LMSC-HREC TRD784753

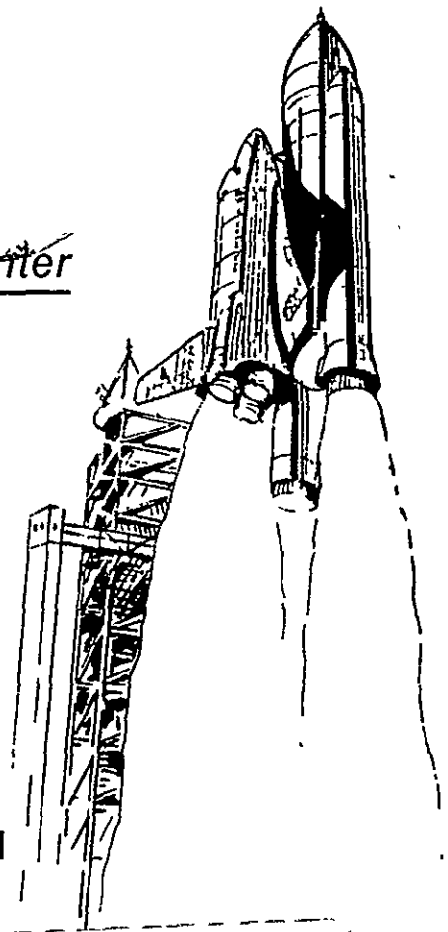
IMPROVEMENT OF ROCKET ENGINE PLUME ANALYSIS TECHNIQUES

FINAL REPORT

Sheldon D. Smith

Lockheed
Missiles & Space Company, Inc.
Huntsville Research & Engineering Center

Cummings Research Park
4800 Bradford Drive
Huntsville, AL 35807



January 1982

Contract NAS9-16256

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TX 77058

FOREWORD

This document presents the results of work performed by the Advanced Fluid Mechanics Section of the Lockheed Missiles & Space Company, Inc., Huntsville Research & Engineering Center for NASA-Johnson Space Center, Houston, Texas.

The contents of this document represent partial fulfillment of the requirements of Contract NAS9-16256 with NASA-Johnson Space Center. The Contracting Officer's Representative for this study was Mr. Barney B. Roberts, EX43.

CONTENTS

1. INTRODUCTION AND SUMMARY

The overall objective of this study was to deliver a nozzle-plume flowfield code that has capabilities which do not presently exist in a single computer code. The RAMP code (Refs. 1 and 2) which was developed by Lockheed under government funding was chosen as the basic code from which to work. The basic RAMP code is of modular construction and had the following capabilities:

- Two-phase with two-phase transonic solution
- Two-phase, reacting gas (chemical equilibrium reaction kinetics), supersonic inviscid nozzle/plume solution
- Operational for inviscid solutions at both high and low altitudes.

During the course of the study the following capabilities were added to the code:

- Direct interface with JANNAF SPF code (Ref. 3)
- Shock capturing finite difference numerical operator
- Two-phase, equilibrium/frozen, boundary layer analysis
- Variable oxidizer-to-fuel ratio transonic solution
- Improved two-phase transonic solution, and
- Two-phase real gas semi-empirical nozzle boundary layer expansion.

Most of the above capabilities already existed in other computer codes. These codes were incorporated into the RAMP code to enhance its usefulness.

This report discusses the capabilities which have been added along with how to use these capabilities. Detailed descriptions of the theories are left to the references from which the codes were taken.

Also included in this report is a detailed input guide for the RAMP code.

2. REACTING AND MULTIPHASE (RAMP) COMPUTER PROGRAM

A precise knowledge of local flow properties in nozzles and exhaust plumes is necessary for performance, radiation, attenuation, heat transfer and impingement analyses. The reacting and multiphase (RAMP) computer program is designed to give detailed flowfield information in the supersonic region of a reacting multiphase two-dimensional or axisymmetric flow field. The boundaries of the flow field may be solid such as in a nozzle or "free" such as in a plume. The analysis may be utilized therefore to predict performances as well as plume characteristics of a given engine system. A printed record of the program results is given for user inspection while a binary tape is provided for subsequent manipulation by other analyses.

The flow of a gas-particle mixture is described by the equations for conservation of mass, conservation of momentum and conservation of energy. In the gaseous phase the state variables P, ρ, R and T are related by the equation of state while for the particulate phase the equations are for the particle drag, particle heat balance and the particle equation of state. Development of these equations is based on the following assumptions:

1. The particles are spherical in shape.
2. The particle internal temperature is uniform.
3. The gas and particles exchange thermal energy by convection and radiation (optional).
4. The gas obeys the perfect gas law and is either frozen and/or in chemical equilibrium, or is in chemical non-equilibrium.
5. The pressure of the gas and the drag of the particles contribute to the force acting on the control volume.
6. The gas is inviscid except for the drag it exerts on the particles.
7. There are no particle interactions.

8. The volume occupied by the particles is negligible.
9. There is no mass exchange between the phases.
10. A discrete number of particles, each of different size or chemical species is chosen to represent the actual continuous particle distribution.
11. The particles are inert.

The supersonic two-phase solution accepts the starting line provided by the internally calculated transonic solution as well as other pertinent data supplied through the read function. The equations of motion under the assumptions just listed are hyperbolic and permit the use of a forward marching scheme; a streamline/normal grid structure is employed where the step lengths in the axial and radial directions are under program control. Both BCD (printer) and unformatted binary output tapes are produced. A Prandtl-Meyer expansion of the gas phase and a free boundary calculation are employed to treat the plume flow solution. The run is terminated when prespecified problem limits are reached.

The two-phase flow analysis will treat an extremely wide range of operating conditions. With few exceptions the limitations are imposed by the theory rather than numerical considerations. In this discussion dimension statement sizes which are arbitrarily set are not considered a limitation. The true limitations are:

- Supersonic regions influenced by embedded subsonic regions.
- Vacuum or limiting expansion limitation — a small region of the expansion fan for a vacuum expansion cannot be treated where the Mach number is so large that treatment by continuous flow assumptions becomes meaningless (this limitation is both numerical and theoretical).
- For two-phase flow the lower boundary can only be horizontal (i.e., nozzle centerline).

A complete derivation of the governing equations are available in Refs. 1 and 2.

A free molecular flow calculation has been provided as an option which permits treatment of the rarefied regions of the plume. As the gas expands it first freezes out the vibrational and rotational modes. During this transition the characteristic equations continue to be employed but the equation of state is modified. At translational freezing, however, the solution switches to an effective source solution. The stream lines are considered straight and the velocity constant. Conservation of mass then determines the density while other properties are found from the equation of state. This option should not be exercised at this time as it has not been checked out with the new modifications which have been added to the code.

2.1 MODIFICATIONS TO THE RAMP CODE

This section deals with the modifications which were incorporated into the RAMP code under this contract.

2.1.1 JANNAF Standard Plume Flowfield (SPF) Code Interface

To perform a plume calculation, the SPF code (Ref. 3) requires nozzle exit properties as initial conditions. The RAMP code was modified to punch or put on tape exit plane data in the format that the SPF code uses. The code will punch data for both single and two-phase cases.

At present, the SPF code can accept a single chemical species distribution which must be applied at all points across the exit. The RAMP code can have a distribution of species, so it was necessary to mass flow average the species distributions across the exit plane to produce a single set of species. This restriction can be easily removed whenever SPF has the capability to handle spatial variations in chemical species.

The code is set up to punch the species information for the various chemical systems that are available in the SPF code. The user must specify which system to punch. If the thermodynamic data is input to the RAMP code using cards then the species mole fractions that are to be

punched for the SPF code must be input for the appropriate system in the same order as listed in Table 1. For finite rate cases these species are determined inside the code and need not be input. The user may also input another system. Additionally, ideal gas cases can also be handled.

Table 1
SPF CHEMICAL SYSTEMS

System 1 — Hydrogen/Oxygen

$H, H_2, H_2O, N_2, O, OH, O_2$

System 2 — Carbon/Hydrogen/Oxygen

$CO, CO_2, H, H_2, H_2O, N_2, O, OH, O_2$

System 3 — Carbon/Hydrogen/Oxygen/Chlorine

$A\ell_2O_3(S), CO, CO_2, C\ell, C\ell_2, H, H_2, H_2O, HC\ell, N_2, O, OH, O_2$

System 4 — Carbon/Hydrogen/Oxygen/Chlorine/Fluorine

$CO, CO_2, C\ell, C\ell_2, F, F_2, H, H_2, H_2O, HC\ell, HF, N_2, O, OH, O_2$

System 5 — Hydrogen/Oxygen/Boron

$BO, BO_2, B_2O_3, H, H_2, H_2O, HBO_2, N_2, O, OH, O_2$

System 6 — Hydrogen/Oxygen/Boron/Chlorine/Fluorine

$BF, BF_2, BF_3, BO, BOC\ell, BOF, BO_2, B_2O_3, CO, CO_2, C\ell, C\ell_2$
$F, F_2, H, H_2, H_2O, HBO_2, HC\ell, HF, N_2, O, OH, O_2$

2.1.2 Shock Capturing Finite Difference Operator

The original RAMP code has the logic for computing any number of right- or left-running shocks using shock fitting techniques. This logic was partially checked out under previous efforts. It is desirable to have the capability to treat shocks that can occur in some nozzles. Shock capturing schemes require no special equations or program logic and are reliable. For most nozzle flows, existing shock capturing techniques are sufficiently powerful to treat the shocks. Additionally, in order to directly interface with the SPF code, it would be desirable to use a shock capturing numerical operator.

For the above reasons a shock capturing algorithm was added to the code. The methodology, equations and grid system which was incorporated into the code is identical to the SPF code (Ref. 3). To obtain more information on the scheme the reader is referred to Ref. 3.

For the shock capturing option, the computational grid are vertical lines and a radial coordinate system normalized by the local wall coordinate. This approach was taken to alleviate the problem of inserting a point per line for a Cartesian system. The computational procedure is as follows: the forward marching algorithm is used to compute the flowfield properties at all interior points. Flowfield properties at the axis and wall are obtained via the method-of-characteristics solution. Once the wall and axis points have been computed, the coordinate system is transformed and the interior points are solved.

The shock capturing routines have been checked out for ideal gas single-phase solutions. Real gas or two-phase flows have not been checked out. It is therefore recommended that shock capturing not be used until the author has fully verified the logic. When this option has been verified the changes to the code will be forwarded to the users. For the present time, the regular streamline-normal computation scheme should be used.

2.1.3 Two-Phase, Equilibrium/Frozen, Boundary Layer Analysis

Nozzle boundary layers are known to influence certain regions of nozzle flow and high altitude exhaust plumes (Refs. 4, 5 and 6). For nozzle designers, the nozzle boundary layer is important in determining the thermal loads to the nozzle, performance losses due to heat transfer and effects on the nozzle pressure distribution due to the displacement thickness effect on the inviscid flow structure. For spacecraft designers the nozzle boundary layer is important because of its effect on the exhaust plume. At high altitudes the nozzle boundary layer causes the plume to expand to large angles (approximately 180 deg). In these backflow regions, spacecraft and sensitive surfaces are subjected to unwanted contamination,

forces, moments and heating rates. For some applications the radiative properties of the expanded boundary layer flow is important. Thus, it is easy to see that for many applications the nozzle wall boundary layer is an important factor.

To date there have been numerous techniques used to account for boundary layer effects of the nozzle and exhaust plume flow fields. Lockheed-Huntsville has an option in the MOC and PIP code (Ref. 7, a version of RAMP) which superimposes a power law boundary layer profile based on a flat plate boundary layer thickness on the exit plane start line. The profile can contain a total temperature variation which has been found to be important (Ref. 7) in the back flow region of the plume. This is a very simplified approach and the method of determining the boundary layer thickness is very crude. Lockheed-Huntsville personnel and other investigators have used various boundary layer codes and the inviscid nozzle results to generate a better set of boundary layer properties which were then superimposed on the nozzle exit plane inviscid results. Next, some investigators have gone a step further and iteratively solved the inviscid nozzle and boundary layer to determine the effect of the boundary layer on the nozzle flow field. Finally, it is possible to do a fully viscous nozzle solution with a method such as Lockheed-Huntsville's GIM code (Ref. 8). However, a fully viscous nozzle solution is beyond the scope of this effort. It should be noted that all techniques except the first require a tremendous amount of effort and hand calculations to finally obtain a plume solution. The purpose of this task was to automate the boundary layer/nozzle solution to arrive at an exit plane start line which includes all the effects mentioned in the above.

