centerline. A representation of typical data is shown in Table 1. Using the body surface coordinates written in the plume system, the distance from the plume reference origin is calculated from the following equation

$$D = \sqrt{x^2 + r^2}.$$

(4-2)

Table 1

REPRESENTATION OF AN ORDERED DATA BLOCK

x_1	r_1	V_1	θ_1	S_1	OF_1	M_1	$TYPE_1$	θ_{rad_1}
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—
x_i	r_i	V_i	θ_i	S_i	OF_i	M_i	$TYPE_i$	θ_{rad_i}
x_{i+1}	r_{i+1}	V_{i+1}	θ_{i+1}	S_{i+1}	OF_{i+1}	M_{i+1}	$TYPE_{i+1}$	$\theta_{rad_{i+1}}$
—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	—
x_n	r_n	V_n	θ_n	S_n	OF_n	M_n	$TYPE_n$	θ_{rad_n}

The data block in which the point properties are to be found is then located by a search of the data block limits data. Equation (4-1) is then employed to

4-5

determine where in the data block the search for points to use in the interpolation scheme should begin. A four (4) point interpolation scheme is used (Fig. 4-4) to obtain the flowfield properties at the point (r, x). Once the four
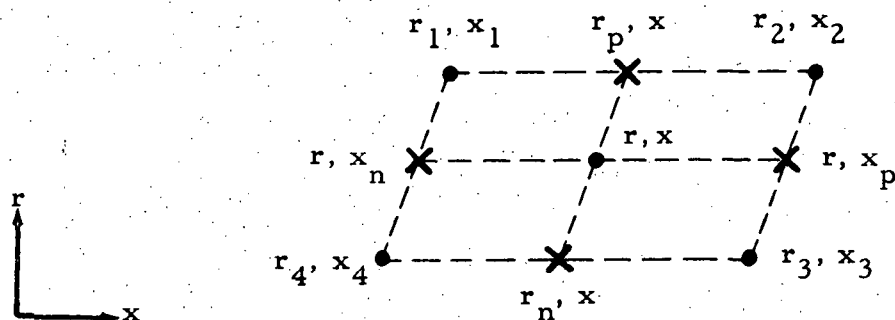

Fig. 4-4 - Sketch of Data Point Orientation Used in the Interpolation Scheme (see description of subroutine JWBTSS, Ref. 4)

points are found, the location of the intersections (r_p, x), (r_n, x), (r, x_p) and (r, x_n) are calculated and the distance between the intersections are determined. The flow properties at the intersections for which the final interpolation distance is smallest are obtained by linearly interpolating between the appropriate base points. Finally the flowfield properties at the point, (r, x), are obtained by linear interpolation between the points (r_p, x) and (r_n, x) or (r, x_n) and (r, x_p).

The body local flow regimes are determined by the value of the local Knudsen number (Kn). Continuum flow is assumed to exist for Kn < 0.01, transitional flow exists for Kn between 0.01 and 10.0 and Kn > 10 defines the non-continuum (free molecule) flow regime. The characteristic lengths used in the Knudsen number calculations are a representative body dimension (i.e., plate dimensions, cylinder diameter and length, etc.) so that the elemental area local flow regime is determined by comparing the mean free molecular path of the local plume to the projected body dimension. A typical analysis of a high-altitude plume will yield a distribution as shown in Fig. 4-5.
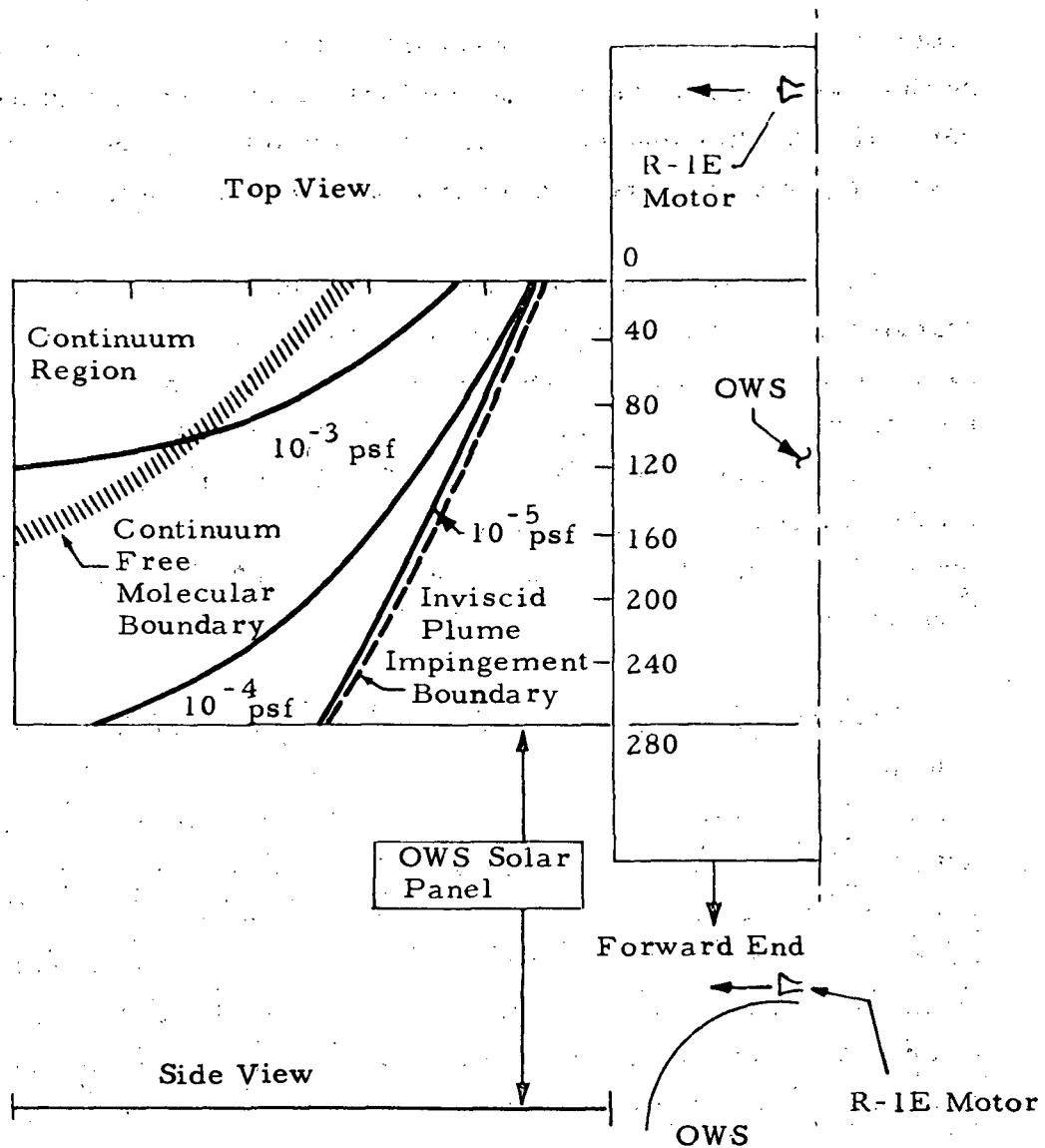
4-6

Top View

Fig. 4-5 - Typical High Altitude Plume (Ref. 7)

In the continuum flow regime, the local impact pressures are computed using modified Newtonian theory which includes a correction factor to account for the higher pressures noted experimentally for small incidence angles (Ref. 8). In the free molecular flow regime, the body local flow properties are assumed to depend only on collisions of the gas molecules with the body surface. Environmental equilibrium is assumed so that a Maxwellian-type flow exists and the body local flow properties are calculated from kinetic theory and Maxwell's law of distribution of molecular velocities. The local force is then computed

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from the sum of the forces produced by the incident and reflected molecules. In the transitional flow regime the local impact pressure is calculated empirically as a function of the local Mach number and Knudsen number to yield a smooth transition from the continuum to the free molecular flow regime.

This program contains several methods for calculating convective heat transfer rates to bodies immersed in rocket exhaust plumes. Each method is applicable to a particular situation, determined either by geometry or by the assumption made in obtaining the local flow properties. No single method currently will suffice for all shapes and flow conditions. In fact, a different method must be frequently used for the various subshapes of an impinged body. The method to be used on a given subshape must be specified in the input data.
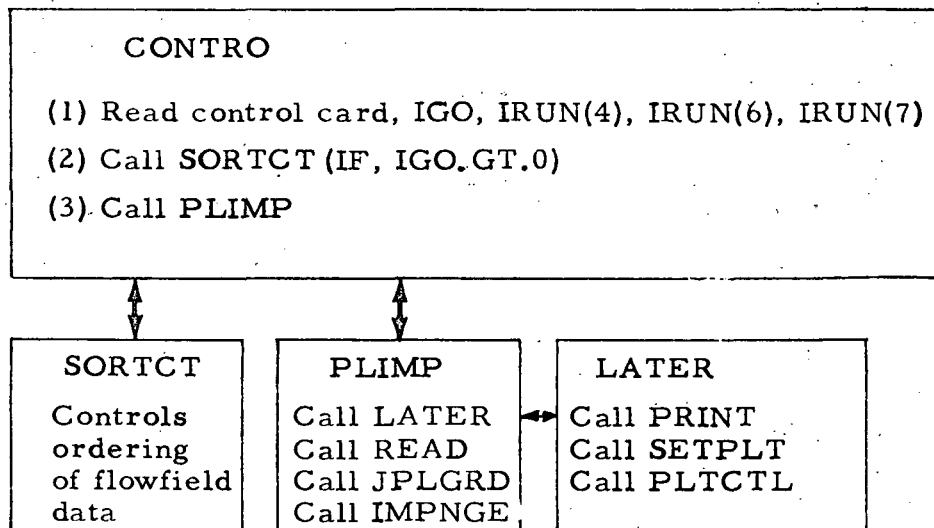
Several options are also available to the user for obtaining the local flow properties for use in the heat transfer analysis. In all of the methods, the local pressure depends on the angle that the local surface makes with the freestream flow. Fortunately, this method is applicable to a majority of hypersonic flow problems. In the leading edge and corner regions, corrections have to be made to the pressure and heating values as calculated by the program. The methods that are available to the user are listed later in this report on page 4-20. The various continuum regime heating rate options that are available to the user are listed on page 4-26. Free molecular heating rates are also calculated at each elemental area from an energy balance-type equation and the decision of which flow regime to consider is simplified by a printout of the applicable flow regime based on the local Kn.

The program can currently analyze the impingement flow properties on six (6) basic subshapes. These are: (1) a surface described by a conical equation, i.e., cylinder, cone, etc.; (2) rectangular flat plate; (3) circular plate; (4) right triangle; (5) airfoil; and (6) a body of revolution in which the surface curvature as a function of the longitudinal axis is described by a polynominal equation. (A maximum of fourth-order curve can be used.)
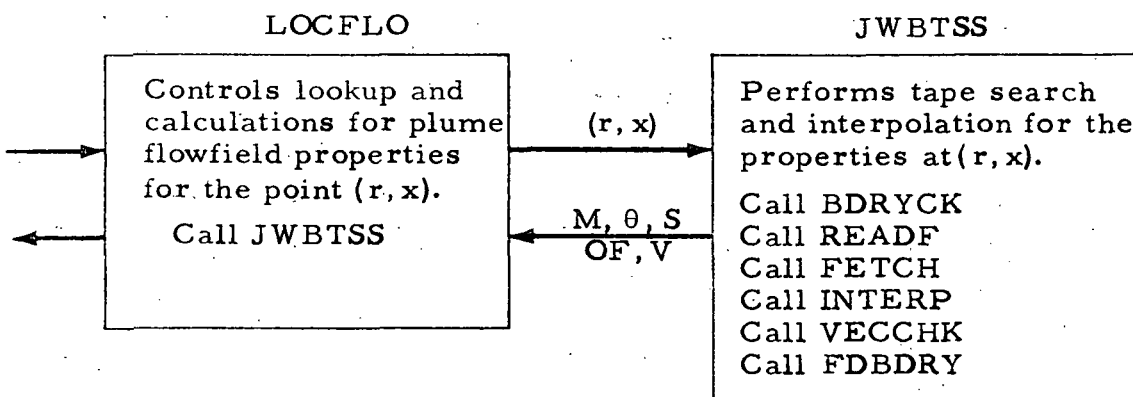
The computer program driver or control routine is entitled CONTRO. This routine reads one data card which is then used to call the appropiate section of the program which will:
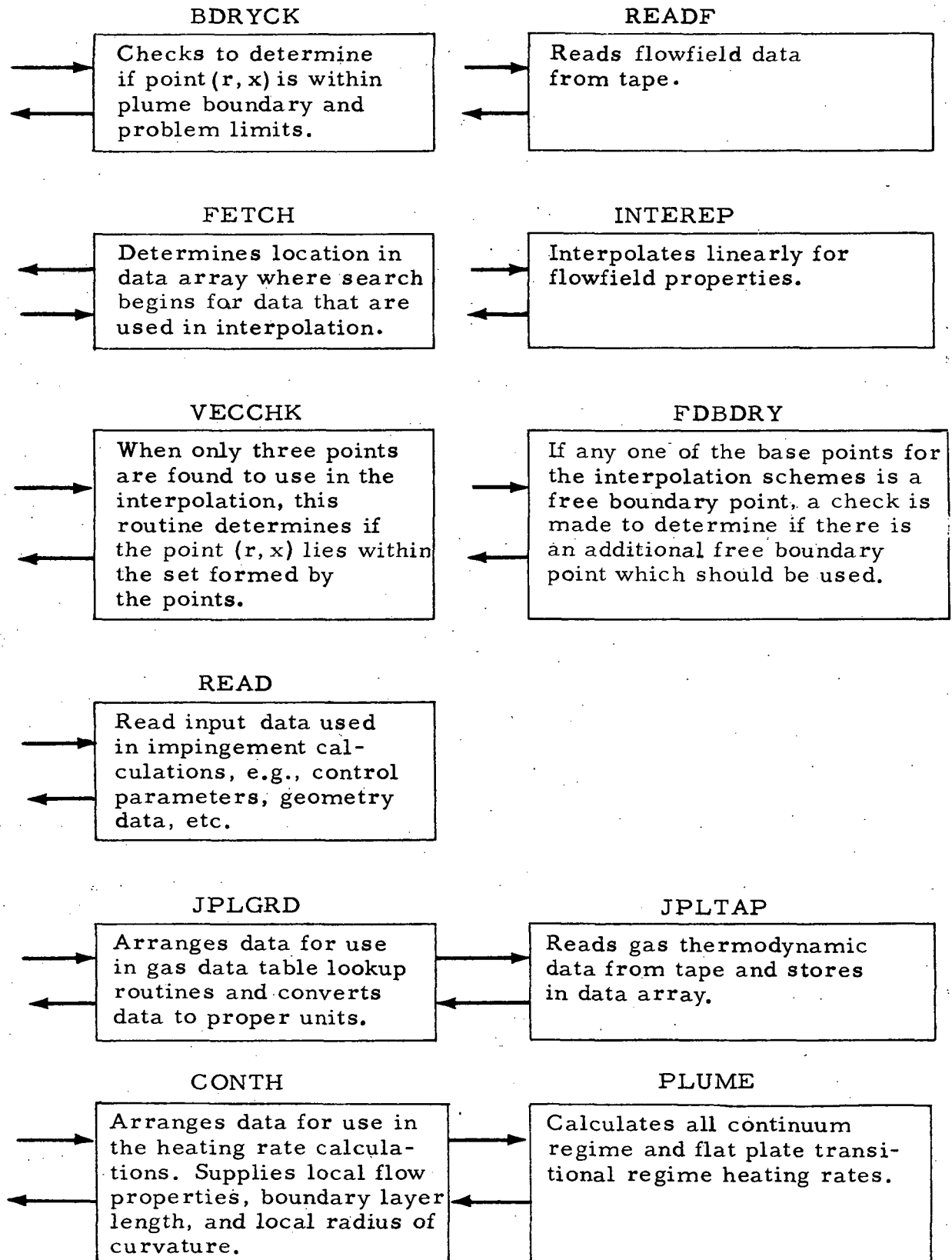
- Order the plume flowfield data
- Perform an impingement analysis
- Read an impingement data tape and print or plot the data stored on it.