The BLIMPJ boundary layer code (Ref. 9) was chosen for the solution of the nozzle wall boundary layer. BLIMPJ is a JANNAF standard boundary layer code for determining boundary layer effects on the performance of a rocket engine. The BLIMPJ code is set up to handle nozzle flows, equilibrium or frozen chemistry, uses the JANNAF standard thermochemistry curve fits and has numerous ways of treating the nozzle wall that allow it to treat liquid engines as well as solid motors with and without ablative walls. At present,

the interface between RAMP and BLIMPJ allows only the following wall options: adiabatic wall, steady state energy balance or a specified temperature distribution. The adiabatic wall option is the default option in the code. The remaining wall options in the BLIMPJ code could be used with a few modifications to the RAMP code. In addition to wall boundary condition options, the user may also select laminar, turbulent, frozen, or equilibrium flows or let the code default to turbulent, equilibrium. A turbulent boundary layer is used when the Reynolds number based on momentum thickness exceeds 250.

All input data for the boundary layer solution are generated inside the RAMP code except the nozzle wall temperature distribution, if that option is specified. Chemical species must be input if the thermochemistry data for the inviscid solution was input via cards.

The BLIMPJ code was too large for conversion to a module for the RAMP code, so if it is desired to generate a nozzle boundary layer and obtain a viscous exit plane start line it is first necessary to run the RAMP code to calculate the inviscid nozzle solution. The RAMP code generates a file with the BLIMPJ input data on it. The BLIMPJ code is then executed (no data cards). The BLIMPJ results are printed out and stored on a file for subsequent use by the RAMP code. The RAMP code is then reexecuted with but a single input card and an exit plane vertical or normal start line is generated. The exit plane start line has the results of the inviscid nozzle and boundary layer solutions merged together. This capability is a considerable improvement over previous methods which required many hand calculations, cross plotting, etc.

For most rocket motors the boundary layer is fairly thin (approximately 5 to 10% of exit diameter) and the resultant effect on inviscid flow properties is minimal. For these cases one pass through the inviscid nozzle solution and boundary layer calculation is adequate. The boundary layer results will then be superimposed on the inviscid nozzle solution and an exit plane start line with boundary layer effects will be generated which can be used to perform a plume expansion.

Some low pressure or low thrust motors have boundary layers which contain a significant portion of the total mass flow of the system. In these cases the entire solution should be iterated for by making two passes through the inviscid nozzle and boundary layer calculations. After the initial nozzle and boundary layer solution has been completed the nozzle solutions will be calculated with the actual wall contour adjusted by the local displacement thickness which was determined from the boundary layer calculation. The boundary layer solution will then be rerun using the new edge conditions from the second nozzle calculation. The results will then be superimposed on the original nozzle contour and second flowfield solution and an exit start-line will be output or saved. This capability is not presently operational. However, for these cases the boundary layer solution is solved a second time with new edge conditions taken from the inviscid results at the edge of the first BLIMPJ boundary layer. Thus, the inviscid and viscous results match very well at the boundary layer edge. This option is controlled internal to the program and requires no user interface.

2.1.4 Particle Tracing Through Boundary Layer

Any particulate matter ($A\ell_2O_3$-solids or unburned propellant droplets in liquid motors) which might enter the nozzle wall boundary layer could be influenced by the boundary layer to be expanded into the backflow region. Thus, there may be certain motor/nozzle configurations in which it is necessary to track particles through the boundary layer in order to obtain the most accurate representation of the nozzle flow properties at the exit plane.

Lockheed-Huntsville added a particle streamline tracing module into the nozzle code. The code which was used as the basic building block of this module was used in predicting the IUS, SSUS particle distributions published in Ref. 10. This code uses initial particle properties (velocity, flow angle temperature and density) and traces the particles through a known flow field. This option is user-selectable. The basic method used is shown in Fig. 1.

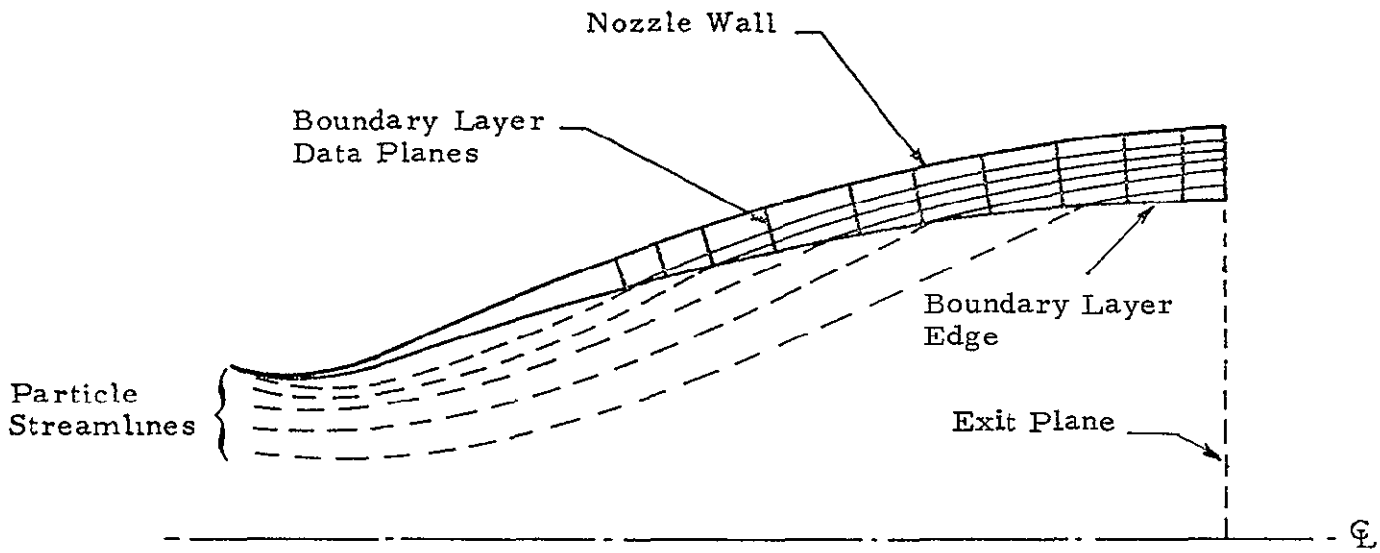


Fig. 1 - Schematic of Particle Trajectory Tracing Method to be Used in the Inviscid Nozzle Code

After the inviscid nozzle solution and boundary layer solutions have been completed, the RAMP code is re-executed and logic is handed off to the particle trajectory tracing module. The first step is to search the boundary layer edge location in the inviscid nozzle solution to determine if any particles are found to penetrate the boundary layer. Then for each particular size group which has been found to penetrate the boundary layer a distribution of individual particle properties will be determined (interpolated off nozzle solution tape) at several stations along the boundary layer edge. This will be done for each size group. Next a map of the boundary layer properties will be generated using the boundary layer data tape. Finally, each particle streamline will be traced through this mapped flow field and particle properties will be determined at the previously determined exit plane. The effect of the particles on the boundary layer flow properties due to energy and momentum interchange are not considered.

Finally, the boundary layer results, the inviscid nozzle solution and the particle properties in the boundary layer are merged, and an exit plane start line for a RAMP restart or SPF run will be generated.

2.1.5 Boundary Layer Expansion at Lip

Another required capability of the nozzle code is a fully automated technique to expand the boundary layer at the lip. After an exit plane start line has been generated it is very straightforward to use the Prandtl-Meyer relationship to expand the flow. The key point here is to get a fully supersonic start line. Numerous investigators have made various assumptions to obtain start lines for plume solutions that account for the nozzle wall boundary layer. The various techniques will be discussed briefly.

Perhaps the most simple method of obtaining a supersonic start line is to discard the subsonic portion of the boundary layer (Refs. 4 and 11) and adjust the spatial distribution of boundary layer points up to the lip. This method throws mass away from the system and will affect the results in the backflow region. For nozzles which have thin turbulent boundary layers,

these effects are probably minimal. For very viscous nozzles (low pressure) or laminar boundary layers the effects of this assumption could severely compromise the plume results in the backflow region (greater than 90 deg). It should be noted that this technique could consider total temperature variations through the boundary layer.

Seubold (Ref. 12) used the technique of replacing the subsonic portion of the boundary layer with mass average properties at a slightly supersonic value. This resulted in a layer of constant properties near the wall. The resultant plume flow had the correct mass flow but did not consider the total temperature variations.

The first two techniques assumed that the static pressure through the boundary layer is constant. Near the lip however the subsonic portion of the boundary layer is influenced by the expansion process (Refs. 13, 14 and 15) as shown in Fig. 2. For highly underexpanded flows the sonic line has been found to attach to the lip (Ref. 13) so that the flow at the wall must rapidly accelerate when it gets near the lip and the static pressure rapidly decreases. For overexpanded flows the subsonic flow merely stays subsonic as it negotiates the lip so that downstream flow conditions can feed back up into the boundary layer.

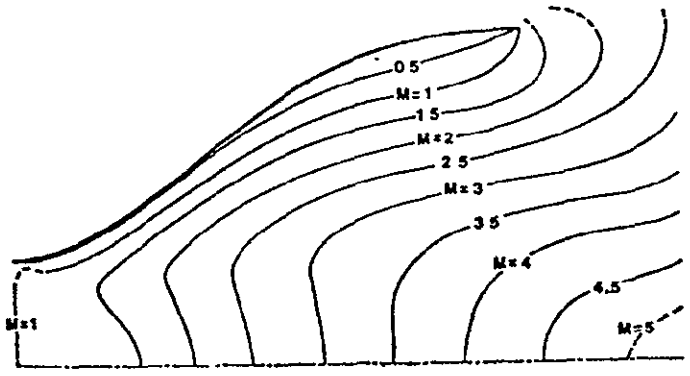


Fig. 2 - Mach Number Contours for an Underexpanded Axially Symmetric Nozzle (Case 6)

Cooper (Ref. 16) went a little further than the first two approaches as far as treatment of the subsonic flow expanding to the sonic lip conditions. He assumed that the flow (M = 0 at wall) just upstream of the lip expanded to M = 1 at the lip. Since the static pressure upstream of the lip at the wall was the same as the wall total pressure and the freestream static pressure, the only way for M = 1 to be reached at the lip was for the wall static pressure to drop. Therefore, there will be a static pressure distribution across the flow at the lip. It was then assumed that the static pressure at specified point in the boundary layer is not affected by the expansion and the pressure distribution is faired into the known lip conditions. This method is not totally rigorous but does include boundary layer effects and has been shown to result in good comparisons with some experimental data in the backflow region.

Finally, there are exact solutions to the corner flow problem. Bird (Ref. 13) uses a direct simulation Monte Carlo method. He set his model up so that it would compute the entire nozzle or the region near the throat. He predicts the attachment of the sonic line for underexpanded nozzles. Baum (Ref. 15) uses a finite difference method along with boundary layer equations to describe the subsonic portion of the boundary layer. His application was for base flow about blunt bodies and compares well with data. Finally, the previously mentioned GIM code can be used to exactly solve the corner problem. All three of these methods are very complex and are outside the scope of this effort.

In the present version of the code the method of Seubold was incorporated. Total temperature variations are included and the mass flow in the boundary layer is conserved. Plume calculations using this method were made for a 5 lbf bipropellant motor. The mass flux predictions compare very well with experimental data.

It is anticipated that further effort will be spent on the lip region so that better calculations may be obtained in the backflow region of the plume.