The basic flow chart for the program is:

```
CONTRO

(1) Read control card, IGO, IRUN(4), IRUN(6), IRUN(7)

(2) Call SORTCT (IF, IGO.GT.0)

(3) Call PLIMP
```

SORTCT	PLIMP	LATER
Controls ordering of flowfield data	Call LATER Call READ Call JPLGRD Call IMPNGE	Call PRINT Call SETPLT Call PLTCTL

A brief description of some of the more important subroutines follows:

LOCFLO   JWBTSS

LOCFLO		JWBTSS
Controls lookup and calculations for plume flowfield properties for the point (r, x). Call JWBTSS	(r, x) → ← $\frac{M, \theta, S}{OF, V}$	Performs tape search and interpolation for the properties at (r, x). Call BDRYCK Call READF Call FETCH Call INTERP Call VECCHK Call FDBDRY

BDRYCK

Checks to determine
if point (r, x) is within
plume boundary and
problem limits.

READF

Reads flowfield data
from tape.

FETCH

Determines location in
data array where search
begins for data that are
used in interpolation.

INTEREP

Interpolates linearly for
flowfield properties.

VECCHK

When only three points
are found to use in the
interpolation, this
routine determines if
the point (r, x) lies within
the set formed by
the points.

FDBDRY

If any one of the base points for
the interpolation schemes is a
free boundary point, a check is
made to determine if there is
an additional free boundary
point which should be used.

READ

Read input data used
in impingement cal-
culations, e.g., control
parameters, geometry
data, etc.

JPLGRD

Arranges data for use
in gas data table lookup
routines and converts
data to proper units.

JPLTAP

Reads gas thermodynamic
data from tape and stores
in data array.

CONTH

Arranges data for use in
the heating rate calcula-
tions. Supplies local flow
properties, boundary layer
length, and local radius of
curvature.

PLUME

Calculates all continuum
regime and flat plate transi-
tional regime heating rates.

4-10

IMPNGE

```
Controls impingement calculations.
─────────────────────────────────────
Initialize control variables

Loop 1
                                      ⎛ CONIC
                                      ⎜ RPLATE
          Call geometry routine,   ⎨ TRINGL
                                      ⎜ WING
                                      ⎝ GENSHP

Loop 2

          Call TABLE (calculate gas thermodynamic data)
Loop 3

          Call FNUDSN (calculate Knudsen number)
          Call CONTIN (calculate continuum properties if Kn < 10)
          Call FMLOAD (calculate free molecular data if Kn > 0.01)
          Call TRNSIT (calculate transitional data if 0.01 < Kn < 10.)
          Sum subshape forces and moments.

Loop 4

          Call CONTH (performs heating rate analysis)
Loop 5

          Call PRINT (print data)
          Call SETPLT (set up plot data if ITPLOT.GT.0)
          Sum composite body forces and moments.

Calculate center-of-pressure location on composite body.

Call PLTCTL (plot data if ITPLOT.GT.0).
```

The program is written in FORTRAN IV computer language and assembly level language. Routines written in assembly level language are entitled ARASSL and CTAB. Subroutine ARASSL sorts data in numerical order. Subroutine CTAB is used by the plot package to print symbols for identifying data. An assembly level version of subroutine ARASSL is available as part of the computer library for most users of the IBM 7094. However, for users of the Univac 1108 it is suggested that the subroutine described here be used.

The program is arranged in an overlay structure for use on the IBM 7090, IBM 7094 and the Univac 1108 time-sharing system. The overlay structure is given in Table 2.

Table 2

OVERLAY STRUCTURE FOR THE PLUME
IMPINGEMENT COMPUTER PROGRAM

```
MAIN
------------
           A1*
           ----------
        A2*
        ------------
                  A3*
                  ------
              B*
              --------------------
                          C3*
                          --------
                          C1*
                          --------------
                          C2*
                          ----
                          C3*
                          ----------
    SEG MAIN               C4*
                          ---
     IN TPFS.CONTRO,.ARASSL      C5*
                          ----------------
    SEG A1*,(MAIN)

     IN TPFS.SORTCT,.DEL,.READB,.SORTC,.TAPED,.GASWT,.ARRNGE,.INTO,.REORDR

     IN TPFS.TRAMS

     SEG A2*,A1

    IN TPFS.PLIMP,.CROSS,.HEAD,.TRANS

    SEG A0*,(A2)

    IN TPFS.JLPTAP,.JPLGRD,.MOVEFL,.MAXMIN,.READ,.TAPMOV

     SEG B*,(A2)

      IN TPFS.ADDV,.COSDOT,.DOT,.EMOFP,.EMOFV,.ERF,.FABLE,.IMPNGE

      IN TPFS.ITSUB,.POFEM,.POSTM,.RHOFEM,.SCALEV,.TABLE,.TOFEM,.TOFV

      IN TPFS.TRNSIT,.UOFEM,.UOFV,.VMAG,.VOFEM

      IN TPFS.LATER
```

Note: The overlay structure shown is for the Univac 1108 Exec 8 system.
However, the routines as they appear in the links are applicable to
the IBM 7090 and IBM 7094 computer. If used on the 7090 and 7094,
the subroutines ARASSL (main link) and CTAB (link C5) are contained
as system library routines which should be used in place of the assem-
bly language version herein.

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Table 2 - (Continued)

SEG CO•,(B)

 IN TPFS.CONIC,.CPLATE,.RPLATE,.TRINGL

IN TPFS.CPCONE

IN TPFS.WING,.FOIL

SEG C1•,(B)

 IN TPFS.FETCH,.INTERP,.JWBTSS,.LOCFLO,.READF,.POINTS,.SHADOW

SEG C2•,(B)

 IN TPFS.CONTIN,.DELTAF,.ESHOCK,.ENTROP,.FMLOAD,.FNUDSN,.WEAK

SEG C3•,(B)

 IN TPFS.CONTH,.FREEM,.FREEMH,.ONEVAR,.PLUME,.PROPTY,.SPECIE,.ENTH

SEG C4•,(B)

IN TPFS.PRINT,.SETPLT

SEG C5•,(B)

IN TPFS.CTAB,.FIGUR,.IDENTF,.GRAPH,.NXV,.NYV,.PLTCTL,.POINTX,.SETUP

IN TPFS.LSJF,.J_SFIT

IN TPFS.XYLIM

IN TPFS.FRAMEX

4-13

4.1 SUBSHAPE OF GEOMETRY AND COORDINATE SYSTEM

The configuration shape is represented in the impingement analysis by a series of simple subshapes. Each subshape has its own coordinate system so that the surface contour is easily described. The locations of the local body points with respect to the plume are obtained by appropriate vector transformations to the plume coordinate system. The velocity vector is then written in the subshape coordinate system and the impingement and heating analysis performed in that coordinate system.

Currently, six subshapes can be utilized in the physical description of a configuration. These are: (1) conic; (2) flat plate; (3) circular plate; (4) triangle; (5) airfoil; and (6) a body of revolution described by a polynominal.

To analyze a problem, the user must input the subshape geometry data, the position vectors for the subshapes and the transformation matrix. As the program is written, a rule of thumb to follow is to input all position and transformation matrices working from the subshape coordinate system to the reference coordinate system, then to the engine coordinate system.

4.1.1 Conic Shape Coordinate System

The representation of the conic subshape is shown in the sketch below:
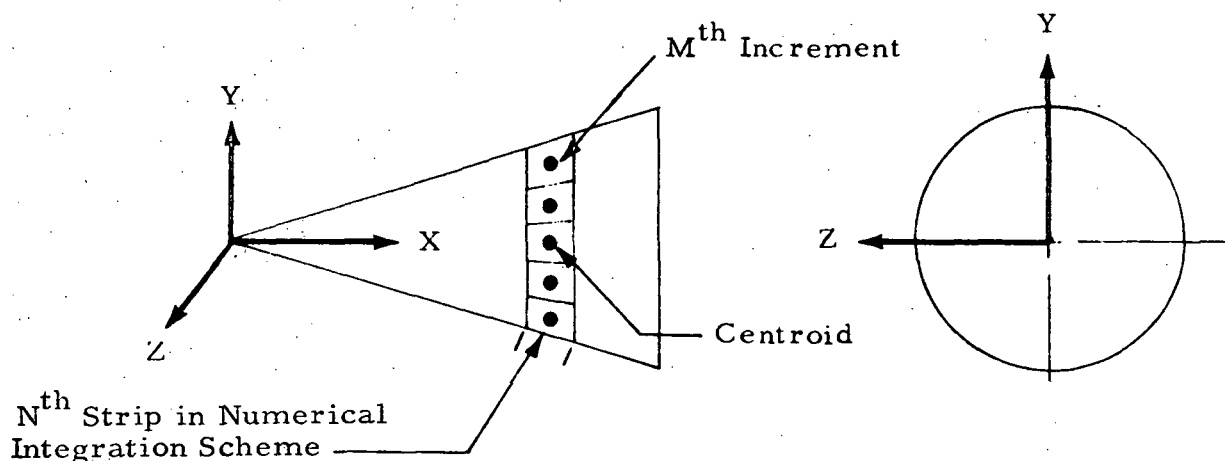
The X axis is always coincident with the longitudinal axis. The direction of the Y axis is determined by the user. A right-hand coordinate system is then used to obtain the cross product of the X and Y unit vectors.

In the numerical integration scheme, the conic subshape is divided into a number of rings (determined by user). Each ring is then further subdivided into a number of radial increments. The position data are obtained at the centroid of each element (see sketch). The unit normal, and projected area are calculated from geometry relations.

4.1.2 Rectangular Flat Plate Subshape Coordinate System
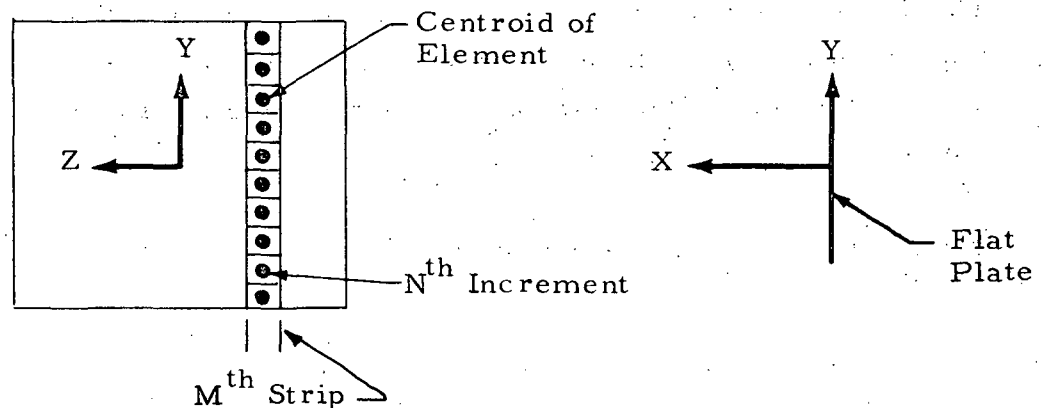
The coordinate system for a flat plate is always located at the centroid of the plate. When the heating rate option is used, the Y axis should be oriented in the direction of flow. The integration scheme divides the plate into N number of strips with each strip divided into M increments. The properties are obtained at the centroid of each element. The X axis is always normal to the plane of the plate.

4.1.3 Circular Plate Coordinate System
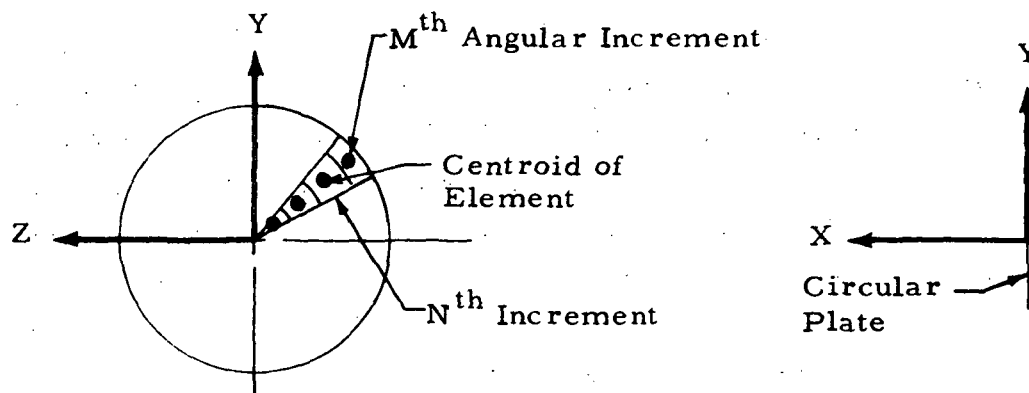
The circular plate is subdivided into N number of angular increments with each angular increment further subdivided into M increments (see sketch). The X axis is set normal to the plane of the plate. The user can designate any angular location of the Y axis. The direction for the Z axis is calculated by the program. The coordinate system origin is assumed to be located at the center of the circular plate.

4.1.4 Rectangular Plate Subshape Coordinate System
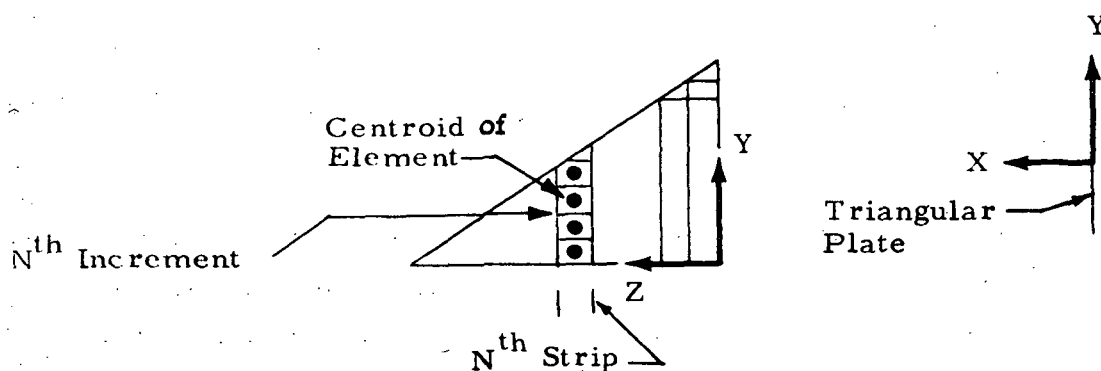
The triangular plate must be a right triangle, and the origin must be located as shown in the sketch. The Y axis should be oriented in the general direction of the plume flow. The X axis is assumed by the program to be normal to the plate. Again the direction of the Y axis is determined by the user with the Z axis set by the program.

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4.1.5 The Airfoil Subshape Coordinate System

Planform View

Chord Section View
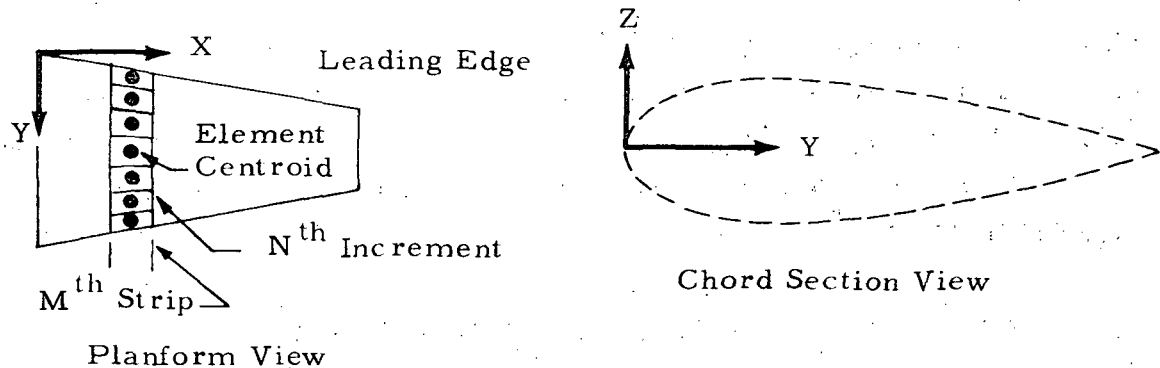
The airfoil section currently used is NACA airfoil 0012-64. However, this can be changed to define any airfoil section characteristics. The origin of the subshape coordinate is assumed to be located on the section mean line (see sketch) at the leading edge of the root chord. A cosine distribution function is used to bias the increment distribution toward the airfoil leading edge since this is a region of rather steep surface gradients.