2.1.6 Variable Oxidizer-to-Fuel Ratio Transonic Solution

Solution of the subsonic transonic region of a liquid rocket engine can vary in complexity from a simple one-dimensional variable O/F streamtube analysis (Ref. 17) to the most detailed model such as that of the Distributed Energy Release (DER, Ref. 18) model. The streamtube analysis performs a multizone one-dimensional calculation to the sonic point given a known O/F distribution just downstream of the injection face. The DER program is a complex model which is initiated upstream of the injector face and continues the solution up through the sonic line. The DER code was used to initiate nozzle solutions in Ref. 19 but is not particularly easy to use and input and requires a good bit of experience of the user to successfully execute. For these reasons it will not be utilized in the nozzle code. On the other hand, a one-dimensional streamtube analysis does not account for two-dimensional effects. A time-dependent scheme (Ref. 20) is a compromise between these two schemes. The approach includes the radial momentum equation which results in a set of mixed partial differential equations. The solution procedure is an unsteady time-dependent finite difference technique with equilibrium chemistry. This technique has both the equilibrium and variable O/F chemistry option and has been utilized (Refs. 21 and 22) previously with excellent results. This code has been incorporated into the RAMP code as a module and has been executed for all combinations of ideal and equilibrium chemistry, constant and variable O/F distributions. Additional inputs required by this module are: (1) combustion chamber geometry down to the throat; (2) average O/F ratio, (3) location of the initial data surface to start the transonic solution; (4) location of the nozzle throat, and; (5) the O/F distribution at the initial data surface.

2.1.7 Improved Two-Phase Transonic Solution

The original transonic module which was incorporated into the RAMP code could handle throat radii of curvature to throat radius ratios above 1.5. Many solid motors have radii of curvature ratios smaller than 1. To alleviate this limitation the improved approximate transonic module was taken from the new Standard Performance Prediction program (SPP, Ref. 23) and put into the RAMP code.

Many transonic solutions using this module have been run for varying upstream and downstream radii of curvature ratios. Unfortunately a problem was encountered for the smaller radii of curvature cases. It was not possible to obtain a true normal for starting the supersonic solution within the domain of the transonic solution. For this reason the old module was put back in the code and the limitation of radii of curvature ratios greater than 1.5 must remain in effect. Work is continuing to interface the transonic with the supersonic solution and the new modules will be forwarded to the users as soon as they are checked out.

2.2 CAPABILITIES AND LIMITATIONS

The RAMP computer program described in this document can be used to solve a wide variety of problems associated with real gas, supersonic, compressible flow. Some of the more important, basic capabilities of the existing program are outlined below:

- The gas may be ideal or real. If the gas is real; frozen, equilibrium, or non-equilibrium chemistry assumptions can be made. The effects of oxidizer/fuel gradients may be considered.
- Two-dimensional or axisymmetric flow problem geometries 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.) (Two-phase problems require the nozzle centerline as a lower boundary).
- A nozzle wall may be curve fit with discrete points.
- 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. Data on a normal surface can be input at points across the flow field within the nozzle or in the plume.
    4. An exit plane startline can be punched.
    5. The program can be restarted from the startline punched in 4 above (except viscous exit plane)
    6. Single phase start line can be calculated using a transonic solution which can handle ideal gas, equilibrium chemistry for both constant and variable oxidizer/fuel ratios
    7. Two phase start line can be set up using a transonic solution.

- Hypersonic or quiescent approach flow options may be used.
- Exit to ambient pressure ratios from over-expanded to highly under-expanded are possible.
- Displacement of the axis of symmetry from the center of flow (i. e., the plug nozzle flow field) is possible for gas only cases).
- There is presently a maximum of 100 points on a normal and 50 input points.
- Reacting gas solutions which are in chemical equilibrium have been facilitated by modifying the TRAN72 (Refs. 24, 25) computer program as described in Section 2 of Ref. 2 to provide binary tape and punched output of its equilibrium or frozen real gas calculations at any desired O/F ratio(s) or total enthalpy(s). The RAMP program has the capability for selecting the proper case from a large set of real gas properties cases stored on a master tape. The method of generating this master tape is outlined in Table 2. 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

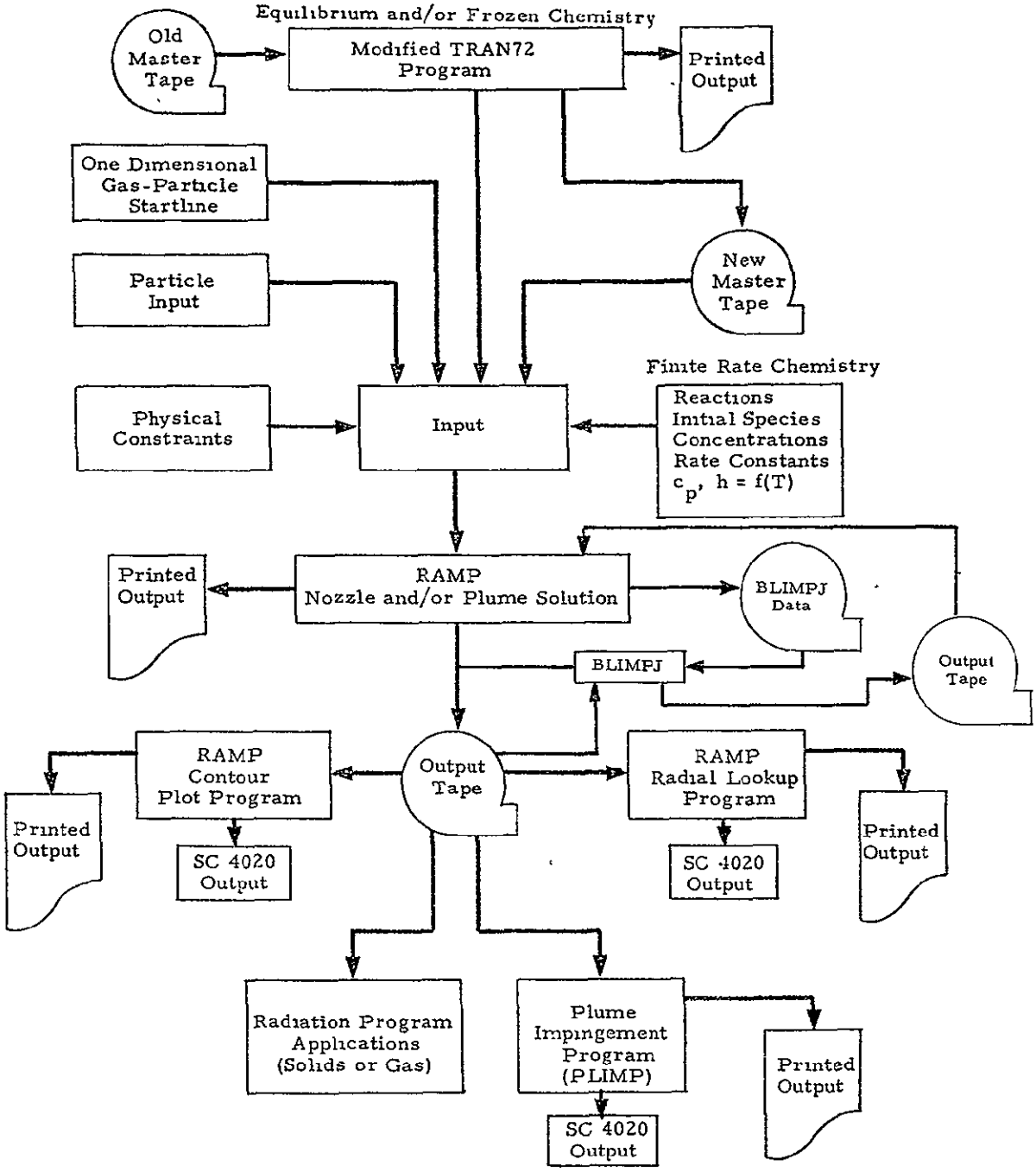
  New cases of general interest may be added to the master tape; however, ad hoc cases should be prepared on a separate tape. Tape preparation sequence and communication with the RAMP program is diagrammed in Table 2.

- Once the gas-particle flowfield solution has been obtained, the output tape may be used by the RAMP Radial Lookup Program (described in Appendix A of Ref. 2) 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. 26) may also be run to determine the effects of the rocket exhaust plume on objects immersed in the plume. Sequencing and communication of auxiliary programs with the RAMP program is shown in Table 2.

- Two-dimensional or axisymmetric solutions are selected by simply loading 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.

Table 2

SEQUENCING AND COMMUNICATION OF AUXILIARY PROGRAMS WITH THE RAMP PROGRAM



- A real gas nozzle boundary layer solution can be performed with no interface between the user and the RAMP code results. A frozen, equilibrium chemistry, turbulent or laminar solution is possible.

- The effect of a nozzle wall boundary layer on particles which enter the boundary layer is treated.

- An exit plane start line can be generated for the SPF code which includes two phase flow and boundary layer effects. Additionally exit plane data is available for use in other codes.

- For two phase transonic solutions the nozzle throat radius of curvature/throat radius ratio must be the same upstream and downstream of the throat and greater than 1.5.

- A restart at the exit plane using a start line that includes the nozzle boundary layer merged with the inviscid results is not possible. Additional logic for mesh and step size control needs to be added.

- Multiple passes through the inviscid nozzle solution with the nozzle contour modified by the BLIMPJ solution displacement thickness is not possible.

- Shock capturing numerical analog logic is not fully checked out and should not be used at this time.

2.3 USER'S INPUT GUIDE FOR THE RAMP PROGRAM

This section outlines in detail the procedures for using the Reacting and Multi-Phase (RAMP) Computer Program. Each card and its use is explained in Section 2.3.1. The program magnetic tape assignments are given in Table 3.

2.3.1 RAMP Program Input Information

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

RAMP Computer Program Input Instructions

Card 1 — Overall Run Control Card — Format (16I5)

Column	Parameter	Value	Description
5	ITRCE	0	All input data are coming from cards except as noted for ICON(1) and ICON(2). Input cards will be written on unit 13 for future use
		1	RAMP code has already been executed for a nozzle and all input data from nozzle run is on unit 13. Nozzle boundary layer has been completed, and the code will generate an exit plane start line which includes boundary layer and particles in the boundary layer (if present).
10	ISTART	0	Do not generate an exit plane start line that includes the boundary layer. Inviscid start line is controlled by Card 5.
		1	Punch a viscous SPF start line.
		2	Punch a viscous normal start line at exit.
		3	Punch a viscous normal and SPF start line.
		4	Punch a viscous normal (or vertical if ICAPTR>0) and SPF (if ISKPY>0) start line and restart at exit. Note: This option is not operational.

Cards 2-4 — Problem Description Required — Format 3(20A4)

Column	Parameter	Description
1-240	HEADER	Problem description may be put on three cards; however only the first 120 columns will be printed while all 240 characters will be written on the data tape. All three cards must be present even if blank.

Card 5 — Run Control Card Required — Format 16I5 (Right Adjusted)

Card 5 (Cont'd)

Column	Parameter	Value	Description
5	ICON(1) Gaseous thermodynamic data control parameter	1	The gas composition is either chemically frozen and/or in chemical equilibrium. The gas properties are read directly from cards 9, 10, 11 and 12.
		2	Same as ICON(1)=1 except gas properties are read directly from a data tape mounted on FORTRAN unit 10.
		3	The gas composition is in chemical non-equilibrium. The gas properties are determined, as a function of temperature in thermodynamic data tables input on card 14.
		4	Same as ICON(1)=3 except gas composition is chemically frozen.
8-9	NTAPE	N	If ICON(2)=2, tape unit number for startline if not input from cards. The program defaults to unit 5 (read cards) for ICON(2)=2. If ICON(2)≠2 and a two-phase transonic solution is being performed NTAPE is the unit on which the transonic startline will be written. In this case the program defaults to unit 8
10	ICON(2) Start line control parameter for gas only solution	0	Generate straight startline with Mach number given.
		1	Generate source startline with A/A^* given
		2	Startline input from cards or tape.
	or	3	Generate startline by conservation of mass using a linear Mach number distribution.
		4	Generate gaseous startline using variable O/F transonic module. This option requires cards 19c, d, e
	Startline control parameter for gas-particle solution	0	Generate startline using transonic approximation.
		2	Startline input from cards.

Card 5 (Cont'd)

13	ICON(3) Control manner in which points along the startline are spaced	0	Points are spaced according to a sine distribution.
		1	Points are evenly spaced (recommended)
		2	Points are evenly spaced on a circular arc based on the input value of the upper limit of the startline (card 19 CORLIP(2))
			NOTE: This option is necessary only if program is to set up its own gaseous startline.
14-15	ICON(3)		Number of startline points. Maximum of 50 (right adjust)**
16-20	ICON(4) Number of upper boundary equations		Upper boundary specification indicator. If specifying upper boundary by equations, set equal to number of equations to be used. Maximum of 100. Right adjust.