4.1.6 The Arbitrary Body of Revolution Coordinate System
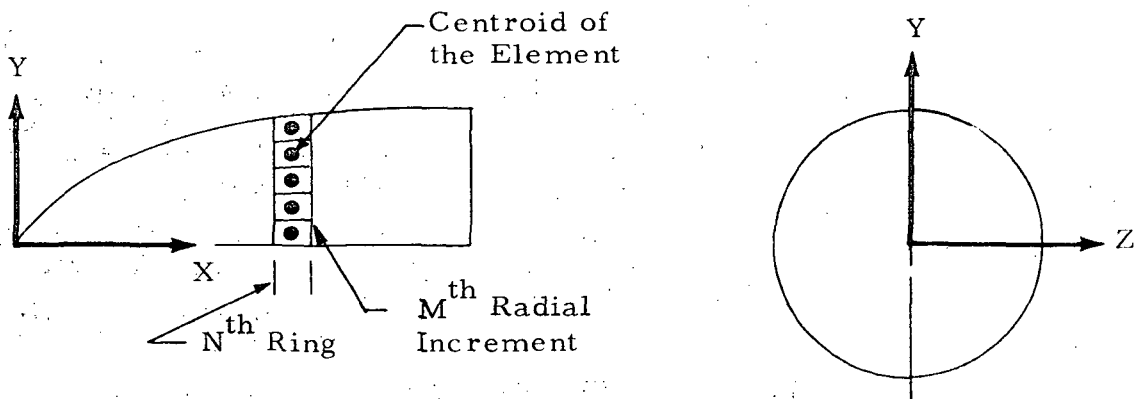
The coordinate system origin is located as discussed for the conic subshape in Section 4.1.1 with the numerical integration scheme programmed in a similar manner.

4.2   USER'S INPUT GUIDE FOR THE IMPINGEMENT PROGRAM

This section outlines in detail the procedures for using the Plume Impingement Computer Program. Each card and its use is explained in Section 4.2.1 and outlines the input guide for the impingement analysis, and Section 4.2.2 outlines the procedure for listing and plotting a data tape generated by the impingement program. The program magnetic tape assignments are given in Table 4-1.

4.2.1   IMPINGEMENT PROGRAM INPUT INFORMATION

The input data are organized into sections determined by their use. The description of these cards is given below.

PLIMP Computer Program Input Instructions

CARD 1:   Program Control Card

Format	Column		Item
4I5	5	IGO = 1	Arrange data generated by MOC program in format used by PLIMP program.
		= 0	Perform impingement analysis only.
	10	IRUN(4)	Used to indicate if impingement calculations are to be made or data is to be listed from tape when subroutine PLIMP is called.
		IRUN(4) =	FORTRAN tape unit on which the impingement data are stored.
		= 0	The impingement data calculations are to be made.
	15	IRUN(6)	Not presently used.
	20	IRUN(7)	Used when IRUN(4) > 0
		= 1	Print data only
		= 2	Plot data only
		= 3	Print and plot data.

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CARD 2: Control card for the ordering section.
Cards 2 and 3 are used only when IGO
(card 1) is greater than zero.

Format	Column	Item
16I5	5	ISTART, Ordering the flowfield data will begin with this characteristic line number.
	10	ISIGN, -1 if the flow field was generated with a reflected shock from the nozzle axis, otherwise leave blank.
	15	NUMBER, Number of flowfield data points desired per data record (max. of 300).
	20	IDEL > 0 if any points are to be deleted from the flow field.
	25	IPRINT > 0 if intermediate data is to be printed as the flow field is ordered by distance from the engine exit plane.
	30	ITERM, characteristic line number, where ordering of flowfield data is to be terminated.
	35	ISEND=1 if plume boundary is to be curve-fitted for use in the interpolation scheme, ISEND=2 if only the cutoff limits read as input data are to be used to see if a point is within a prescribed boundary.
	40	ISKIP, if ISEND = 1 every ISKIP line will be examined for a free boundary point.

CARD 3:

Format	Column	Item
6E10.6	1-10	RREF*, radial coordinate to which each flowfield data point will be referenced.
	11-20	XREF*, axial coordinate to which each flowfield data point will be referenced.
	21-30	DELETE if IDEL > 0. One of two points with a distance between them less than DELETE will be deleted from the flowfield data.
	31-40	DIAM, reference factor, units consistent with plume dimensions. Can be used to scale, etc., the local plume coordinates.

* The coordinates XREF, RREF are used to accomplish any desired coordinate system translation.

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CARD 4: Title or heading which is used for run identification.

Format	Column		
12A6	1-72		Title or Heading

CARD 5: Input options necessary to control program execution.

Format	Column		
16I5	5	IOPT(1)	Flowfield type
		1	Flow field is axisymmetric
		0	Flow field is two-dimensional
	10	IOPT(2)	Desired Heating Options
		0	Calculate continuum and free molecular heating
		1	Calculate continuum heating only
		2	Calculate free molecular heating only
		3	None
	15	IOPT(3)	Uniform Flow Assumptions
		0	Composite vehicle in uniform flow
		1	Subshapes in uniform flow
		2	Elemental rings in uniform flow at maximum impingement
		3	Elemental areas in uniform flow
	18-20	IOPT(4)	Number of Subshapes in Composite Body
		N	Number of subshapes
	25	IOPT(5)	Type Output Desired
		0	Full output (data at each elemental area)
		1	Force and torque summary only
	30	IOPT(6)	Local Flowfield Chemistry
		0	Consider property variation with entropy
		1	Neglect entropy effects (use only one gas table)
	35	IOPT(7)	Option for Boundary Layer Chemical Species
		0	Use species on flowfield tape
		N	Number of species input
		IOPT(8)	
	37	1	Multiply resultant forces and moment by PCRAT (Card 10)
	38	0	Plume loading only
		1	Subtract P_{N_∞} (Newtonian) from P_{impact} for points within plume
		2	Calculate $P_{N_{\infty impact}}$ for points outside plume
		3	Subtract P_{N_∞} (Newtonian) over entire body surface

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CARD 5 (Continued)

Format	Column		Item
16I5 (Cont.)		IOPT(8) (Cont.)	
	39	1	Plume P_∞ used for points in plume boundary but shaded from the flow
	40	1	Multiple cases with limited changes to input data
	45	IOPT(9)	Type of Local Impact Pressure Calculation (continuum regime only)
		1	Newtonian assumption ($C_p = 2.0$)
		2	Modified Newtonian ($C_{p_s} K_{c_p}$) (calculate stagnation pressure coefficient, multiply by K_{c_p})
		3	Isentropic expansion
		4	Oblique shock
		5	Modified Newtonian (C_{p_s})
	46-50	IOPT(10)	Debug Flag if 0
		N	Input the number of subshapes at which debug printout is desired (look out!)
	51-55	IOPT(11)	Plot Control Flag (input as below)
	51	0	Do not connect plotted data points
		1	Connect plotted points with lines
	52-53	N	Number of tape drive on which plot data will be stored, usually 14 on Univac 1108 if zero data will not be written on tape for further use
	54-55	N	ITPLOT, number of parameters to be plotted
	56-60	IOPT(12)	Case Number
	65	IOPT(13)	
		0	Impingement program dimensions in inches
		1	Impingement program dimensions in feet
	70	IOPT(14)	
		0	Flowfield dimensions in inches
		0	Flowfield dimensions in feet
	75	IOPT(15)	Local Property Printout
		0	No intermediate printout of properties
		1	Print local properties
		8	Intermediate printouts in heating routines
	79-80	IOPT(16)	
	79	1	The configuration to be analyzed is a shuttle-type vehicle
	80	0	No body-on-body shading calculations to be performed
		1	Body-on-body surface shading to be considered (input additional shading data after each subshape geometry card)

CARD 6: Position vector defining the relative positions of the engine and reference coordinate systems.

This card contains values for a position vector ($\overrightarrow{REC}$), a moment transfer vector ($\overrightarrow{RECD}$), and three control flags (ITU, ITV, ITW). These flags control the use of the position vector and its transformation matrix, and the moment transfer vector. The position vectors ($\overrightarrow{REC}$ and $\overrightarrow{RECD}$) are measured in inches or feet, consistent with the IOPT(13) control flag of Card 5.

Format	Column		
6E10.6, 3I5	1-10	REC(x)	
	11-20	REC(y)	Components of engine position vector
	21-30	REC(z)	
	31-40	RECD(x)	
	41-50	RECD(y)	Components of moment transfer vector written in reference system
	51-60	RECD(z)	
	65	ITU	Engine position vector control flag
			=0, the engine position vector ($\overrightarrow{REC}$) is measured in the engine system and locates the reference with respect to the engine
			=1, the position vector ($\overrightarrow{REC}$) is measured in the reference coordinate system and locates the engine system with respect to the reference system
	68-70	ITV	Engine-Reference System Transformation Matrix Control Flag. Input is right adjusted.
		>0	The three axes angles of rotation will be read from Card 7. The program will compute the transformation matrix. User must specify order of rotation(s) with this flag, ITV, as a three-digit coded number using the code:
			1 $\implies$ x-axis rotation, φ degrees 2 $\implies$ y-axis rotation, θ degrees 3 $\implies$ z-axis rotation, ψ degrees
		=0	The components of the I and J unit vectors of the transformation matrix will be read from Card 7.
16I5	75	ITW	Moment Reference Point Control Flag =1, the resultant moments are to be referenced to the point defined by $\overrightarrow{RECD}$

CARD 7: Transformation matrix from reference to engine coordinate systems or angles of axis rotation to calculate the transformation matrix.

This card contains values for the direction cosines of the reference system unit vectors (IC and JC). The unit vectors are measured in the exit (E) reference system. If the control variable, ITV (Card 6), is greater than zero, the axis rotation angles (φ, θ, ψ) are input and the cosines computed by the program.

Format	Column	
6E10.6		x, y, z direction cosines of x_R in E system or φ, θ, ψ if ITV greater than zero.
	1-10	IC(x) or φ in degrees
	11-20	IC(y) or θ in degrees
	21-30	IC(z) or ψ in degrees
		x, y, z direction cosines of y_R in E system not used if ITV greater than zero.
	31-40	JC(x)
	41-50	JC(y)
	51-60	JC(z)

CARD 8: Plot Identification Card, used only if ITPLOT   0 (IOPT(11))

Below is a list of the impingement parameters that can be plotted. Format 16I5. The parameters to be plotted are input in integer form in Columns 1-70 (only if IPLOT.GT.O).

1. Laminar Convective Heating Rate

2. Turbulent Convective Heating Rate

3. Transitional Flow Convective Heating Rate

4. Free Molecular Flow Convective Heating Rate

5. Local Reynolds Number Based on Momentum Thickness

6. Impact Pressure

7. Impact Pressure-to-Chamber-Pressure Ratio

6. Impact Pressure

7. Impact Pressure-to-Chamber-Pressure Ratio

8. Impact Force Distribution

9. Oxidizer-to-Fuel Ratio Distribution

10. Incident Mass Flow Rate

11. Freestream Mach Number

12. Local Mach Number

13. Local Temperature

14. Local Plume Impingement Angle.

Note: Variables do not have to be input in order indicated.

Col. 75   Point deletion criteria. Every n^{th} point will be plotted.

Col. 80   Line deletion criteria. Every n^{th} line will be plotted.

CARD(S)9:   Specie Concentration Cards (used when IOPT(7) > 0)

Format

3 (A6, 4X, E10.6)

This card specifies the mole fractions of the flowfield gas composition. Input only the 10 most dominant species (used only if IOPT(7) > O and IOPT (2) < 2).

Column
1-6, 21-26, 41-46,   Chemical specie name, i.e. H_2, ClO_2, etc.
11-20, 31-40, 51-60 Mole Fraction.

The specie names are left adjusted.

CARD(S) 10, 11, 12: Parameters for loads and heating rate calculations.

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Format

(8E10.6/7E10.6, 1X, A4)

CARD 10: Reference Parameters

Column	Item
1-10	(XTE)* Transfer distance from engine gimbal to exit plane (inches or feet, consistent with IOPT(14), Card 6).
11-20	XMIN Minimum distance from engine reference system at which impingement calculations are to start.
21-30	(DIA) Molecular diameter (inches or feet, consistent with IOPT(13)) for use in calculation of the Knudsen No.
31-40	Engine scale factor if plume coordinates are non-dimensional, or to be scaled (units consistent with IOPT(14), Card 6).
41-50	RICH Diameter of nozzle at exit plane for use in nondimensionalizing program output (units consistent with IOPT(13)).
51-60	PC Engine chamber pressure, (psi), nondimensionalizes pressure output.
61-70	PCRAT Ratio of desired plume chamber pressure for which heating rates, forces and moments are desired to the chamber pressure at which the plume flowfield was generated.
71-80	(DELPHI) Constant angular increment off stagnation line (degrees) at which impingement calculations are desired.

CARD 11: Conditions External to Plume

Format
6E10.6

Column	Item
1-10	(PAMB) Static pressure, psf
11-20	(TAMB) Static temperature
21-30	(EMAMB) Mach number, dimensionless
31-40	(GAMAMB) Ratio of specific heats, gamma
41-50	(RAMAMB) Gas constant, $ft^2/sec^2/°R$
51-60	(CPN) Newtonian pressure coefficient, dimensionless

*This option used primarily when the orientation of the engine coordinate system with respect to the reference system is about the engine gimbal point.

CARD 12: Heating Rate Reference Parameters

Format

7E10.6, IX, A4

Column	Item
1-10	Not presently used
11-20	(TAME) Trajectory time if surface temperature calculations are to be made.
21-30	(XSTAG) Axial distance from subshape origin to stagnation point. Units consistent with IOPT(13), Card 6.
31-40	(TW) Wall temperature, °R.
41-50	(TD) Temperature of the gas in the boundary layer at the stagnation point at onset of dissociation, °R
51-60	(RS) The reference radius (r*) at the stagnation point for use in velocity gradient calculation.
61-70	(FUDGE) = 1 if r* input in feet. = 12 if r* input in inches.
72-75	(SHAP) Nose shape. = 3DHM, Hemisphere = 2DHM, Cylinder = 3DDS, Circular Disk = 2DFP, Rectangular flat plate

CARD(S) 13

This card contains the body reference dimensions to be used in determining the local flow regime. There are N number of sets of data indicated by IOPT(4).

Format

6E10.6

Column	Description
1-10	(REFL) Reference length (inches or feet, consistent with IOPT(13)) } Subshape No. 1.
11-20	(REFD) Reference diameter (inches or feet)
21-30	REFL } Subshape No. 2.
31-40	REFD
41-50	REFL } Subshape No. 3.
51-60	REFD

CARD(S) 13(a): Subshape Geometry Card

The se cards identify the type of surface (conic, rectangular plate, circular plate, etc.), and the coefficients of the surface equation. There will be as many of these cards as there are subshapes (maximum of 10). Cards 13a, 13b, 13c are read as a set for each subshape.

Format	Column	Item
I1, I9, 7E10.6	1	Surface identification

ID = 1   conic
= 2   rectangular plate
= 3   circular plate
= 4   right triangular plate
= 5   wing
= 6   surface described by a polynomial
= 7   trapezoid

2-4		Surface integration control (NPHI increments)
5-7		Surface integration control (NX increments)

these are applied as follows:

Subshape	NPHI	NX
1. Conic	Angular (60 max)	X (unlimited)
2. R. Plate	Z (unlimited)	Y (60 max)
3. C. Plate	Angular (unlimited)	Radial (60 max)
4. T. Plate	Z (same as Y)	Y (60 max)
5. Wing	Span	Chord (60 max)
6. Polynomial	Angular (60 max)	X (unlimited)
7. Trapezoid	*Z (unlimited)	Y (60 max)

*The NPHI increment applies to the rectangular portion of the plate. Each triangular portion of the plate will have the same number of z increments as there are y increments.

8	The type of impingement pressure calculation for the subshape if different from option specified by IOPT(9). If left blank, the option specified by IOPT(9) will be used.
9	0 - Calculate heating rates on all surface strips.
	1 - Heating rate calculations or data output on specified subshape strip numbers, if IOPT(5=1), Strip numbers specified by card(s) 13c.
	2 - No heating rate calculations on subshape.
	3 - Surface temperature calculations on selected strips specified by card 13c.

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Column	Item
10	IHT Continuum regime heat transfer rate method.
	=1 Eckert Reference Enthalpy method for unyawed cones.
	=2 Eckert Reference Enthalpy method for flat plates.
	=3 Yawed cone heating rates using swept infinite cylinder theory.
	=4 Stagnation point heating rates using Marvin and Deiwert method. (Need additional input data on Card 11).
	=5 Wings and cylinder heating rates using yawed infinite cylinder theory.

Coefficients of subshape equations, subshape coordinate system.

Column	Item	
11-20	A	
21-30	B	Refer to sketches below for definitions
31-40	C	of coefficients; units of coefficients are
41-50	D	consistent with IOPT(13). Subshape
51-60	E	coordinate system orientations must
61-70	XN	be located as shown*
71-80	XB	

Conic Subshape, ID = 1
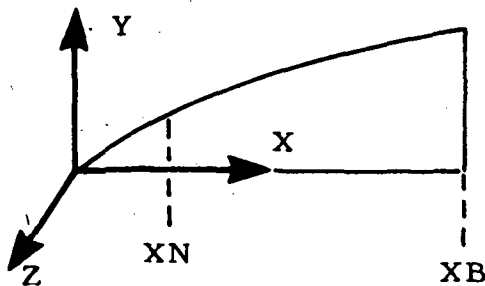
Surface Equation:

$$R = A\left(\sqrt{B + CX + DX^2} + E\right), \text{ for } XN \leq X \leq XB$$

$$DA = R\,\Delta S\,\Delta\varphi, \text{ where } \Delta S = \sqrt{\Delta X^2 + \Delta R^2}$$

Rectangular Subshape, ID = 2
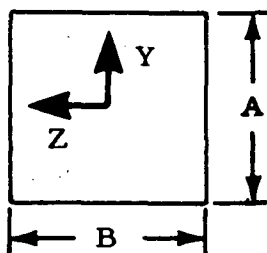
Coordinate system is located at the geometrical center. The X axis is normal to the plane of the plate. The Y axis should be oriented in the general direction of flow if heating rate calculations are made.

$$DA = \Delta Y \Delta Z$$

---

*For flat plates (rectangular, triangle, circular, trapezoid), the body X axis must be oriented in a general direction toward the engine.
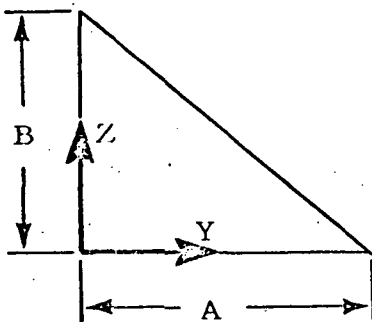
Circular Plate, ID = 3
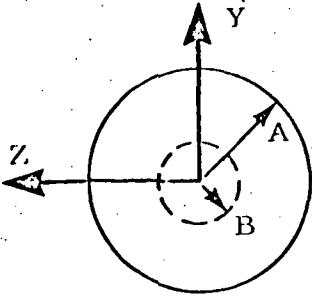
Coordinate system is located at the geometric center. The X axis is normal to the plane of the circular plate. Orientation of the Y, Z axes directions are established by the user.

A = maximum radius of circular plate

B = inner radius of circular plate

$DA = R\Delta R\Delta\varphi$, $B \le R \le A$

Right Triangular Plate, ID = 4

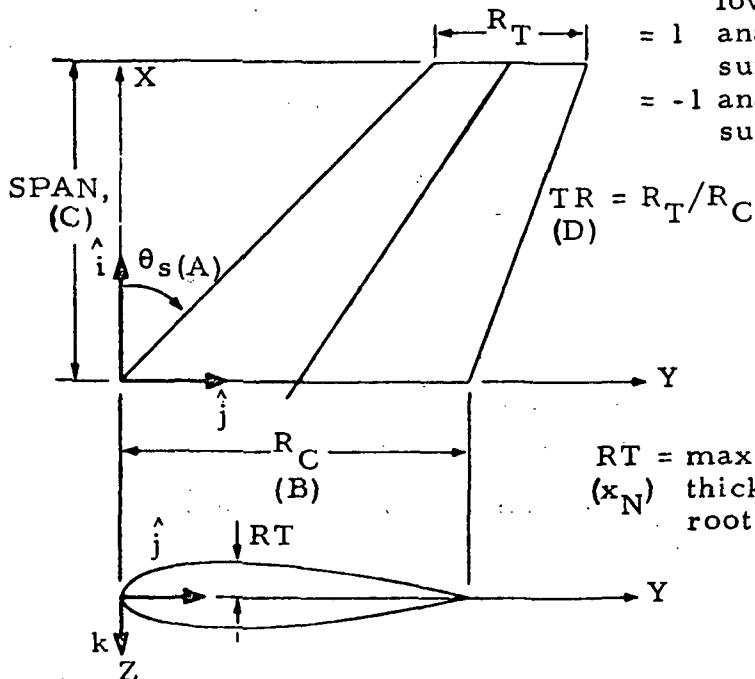The X axis is normal to plane of plate. Orientation of the Y axis should be in general direction of flow.

$A = Y_{max}$

$B = Z_{max}$

Wing Subshape

E = 0, use airfoil section coefficients NACA 0012-64. E=105, airfoil section coefficients input by program Cards 19.

XB = 0 analyze upper and lower wing surfaces

= 1 analyze upper wing surface

= -1 analyze lower wing surface

$TR = R_T/R_C$ (D)

RT = maximum half (x_N) thickness of root chord

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Polynomial Subshape, ID = 6
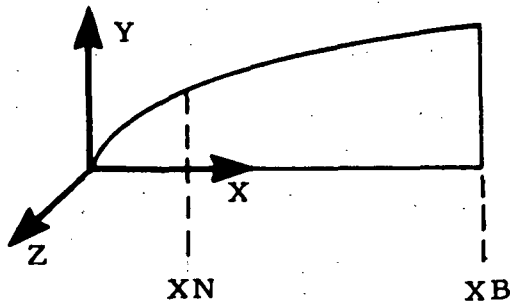
Surface Equation

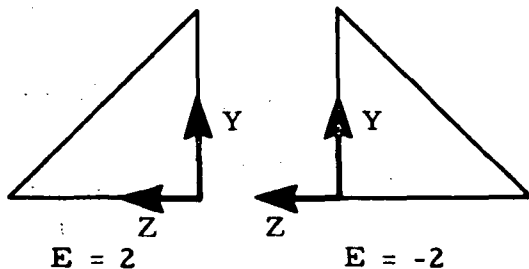$$R = A + BX + CX^2 + DX^3 + EX^4, \quad XN \le X \le XB$$

$$DA = R\,\Delta S\,\Delta\varphi, \quad \text{where } \Delta S = \sqrt{\Delta R^2 + \Delta S^2}$$

Trapezoid Subshape, ID = 7
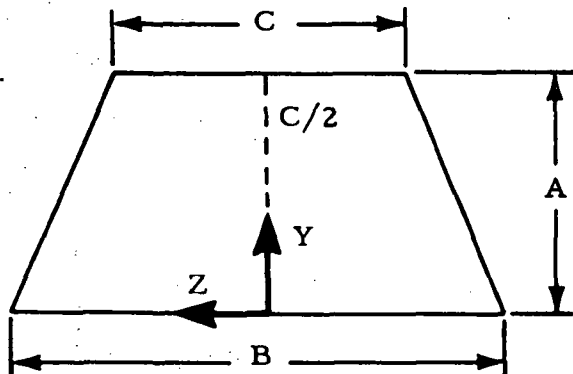
The subshape coordinate system must be orientated as shown. The program will work from the +Z toward the -Z direction

D = 1, flow is +Y direction
  -1, flow is -Y direction

E = 1 look at +Z side of trapezoid only
  = -1 look at -Z side of trapezoid only
  = 2 look at triangle on +Z side only
  = -2 look at triangle on -Z side only
  = -3 look at rectangular part only.

NOTE: The trapezoid routine can analyze a triangular plate and a rectangular plate. But, a substantial amount of execution time may be conserved if these simple subshapes are analyzed with their respective routines. The reason for this is due to the more complex computer logic involved in the trapezoid routine.

CARD(S) 13(b): Body shading data (input only if shading option is flagged, IOPT(16), Col. 80=1)

Format	Column	Item
10I2	1-2	Relative number(s) of the body(s) according to
	3-4	the order in which they are input which are to be checked for its shading on the body currently
	5-6	being input. (Input body numbers right justified.)

Note: Scan for surfaces to check is terminated by reading a zero — a maximum of ten surface numbers may be input.

CARD 13(c): Surface Temperature Identification Card

Format	Column	Item
5I6, 5E10.6	1-2	Strip number at which heating rate calculations or full output is desired.
	3-4	Node number on strip at which surface temperature calculations are to be made if this option is flagged.
	5	Surface material number.

The above is repeated until all strip numbers are identified (5 max)

	21-40	Material thickness for node on strip 1.
	41-50	Material thickness for node on strip 2.
	-----	Repeat until material thicknesses for nodes
	-----	on remaining strips are read in.

CARD(S) 14: Subshape Position Vector Cards

These cards contain the position vectors (RCI) from the reference system to the subshape origins. RCI is measured in the composite system reference frame. There will be as many of these cards as there are subshapes which are read successively. The units are consistent with IOPT(13). These cards are read in the same order as the geometry data (Cards 13).

Format	Column	Item
3E10.6, 2X, I3	1-10	RCI(X) x component of position vector.
	11-20	RCI(Y) y component of position vector.
	21-30	RCI(Z) z component of position vector.

Note: $\overrightarrow{RCI}$ is measured in the reference (C) system and "points" to the subshape origins.

Format	Column		Item
	33-35*	ITX	Reference-Subshape system status flag.
		0	matrix of direction cosines will be read
		>0	angles of axes rotation(s) are to be read. program will compute transformation matrix. User must specify order of rotation(s) using the following code:

$1 \Longrightarrow$ rotation about x axis, φ degrees
$2 \Longrightarrow$ rotation about y axis, θ degrees
$3 \Longrightarrow$ rotation about z axis, ψ degrees

CARD(S) 15: Subshape Direction Cosines or Axes Rotation Angles

These cards contain either the subshape direction cosines of the unit vectors (II and JI) or the axes angles of rotation, depending on the value of ITX (Card 14). There will be one of these cards for each subshape. These parameters are measured in the composite system reference frame. These cards are read in the same order as the geometry data (Cards 13) immediately after Cards 14.

Format	Column		
6E10.6	1-10	φ, deg or II(X)	
	11-20	θ, deg or II(Y)	Components of Unit Vector I.
	21-30	ψ, deg or II(Z)	
	31-40	JI(X)	
	41-50	JI(Y)	Components of Unit Vector J.
	51-60	JI(Z)	

Note: The program will compute the Unit Vector K.

CARD(S)16) Angular Integration Control Card

These cards enable the program to limit the calculations to the area of interest on a conic, and a general body of revolution and a circular plate by limiting the angular surface integration. For all other bodies, blank cards should be used. There are as many of these cards as there are subshapes and read in order immediately after the subshape direction cosines Card(s) 16.

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*Input is left-adjusted.

Format	Column		Item
2E10.6	1-10	PHIM1	Angle in degrees measured in the y-z plane from the +y axis at which calculations are to be started.
	11-20	PHIM2	Angle measured same as PHIM1 at which calculations are to be terminated.

CARD 17

This card contains the necessary information to limit the calculations to those areas of interest. This scheme is employed in order to make the program efficient for the many problem orientations which are possible (see example for illustration of its use). Units are consistent with IOPT(14).

Format	Column		Item
Cols. 1-10	CUTDAT		Radial coordinate defining upper cutoff.
Cols. 11-20	CUTDAT		Axial coordinate defining upper cutoff.
Cols. 21-20	CUTDAT		Angle cutoff line makes with horizontal.
Cols. 31-40	CUTDAT		Radial coordinate defining downstream cutoff.
Cols. 41-50	CUTDAT		Axial coordinate defining downstream cutoff.
Cols. 51-60	CUTDAT		Angle cutoff line makes with horizontal.

CARD 18   This card contains either the direction cosines of the unit vectors or the three axes angles of rotation written in the reference coordinate system for the plume external approach flow. NOTE: This card is input only if Column 38 of Card 5 > 0.

Format	Column		
6E10.6, 2X, I3	1-10	φ, deg or II(X)	
	11-20	θ, deg or II(Y)	Components of unit vector I.
	21-30	ψ, deg or II(Z)	
	31-40	JI(X)	
	41-50	JI(Y)	Components of unit vector J.
	51-60	JI(Z)	
	63-65*	IFL	

If IFL = 0 This card contains the six components of the transformation matrix.

---

*Input for IFL is left-adjusted.

If IFL > 0   This card contains the three axes angles of rotation   to allow the program to calculate the transformation matrix.

IFL   is a three-digit coded number which specifies the desired order of rotation(s) using the code

$$1 \Longrightarrow x \text{ axis rotation, } \varphi \text{ degrees}$$
$$2 \Longrightarrow y \text{ axis rotation, } \theta \text{ degrees}$$
$$3 \Longrightarrow z \text{ axis rotation, } \psi \text{ degrees.}$$

Note: The program will calculate the unit vector K.

CARD(S) 19:   Wing Section Coefficients

If indicated by Card 13a, the half thickness (z) for the following chord locations are to be read $y = 0., \ldots$ and the leading edge radius of curvature. All data are read-in in terms of percent chord.

CARD 19a

Format	Column	Item
10F8.5	1-8	z_1, section half thickness, in percent chord.
	9-16	z_2

	73-80	z_8
CARD 19b	1-8	z_9
	9-16	z_{10}

	44-56	z_{15}
	57-63	R_{LE}, radius of curvature of section leading edge, in percent chord.

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CARD 20

End of input data card. The program will analyze as many cases as the user desires for each computer run. The program execution is terminated by end of case card.

Format	Column	Item
A3	1-3	END, causes program execution to terminate.

If additional cases are to follow in which a limited number of data cards are changed, Column 40 Card 3   0, the data are read into the program via a name list entitled CHNGE. The variables contained in the name list are described in the input cards. They are as follows: HEADER, IOPT, REC, UNITIC[*], UNITJC[*], ICONIC[**], PCRAT, TAME, PAMB, TAMB, EMAMB, GAMAMB, RAMAMB, CPINF, ITU, ITW, ITV, ISELT, RCL.

The program will continue to read cases in this manner until column 40 of Card 3 (IOPT(2) is set to zero or an END card is encountered.

4.2.2 INPUT FOR THE TAPE LISTER AND PLOT PROGRAM

This section of the computer program operates independently of the actual impingement analysis. The control routine is entitled LATER and it is called from Subroutine PLIMP (see Card 1). However, the routines used to print and plot the data are the same as those used by the impingement section of the program.

One data card is read by Subroutine LATER. The data are read using a namelist entitled INPT2. The variables contained in the namelist are:

---

[*]These variables are the data read in on Card 7. If the angles of rotation are being input, all three must be reset through the namelist input.

[**]The variable ICONIC contains the information read in on Columns 2-10, Card 13a.

IOPT, IPSLYM, PRATIO, RICH, PCRAT, ITPLOT, TUNIT, IRUN, ICON, ITHRU. See Table 5-2 for a description of the variables.

By use of the namelist, the user has the option to change any of the control variables listed above in order to examine the impingement from a different point of view. For instance, the user can: (1) non-dimensionalize the data; (2) reference the data to a different chamber condition; (3) plot the data; or (4) obtain a new listing.

Table 4-1

MAGNETIC TAPE ASSIGNMENTS FOR THE
PLUME IMPINGEMENT PROGRAM

PLIMP*	Tape Units U-1108	Tape Unit Function
Section 1 SORTCT Subroutine SORTCT is the controlling routine for this section which arranges the MOC output in the form used by the data acquisition routines. This section is used once per flowfield calculation.	10 8 2 3	Flowfield tape generated by MOC program—input. Flowfield data ordered for use by impingement analyses — output. Flowfield limits data — output. Scratch tape.
Section 2 IMPINGEMENT ANALYSIS This section performs the impingement analysis.	3 8 2 13 11 IUNIT	Scratch tape. Ordered flowfield data generated by Section 1 — input. Flowfield limits data generated by Section 1 — input. Coefficients data used in heating analysis — input. Scratch tape used by plot package. Variable tape unit number on which impingement data are to be stored.
Section 3 LATER This section of the program will print and/or plot impingement data stored on magnetic tape.	IUNIT 11	Variable tape unit number on which data are stored. Scratch tape used by plot package.

*Program operates as a composite package with the various sections called
by the control variables.

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Table 4-2

Description of the Namelist Variables Read by Subroutine LATER

Name	Dimension	Description
IOPT	16	See Card 5 of input guide
IPSLYM	14	See Card 8 of input guide
PRATIO	1	Engine chamber pressure, psi
RICH	1	Engine exit diameter, units consistent with the MOC flowfield solution.
PCRAT	1	See Card 10 of input guide
ITPLOT	1	Number of parameters to plot
TUNIT	1	1 - units of surface in feet 12 - units of surface in feet
IRUN	10	IRUN(4) and IRUN(5) are input in columns 75 and 80 of Card 8 of the input guide
ICON	16	ICON(12) is greater than zero if a curve is to be drawn through the plotted data
ITHRU	1	Not presently used

Section 5

METHOD-OF-CHARACTERISTICS PLOT PROGRAM

The Method-of-Characteristics Plot Program (Ref. 10) was developed for plotting flowfield properties, i.e., Mach number, static pressure, static temperature, pitot pressure, gamma, molecular weight, density, entropy, mass flow streamlines, heat rates, velocity, oxidizer-to-fuel ratio, characteristic lines and flow angle. The properties are plotted using the flowfield tape output by the Variable O/F Method-of-Characteristics (MOC) Program described in Volumes I and III of this report (Refs. 5 and 9).