Option for ICON(4) when upper boundary is described by individual points and slopes

ICON(4)	1N000 + Number of discrete points (no boundary equation following last point) (slope at each point in radians)
	2N000 + Number of discrete points + 1 (an upper boundary equation follows last point) (slope at each point in radians)
	3N000 + Number of discrete points (no boundary equation following last point) (slope at each point in degrees)
	4N000 + Number of discrete points + 1 (an upper boundary equation follows last point) (slope at each point in degrees)

N ~ number of points to use for Lagrangian Integration (5 max).

If N is set to zero, a linear assumption will be made.

NOTE: If a nozzle is being run the throat must also be specified by discrete points.

**NOTE: If particles are present and supersonic startline is generated by transonic approximation then total number of points on startline may be adjusted by transonic program depending on particle distributions.

Card 5 (Cont'd)

Column	Parameter	Value	Description
21-25	ICON(5) Number of lower boundary equations		Lower boundary specification indicator. Same description and option as ICON(4).
27-28	ICON(3)	N	N is the boundary equation number at which the SKIPPY start line is to be punched. The code uses the XMAX (see card 7) for this boundary equation as the station to punch.
29	IUNIT	0	Punch SPF start line
		1	Put SPF start line on unit 12.
30	ISKPY	0	Do not generate SPF start line.
		1	Chemical system 1 SPF start line (see Table 1)
		2	Chemical system 2 SPF start line (see Table 1)
		3	Chemical system 3 SPF start line (see Table 1)
		4	Chemical system 4 SPF start line (see Table 1)
		5	Chemical system 5 SPF start line (see Table 1)
		6	Chemical system 6 SPF start line (see Table 1)
		7	Input chemical system via card
		8	Ideal gas SPF start line.
33	ICAPTR	0	Streamline-normal solution
		1	Shock capturing numerical operator (This option not fully operational.)
34	IBL	0	Do not generate data for boundary layer calculation.
		1	Generate data for boundary layer calculation and store it on unit 1.
35	ICON(7)	0	Two-dimensional flow problem geometry.
		1	Axisymmetric flow problem geometry.

Card 5 (Cont' d)

38	INOZ	2	Calculations terminated at nozzle exit. Set if boundary layer is to be calculated.
39	ICON(8) Data output control, used in conjunction with ICON(16)	0	Full printout
		1	Print only boundary, shock, input, Prandtl-Meyer, and particle limiting streamline points.
40	ICON(8)	1	Print 1 line (R, X, M, θ, S and shock angle)
		2	Print above plus Mach angle, P, ρ, T, V.
		3	Print all of above plus MWT, γ, TO^*, PO^*, S^*.
42	MORFT Compliments ICON(9)		For English system of units.
		0	Dimensions are in feet.
		1	Dimensions are in inches.
			For metric system of units.
		2	Dimensions are in centimeters.
		3	Dimensions are in meters
		4	System of units specified by user.
43	ICON(9) Units indicator	0	Use English system of units.
		1	Use metric system of units.
			This option controls the units in which the flow field is calculated. The program assumes that the boundary equations are input in the same units as the units indicator (ICON(9)). This option will not override the units specification on cards 9 and 31 but will convert the units of the gas and particle thermodynamics to correspond to the units of this indicator.
44-45	ISPECS		Number of discrete particle sizes used to represent particle distribution (10 max). If gaseous only flow set equal to 0 (right adjust).
48-50	ICON(10)		Maximum iterations allowable for each point in flow field. If set to 0 program assumes value of 100. Right adjust.

Column	Parameter	Value	Description
51-55	ICON(11)		Case number printed at top of each page.
60	ICON(12)	0	Calculate shock wave.
		1	No rotation option.
61	ICON(13)	0	Flowfield data will be output on FORTRAN unit 3. Must be set if generating boundary layer
		1	Data will not be written on tape.
65	ICON(13)	0	Free molecular calculations will not be considered.
		1	Free molecular calculations will be considered.
68-70	ICON(14)	0	No intermediate printout in solution iteration.
		N	Print intermediate results for N^{th} line. Right adjust.
71-75	ICON(15)	0	No intermediate printout.
		M	Print intermediate results from M^{th} point on each line from the N^{th} (ICON(14)) line on. Right adjust.
76	ICON(16)	0	No punched cards output.
		1	Punch data line at nozzle exit
77-78	ICON(16)	0	Print every line.
		N	Print every N^{th} line (use with ICON(8)). Put 0 in column 77 if N < 10.
79-80	ICON(16)*		Time (SEC) before end of allotted run time when new startline is to be punched. Put 0 in column 79 if time less than 10 seconds.

Card 6 — Finite Rate Chemistry Run Control Card (Required if ICON(1)>2) — Format 8I5 (Right Adjusted)

Column	Parameter	Value	Description
1-5	NT		Number of temperature points in thermodynamic data tables.
6-10	NS		Number of gaseous species (excluding 3rd bodies)

*NOTE: Applicable for Univac 1108 only.

Column	Parameter	Value	Description
11-15	NM		Number of 3rd bodies.
16-20	NR		Number of reactions specified.
25	NPRINT	0	No intermediate printout in chemistry calculations.
		1	Echo print of input data.
		2	Print intermediate results of chemistry calculations.
30	ICTAPE	0	Species concentrations for start-line read directly from cards.
		1	Species concentrations read directly from a data tape mounted on FORTRAN unit 10.
35	KGUP	≥ 2	Number of normals calculated before finite rate chemistry contributes to dS and dH.
40	IDIDO	0	Uniform species concentrations along startline.
		1	Non-uniform species concentrations along startline.

Card 7 Upper Boundary Description Required*

If ICON(4) < 10000 use following format (I1, 3X, I1, 5X, 6E10.6).

Column	Parameter	Value	Description
1	IWALL(K, 2)	1	Conic equation $R = A\left[(B+CX+DX^2)^{1/2}+E\right]$ Represents throat region. (See page 3-27 for an example and description.)
		2	Polynomial equation $R = AX^4+BX^3+CX^2+DX+E$
		3	Free boundary equation $P = P_\infty(1+E_\infty X)(1+\gamma_\infty(M_\infty \sin(\theta_B-\theta_\infty))^2)$ (See page 3-27 for an example and description.)
		6	Same as IWALL=3 except oblique shock solution for plume boundary. Use if $1.5 < M_\infty < 5.5$.

*NOTE: If gas only transonic calculation is to be performed the boundary conditions upstream of the throat have to be input.

Column	Parameter	Value	Description
5	ITRAN(K, 2)	0	No discontinuity follows this equation.
		1	Expansion corner follows.
		2	Compression corner follows.
11-20	WALLCO(K, 1, 2)		Coefficient A or P_∞ (psfa or N/m^2). (Units must be consistent with R in ft or m.)
21-30	WALLCO(K, 2, 2)		B or γ_∞
31-40	WALLCO(K, 3, 2)		C or M_∞
41-50	WALLCO(K, 4, 2)		D or θ_∞ (deg)
51-60	WALLCO(K, 5, 2)		E or E_∞
61-70	WALLCO(K, 6, 2)		Maximum value of X applicable to equation (feet if ICON(9)=0 meters if ICON(9)=1).
71-80	RSTAR		Throat radius (ft or m) required only on card for last equation. Required for 2-phase trans. solution and boundary layer solution.

If 10000 < ICON(4) < 20000 use following format (I5, 5X, 3E10.6, I5, 5X, 3E10.6).

Column	Parameter	Value	Description
5	ITRANS(K, 2)		Same as before.
11-20	WALLCO(K, 3, 2)		Axial displacement (X) of point K (ft or m).
21-30	WALLCO(K, 1, 2)		Radial displacement (R) of point K (ft or m).
31-40	WALLCO(K, 2, 2)		Wall angle (θ) at point K (rad).
45	ITRANS(K+1, 2)		Same as before.
51-60	WALLCO(K+1, 3, 2)		X at point K+1 (ft or m).
61-70	WALLCO(K+1, 1, 2)		R at point K+1 (ft or m).
71-80	WALLCO(K+1, 2, 2)		θ at point K+1 (rad).

NOTE: Card 6, in the above format, is repeated for each equation until all necessary equations have been input. That is, repeat Card 7, in succession in order of increasing XMAX, for K=1, 2, . . . , ICON(4). All units for lengths for two-phase calculations are consistent with ICON(9), otherwise units for lengths are input at user's discretion.

Repeat Card 7, in above format, in succession, and in order of increasing X, until all required points have been input.

If 20000 < ICON(4) < 30000 the above format is used except the last segment of the upper boundary is input via an equation. The equation is input with the format for ICON(4) < 10000 except the throat radius RSTAR is not required.

If 40000 < ICON(4) < 50000, the format for 20000 < ICON(4) < 30000 is used except θ is input in dimension of degrees.

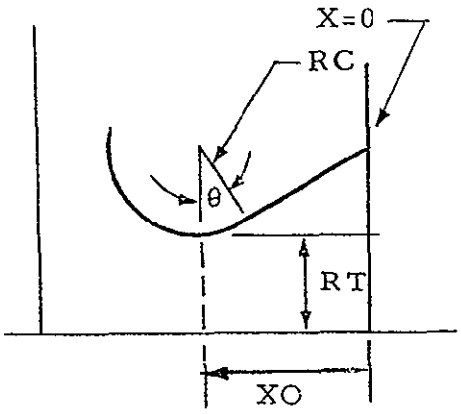
Card 7a Format E10.6

Card 7a is used only when running a two-phase case where the upper boundary (nozzle wall) is specified by discrete points (ICON(4) > 10000). Do not input this card for any other cases.

Column	Parameter	Description
1-10	RSTAR	Throat radius (ft or m).

Card 8 Lower Boundary Description Required

The formats and options for Card 8 are controlled by ICON(5) and are the same as for Card 7 (Upper Boundary) with the following exceptions: (1) the distance from the nozzle throat to the center (X=0) of the coordinate system for the wall equations is read in place of RSTAR. This is only necessary for two-phase cases where a transonic solution is desired and where X≠0 at the nozzle throat. This distance is positive if the center of the coordinate system is downstream of the throat and negative if the center of the coordinate system is upstream of the throat. It is not possible to run a two-phase case with the lower boundary specified by points, therefore there is no Card 7a; (2) the indices of the parameters are (–, –, 1) instead of (–, –, 2), e.g., WALLCO(K, 1, 1) instead of WALLCO(K, 1, 2). A nozzle throat region showing the coefficients of a circular throat and free boundary are shown in the sketch on the following page.



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 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)

$B = RC^2 - XO^2$

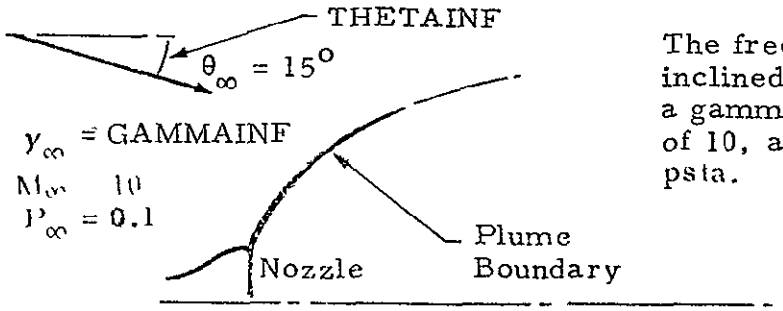
$C = 2XO$

$D = -1$

$E = -(RC + RT)$

$Xmax = RC \sin\theta + XO$

An example of a free boundary is shown in the sketch below.



The freestream approach flow is inclined at 15 deg to the plume with a gamma (γ) of 1.4, a Mach number of 10, and a static pressure of 0.1 psia.

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

Card 9 Gas Property Control Format 6A4, 5X, A3, 6X, I2, 3X, I2

This card is required whether gas data input by cards or tape.

Column	Parameter	Description
1-24	ALPHA(I)	Gas name for real gas on tape. If inputting gas data via cards, may be any name.
30-32	UNITS (Independent of ICON(9))	ENG Input gas data with English units (cards only). MKS Metric units (cards or tape).
39-40	IOF	Number of O/F tables for gaseous only solution or number of gas total enthalpy tables for two-phase solution
44-45	IS	Number of entropy tables per IOF entry, 1 for gas, 2 maximum for gas chemical equilibrium solution.