The basic program consists of 30 separate routines to perform various flow property calculations, shock calculations, and tape search and plotting operations. The flowfield characteristic lines are searched point by point for lines of constant properties (contours). Once located the contours are output on SC 4020 plots and as printed output.

An additional plot program is under development which will plot radial distributions of flowfield properties at fixed axial stations (Ref. 3).

5.1 BASIC CAPABILITIES AND LIMITATIONS

The program is:

1. Able to pick out sections of plume which may be plotted. This is obtained by selecting the minimum and maximum radial and axial coordinate range within which the program will consider data for plotting.

2. Able to plot any combination of the 14 flowfield properties.

3. Capable of speeding up plotting by plotting every N^{th} characteristic where N is input via ICON(2).

4. Able to setup the isovalue contour values to be plotted for each property, or the isovalue contour values may be input.

5. Capable of plotting shock, input and boundary points.

6. Capable of plotting properties with the R and X coordinates non-dimensionalized or normalized in the form R/REFD and X/REFD, where R and X are the coordinates as read from flowfield tape and REFD is a factor read in from Card 5.

7. Designed so that axial coordinates may also be offset or shifted by a reference distance, REFL (Card 5). This is useful for nozzle/flowfield plumes where the origin is desired at the exit plane of the nozzle. By inserting the nozzle length as REFL, the program will subtract the nozzle length from all X coordinates which in effect moves the origin from the nozzle throat to the exit plane.

8. Capable of outputting pressure, temperature and density in the nondimensionalized or normalized form of P/PREF, P_o*/PREF, T/TREF and ρ/RHOREF. P, P_o*, T, ρ represent pressure, pitot pressure, temperature and density. PREF, TREF and RHOREF are reference pressure, temperature and density as input from Card 5.

9. Designed so that program calculated contours can be rounded off using the input option IDIGIT or an option on Card 4.

10. Capable of plotting stagnation point heating rates assuming a constant O/F, frozen plume.

11. Capable of plotting mass flow streamline contours. Streamlines are output as percent of mass flow contours under which a certain percent of the total mass flow of the plume is passing. The streamlines are calculated using the mass flows which were written on the flowfield tape output by the Variable O/F Method-of-Characteristics program. The total mass flow passing through the nozzle must be input to obtain streamline plots.

12. Able to read input values for flowfield property contours in order to plot the user's predetermined contour values.

5.2 PROGRAM USAGE

The following subsection contains a detailed description of the input and output schemes utilized by the program.

5.2.1 Input Data Tape

This program requires an input tape on FORTRAN Unit 3 for input of the flowfield properties. It is mandatory that this tape be generated by the

Variable O/F Method-of-Characteristics Program, described in Refs. 5 and 9.

5.2.2 Card Input Instructions

Card 1

This card contains input options necessary to control program execution. (See Section 2.2.5 for a description of each input parameter.)

Format	Column/Option	Item Description
16I5	4-5/NFIND	
		Number of properties to be plotted (14 max) (i.e., pressure, Mach no., temperature, etc., Ref. Card 4).
	9-10/NUMBER	
		Number of contours plotted per property (20 max). Note: The program uses this option only if the number of contours per property are not specified on Card 4.
	15/IREF	
	0 -	Program plots dimensional values of pressure, density, temperature, or radial and axial station.
	1 -	Program will non-dimensionalize pressure, density, temperature or radial and axial stations using reference values as read in from Card 5.
	20/IWRITE	
	0 -	Not presently used.

Card 1 (Continued)

Format   Column/Option   Item Description

1615   21-25/ISTART

The number of the characteristic line at which the program will begin searching for contour points.

30/IAXO2D

Flowfield type

0 - Flow field is two-dimensional

1 - Flow field is axisymmetric

35/IDIGIT

The number of significant places retained for property contours values, (max of 5), if IDIGIT is input as 0 to the program will set IDIGIT to 3 automatically. An option on Card 4 may override this option for each individual property.

39-40/ICARD

This option allows the property contours to be read in from cards. ICARD is the total number of properties whose contours are to be read in from cards. (Ref. Cards 4 and 6).

45/IALL

0 - If the program is to setup any of the property contour values Card 2 is to be read in.

1 - All the contours for each property will be input using Cards 6.

50/IMASS

0 - Not presently used.

55/IRUN(6)

0 - Not presently used.

Card 1 (Continued)

Format	Column/Option	Item Description
16I5	60/ICON(2)	

        0 - Program searches every characteristic line for contour values.

        N - (N-1) Number of characteristics lines skipped between searches.

Card 2

This card reads in maximum and minimum flow properties for use in setting up contours. These values should be based on the flowfield region which is to be mapped. Use this card only if IALL was set to zero.

Format	Column	Item	
8E10.6	1-10	EMMAX	- Maximum Mach Number
	11-20	EMMIN	- Minimum Mach Number
	21-30	SMAX	- Maximum Entropy
	31-40	SMIN	- Minimum Entropy
	41-50	THETMX	- Maximum Flow Angle (Degrees)
	51-60	THETMN	- Minimum Flow Angle (Degrees)
	61-70	OFM	- Maximum O/F Ratio
	71-80	OFN	- Minimum O/F Ratio

Card 3

This card contains the necessary information for setting up the maximum and minimum radial and axial coordinates within which the program will operate.

Format	Column	Item	
8E10.6	1-10	RMIN	- Minimum Radial Coordinate
	11-20	RMAX	- Maximum Radial Coordinate
	21-30	XMIN	- Minimum Axial Coordinate
	31-40	XMAX	- Maximum Axial Coordinate

Note: The units should be consistent with those on the flowfield tape.

Card 4

This card is the plot control card which identifies the properties to be plotted, sets the number of contours for each property and sets the number of significant places to be used for each set of property contours.

The first column of each 5-column array will determine the number (5 max) of significant figures the particular set of property contours will have. If a zero is used, the number of significant figures will be set equal to IDIGIT. The second and third column will set the number (20 max) of contours to be plotted. The fourth and fifth column will identify the property to be plotted.

Format	Column/Property	Item
1 6I5/Right Adjusted		J
	4-5/J	1 - Mach Number
	9-10/J	2 - Pressure-Static
	14-15/J	3 - Temperature-Static
	19-20/J	4 - Pressure (Stag Norm Shock)
	24-25/J	5 - Gamma
	29-30/J	6 - Molecular Weight
	34-35/J	7 - Density
	39-40/J	8 - Entropy
	44-45/J	9 - Mass Flow
	49-50/J	10 - Heat Rate
	54-55/J	11 - Velocity
	59-60/J	12 - O/F Ratio
	64-65/J	13 - Characteristic Lines
	69-70/J	14 - Flow Angle

Note: The order of these properties is arbitrary except that those properties whose contours are to be read in from cards must follow all the properties whose contours are to be selected by the program (Ref. Card 6).

Example: Flow angle and Mach number are desired with
2 significant figures for both properties and
20 flow angle contours set by the program and
9 Mach number contours read in from a card.

Cols. 1 2 3 4 5 6 7 8 9 10

       2 2 0 1 4 2 0 9 0 1

Flow Angle   Mach No.

5-7

Card 5

This card is used if IREF is set to 1. This card contains information the program may use in referencing pressure, density, temperature and radial/axial stations, (i.e. plots P/P_{ref} instead of P).

Format	Column		Item
8E10.6	1-10	RHOREF -	Reference Density by Which Density Contours are Divided After Contour Points are Found.
	11-20	PREF -	Reference Pressure by Which Pressure Contours are Divided After Contour Points are Found.
	21-30	TREF -	Reference Temperature by Which Temperature Contours are Divided After Contour Points are Found.
	31-40	REFD -	Reference Distance by Which Axial and Radial Lengths are Divided After a Contour Point is Found.
	41-50	REFL -	A Reference Distance by Which the Axial Location of the Origin is Shifted.

NOTE: If any of the variables are not to be normalized use a 1.0 except for REFL which should be a 0.0.

Card(s) 6

These cards are used to read in contours for desired properties. Each card may contain 8 contours and up to 20 contours may be read in for each property. The total number of sets of these cards must equal ICARD. Arrange the sets in the same order in which the properties are read from Card 5, the plot control card. Use these cards only if ICARD was set greater than zero.

Format
8E10.6

Example: Use example for Card 4. Flow angle and Mach number are to be plotted. ICARD is set to 1, therefore flow angle contours will be set up by the program and Mach number contours will be read in from cards. Since nine contours are desired for Mach number, two cards are necessary.

Card 6a

Column	Mach No. Contour
1-10	2.0
11-20	4.0
21-30	6.0
31-40	8.0
41-50	10.0
51-60	12.0
61-70	14.0
71-80	16.0

Card 6b

Column	Mach No. Contour
1-10	18.0

Card 7

This card is used to read in the total mass flow for finding mass flow streamlines. Set WTFLOW to the total mass flow as output by MOC program. Use this card only if mass flow streamlines are to be plotted.

Format	Column	Item
8E10.6	1-10	WTFLOW - The Total Mass Flow Passing Through the Nozzle.

Card 8

This card is used to read in information necessary for computing stagnation heating rates in the plume. (Assuming frozen chemistry and constant O/F ratio throughout plume.) Use cards 8 and 9 only if heating rates are to be plotted. (See Sections 5.2.5 and 5.2.6)

Format	Column	Item
I5, 5X, 7E10.6	5	NNN - Number of Nth Chemical Specie of Flow Field Gas. N is the Highest Non-Zero Mole Fraction of the Species as Follows:

N
1 - CO_2
2 - H_2
3 - H_2O
4 - HI
5 - OH
6 - CO
7 - N_2
8 - O_2

	11-20	AMWE - Molecular Weight of the Mixture.
	21-30	TWALL - Wall Temperature (^{O}R)
	31-40	TD - Temperature of Gas at the Stagnation point for Onset of Dissociation (^{O}R).
	41-50	RB - The Reference Radius (r^*) at the Stagnation point for Use in Velocity Gradient Calculation.
	51-60	FUDGE

1 - r^* Input in ft
12 - r^* Input for in.

61-70 SHAPE

1.414 - Hemisphere
1.414 - Circular Disc
1.000 - Cylinder
1.000 - Flat Plate

V → RB

Stagnation Point

5-10
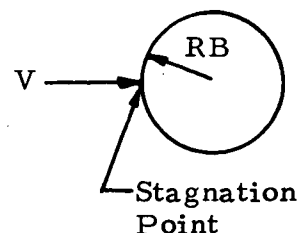
Card 9

This card reads the mole fractions of the flowfield gas composition. There are presently eight of the most common constituents being considered and they must be input in the correct order. The sum of the mole fraction must equal one (1).

Format	Column*	Item
8E10.6	1-10	CO_2 Mole Fraction
	11-20	H_2 Mole Fraction
	21-30	H_2O Mole Fraction
	31-40	H_1 Mole Fraction
	41-50	OH Mole Fraction
	51-60	CO Mole Fraction
	61-70	N_2 Mole Fraction
	71-80	O_2 Mole Fraction

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* If species other than these are required, the data statements in subroutine PROPTY must be changed.

5.2.3 Program Output

The printed output of the program begins with the gas property tables as read from the flowfield tape. The second and third pages contain print-outs of input data. The fourth page contains contours for each property. The units of all the printout are consistent with those of the Method-of-Characteristics (MOC) program. The remainder of the printout is explained in the following list in order of printout proceeding across the page.*

LINE — The characteristic line on which the contour point was found. For upper and lower wall points the contour point was actually found between the line number printed out and the previous line.

POINT } — The two characteristic points between which the contour
POINT } point was found.

IFIND — The property being plotted.

R — Radial Coordinate of the contour point. If distance was to be non-dimensionalized the radial coordinate will be R/REFD.

X — The axial coordinate of the contour point. If distance was to be non-dimensionalized the axial coordinate will be X/REFD. If the axial coordinates were to be shifted by REFL the axial coordinate will be (X-REFL)/REFD.

P — Value of the property contour; i.e., T, ρ, P, M

POPREF — If pressure, density or temperature were to be non-dimensionalized (POPREF) will be P/PREF, P/RHOREF or P/TREF, otherwise, POPREF will be the same as P.

The next figure encountered is the plotting symbol of the contour.

The next column indicates whether the contour point is an upper-wall, a lower wall or an interior contour point. There is no printout for an interior point. If the point is an upper or lower wall point the point is flagged as such.

_____

*See Section 2.8 of Ref. 10 for example of output.

The last column is a counter on the number of contour points the program has found. When 200 points have been found the program plots these points then starts searching for additional contour points. The program is not limited to 200 contour points for each property.

For characteristic line plots there is no printout other than a statement saying that the plotting of characteristic lines is complete.

The program output for mass flow streamlines is explained with the following list in order of printout across the page

LINE — The characteristic line on which the streamline point was found

$\left.\begin{array}{l} I \\ I+1 \end{array}\right\}$ — The two characteristic points between which the streamline point was found.

WDOT — The percent mass flow streamline of which the point is a part. A mass flow streamline is defined as a streamline under which flows a certain percent of the total mass flow passing through the nozzle.

Note: In the case of an inverted plume the actual percent mass flow streamline will be (1.-WDOT), i.e., if WDOT is printed out .90, the real WDOT will be .10.

R — The radial coordinate of the streamline point. If distance was to be non-dimensionalized, the radial coordinate will be R/REFD.

X — The axial coordinate of the streamline point. If distance was to be non-dimensionalized, the axial coordinate will be X/REFD. If the axial coordinate was to be shifted at REFL, then X = (X-REFL)/REFD.

5.2.4 SC 4020 Output

Part of the output of the Variable O/F Plot Program consists of SC 4020 plots. Typical output consists of a title frame, an index frame and grid frame for each property, a frame with boundary, shock and input points, and the closing or ENDJOB frame. (See Section 2.8 Ref. 10 for example of output.)

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The first frame or title frame contains the name of the programmer, the distribution code, the run ID, the job number and the date and time.

The next frame is a list of the values and corresponding symbols for each contour of the first property. The following frame contains the actual contour plots for the property. Each property will consist of the above two frames except characteristic plots which will not have the index of contours frame. After the last property is plotted the program outputs a frame with shock, boundary and input points plotted.

The closing frame contains the statement ENDJOB and the run ID. This indicates to the computer that plotting for the particular run has been terminated.

5.2.5 Description of FORTRAN Input/Output Symbols

The following is a list of each program input and output symbol along with a description, use and the units of the symbol. The symbols are listed in the same order in which they are input and output by the program.