Card 10 Mixture Ratio or Total Enthalpy (This card is not used if ICON(1)≥2) Format E10.6, 8X, I2

Column	Parameter	Description
1-10	OFRAT(M)	For gaseous only flow input O/F ratio, for particle flow input gas total enthalpy (cal/gm for metric, Btu/lbm for English, units specified by Card 9).
11-20	H0(M)	For gas only transonic case input total enthalpy (cal/gm for metric, Btu/lbm for English). If real gas get data from NASA-Lewis run. If ideal $HO = C_p T_o$ where $C_p = \gamma R/(\gamma-1)$

Card 11 Entropy (This card is not used if ICON(1)≥2) Format E10.6, 8X, I2

Column	Parameter	Description
1-10	STAB(M, I)	Entropy of gas (cal/gm-^{o}K or Btu/lbm-^{o}R, units specified by Card 9).
19-20	IVTAB(M, I)	Number of Mach numbers for this entropy value (13 max).

Card 12 — Gas Properties (This card is not used if ICON(1)≥2; units specified by Card 9) — Format 8E10.6

Column	Parameter	Description
1-10	XSIDIM(1)	Mach number associated with above entropy.
11-20	XSIDIM(2)	Molecular weight of gas (gm/g-mole or lbm/lb-mole).
21-30	XSIDIM(3)	Gamma (C_p/C_v)
31-40	XSIDIM(4)	Temperature (^oK or ^oR)
41-50	XSIDIM(5)	Pressure (atm)
51-60	XSIDIM(6)	Prandtl number (dimensionless)
61-70	XSIDIM(7)	Absolute viscosity (poise)
71-80	XSIDIM(8)	Ideal gas (1 velocity cut per table) — viscosity temperature exponent. Real gas — C_p (cal/gm-^oK or Btu/lbm-^oR).

To illustrate the arrangement of Cards 10, 11 and 12, let IOF=2 and IS=2; then the proper arrangement is:

Card 10
11
12 (1-13 such cards)
11
12 (1-13 such cards)
10
11
12 (1-13 such cards)
11
12 (1-13 such cards)

Card 13 — Gas Properties (This card is required if ICON(1)>2) — Format 3E10.6

Column	Parameter	Default Value	Description
1-10	PR	0.7	Prandtl number (dimensionless).
11-20	VISO	1.0E-04	Absolute Viscosity (poise).

Card 13 (Continued)

Column	Parameter	Default Value	Description
21-30	EX	0.6	Viscosity temperature exponent.

Card 14 Gas Thermodynamic Data (The following cards are required if ICON(1)>2)

The following set of cards contain species thermodynamic data. The first card contains the species name, molecular weight and heat of formation. The second and remaining cards contain the temperature and corresponding specific heat, entropy and enthalpy for that species. Two temperatures and corresponding thermodynamic data are placed on each card. The input table can contain up to a maximum of 30 temperature points. The data are input exactly as presented in the JANAF tables (Ref. 27) with the temperature points being the same for all species. Cards 14.1, 14.2, 14.3, etc., are repeated for each species. If a SPF start line is to be punched (0<ISKPY<7) then the species must be input in same order as they appear in Table 1.

Card	Column	Description	Format
14.1	1-8	Name of first species (Left adjusted)	2A4
	11-20	Molecular weight	E10.3
	21-30	Heat of formation, h_{298_i} (kcal/mole)	E10.3
14.2	1-10	First temperature point (^{o}K)	F10.4
	11-20	c_{p_i} (cal/mole-^{o}K)	F10.4
	21-30	S_i (cal/mole-^{o}K)	F10.4
	31-40	$h_i - h_{298_i}$ (kcal/mole)	F10.4
	41-50	Second temperature point (^{o}K)	F10.4
	51-60	c_{p_i} (cal/mole-^{o}K)	F10.4
	61-70	S_i (cal/mole-^{o}K)	F10.4
	71-80	$h_i - h_{298_i}$ (kcal/mole)	F10.4
14.3	1-10	Third temperature point	F10.4
		⋮	
		etc.	

Cards 15 Catalytic Species Weighting Factor Data
(The following cards are required if ICON(1)>2 and NM>0)

The following set of cards specify the catalytic species (M1, M2, M3, . . .) and their respective composition in terms of the species participating in the reactions. Weighting factors must be read in the same order in which the thermodynamic data sets are read.

Card	Column	Description	Format
15.1.1	1-8	AID(NS+1) — Name of first catalytic species (e.g., M1) (Left Adjusted)	2A4
15.1.2	1-5	WF(1, 1) — Weighting factor of first species (for first catalytic species). Set weighting factor to zero for any reactant which does not contribute to the respective catalytic species.	16F5.2
	6-10	WF(1, 2) — Weighting factor of second species contributing to first catalytic species.	
	⋮		
	75-80	WF(1, 16) — Weighting factor of 16th species contributing to first catalytic species.	
15.1.3	1-5	WF(1, 17) — Weighting factor of 17th species contributing to first catalytic species, etc.	16F5.2
15.2.1	1-8	AID(NS+2) — Name of second catalytic	2A4
15.2.2	1-5	WF(2, 1) — Weighting factor of first species contributing to second catalytic species, etc.	16F5.2
15.NM.1	1-8	AID(NS+NM) — Name of last catalytic species, etc.	2A4

Cards 16 Chemical Reaction Mechanisms
(The following cards are required if ICON(1)>2 and NR>2)

The following set of cards specifies the chemical reaction mechanisms for a particular problem, one card for each reaction. No particular order is required. Species names are left adjusted.

Card	Column	Description	Format
16.1	1-8	Species A	2A4
	9	+ sign	
	10-17	Species B (or M)	2A4

Cards 16 (Continued)

Card	Column	Description	Format
16.1	18	+ sign	
	19-22	Blank (or M)	A4
	23	= sign	
	24-31	Species C	2A4
	32	+ sign (if needed)	
	33-40	Species D (or M)	2A4
	41	+ sign (if needed)	
	42-49	Species E (or M)	2A4
	50-51	Reaction type, 1 to 12	I2
	52	Rate constant type, 1 to 5	I1
	53-59	A, pre-exponential factor (cm-particle-sec units)	E7.1
	60-64	N, temperature exponent	F5.2
	65-74	B, activation energy (cal/mole)	F10.1
	75-80	M, temperature exponent	F6.2
16.2		Next reaction	
16.NR		Last reaction	

Cards 17 Startline Data (The following cards are required if ICON(1)>2 and ICTAPE=0) Format 7E10.3

The following cards contain the species mole fractions on the startline. Mole fractions must be read in the same order in which the thermodynamic sets are read.

Card	Column	Description
17.1	1-10	Mole fraction of first species at the first point on the startline.
	⋮	
	61-70	Mole fraction of seventh species at the first point on the startline.

Cards 17 (Continued)

Card	Column	Description
17.2	1-10	Mole fraction of eighth species at the first point on the startline.
	⋮	
	61-70	Mole fraction of the fourteenth species at the first point on the startline.
		⋮
		etc.

Cards 17.1 and 17.2, etc., are repeated for each point on the startline. For a uniform startline (IDIDO=0), mole fractions are read for 1 point only.

Card 18 Chamber Condition Data Format 2E10.3
(This card is used if ICON(1)>2 and ICTAPE=0)

Column	Parameter	Description
1-10	PC	Chamber pressure (atm)
11-20	TC	Chamber temperature (^{o}K)

Card 19 Startline Data Format 8E10.6
(This card is not used if ICON(2)=2 or for gas particle flow).

Use Card 19a if ICON(1)≤2 and ICON(2)≤3. Use Card 19b if ICON(1)>2. Use Cards 19c, d, e if ICON(2)=4

Card	Column	Parameter	Description
19a*	1-10	CORLIP(2)	Axial coordinate of upper limit of startline (ft or m, see Fig. 3a)
	11-20	CORLIP(6)	Axial coordinate of lower limit of startline (ft or m, see Fig. 3a). (If ICON(3) point spacing option = 2 this value is recalculated using CORLIP(2)).
	21-30	CORLIP(4)	Mach number (ICON(2)=0) or A/A^* (ICON(2)=1) for startline
	31-40	CORLIP(5)	Entropy of startline (cal/gm/^{o}K or Btu/lbm/^{o}R)
	41-50	CORLIP(8)	Mixture ratio (O/F) of startline

*Card 19a is used to input the gas startline information when the gas chemical equilibrium, frozen or ideal gas option is utilized in the solution. If a gas phase transonic solution is desired then this card reads in data for the transonic solution.

Card 19 (Continued)

Card	Column	Parameter	Description	
19b*	1-10	CORLIP(2)	Axial coordinate of upper limit of startline (ft or m, see Fig. 3a)	
	11-20	CORLIP(6)	Axial coordinate of lower limit of startline (ft or m, see Fig. 3a) ,	
	21-30	CORLIP(4)	Mach number (ICON(2)=0) or A/A^* (ICON(2)=1) for startline	
	31-40	P	Pressure for startline (atm)	
	41-50	T	Temperature for startline ($^{\circ}R$ or $^{\circ}K$)	
19c	1-10	CORLIP(2)	Mass flow of nozzle (lbm/sec, gm/sec). If set = 0.0 then the average O/F ratio (CORLIP(8))will be used to calculate the nozzle mass flow.	8E10.6
	11-20	CORLIP(6)	Initial station to start transonic solution (ft, m) consistent with boundary equations. This station should be just upstream of the point in the nozzle inlet where it begins to contract.	
	21-30	CORLIP(4)	Axial position of nozzle throat (ft, m)	
	31-40	CORLIP(5)	Axial station to stop the transonic solution (ft, m). Usually a station corresponding to an area ratio of around 3.	
	41-50	CORLIP(8)	Engine mass average O/F ratio	
19d	1-5	IOFS	Number of tables of O/F ratio versus radial position on the initial station (CORLIP(6)) (Maximum of 20). If IOFS=1 then constant O/F case will be run using CORLIP(8) and card 19e is not used.	I5

*This card is used to input the gas startline information when the gas chemical non-equilibrium option is utilized in the solution.

NOTE: Use card 19e when IOFS>1. Points should be input starting at nozzle centerline and going toward wall. This card inputs O/F distribution on the transonic initial station (CORLIP(6)).

19e	1-10	OFST(I, 1)	Radial position on transonic start line	8E10.5
	11-20	OFST(I, 2)	O/F ratio at above radial coordinate on start line	
	21-30	OFST(I+1,1)	R	
	31-40	OFST(I+2,2)	O/F	
	41-50	OFST(I+2,2)	R	
	51-60	OFST(I+2,2)	O/F	
	61-70	OFST(I+3,1)	R	
	71-80	OFST(I+3,2)	O/F	

NOTE: Use as many cards 19e as required to read in IOFS points.

Card 20 Startline Data Format 6E13.7

Do not use this card if ICON(2)≠2 or for gas-particle flow. Use feet if ICON(9)=0, meters if ICON(9)=1. Use Card 20a if ICON(1)≤2. Use Card 20b if ICON(1)>2.

Repeat this card in succession and in order of increasing R for I=1, 2, . . . , ICON(3).

Card	Column	Parameter	Description
20a**	1-13	R	Radial coordinate (R) of point I on startline (ft or m)
	14-26	X	Axial coordinate (X) of point I (ft or m)
	27-39	EM	Mach number at point I (dimensionless)
	40-52	THETA	Flow angle at point I (deg)
	53-65	S	Entropy at point I (cal/gm/^{o}K or Btu/lbm/^{o}R)
	66-78	OF	Mixture ratio at point I (O/F)
20b*	1-13	R	Radial coordinate (R) of point I on startline (ft or m)

*This card is used to input the gas startline information when the gas chemical non-equilibrium option is utilized in the solution.

**Card 20a is used to input the gas startline information when the gas chemical non-equilibrium, frozen or ideal gas option is utilized in the solution.