FORTRAN Symbol	Description	Units (if applicable)
NFIND	The total number of properties which are to be plotted by the program. Characteristic lines are considered to be a property. NFIND is used by the program as a limit on do-loops to read in information on each property.	N/A
NUMBER	The total number of contours to be calculated for each property (20 max). If not set, the program will assume 20. The program will use this number only if the number of contours per property are not specified on Card 4. The number of contours for each property is stored in the LAP(I) array then recalled when plotting for the specific property begins.	N/A

FORTRAN Symbol	Description	Units (if applicable)
IREF	Determines whether the program plots dimensional values of pressure, temperature, density, or radial and axial station, or non-dimensional values using reference values as read in from Card 5.	N/A
IWRITE	A flag which determines if the program should print out information at intermediate points in the program. This is useful for program checkout.	N/A
ISTART	The number of the characteristic line at which the program will begin searching for contour points.	N/A
IDIGIT	The number of digits retained for property contour values (max. 5). If input as 0, the program will select 3 automatically. This value will be used only if not specified on Card 4.	N/A
ICARD	The total number of properties whose contours are to be read in from cards. ICARD is used by program to read in property contours from cards. Also allows the program to skip contour calculations for input property contours.	N/A
IALL	IALL is a flag which tells the program whether all property contours are to be read in from cards or contours will be set up by program. If any contours are to be set up a 0 will tell the program to read in max and min properties from Card 2. If a 1 is used the program will not read in the properties and will also skip contour calculations.	N/A
IRUN(6)	A flag which informs the program whether or not flow properties are printed out at mass flow streamline points. A 1 will allow printout and a 0 will not allow printout.	N/A
ICON(2)	ICON(2) is a parameter which allows the program to skip characteristic lines between searches for contour points. The program increments the first characteristic line (ISTART) with ICON(2) and skips characteristic lines until the (ISTART + ICON(2)) line is reached at which point the program again starts searching for points. The process is repeated after each search.	N/A

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FORTRAN Symbol	Description	Units (if applicable)
EMMAX	The maximum Mach number which is expected to be encountered in the plotted region of the plume. The program uses the difference in Mach number between EMMAX and EMMIN in setting up contours.	N/A
EMMIN	The minimum Mach number which is expected to be encountered in the plotted region of the plume.	N/A
SMAX	The maximum entropy which is expected to be encountered in the plotted region of the plume. Like Mach number, the program uses the difference in SMAX and SMIN in setting up contours.	$ft^2/sec^2-°R$
SMIN	The minimum entropy which is expected to be encountered in the region of the plume to be plotted.	$ft^2/sec^2-°R$
THETMX	The maximum flow angle which is expected to be encountered in the region of plume to be plotted. The program uses the difference between THETMX and THETMN in setting up flow angle controls.	deg
THETMN	The minimum flow angle which is expected to be encountered in the region of the plume to be plotted.	deg
OFM	The maximum O/F ratio which is expected to be encountered in the region of the plume to be plotted. Like Mach number and entropy, the program uses the difference between OFM and OFN in setting up contours.	N/A
OFN	The minimum O/F ratio expected to be encountered in the region of the plume to be plotted.	N/A
RMIN	The minimum radial coordinate of a characteristic point that will be considered by the program in locating contour points. RMIN is also used by the program in the plotting routines for setting the minimum radial coordinate on the SC 4020 plots.	Consistent with the units output by MOC

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FORTRAN Symbol	Description	Units (if applicable)
RMAX	The maximum radial coordinate of a character-istic point that will be considered by the program in locating contour points. RMAX is also used by plotting to set up the maximum radial coordinate on the SC 4020 plots.	Consistent with the units output by MOC
XMIN	The minimum axial coordinate of a character-istic point that will be considered by the program in locating contour points. XMIN like RMAX and RMIN is used by plotting routines in setting the minimum axial coordinate on the SC 4020 plots.	Consistent with the units output by MOC
XMAX	The maximum axial coordinate of a character-istic point that will be considered by the program in locating contour points. Also used by plot routines in setting the maximum axial coordinate on the SC 4020 plots.	Consistent with those output by MOC
ICURVE(I)	A 5 digit array for each property to be plotted. The program uses this array to determine the property to be plotted, the number of contours to be set up or read in from cards and the number of significant decimal places each contour will have. The first digit in the array is set to IDIGIT and will be used for the number of significant places each contour will have. The second and third digit is the number of contours (NUMBER) that will be set up by the program or the number of contours to be read in from cards, the fourth and fifth digit is the number identifying the property to be plotted (see Card 4 of input instructions).	N/A
RHOREF	Reference density by which density contours are divided after contour points are found. The program uses RHOREF to obtain normalized density (POPREF) of the printed output and the index of contours on the SC 4020 plots.	$slug/ft^3$
PREF	Reference pressure by which pressure contours are divided after contour points are found. Like RHOREF the program uses PREF to obtain normalized pitot pressure and static pressure, listed under POPREF, of the printed output and normalized table of contours on the SC 4020 plots.	psfa

FORTRAN Symbol	Description	Units (if applicable)
TREF	Reference temperature by which temperature contours are divided after contour points are found. Like PREF and RHOREF, the program uses IREF to obtain normalized temperature contours, listed under POPREF of the printed output and normalized table of contours of the SC 4020 plots.	^{o}R
REFD	Reference distance by which all axial and radial coordinates of contour points are divided before being printed out by program. The program uses REFD to output all contour points in the form R/REFD and X/REFD where R and S represent the actual coordinates as they appear on the MOC input tape.	As desired by user
REFL	A reference length by which the axial location of the origin is shifted. This is accomplished by subtracting REFL from the axial coordinate of all the contour points. The origin is thus shifted REFL to the right.	Consistent with those output by the MOC program
WTFLOW	The total mass flow passing through the nozzle as output by the MOC program.	lb_m/sec (assumes R, X are in feet)
NNN	The number of the Nth chemical specie of the const O/F frozen flow field gas. N is the highest non-zero mole fraction of the species listed on page	N/A
AMWE	The molecular weight of the frozen gas mixture which constitutes the flow field plume.	N/A
TWALL	The initial skin temperature of the body at which heating rates are desired. $500^{o}R$ is a typical value of TWALL	^{o}R
TD	The temperature of the gas in the boundary layer at the stagnation point at onset of dissociation. This temperature is defined as the temperature at which the molecular weight starts to deviate by more than 1% of the wall value.	^{o}R
RB	The reference radius at the stagnation point for use in velocity gradient calculations. A general value of RB is considered to be 1.0 ft.	ft or in.

FORTRAN Symbol	Description	Units (if applicable)
P	The numerical value of the property contour	Pressure-psfa Temperature-$^{\circ}$R Density-slugs/ft^3 Entropy-ft^2/sec^2-$^{\circ}$R Heat Rate-Btu/ft^{2}sec Velocity-ft/sec Flow Angle-deg $R - \dfrac{1545. \times 32.17}{MWT}$
POPREF	Non-dimensionalized or normalized form of P in the form P/PREF is pressure, T/TREF is temperature and P/RHOREF is density. If the property was not to be non-dimensionalized (TREF = 0, Card 1) POPREF will be the same as P.	Same as above unless P was to be non-dimensionalized
AA	The 4020 plotting symbol of the contour point.	N/A
BOUT	Type of contour point. Upper wall or lower wall if the contour point is an interior flowfield point nothing will be printed out for BOUT.	N/A
KSAV	The number of contour points which the program has located. After 200 points have been found the counter is reset to zero and the previous 200 points are plotted before continuing.	N/A
LINE	The characteristic line number on which the mass flow streamline point was located. (Mass flow output)	N/A
I I+1	The two characteristic points between which the streamline point was found. (Mass flow output)	
XM	The percent mass flow streamline	N/A

FORTRAN Symbol	Description	Units (if applicable)
FUDGE	If RB is in ft then FUDGE is a 1.0. If RB is in inches then FUDGE is a 12.0. FUDGE is a conversion factor between feet and inches.	in/ft ft/ft
SHAPE	The type of nose shape which the plume is impinging on. For a hemisphere and circular disc a value of 1.414 should be used and for a flat plate and cylinder a 1.000 should be used. The heating rates calculated by the program are for a sphere. Shape corrects the calculated heating rates for bodies other than spheres.	N/A
XMFW(10)	The mole fractions of the species making up the plume flowfield.	N/A
LINEN	The characteristic line on which the contour point was found. This number is listed under line under the output. For upper and lower wall points the contour point was actually located between the line number printed out and the previous line.	N/A
JJ, IK	The two characteristic points between which the contour point was located. These numbers are listed under point on the printed output.	N/A
AOUT	The name of the property contour point being plotted. Listed under IFIND on the printed output.	N/A
RP	The radial coordinate of the contour point in the normalized form R/REFD. If the radial and axial coordinates were not to be normalized this coordinated will correspond to the actual plume coordinate as input from the flowfield tape. RP is printed out under R.	If R is not normalized the units will be same as MOC.
XP	The axial coordinate of the contour point in the normalized form (X-REFL)/REFD, where X is the actual coordinate as obtained from MOC tape, REFL is the distance by which the origin is shifted and REFD is the distance scale factor. XP is printed out under X.	If X is not normalized the units will be same as MOR

FORTRAN Symbol	Description	Units (if applicable)
R	The radial coordinate of the streamline point in the normalized form R/REFD. If the radial and axial coordinates were not to be normalized this coordinate will correspond to the actual plume coordinate as input from the flowfield tape.	If R is not normalized the units will be same as MOC
X	The axial coordinate of the streamline point in the normalized firm (X-REFL)/REFD, where X is the actual coordinate as determined from the flowfield, REFL is the distance by which the origin is shifted and REFD is the distance scale factor.	If X is not normalized the units will be same as MOC

5.2.6 Helpful Hints

This subsection is intended to help the user avoid some common pitfalls which can be encountered while using the plot program. Included are some hints, common problems and some suggested solutions to certain problems.

- If it is desirable to non-dimensionalize or normalize a property or parameter using Card 5, it is important to set any reference value which is not used to 1.0. The exception is REFL which should be input as 0.0 if it is not desired to offset the origin.

- The properties whose contours are to be read in from cards must occur last on Card 4 in the same order in which the sets of cards (Cards 6) are placed in the data. The number of contours for each property (from cards) on Card 4 should be the same as the number of contours on Card(s) 6 for that property.

- The program uses Mach number, entropy and O/F rates from Card 2 to set up contours. The program is sensitive to O/F rates in setting up contours. This may result in a flowfield property contour map that does not satisfactorily map the plume. When this occurs, it is best to input contours for the property which will fill in any large voids in the mapped plume.

    Note: Do not input a subsonic Mach number or the program will error off.

- The heating rate calculations made by the program are stagnation heating rates assuming a constant O/F and frozen flow. The species concentrations which should be input are the mole fractions of the species after the flow has frozen. The wall temperature (TWALL) referred to in the input guide is the ambient wall temperature of the object at which the heating rates are desired. A commonly used value of TWALL is $500^{\circ}F$. A common value of RB, the nose radius is 1 ft. The heating rates output for a 1 ft. radius will be the heating rates encountered on a 1 ft. radius sphere located at any particular point in the plume. Heating rate calculations using variable O/F are not made because of the detail required to perform the calculations.

- There may be instances when a flow field tape goes bad and the plot program will be unable to read it. When this occurs an I/O error or a list exceeds logical record length error will be indicated in either sub-routine GTAP or READF. Resubmit the run. If the same error is encountered again, regenerate the flow-field tape.

- When the program errors off the first area to check is the input data. If any extra cards are used the program will probably error off.

5.2.7 Deck Setup (1108 Exec VIII)

```
                                    ∇FIN
                              ∇FIN
                        DATA DECK
                   ∇XQT,D
                ∇PRT,T
             ∇FREE PLOT
          ∇COPIN  PLOT,TPF
       ∇MOVE PLOT, 1
    ∇USE 3, FLOW
  ∇ASG,T FLOW,T,34914
 ∇ASG,TM PLOT,T,30777
∇RUN,T
```
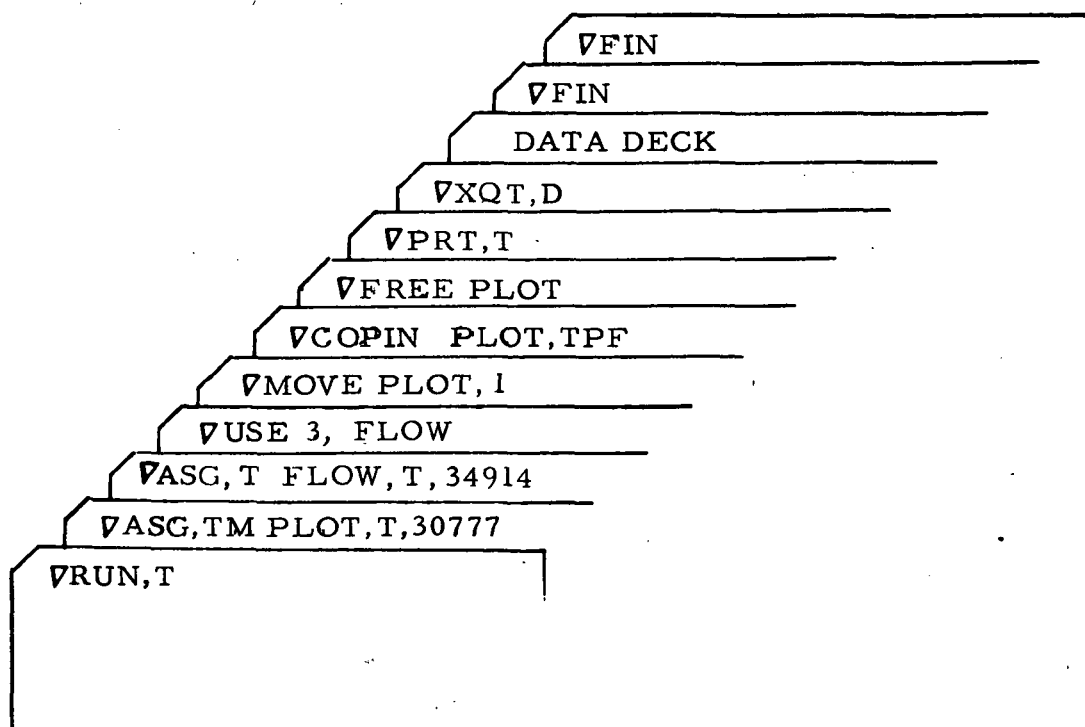
Notes:

(1) ∇ = 7/8 punch

(2) The plot program is assumed to be on the second file of tape 30777

(3) FORTRAN Unit 3 is the input unit for the flowfield type 34914

(4) The XQT, D option tells the operator to mount a plot tape for 4020 output.

Sample SC 4020 output of the plot program is contained on the following two pages.

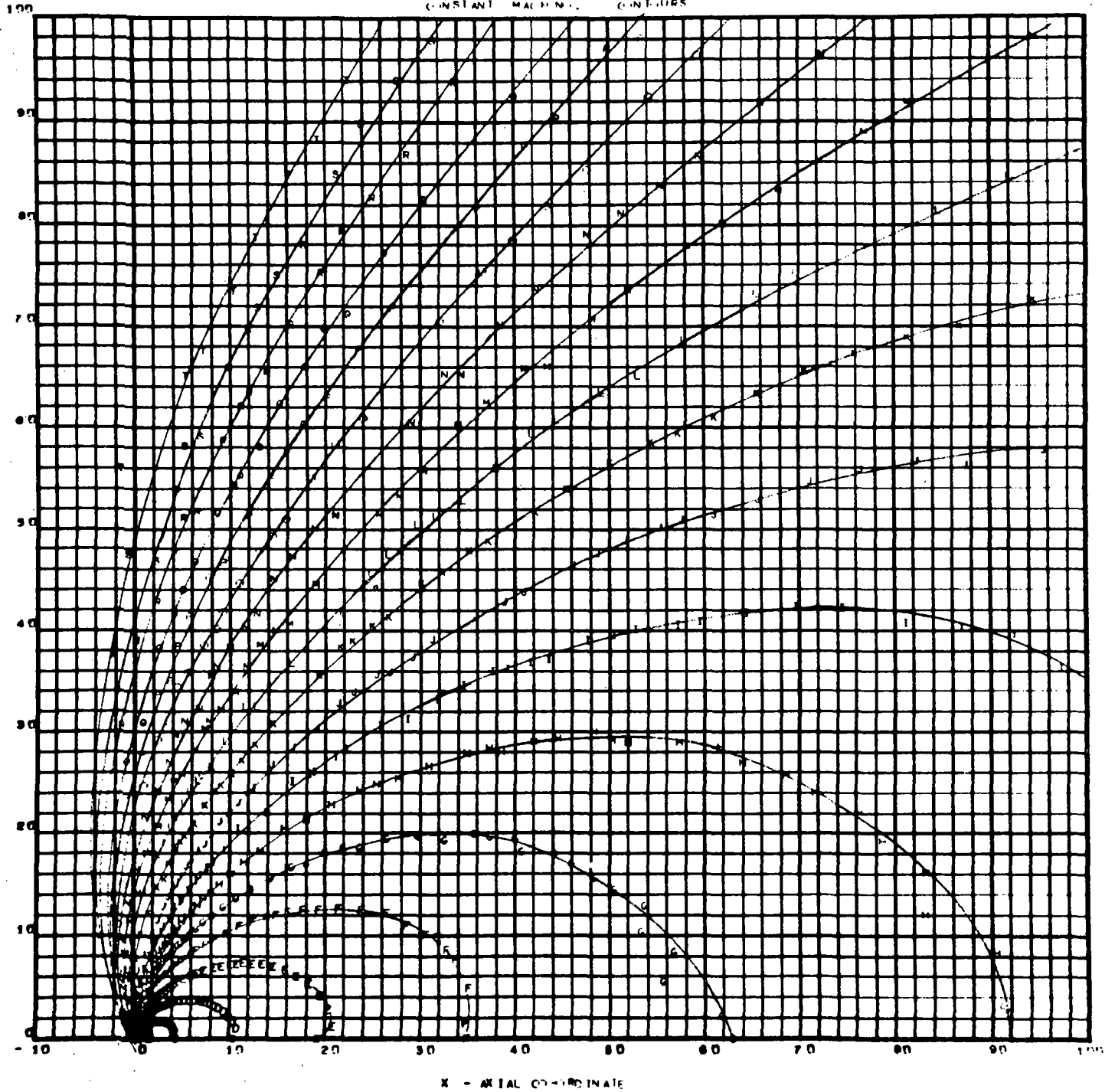VARIABLE O/F IBFF FLOW FIELD STUDY - SCALE J2 ENGINE - 6 INCH EXIT DIA. NO. 479370   PAGE   3

CONSTANT MACH NO.   CONTOURS

VALUES	SYMBOL
$1.50000 \times 10^{+00}$	A
$2.67500 \times 10^{+00}$	B
$3.85000 \times 10^{+00}$	C
$5.02500 \times 10^{+00}$	D
$6.20000 \times 10^{+00}$	E
$7.37500 \times 10^{+00}$	F
$8.55000 \times 10^{+00}$	G
$9.72500 \times 10^{+00}$	H
$1.09000 \times 10^{+01}$	I
$1.20750 \times 10^{+01}$	J
$1.32500 \times 10^{+01}$	K
$1.44250 \times 10^{+01}$	L
$1.56000 \times 10^{+01}$	M
$1.67750 \times 10^{+01}$	N
$1.79500 \times 10^{+01}$	O
$1.91250 \times 10^{+01}$	P
$2.03000 \times 10^{+01}$	Q
$2.14750 \times 10^{+01}$	R
$2.26500 \times 10^{+01}$	S
$2.38250 \times 10^{+01}$	T

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VARIABLE O/F 1FF FLOW FIELD STUDY - SCALE J2 ENGINE - 6 INCH

X - AXIAL CO-ORDINATE

Section 6
CEC – A COMPUTER PROGRAM FOR THE CALCULATION OF CHEMICAL EQUILIBRIUM COMPOSITIONS WITH APPLICATIONS

The CEC (Ref. 2) program provides a means for computing chemical equilibrium in complex systems. The equilibrium compositions are obtained by a Newton-Raphson iteration. The iteration equations are those of the modified Huff method and are independent of choice of components. The program permits calculations such as: chemical equilibrium for assigned temperatures and pressures; theoretical rocket performance for both frozen and equilibrium compositions during expansion; and Chapman-Jouquet detonation properties. The basic CEC program has been modified to output the equilibrium rocket expansion on tape and in card form for use with the VOFMOC program (Ref. 5).

6.1   DESCRIPTION OF CEC PROGRAM INPUT

Program input data for a computer program for the Calculation of Chemical Equilibrium Compositions with Applications (CEC) are discussed under four categories.   Three of the categories are required and one is optional. The three required categories and the code names by which they are referred are: (1) Library of thermodynamic data for reaction products (THERMO data); (2) Data pertaining to reactants (REACTANTS cards); and (3) Namelist data which include the type of problem, required schedules, and options (NAMELISTS Input).   The optional category of data are chemical formulas of species which are singled out for special purposes (OMIT and INSERT cards).

The words THERMO, REACTANTS, NAMELISTS, OMIT and INSERT are control codes used by the program to identify the input read from data cards. The THERMO, REACTANTS, and NAMELISTS codes are punched on separate cards, each preceding their appropriate data cards.   The OMIT and INSERT codes are on the same card as the data.

6-1

The required order of the data cards is:

1. THERMO code card
2. THERMO data (these cards and the preceding THERMO code card may be omitted if the data are to be read from tape).
3. REACTANTS code card
4. REACTANTS cards
5. OMIT and INSERT cards (if any)
6. NAMELISTS code card
7. NAMELISTS data

In a particular run, there may be any number of sets of REACTANTS cards (items 3 and 4 above), each followed by any number of sets of NAMELISTS input (items 6 and 7 above).

6.1.1 THERMO Data

The library of thermodynamic data for reaction products may be read either from cards or from tape. If the data are read in from cards, the program will write these data on tape 12. During a computer run, the appropriate reaction product data for each new set of REACTANTS cards will be selected from tape 12 and stored. THERMO data my be read in from cards for each run. However, a permanent tape or disc containing the data may be made during any run by using the required type of control cards preceding the operating deck. Two advantages of using a permanent tape or disc is that the scratch tape will not be made for each run and handling the cards is eliminated.

6.1.2 REACTANTS Cards

This set of cards is required for all problems. The first card in the set contains the word REACTANTS punched in card columns 1-9. The last card in the set is blank. In between the first and last cards may be any number of cards up to a maximum of 15, one for each reactant species being considered. Details on the preparation of the cards are given in Table 6-2. Except for the first card, which contains the code REACTANTS, the cards are the same as the cards required for the program described in NASA TN D-1454 and TN D-1737.

6.1.3   NAMELIST Input

The program contains two namelists for input. Namelist INPT2 is required for all problems, while namelist RKTINP is required only for the RKT problem.

Namelist INPT2 must be preceded by a card with NAMELISTS punched in card columns 1-9. A list of variables and their definitions for INPT2 is given in Table 6-3.

The first namelist, INPT2, must indicate:

1. the type of problem (TP, HP, RKT, or DETN),
2. at least one pressure (P) for any type of problem,
3. at least one temperature for assigned temperature problems (TP and RKT with an assigned chamber temperature),
4. the relative amounts of fuel(s) and oxidant(s).

Relative amounts of fuel(s) and oxidizer(s) — These quantities may be specified by assigning a value for either OF, FPCT, FA or EQRAT. If no value is assigned for any of these, the program assumes the relative amounts of fuel(s) and oxidizer(s) to be those specified on the REACTANTS cards.

Pressure units — The program assumes the pressures in the P schedule to be in units of atmospheres unless either PSIA = T or MMHG = T.

TP Problem — Thermodynamic properties will be calculated for all combinations of assigned values for pressure P and temperature T in the schedules. Thus, if 26 T values and 26 P values are included in the INPT2 list, properties will be calculated for 676 P and T combinations.

HP Problem — Combustion temperature and corresponding properties will be calculated for each pressure in the P schedule.

DETN Problem — The temperatures and pressures in the T and P schedules refer to the unburned gas.

If no T value is given in the schedule, the program uses the temperature and enthalpies on the reactant cards. When T values are assigned in the INPT2 schedule, the program calculates the enthalpy from the library of THERMO data if the following two conditions are satisfied:

1. The reactant card has zeros punched in card columns 37 and 38.
2. The reactant is a species in the library of THERMO data.

RKT Problem — One pressure value P is required for the chamber pressure. The T schedule is used only if expansion from an assigned chamber temperature is desired (such as for a nuclear rocket). Otherwise it should be omitted.

The RKT problem requires a second namelist for input (RKTINP) discussed in the next section.

RKTINP namelist (RKT problems only) — This namelist is required for RKT problems. It follows the INPT2 namelist. A list of variables and definitions is given in Table 6-4.

The pressure ratio schedule (PCP) is the only variable in RKTINP which is required. All other variables are optional.

The program will calculate both equilibrium and frozen performance unless RKTINP contains FROZ = F or EQL = F. If FROZ = F, only equilibrium performance will be calculated. If EQL = F, only frozen performance will be calculated.

The subsonic area ratio values (SUBAR) and/or the supersonic area ratio values (SUPAR) are optional. When assigned area ratios are included, the PCP schedule should contain values of pressure ratios whose corresponding ratios will be in the range of the assigned area ratios.

To generate a thermochemical data tape MOCT must be set equal to 1. The data are then output on tape unit 9. If it is desirable to have the thermochemical data punched on cards simultaneously or in place of making the tape, MOCP must be set equal to 1. Both variables are preset equal to 0 before the data are read in.

If it is desirable to use the pressure freeze option, the variable PCEF must be set equal to the chamber pressure to local pressure ratio at which chemical freezing is desired.

6.1.4 Omit and Insert Cards

OMIT and INSERT cards are optional. They contain the names of particular species in the library of thermodynamic data for the specific purposes discussed below. Each card contains the word OMIT (in card columns 1-4) or INSERT (in card columns 1-6) and the names of from 1 to 4 species starting in columns 16, 31, 46, and 61. The names must be exactly the same as they appear in the THERMO data.

OMIT cards — These cards list species to be omitted from the THERMO data. If OMIT cards are not used, the program will consider as possible species all those species in the THERMO data which are consistent with the chemical system being considered. Occasionally it may be desired to specifically omit one or more species from considerations as possible species. This may be accomplished by means of OMIT cards.

INSERT cards — These cards contain the named condensed species only. They have been included as options for two reasons.

The first and less important reason is that if one knows that one or several particular condensed species will be present among the final equilibrium compositions for the first assigned point, a small amount of computer time can be saved by using an INSERT card. Those condensed species whose chemical formulas are included on an INSERT card will be considered by the

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program during the initial iterations for the first assigned point. If the INSERT card were not used, only gaseous species will be considered during the initial iterations. However, after convergence, the program will automatically insert the appropriate condensed species and reconverge. Therefore, it usually is immaterial whether or not INSERT cards are used. For all other assigned points the inclusion of condensed species is handled automatically by the program.

The second and more important reason for including the INSERT card option is that, in rare instances, it is impossible to obtain convergence for assigned enthalpy problems (HP or RKT) without the use of an INSERT card. This occurs when, by considering gases only, the temperature becomes extremely low (say several degrees Kelvin). In these rare cases, the use of an INSERT card containing the name of the required condensed species will eliminate this kind of convergence difficulty. When this difficulty occurs, the following message is printed by the program: "LOW TEMPERATURE IMPLIES CONDENSED SPECIES SHOULD HAVE BEEN INCLUDED ON AN INSERT CARD."

6.1.5 Data Generation For Use With Variable O/F Method-of-Characteristics Program

Data can be generated for use with the variable O/F method-of-characteristics program in either card form (punched data) or on magnetic tape. These options can be used simultaneously or individually. To generate punched data the variable MOCP is set to one in $INPT2 NAMELIST list. To generate data on magnetic tape, the variance melt is set to one on the same NAMELIST. In either instance the O/F ratio data sets must be input to the CEC program with the O/F values in ascending order to be compatible with the VOFMOC programs gas data continued.

Table 6-1

THERMO DATA CARDS

Order	Contents	Format	Card Column
1	THERMO	3A4	1-6
2	Temperature ranges for 2 sets of coefficients: lowest T, common T, and highest T	3F10.3	1-30
3	Species name	3A4	1-12
	Date	2A3	19-24
	Atomic symbols and formula	4(A2, F3.0)	25-44
	Phase of species (S, L, or G for solid, liquid, or gas respectively)	A1	45
	Temperature range	2F10.3	46-65
	Integer 1	I15	80
4	Coefficients a_i (i = 1-5) in equations 1-4 for upper temperature interval)	5(E15.8)	1-75
	Integer 2	I5	80
5	Coefficients in equations 1-4 (a_6, a_7 for upper temperature interval and a_1, a_2, and a_3 for lower)	5(E15.8)	1-75
	Integer 3	I5	80
6	Coefficients in equations 1-4 (a_4, a_5, a_6, a_7 for lower temperature interval)	4(E15.8)	1-60
	Integer 4	I20	80
	Repeat cards numbered 1-4 in card column 80 for each species		
(final card)	END (Indicates end of thermodynamic data)	3A4	1-3

Table 6-2

REACTANT CARDS

Order	Contents	Format	Card Column
First	REACTANTS*	3A4	1-9
Any	One card for each reactant species (maximum 15). Each card contains:		
	(a) Atomic symbols and formula numbers (maximum 5 sets)	5(A2, F7.5)	1-45
	(b) Relative weights** or number of moles	F7.5	46-52
	(c) Blank if (b) is relative weights, or M if (b) is number of moles	A1	53
	(d) Enthalpy in calories/mole (not required for assigned tempera- ture problems, i.e., TP)	F9.5	54-62
	(e) State: S, L, or G for solid, liquid, or gas respectively	A1	63
	(f) Temperature associated with enthalpy in (d)	F8.5	64-71
	(g) F if fuel or O if oxidant	A1	72
	(h) Density in g/cc (optional)	F8.5	73-80
Last	Blank		

*All reactants must be given in relative weights or all in number of moles.
**Relative weight of fuel in total fuels or oxidant in total oxidants.

Table 6-3

VARIABLES IN INPT2 NAMELIST

Variable Name	Dimen.	Type	Common Label	Value before Read	Definition and Comments
KASE	--	I	INDEX	0	Optional assigned number associated with case
P	26	R	POINTS	0	Assigned pressures. Chamber pressure (one value) for rocket problems. Values in atm unless PSIA or MMHG = T (see below)
T	26	R	POINTS	0	Assigned temperature in °K
EQRAT	--	R	MISC	0	Equivalence ratio
OF**	--	R	MISC	0	Oxidant to fuel weight ratio
FPCT	--	R	MISC	0	Percent fuel by weight
FA	--	R	-----	0	Fuel to air weight ratio
TP	--	L	INDX	False	*Assigned temperature and pressure problem
HP	--	L	INDX	False	*Assigned enthalpy and pressure problem
RKT	--	L	-----	False	*Rocket problem
DETN	--	L	-----	False	*Detonation problem
PSIA	--	L	-----	False	*Pressure in psia units. Values are converted to atm internally
MMHG	--	L	-----	False	*Pressure in mm mercury. Values are converted to atm internally.
MOCT	--	I		0	Generate thermochemical data tape for streamtube and VOFMOC application***
MOCP	--	I		0	Punch thermochemical data for VOF
IONS	--	L	INDX	False	*Consider ionic species
IDEBUG	--	L	INDX	False	*Print intermediate output

*If variable is set to be true ....
**If variable mixture ratio (O/F) gas tape is being generated for use with VOFMOC program, the mixture ratio cases must be input in ascending order.

Table 6-4

VARIABLES IN RKTINP[*] NAMELIST

Variable Name	Dimen.	Type	Common Label	Value before Read	Definition and Comments
EQL	--	L	PERF	True	Calculate rocket performance assuming equilibrium composition during expansion[**]
FROZ	--	L	PERF	True	Calculate rocket performance assuming frozen composition during expansion[**]
PCP	26	R	PERF	0	Ratio of chamber pressure to exit pressure. List should not include values for the chamber and throat. Storage allows for 22 values. Values should be in increasing order.
SUBAR	13	R	PERF	0	Subsonic area ratios (optional)
SUPAR	13	R	PERF	0	Subsonic area ratios (optional)

[*]Required for rocket problems only.

[**]Set variable false if these calculations are not desired.

[***]Set variable equal to one if these processes desired.

Sample output from this program is contained in Ref. 2.

Section 7

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Appendix A
ON THE ACCURACY OF PREDICTED EXHAUST PLUME
FLOWFIELD VARIABLES

ON THE ACCURACY OF PREDICTED EXHAUST PLUME FLOWFIELD VARIABLES[*]

by

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ABSTRACT

Various assumptions are used by many organizations to compute rocket
motor plumes. In applying plume data, the question of accuracy invariably
arises. Some guidelines are therefore needed to estimate the accuracy
of the plume data based upon the assumptions that are employed. This paper
is intended to serve as a guide for estimating plume accuracy and to alert
the plume analyst to the magnitude of error which might be expected if
certain assumptions are used. Much of the information contained in this
paper, however, is based upon somewhat subjective data and/or certain cases
from which some experience has been gained. The data presented should,
therefore, be used judiciously, the problem at hand should be carefully
considered, and the fact that the error bands have been somewhat grossly
estimated should be kept in mind.

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INTRODUCTION

During the past several years sophisticated techniques for computing rocket motor exhaust plumes have been developed. The prediction methods can take into account such influencing parameters as combustion chamber losses, flow striations, reaction kinetics and non-continuum effects. When a plume flow field is to be computed, the degree of analytical sophistication that will be used should be based on an assessment of such factors as: (1) ultimate purpose of the data; (2) time available to accomplish the calculations; and (3) degree of accuracy required. In most cases, all effects that can be calculated should be included in the calculations. To include all effects may, of course, be time-consuming; this is not always practical if schedules are to be met. Plume data are therefore sometimes generated which circumvent the various effects that are felt to be small. Since much plume data are generated by using various assumptions, some guidelines are needed to estimate the accuracy of the resulting plumes based upon the assumptions that are employed.

Although an absolute accuracy cannot at this time be assigned to the final numbers generated for any given plume calculation, at least a reasonable estimate can be made of the anticipated accuracy, depending upon the various assumptions. Some of the assumptions influence specific regions of the flow field, and the accuracy of the calculations varies with position in the plume.

This document is intended to serve as a guide for estimating the accuracy of axisymmetric plume flowfield calculations. Much of the information, however, is based upon somewhat subjective data and/or certain cases (perhaps even unique cases) from which some experience has been gained. Also, only steady state rocket motor operation is considered. Ignition and shutdown transient influences are omitted.

DISCUSSION

The effects which are considered important in plume calculations are categorized and discussed in this section. Tables I and II summarize the important flowfield parameters and the estimated percentage of error that may be introduced by each item. The error that is discussed is the error which could exist if an accurate evaluation of the influence of the item is not included in the plume flowfield analysis. The error bands in Table I are considered to correspond to worst-on-worst or three-sigma cases for a 95 percent confidence interval. The error bands are rather large since they reflect the maximum values which have been observed. Most rocket motors will not encounter these effects to the extent shown in Table I. A set of data corresponding to an estimated one-sigma deviation for a 95 percent confidence interval is presented in Table II. The items which contribute to the accuracy bands shown in Tables I and II are discussed in the following paragraphs.