Card	Parameter	Description
14-26	X	Axial coordinate (X) of point I (ft or m)
27-39	EM	Mach number at point I (dimensionless)
40-52	THETA	Flow angle at point I (deg)
53-65	T	Temperature at point I (^{o}R or ^{o}K)
66-78	P	Pressure at point I (atm)

Card 21 Cutoff Limits Data Format 8E10.6

Required (See Fig. 3b)

Column	Parameter	Description
1-10	CUTDAT(1)	Radial coordinate defining upper limit of calculation regime (ft or m)
11-20	CUTDAT(2)	Axial coordinate defining upstream cutoff limit (ft or m)
21-30	CUTDAT(3)	Angle upper limit of calculation regime makes with horizontal (deg)
31-40	CUTDAT(4)	Radial coordinate defining downstream cutoff limit (ft or m)
41-50	CUTDAT(5)	Axial coordinate defining downstream cutoff limit (ft or m)
51-60	CUTDAT(6)	Angle downstream cutoff line makes with horizontal (deg)

Card 22 Mesh Control Fromat 8E10.6

Required (See Section 3.5.1 of Ref. 2)

Column	Parameter	Description
1-10	STEP(3)	Interior point insertion criteria (ft or m). See Section 3.5.1 of Ref. 2.
11-20	STEP(6)	Axis point insertion criteria (ft or m). See Section 3.5.1 of Ref. 2.
21-30	STEP(9)	Particle limiting streamline insertion criteria.
31-40	STEP(7)	Point deletion criteria.
41-50	STEP(1)	Prandtl-Meyer integration step size (deg).
51-60	STEP(8)	Interpolation factor for calculating lower wall.

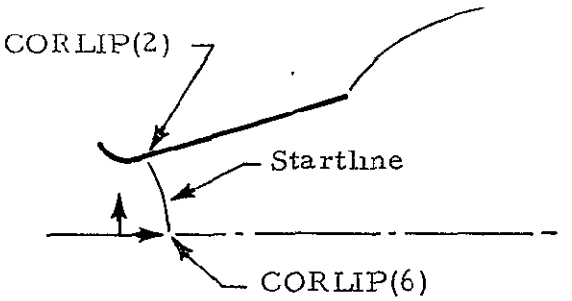
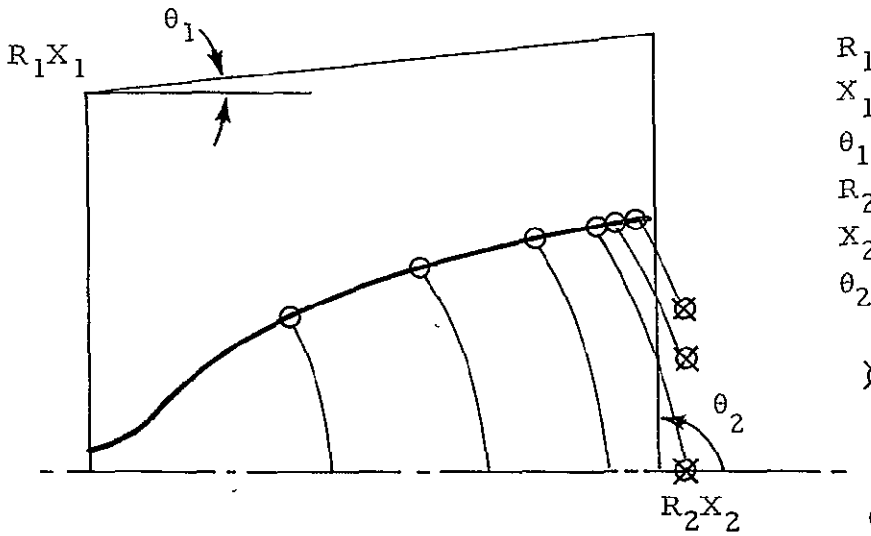


Fig. 3a – Startline Geometric Set-Up



NOTE: The normals must terminate on an upper boundary. Therefore, R_1, X_1, θ_1 must have values such that the cutoff box will always be above the plume or solid boundary. The code will attempt to fill up the cutoff box with normals until fewer than six points remain on the normal.

Fig. 3b - Cutoff Limits

Card 23 Free-Molecular Control Variables Format 6E10.6
(This card is not used if ICON(13)=0)

Column	Parameter	Description
1-10	VIBNO	Reciprocal of the Knudsen number at which the vibrational energy mode thermally freezes.
11-20	ROTNO	Reciprocal of the Knudsen number at which the rotational energy mode thermally freezes.
21-30	TRANNO	Reciprocal of the Knudsen number at which the translational energy mode thermally freezes.
31-40	CHARL	Characteristic length used in the Knudsen number calculation (nomally the nozzle exit radius).
41-50	VISCC	Reference viscosity (poise) if not input in thermo tables.
51-60	CONMM	Viscosity relation temperature exponent if not input in thermo tables.

Cards 24 through 36 are input only for two-phase solution.

Card 24 Particle Solution Control Format 16I5
(Use only if ISPECS > 0)

Column	Parameter	Value	Description
4	IZO	0	Nozzle wall equations are referenced to the nozzle throat.
		1	Nozzle wall equations are referenced to the nozzle exit plane.
5	IWRITE (particle print flag)	0	1 line of print for each particle (V, θ, ΔM, h, P, T)
		1	Above plus Re, ΔV, ΔT, viscosity, C_p, Pr
		2	All of above plus T_o, P_o, C_D/C_{DS}, Nu/Nus, A, B
6-10	IDRAG	0	Use drag table coded in Kliegel program (Ref. 28).
		1	Use C. J. Crowe drag table coded internal to program (Ref. 29).

Card 24 (Continued)

Column	Parameter	Value	Description
14-15	NSETS	0	Startline calculated by program (ICON(2)≠2)
		N	Number of startline points at which particles are present for given startline. ICON(2)=2, N ≤ ICON(3). Right adjust.
18	IPCHS	0	No punch.
		1	Punch startline from transonic program.
24	JTEM(1)		The elements of the JTEM(M) arrary indicate which temperature/enthalpy table is to be used for particle species M. The value of JTEM(1) is always set equal to 1 for particle species 1.
25, 30 . . . 65	JTEM(M) M = 2, ISPECS	0	Indicates that the particle species M temperature/enthalpy table will be the same as that for particle species 1. Cards 31, 32 and 33 are not required for particle species M.
		M	Indicates that the particle species M temperature/enthalpy table will be input on Cards 31, 32 and 33 as Table M.
		N	Indicates that the particle species N temperature/enthalpy table will be the same as that for particle species M. (N < M). Cards 31, 32 and 33 are not required for particle species N.

Card 25 Particle — Format 8E10.6

Column	Parameter	Description
1-10	XMASSP	Ratio of particle total mass flow rate to gas mass flow rate.

Card 26 Particle Mass Flow Rate Fractions (Use only if ISPECS > 0) — Format 8E10.6

Column	Parameter	Description
1-10	PERTG(1)	Ratio of particle No. 1 mass flow rate to total particle mass flow rate.

Card 26 (Continued)

Column	Parameter	Description
11-20	PERTG(2)	Ratio of particle No. 2 mass flow rate to total particle mass flow rate.
.	.	.
.	.	.
.	.	.
	PERTG(ISPECS)	Ratio of particle No. ISPECS mass flow rate to total particle mass flow rate.

Card 27	Particle Size Data (Use only if ISPECS>0)	Format 8E10.6

Column	Parameter	Description
1-10	PSP(2, 1)	Radius of particle No. 1 (microns).
.	.	.
.	.	.
.	.	.
	PSP(2, ISPECS)	Radius of particle No. ISPECS (microns).

Card 28	Particle Mass Density (Use only if ISPECS>0)	Format 8E10.6

Column	Parameter	Description
1-10	PSP(1, 1)	Mass density of particle No. 1 (lbm/ft^3, or kg/m^3)
.	.	.
.	.	.
.	.	.
	PSP(1, ISPECS)	Mass density of particle No. ISPECS (lbm/ft^3, or kg/m^3).

Card 29	Emissivity Data* (Use only if ISPECS>0) (ϵ in Eq. (3.6) of Ref. 2)	Format 8E10.6

Column	Parameter	Description
1-10	EMISS(1)	Emissivity of particle No. 1.
.	.	.
.	.	.
.	.	.
	EMISS(ISPECS)	Emissivity of particle No. ISPECS

*The emissivity and accommodation coefficients are used to determine the local energy exchange between the gas and particles via radiation. They normally produce negligible affects on solution and usually are set to 0 (zero).

Card 30 — Accommodation Coefficients* (Use only if ISPECS>0) (α in Eq. (3.6) of Ref. 2) — Format 8E10.6

Column	Parameter	Description
1-10	ACC(1)	Accommodation coefficient of particle No. 1.
.	.	.
.	.	.
.	.	.
	ACC(ISPECS)	Accommodation coefficient of particle No. 1 ISPECS.

Card 31 — Particle Equation of State (Use only if ISPECS>0) — Format 4A6, I3, A6

Column	Parameter	Description
1-24	ALPHA	Particle name (any name).
28-33	UNIT (Independent of ICON(9))	ENG Data input in English units MKS Use metric units

Card 32 — Particle Data (Use only if ISPECS>0) — Format I3, 12A6

Column	Parameter	Description
1-3	NPTM(I)	Number of temperature-enthalpy data points for this particle. If equal to 1, input liquid and solid heat capacities (see Card 33). Right adjust.

Card 33 — Particle Enthalpy Data (Use only if ISPECS>0; units specified by Card 31). — Format 7E10.6

Column	Parameter	Description
1-10	TM(I)	Melting point temperature of particle No. I (^{o}R in English units, ^{o}K in MKS units).

*The emissivity and accommodation coefficients are used to determine the local energy exchange between the gas and particles via radiation. They normally produce negligible affects on solution and usually are set to 0 (zero).

Card 33 (Continued)

Column	Parameter	Description
11-20	HS(I)	Enthalpy of solid phase of particle No.I at melting point temperature (Btu/lbm or cal/gm).
21-30	HM(I)	Enthalpy of liquid phase of particle No.I at melting point temperature (Btu/lbm or cal/gm)
	If NPTM(I)=1, use following format.	
31-40	APHO(1, 1, I)	Heat capacity of liquid phase of particle No.I (Btu/lbm-^{o}R or cal/gm-^{o}K).
41-50	APHO(1, 2, I)	Heat capacity of solid phase of particle No.I (Btu/lbm-^{o}R or cal/gm-^{o}K).
	If NPTM(I) > 1 use following format.	
31-40	APHO(1, 1, I)	Temperature for T-H table for particle No.I (^{o}R or ^{o}K).
41-51	APHO(1, 2, I)	Enthalpy for T-H table for particle No.I (Btu/lbm or cal/gm).
51-60	APHO(2, 1, I)	Second temperature in T-H table for particle No.I (^{o}R or ^{o}K).
61-70	APHO(2, 2, I)	Second enthalpy in T-H table for particle No.I.

The above format (APHO(J, 1, I), APHO(J, 2, I)) is continued on successive cards of format 7E10.6 for J=1, 2, . . . , NPTM(I).

There are as many sets of cards 31, 32 and 33 as there are different chemical species.

Card 34 Input Startline Format 6E13.7
(The following cards are required if ICON(2)=2 and ISPECS > 0).

Use Card 34a if ICON(1) $\leq$ 2. Use Card 34b if ICON(1) > 2.
Repeat this card for I=1, 2, . . . , ICON(3) starting at point on nozzle axis.

Card 34a*

Column	Parameter	Description
1-13	R	Radial coordinate of startline point I (ft or m).
14-26	X	Axial coordinate of startline point I (ft or m).

*This card is used when gas chemical equilibrium, frozen or ideal gas option is selected.

Card 34a (Continued)

Column	Parameter	Description
27-39	EM	Mach number at point I.
40-52	THETA	Flow angle at point I (deg).
53-65	S	Entropy at point I (Btu/lbm-^{o}R or cal/gm-^{o}K).
66-78	OF	Gas total enthalpy (Btu/lbm or cal/gm).

Card 34b*

Column	Parameter	Description
1-13	R	Radial coordinate of startline point I (ft or m).
14-26	X	Axial coordinate of startline point I (ft or m).
27-39	EM	Mach number at point I.
40-52	THETA	Flow angle at point I (deg).
53-65	T	Temperature at point I (^{o}R or ^{o}K)
66-78	P	Pressure at point I (atm).

Card 35 Startline Particulate Data Format I5, 5X, 4E13.7
(The following cards are required if ICON(2)=2 and ISPECS>0).