Motor Operating Conditions: Motor operating conditions refers to the fact that rocket motors are generally specified to operate at a nominal set of conditions (chamber pressure, mass flow rate, and oxidizer-to-fuel ratio (O/F)). Variations from nominal conditions frequently occur during actual operation. A band of ± 10 percent was arbitrarily assigned for chamber conditions (pressure, O/F ratio, mass flow). Influences of this ± 10 percent band on other motor and plume environmental conditions are shown in Table I and Table II.

Combustion Chamber Momentum Loss and Efficiency: Combustion chamber momentum loss and efficiency is included because combustion in a rocket motor does not take place at zero velocity as implied by an equilibrium, infinite area ratio calculation. The situation actually is analogous to heat addition in a finite area duct which results in a decrement in total pressure. The maximum momentum loss that can occur is a function of the propellant system and motor geometry and it can be as high as 20 percent of the actual pressure immediately downstream of the injector face. Most motors, however, fall in the range of 2 to 15 percent momentum loss (Ref. 1).

Coupled with the momentum loss is combustion efficiency; i.e., incomplete mixing and/or reaction of the incoming propellants. This anomally first appeared when experimental performance data were compared with computed data. Even when all known performance losses were included in the analytical prediction, some descrepancy still existed. This discrepancy has been termed combustion efficiency and several theories have been proffered as possible explanations. The JANNAF Performance Standardization Committee has recommended an arbitrary reduction in the initial propellant energy to account for this loss (Ref. 2). Recently, however, this committee has been working on a droplet varporization model which will be recommended as the explanation for combustion efficiency. Whatever its source, combustion efficiency must be properly estimated to increase the accuracy of the exhaust plume calculation. The most striking result of combustion efficiency is a temperature prediction considerably below that predicted by the usual adiabatic flame calculation. In this paper, the momentum loss and combustion efficiency problems are combined and assigned a maximum error, which corresponds to the deviations that have been observed between motor performance test data and theoretical results for no-momentum loss and for complete equilibrium chemistry combustion at a nominal motor operating value of O/F.

Flow Striations (O/F Ratio Gradient): The flow striation problem is a result of non-uniform distribution of propellant mixture ratio within the combustion chamber. Flow striations may be deliberately induced in the nozzle flow, as in the case of film cooling, or it may result from incomplete mixing and/or combustion in the combustion chamber. The effects that are introduced are variations of the thermochemical data due to combustion at a local O/F ratio which is different from the nominal O/F value (Ref. 3). Tables I and II show error bands relative to the nominal O/F value.

The flow striation effect may be closely related to the combustion efficiency problem; however, these effects are considered independently in this paper.

Reaction Kinetics: Reaction kinetics, as used here, involves the problem of appropriately defining the location in the flow field where the chemical reactions deviate from equilibrium enough that the flow can be considered chemically frozen. From this point on, the species concentrations are constant and the thermodynamic properties vary only with temperature. The problem thus is one of correctly assessing a representative freeze point. The error bands shown in the charts relate the error magnitudes resulting from comparison of results for a finite rate chemistry analysis (Ref. 4) and results obtained by an assumed freeze point based on an equilibrium/frozen chemistry analysis. The errors presented are the range of values which can be expected in the highly expanded plume. The errors in the field nearer the freeze point are not nearly as large. The major source of the errors is related to differences in the values of the thermodynamic properties used to calculate the flow field.

Non-Continuum Effects: The error caused by non-continuum effects is due to the lack of rigorous flow models which can consider the gradual deviation in thermodynamic properties which result as the rate of intermolecular collisions is reduced below a value corresponding to thermodynamic equilibrium. The error bands which are listed in Tables I and II for this item refer to variations which occur between a rigorous non-continuum solution (Refs. 5 and 6) and a sudden-freeze solution which uses continuum flow equations until a "free-molecular" condition is reached (Ref. 7). When this freeze point is reached, the flow calculation is handled as a free molecular calculation. In the transition flow region (Knudsen number greater than 0.1) the error increases until the sudden freeze condition is reached. The maximum error occurs near the freeze point and is the error shown in Tables I and II. Beyond the freeze point, the rigorous solution and the sudden freeze solution tend to converge toward common values (Knudsen number greater than 1.0). The sudden freeze solution yields results which show significant deviation in static temperature. Density and velocity calculations, however, are not greatly affected.

The error bands shown in Tables I and II are based upon the differences found between cases analyzed with: (1) a sudden freeze analysis; and (2) with a rigorous theoretical solution. An additional large error, not shown in the charts, would appear if the rigorous analysis were compared with an all continuum analysis. This would result from the fact that the temperature in a continuum analysis approaches a zero limit while the rigorous solution indicates that the temperature approaches a low but finite value.

Calculational Accuracy: This item is an arbitrary estimate of the maximum error conceivable for the numerical computational procedures used.

Viscous Effects (Boundary Layer): The viscous (boundary layer) effects of the nozzle flow have been shown to be of minor consequence on the inviscid flow in the nozzle. (That is, if the boundary layer is considered in terms of displacement thickness to alter the nozzle contour, the effect on the nozzle flow is generally negligible.) The effect considered here is that the boundary layer will influence the plume flow field to some degree and will cause the maximum expansion angle at the nozzle lip to be significantly different. Basically, the boundary layer will tend to: (1) permit the flow to expand well beyond the limiting inviscid expansion angle at the nozzle lip; and (2) alter the temperature, pressure and density in the portion of the theoretically inviscid plume which is influenced by the boundary layer.

The boundary layer affects the entire plume to some extent but the most pro-
nounced effect is in the outer 40 percent of the mass flow within the plume
(Refs. 8 and 9).

Condensation: For a rocket motor, the influence of gases condensing in
low temperature flow fields has been numerically evaluated only to a limited
extent. The condensation will usually occur at low temperatures, at low
pressures, and at velocities near the limiting velocity of the gas (Ref. 10).
The influences will occur in the highly expanded regions of a flow field cor-
responding to temperatures below the condensation temperature of the gas.
(The flow upstream of the condensation point is not influenced.) Normally
the condensation will occur at points in the flow field where the temperature
is some 10 to 50°K below the equilibrium condensation point. After initial
condensation takes place, the temperature/pressure relations of the flowing
system will tend initially to be parallel to and then to converge toward the
temperature/pressure variation of a static system in equilibrium. Condensa-
tion will cause local static pressures to be different than they would other-
wise be by factors of 0 to -100 (condensation causes lower static pressures).
Static temperatures will be influenced (with respect to the no-condensation
case) by factors of zero to +5 (condensation increases static temperatures).
The influence of condensation on some of the other parameters has not cur-
rently been defined to a sufficient degree but consequential effects can be
expected.

Start Line: The influence of the starting flow conditions has been ob-
served to have significant effects for regions close to the start line (Refs.
9, 11, 12, 13, 14) but these effects tend to weaken farther downstream (2 to
4 start line diameters downstream of the nozzle exit). Near the start line
some parameters may be locally in error by almost a factor of 10 (between an
estimated and an accurate start line). Downstream the errors will tend to be
smaller (on the centerline, less than 25 percent; in the expansion region, as
much as 50 to 100 percent). Plume calculations that are begun at the nozzle
throat tend to be relatively free from start line effects. Plume calcula-
tions initiated at the nozzle exit tend to permit errors in local properties
that correspond to a position error in the flow field of plus or minus one
startline diameter.

Shock Waves: If shock waves in the nozzle and flow field are not con-
sidered, and a plume is computed as an isentropic flow, the errors in the
plume flow field are similar in magnitude to those associated with start line
effects (Item 9), (Refs. 8 and 9) except that in the immediate vicinity of
the shock wave, variations in flow properties can be extremely different from
the "no-shock" case. The greatest influence tends to occur along the center-
line of the plume where the shock wave is strongest. In the highly expanded
portion of a high-altitude (near vacuum) plume calculation the influence of
the shock waves diminishes as the shock waves become weaker and weaker.
Tables I and II present the maximum error band values anticipated along the
centerline of a plume.

Error Band Application: Tables I and II list plume flowfield parameters
and the estimated maximum percentage error imposed upon them by the various
items (1 through 10) listed in the preceding discussion. Their application
is restricted to locations in the plume specified in Table III and in the
preceding discussion of each item. Application of the error bands should be

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made considering that each error contribution may only partially exist for a particular plume, and the rms values of the sum should normally be used. In the application of error bands to design data, often a simple means of expressing the error band is needed. As a result, a nominal accuracy (or error band) representation has been devised for use on a general basis. This nominal accuracy should be based upon and reflect, for any particular plume, an rms summation of various error contributions cited in this paper. The rms errors should be resolved into a maximum percent error of combined spatial position and flow parameter value. The spatial accuracy band is arbitrarily assigned as being equal in percentage magnitude to the quantitative accuracy band. Results of numerous plume calculations and experimental calculations indicate that the flowfield structure (shock wave locations, etc.) can be in error as a result of the various factors. Some of the effects which produce flowfield parameter quantitative errors, also produce flowfield structure positional errors. Conversely, a highly accurate plume calculation will necessarily reflect accurate flowfield positional accuracies. Consequently, combining the spatial and quantitative accuracy bands is logical. For example, a plume nominal accuracy band might, by the inspection process, be assessed at ±20 percent, which means that the calculated location of a particular flow feature (a shock wave for instance) may be in error by ±20 percent in both the axial and radial position; also, the magnitude of the flowfield parameters may additionally be in error by ±20 percent.

In summary, the process of defining a nominal plume accuracy should be accomplished by:

1. Assessing the applicability of the various items which contribute errors to the computed plume flow field at various plume locations

2. Determining the rms error band for each flowfield parameter for numerous points in the plume

3. Obtaining a "nominal plume accuracy band" rms value by averaging the rms error bands of the various points in the flow field.

CONCLUSIONS

Factors that affect the accuracy of plume calculations have been categorized, and anticipated ranges of errors associated with each plume parameter have been estimated. This information is provided for reference and is intended to serve as a guide in estimating the overall accuracy of any given plume analysis based upon the assumptions employed for the plume calculation. Absolute values of accuracy are almost impossible to assign to plume calculations. Therefore, the data presented should be used judiciously, and the problem at hand carefully considered, including the fact that the error bands have been somewhat grossly estimated.

SYMBOLS AND NOTATION

Force	force
M	Mach number
$\dot{m}$	mass flow rate
O/F	oxidizer/fuel ratio

P	static pressure
P_T	total pressure
P_{T_2}	pitot total pressure
T	static temperature
T_T	total temperature
V	velocity
σ_i	i^{th} species
γ	isentropic exponent
ρ	density

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TABLE I. ESTIMATED RANGE OF PERCENTAGE OF ERROR FOR VARIOUS PARAMETERS IN PLUME FLOW FIELD FOR A 3-SIGMA DEVIATION AT 95% CONFIDENCE INTERVAL

Item / Affected Parameter	1. Engine Operating Condition (P_c, O/F, ṁ), ±10% Variation	2. Chamber Combustion Efficiency and Momentum Loss not Included in Plume Analysis	3. Fuel Striations (Oxidizer/Fuel Gradients) not Included in Plume Analysis	4. Reaction Kinetics (Finite Rate Effects) not Included in Plume Analysis	5. Non-Continuum Flow Effects not Included in Plume Analysis	6. Computational Accuracy	7. Viscous Effects (Boundary Layer) Not Included in Plume Analysis	8. Flow Condensation Not Included In Plume Analysis	9. Approximate Start Line Used in the Analysis	10. Shock Waves Not Included in the Analysis
P_{T_2}	± 10	+ 0 / - 20	± 10	0	*	± 5	**	Δ	0	± 25
T_T	± 3	+ 0 / - 20	+ 0 / - 50	+ 0 / - 25	*	± 5	**	Δ	0	± 25
P	± 10	+ 0 / - 20	± 5	± 100	± 10	± 5	**	+1000 / - 0	±100	±100
T	± 3	+ 0 / - 20	+ 0 / - 50	± 100	+ 100 / - 0	± 5	**	+ 0 / -100	±100	±100
ρ	± 10	+ 0 / - 20	+ 100 / - 0	± 100	± 5	± 5	**	±50	±100	±100
V	± 5	+ 0 / - 10	- 40 / + 0	± 5	± 3	± 5	**	± 5	± 10	± 10
γ	± 3	± 3	± 50	± 25	± 40	± 5	**	Δ	± 0	± 10
$α_i$	± 1	± 25	± 100	± 100	± 1	± 5	**	Δ	± 0	± 5
F (impingement force) & P_{T_2}	± 10	+ 0 / - 20	± 10	± 5	± 20	± 10	**	±20	± 10	± 10
M	± 2	± 5	+ 5 / - 10	± 15	- 0 / + 50	± 5	**	±20	± 10	± 15

* Not meaningful
** Affects mainly the outer 40% of the mass flow (see Discussion)
Δ Not defined

TABLE II. ESTIMATED RANGE OF PERCENTAGE OF ERROR FOR VARIOUS PARAMETERS IN CALCULATED PLUME FLOW FIELDS FOR 1-SIGMA DEVIATIONS AT 95% CONFIDENCE INTERVALS

Item / Affected Parameter	1. Engine Operating Condition (P_c, O/F, $\dot{m}$), ±10% Variation	2. Chamber Combustion Efficiency and Momentum Loss Not Included in Plume Analysis	3. Fuel Striations (Oxidizer/Fuel Gradients) Not Included in Plume Analysis	4. Reaction Kinetics (Finite Rate Effects) Not Included in Plume Analysis	5. Non-Continuum Flow Effects Not Included in Plume Analysis	6. Computational Accuracy	7. Viscous Effects (Boundary Layer) Not Included in Plume Analysis	8. Flow Condensation Not Included In Plume Analysis	9. Approximate Start Line Used in the Analysis	10. Shock Waves Not Included in the Analysis
P_T	± 2	+ 0 / - 3	± 2	0	*	± 2	**	Δ	0	± 25
T_T	± 1	+ 0 / - 3	+ 0 / - 10	+ 0 / - 25	*	± 2	**	Δ	0	± 25
P	± 2	+ 0 / - 3	± 2	± 15	± 10	± 2	**	+ 50 / - 0	± 25	± 100
T	± 1	+ 0 / - 3	+ 5 / - 10	± 15	+ 100 / - 0	± 2	**	+ 0 / - 20	± 25	± 100
ρ	± 2	+ 0 / - 3	- 20 / - 5	± 15	± 5	± 2	**	± 10	± 25	± 100
V	± 1	+ 0 / - 2	- 10 / + 5	± 2	± 3	± 2	**	± 2	± 2	± 10
γ	± 1	± 1	± 5	± 5	± 40	± 2	**	Δ	0	± 10
$α_i$	±0.5	± 4	± 10	± 15	± 1	± 2	**	Δ	0	± 5
F (impingement force) & P_{T_2}	± 2	+ 0 / - 3	± 2	± 2	± 20	± 4	**	± 5	± 2	± 10
	± 2	± 2	+ 2 / - 5	± 10	- 0 / + 50	± 2	**	± 10	± 10	± 50

* Not meaningful
**Affects mainly the outer 40% of the mass flow (see Discussion)
Δ Not defined

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TABLE III.   REGIONS OF THE PLUME WHERE ERROR BANDS APPLY

Item	Region of Plume Where Error Bands Apply if the Item is Not Included in the Analysis
1. Engine Operating Conditions	Entire Flow Field
2. Chamber Combustion Efficiency and Momentum Loss	Entire Flow Field
3. Flow Striations	Entire Flow Field
4. Reaction Kinetics	Small errors near nozzle exit, progressively larger errors in the far plume.
5. Non-Continuum Effects	Error applies in the transition flow regime. The error is zero at the onset of transition flow, maximum at the sudden freeze point, and decreases as free molecular flow occurs.
6. Calculational Accuracy	Entire Flow Field
7. Viscous Effects	Error increases in the region of the plume outside of approximately the 60% mass flow streamline (where minor errors exists). Major errors occur outside the inviscid plume region.
8. Condensation	Error is zero upstream of the point in the flow field where the equilibrium condensation temperature exists. Downstream, the error can grow with increasing distances from the equilibrium point.
9. Start Line	Error is maximum near the startline, decreases to smaller values 2 to 5 startline diameters (nozzle throat or exit) downstream.
10. Shock Waves	Error is maximum near the centerline and in the regions where the shock should be; decreases away from the centerline.

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