Column	Parameter	Description
5	J1	Particle number
11-23	H1	Particle enthalpy at point I (Btu/lbm or cal/gm).
14-36	RHO1	Particle density at point I (slug/ft^3 or kg/m^3).
37-49	U1	Particle axial velocity at point I (ft/sec or m/sec).
50-62	V1	Particle radial velocity at point I (ft/sec or m/sec).

Card 35 is repeated for each discrete particle size at each point on the start line where particles are present, starting at the nozzle wall and going toward the axis (reverse order of Card 34).

Card 36 Transonic Flow Data (Use only if ISPEC > 0 and ICON(2) ≠ 2) Format: Namelist

Although there are many parameters that may be input via the namelist DATA, most of these have already been assigned values in the previous 35 input cards; and some of the parameters do not apply to the transonic calculation. Only those namelist parameters that could have a significant effect on the program are included below. The namelist data begins in Column 2 with $DATA. The last card begins in Column 2 and contains only $END.

Parameter		Assumed Value
THID	Throat inlet half angle (deg)	None
THFD	Fairing angle (deg) (If THFD > THID no fairing)	5.0
THJD	Angle defining farthest downstream zone in transonic region (deg)	9.0
THIW	Angle where start line intersects nozzle wall (deg)	12.0
RRT	Throat wall radius of curvature divided by throat radius (>2.0)	None
ZAX	Value of X where startline intersects nozzle axis, normalized by throat radius (If ZAX is not input the program will calculate a value.)	None

(See Fig. 4 for an illustration of above parameters.)

ZI	Number of zones into which the upstream portion of transonic zone is divided*.	3.0
ZJ	Number of zones into which the downstream portion of transonic zone is divided*	2.0

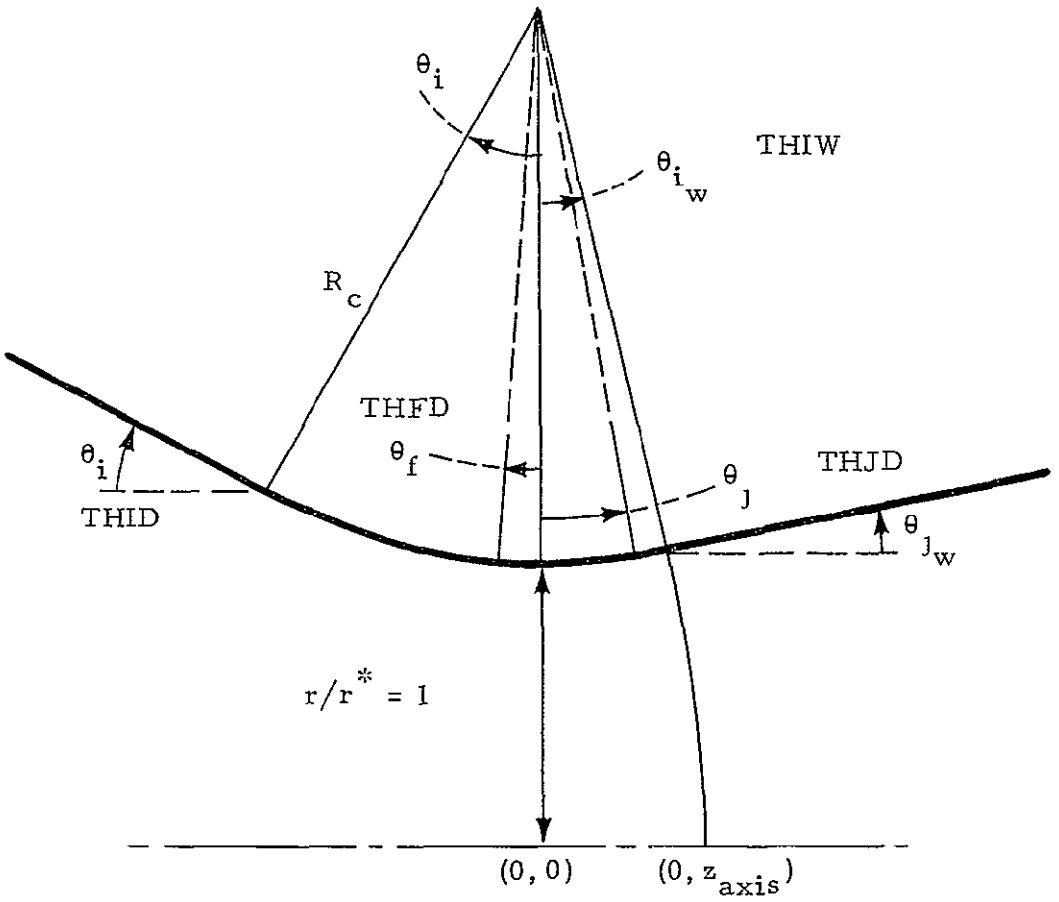


Fig. 4 - Inlet and Throat Parameters for a Gas-Particle Transonic Solution (see Ref. 28)

If ISKPY=7 read in cards 37, 38 otherwise leave out.

Card 37 Format: I5 Format: I5

Column	Parameter	Description
1-5	INUM	Number of chemical species to be read in for this chemical system (maximum of 25)

Card 38 Card 38 reads in the species names for chemical system which does not appear in Table 1. 18A4

Column	Parameter	Description	
1-12 (Left Adjusted)	(SNAME(7, I, J), J=1, 3)	Species name (consistent with JANNAF	3A4
13-24	I+1		3A4
25-36	·		3A4
37-48	·		3A4
49-60	·		3A4
61-72	(SNAME(7, I+7, J), J= 1, 3)		3A4

Use as many cards 38 as required to read in INUM species.

If $1 \leq ISKPY \leq 7$ and ICON(1)=1 card 39 is required, otherwise leave out.

Card 39 Species mole fraction card for SPF start line. Format: 8E10.6

Column	Parameter	Description
1-10	SIFROZ(I)	Species mole fraction
11-21	SIFROZ(I+1)	Species mole fraction
·		·
·		·
·		·
71-80	SIFROZ(I+7)	Species mole fraction

Card 39 (Cont'd)

As many species mole fractions must be read in as there are species in the particular chemical system (see Table 1). If ISKPY=7, there should be INUM species. The order must be the same as the species appearing in Table 1 or were read in under card 38. Use as many cards 39 as necessary to read in all species mole fractions (25 maximum).

Cards 40, 41, 42, 43 may be required only if a boundary layer calculation is to be performed (IBL>0, card 5) otherwise they must be left out.

Card 40 Boundary Layer Run Option Card — Format: 5I5, 5X, E10.5)
This card must be input if IBL>0

Column	Parameter	Value	Description
1-5	KR7	0	Turbulent boundary layer, calculation starts off laminar and will trip to turbulent when the Reynolds number based on momentum thickness exceeds 250. The program will select whether the flow is frozen or in equilibrium.
		1	Laminar boundary layer, frozen chemistry
		2	Laminar boundary layer, equilibrium chemistry
		3	Turbulent boundary layer if momentum thickness Reynolds number exceeds 250. Equilibrium chemistry.
		4	Same as 3 except frozen chemistry
6-10	KR9	0	Adiabatic wall nozzle wall
		2	Specified wall temperature distribution. (Requires cards 43).
		4	Wall steady state energy balance
11-15	ITPTS	N	where N is the number of wall points to input the nozzle wall temperature. This is used only if KR9=2 (25 max.)

Card 40 (Continued)

Column	Parameter	Value	Description
16-20	ISPEC	N	N is the number of chemical species in the boundary layer edge gas. This is required only if ICON(1)=1 (thermo data read from cards).
21-25	NUNIPP	0	Do not punch the BLIMPJ input data.
		1	Punch the BLIMPJ input data.
31-40	XSTART		Distance from the beginning of the boundary layer. Program defaults to 1/2 a throat radius.

Card 41 Boundary Layer Edge Species Format: 4(2A4, 2X, E10.6)

NOTE: This card is required only if ICON(1)=1. The order in which the species are read in does not matter.

Column	Parameter	Description
1-8	SPECN(1)	Chemical species name (Left Adjusted)
11-20	SPECMF(1)	Species mole fraction
21-28	SPECN(2)	2nd chemical species name
31-40	SPECMF(2)	2nd chemical species mole fraction
etc.		

As many card 41 are used as are required to read in ISPEC species, 4 to a card.

Card 42 Transport Property Card Format: 2E10.5

NOTE: This card is required only if ICON(1)=1 and the case being run is not a two phase case (ICON(9)=0).

Column	Parameter	Description
1-10	XMU	Gas viscosity in the combustion chamber (poise)
11-20	PRFR	Turbulent Prandtl number

Card(s) 43 Nozzle Wall Temperature Distribution Format: 8E10.5

NOTE: Card(s) 43 are only required if the wall temperature distribution option is selected (KR7=2). Input points starting from nozzle throat to the lip.

Column	Parameter	Description
1-10	TWA(1, 1)	Axial coordinate of wall location (ft, m)
11-21	TWA(1, 2)	Wall temperature at above location (deg R, deg K)

Input ITPTS pairs of location and temperature. Four pairs per card.

Table 3

MAGNETIC TAPE ASSIGNMENTS
FOR TRAN72/RAMP/BLIMPJ PROGRAMS

Unit	Tape Unit Function
1, 8, 9, 11, 12, 13	Internal Temporary Use Files
2	BLIMPJ Output File
3	Flowfield Data Generated by RAMP Program (Output)
4	TRAN72 Thermo Data (Input)
10	Gas Properties Data Generated by TRAN72 Program (Input)

2.3.2 Control Card Set-Up for Univac 1108 Exec 8 and Program Overlay Structures

A typical run stream set-up for the Univac Exec 8 computer is presented in this section. Also included is a table which gives the overlay structure for the RAMP program.

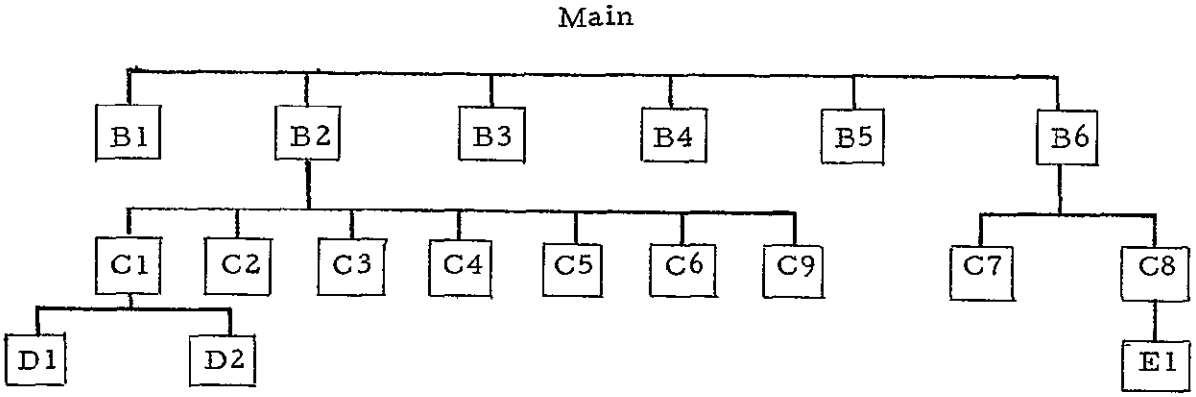
NOTE: This schematic is typical of a run control scheme for the Univac 1108 Exec 8 computer. It is presented to acquaint the user with magnetic tape and scratch area assignments.

Table 4 gives the program overlay structure for the RAMP program.

```
'RUN                                    . RUN CONTROL CARD
'ASG,T 1,F///500
'ASG,T BI T,F///500
'USE 2,BI T
'ASG,T BI P,F///500
'USE 3,BI P
'ASG,T PROD,F///300
'USE 4,PROD
'ASG,T DUM,F///500
'USE 8,DU
'ASG,T 9,F
'ASG,T GAS,F
'USE 10,GAS
'ASG,T 11,F
'ASG,T 12,F
'ASG,T PL IN,F///300
'USE 13,PLIN
'FREE TPF$                              . CORE ASSIGNMENT
'ASG,T TPF$,F///500                     . CORE ASSIGNMENT
'ASG,TF STK,UOS,04129                   . PROGRAM AND PRODUCT DATA TAPE
'MOVE STK,3                             . MOVE TAPE TO 4 TH FILE
'COPY STK,PROD                          . COPY PRODUCTS DATA ONTO UNIT 4
'REWIND STK                             . REWIND PROGRAM TAPE
'COPIN STK,TPF$                         . COPY TRAN72 PROGRAM INTO CORE
'XQT A                                  . EXECUTE TRAN72 PROGRAM
   *********     TRAN72 DATA     *********
'FFS                                    . ERASE CORE
'FREE TPF$                              . CORE ASSIGNMENT
'ASG,T TPF$,F///500                     . CORE ASSIGNMENT
'REWIND STK
'MOVE STK,1                             . MOVE PROGRAM TAPE TO SECOND FILE
'COPIN STK,TPF$                         . COPY RAMP CODE INTO CORE
'COPIN STK,TPF$                         . COPY BLIMPJ CODE INTO COPE
'FREE STK                               . RELEASE PROGRAM TAPE
'XQT GO                                 . EXECUTE RAMP CODE FOR NOZZLE SOLUTION
   *********     RAMP NOZZLE DATA     *********
'XQT BLIMP                              . EXECUTE BLIMPJ CODE FOR NOZZLE BOUNDARY LAYER
   *****     NO BLIMPJ J DATA IT CAME FROM RAMP OUTPUT FILE  *****
'XQT GO                                 . EXECUTE RAMP FOR PARTICLE BL CALC AND STARTLINE
   *****  1 CARD OF RA IP DATA FOR PARTICLE TRAJECTORY AND EXIT STARTLINE ****
   *****     REST OF DATA WAS LOADED ON UNIT 13 IN FIRST RAMP EXECUTION     ***
'FIN
'FIN
```

Table 4

RAMP OVERLAY STRUCTURE



Main

MAIN
DRIVER
BLKDAT
BOUND
EMOFV
ITSUB
POFEM
RHOFEM
TEMTAB
TOFEM
PAGE
ERRORS
DROGCP
VOFEM
THERMO
THERM1
LAGRNG
SITER
REPEAT
ALGINT
VOFEM
RITE
KIKOFF
UOFV
TKEY
TOFV
IDMPFP
DRAGMR
SPCTX
TAB
FABLE
TOFH
XSI

B1

PLUMIN
RGVOFM
IDTAPE
IDMXSI
IDMTAB
PARTIN
WTT
WG
OUTPUT
POINT
THERMT
MASS
OFSET
INITP
GASRD
GASTAP
IMPUT
LIPIN
WXANDR
PAGVOF
AXIS
LOGIC
MAXT
PHI
IDMPHI
IBOUND
STARTV
WOFA
AOASTR
SETHTG
PARTPH
MASCON
PLMOUT

B3

TRANS
PARTIL
ONED
JAMES
PROP
FIND11
WDGI
DCALC
LEGS
TRACE
SITER
FCALC
NEWT
ABCALC
CCALC
PCALC
STRMLN

B2

PHASE1
PPATPT DOTPRD
GAPPBI VEMAG
SLDP SOKINT
CHEM ROTERM
EMOFP MAXTIM
RGMOFP FNEWTN
COEFEQ VMOD1
NEWENT VMODEL
COEFF3 INRSCT
CHECK

C1

STRNOR
SOKSOL
PHYSOL

D1 D2

CARCTR AVERAG
SEPLIN STGMOD

C9

MCCRMK
DECODE
CODEH
CODEE
CODEF
REDIST

C2

MASSCK
THRUST
INTEGR

C3

OUT
SLSKIP OUTBIN
ENTROP VMOD2
DELTAF POJH
WEAK NORSCK
ESHOCK TOFENH
TURN

C4

EXPCOR
PAFH HYPER
MOCSOL PRANDT
OVEREX THETPM

C5

FREEMC
PRFRBD WTFLOF
BOUNDA ITARM

C6

IRAD
ITERM
LIMITS

B4	B5
PUNEX	BLMPIN
ARASSL	IDMTAB
SPECIE	SPECIB
IDMPOP	WALPRP
POP	TOB

B6

WTFLOP
IDMPRO
PRO
IDMPDT
PDT

C7	C8	E1
PARLOK	TRACEP	DUMSYS
INRSCP	GAS	
TAPMOV	START	
READF		
INTERP		

2.3.3 Description of Unformatted Binary Output

The binary tape output on unit 13 is described in this section. Initial input data are written on the first part of the data tape and gaseous and particle data are written out for each data point in the flow field. This tape is formatted so that it may be used by other auxiliary routines (plot, plume impingement or radiation).

GROUP I — General Information

Number of Records = 1

Write ( ) (HEADER(I), I=1, 60), ISPECS, IMETRIC

- HEADER
  - run identification (2A4)
  - date (3A4)
  - description (55A4)
- ISPECS = number of particle species to be considered
- IMETRIC* = 0 English flowfield units
  = 1 Metric flowfield units

GROUP II — Gas Data

Number of Records = 1 + IOF*IS

Write ( ) (BETA(I), I=1, 6), IOF, IS

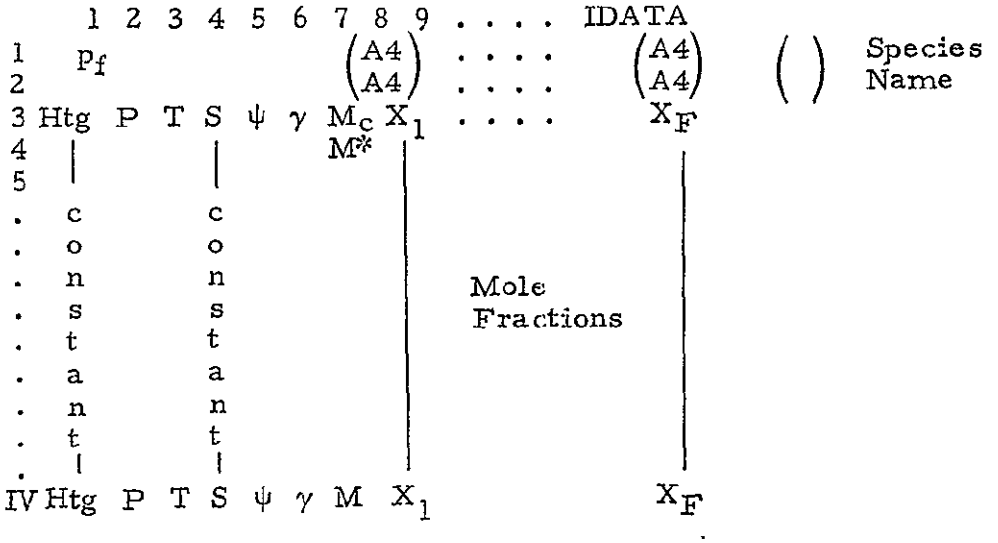
- BETA is gas identification name (6A4)
- IOF number of total enthalpy cuts through "Mollier chart" (max = 10)
- IS number of entropy cuts (max = 2)

DO M=1, IOF
DO I=1, IS

Write ( ) IV, IDATA, ((TEMP(J, K), K=1, IDATA), J=1, IV), IVT, ((CPM(J, K), K=1, 3), J=1. IVT), RSTAR, PINF, EMINF, GAMINF, FINF, EXINF, XSHIFT

*Determined from ICON(9).

- IV — number of velocity cuts through "Mollier chart" for this total enthalpy and entropy + 2 (max = 15)
- IDATA — number of gaseous species present for this total enthalpy and entropy (max = 98)
- GAMINF — freestream isentropic exponent
- IVT — = IV-2
- RSTAR — throat radius (ft or meters)
- PINF — ambient pressure (psf or Newtons/m^2)
- EMINF — freestream or external stream Mach number
- EXINF — limit to which equation applies
- FINF — linear static pressure gradient (slope) θ approach
- TEMP — contains the following information for each value of IOF, IS
- XSHIFT — nozzle length (ft or meters)



- p_f — freeze pressure (atm)
- Htg — total enthalpy of the gas (cal/gm)
- P — pressure (atm)
- T — temperature (^oK)
- S — entropy (cal/gm-^oK)
- ψ — molecular weight (gm/gm-mole)

- γ isentropic exponent
- M_c chamber Mach number = 0
- M^* throat Mach number = 1
- M Mach number for this table entry
- CPM contains the following information

	1	2	3
	Pr	μ	C_p
1			
2			
3			
.			
.			
IVT			

- Pr Prandtl number
- μ viscosity (poise)
- C_p specific heat at constant pressure (cal/gm-^oK)

GROUP III – Gas Particle Data

Number of Records = ISPECS+1

Write ( ) IDUM, ((PSP(I, J), I=1, 2), J=1, ISPECS)

- IDUM dummy word
- PSP(1, J) mass density of j^{th} particle (slug/ft^3 or kg_m/m^3)
- PSP(2, J) radius (ft or m)

DO I=1, ISPECS

Write ( ) NTAB1, TMELT, HSOL, HLIQ, (HFIT(N, 1, I), HFIT(N, 2, I), N=1, NTAB)

- NTAB1 number of table entries for this species
- TMELT melt temperature (^oR or ^oK)
- HSOL enthalpy before phase change (ft^2/sec^2-^oR or m^2/sec^2-^oK)
- HLIQ enthalpy after phase change (ft^2/sec^2-^oR or m^2/sec^2-^oK)
- HFIT(N, 1, I) temperature (^oR or ^oK)
- HFIT(N, 2, I) enthalpy (ft^2/sec^2 or m^2/sec^2)
- NTAB number of table entries for this species

Note that if NTAB=1 species is ideal and HFIT(1, 1, I)= C_{PL} (specific heat of liquid) and HFIT(1, 2, I)= C_{PS} (specific heat of the solid).

GROUP IV — Flowfield Data

Number of Records = 1 + 2 * ILAST

Write ( ) (ILAST, I=1, 7), THRUST, AEXIT, IEXIT

- ILAST — number of data points on the following normal surface. If ILAST = 0 there is no information to follow
- THRUST — thrust (lb_f or Newtons)
- AEXIT — exit plane area (ft^2 or m^2)
- IEXIT — exit flag { 0 if no exit; 1 if exit

Write ( ) ((ITYPE, R, X, M, θ, S, μ, δ, Htg), I=1, ILAST), (V, I=1, ILAST), ($\dot{W}_g$, I=1, ILAST), ((ρ, P, T, γ, $\hat{R}$), I=1, ILAST)

- ITYPE — identifies type of point (wall, shock, interior, etc.)

0	input point
1	interior point
2	wall point
3	free boundary
4	upstream shock point
5	Prandtl-Meyer point
6	downstream shock point
7	slip line
8	shock intersection point
9	vibrational mode frozen
10	rotational mode frozen
11	translational mode frozen

- R — radial coordinate (ft or m)
- X — axial coordinate (ft or m)
- M — Mach number
- θ — flow angle (rad)
- S — entropy (ft^2/sec^2-^oR or m^2/sec^2-^oK)
- μ — Mach angle (rad)
- δ — shock angle (rad)
- Htg — gas total enthalpy (ft^2/sec^2 or m^2/sec^2)

- V — velocity (ft/sec or m/sec)
- $\dot{W}_g$ — mass flow between this streamline and axis (slug/sec or kg_m/sec)
- ρ — gas density (slug/ft^3 or kg_m/m^3)
- P — pressure (lb_f-ft^2 or N/m^2)
- T — temperature (^oR or ^oK)
- γ — isentropic exponent
- R — universal gas constant divided by molecular weight (ft^2/sec^2-^oR or m^2/sec^2-^oK)

DO I = 1, ILAST

Write ( ) (SPECN, I=1, NS)

- NS — number of gas species
- SPECN — species mole fractions

Output only for finite rate cases

Write ( ) (PO, I=1, ILAST)

- PO — pitot total pressure

Output only if 3 line printout selected ICON(8)

DO I = 1, ILAST

Write ( ) ISP, ((U, V, T, H, ρ), J=1, ISP), ILIMIT

- ISP — number of particle sizes at this point
- U — axial velocity component (ft/sec or m/sec)
- V — radial velocity component (ft/sec or m/sec)
- T — temperature (^oR or ^oK)
- H — enthalpy (ft^2/sec^2 or m^2/sec^2)
- ρ — particle density (slug/ft^3 or kg_m/m^3)
- ILIMIT — 0 } not a limiting streamline; 1 } is a limiting streamline

NOTE: The flowfield data are repetitively stored on tape as indicated above — normal surface after normal surface. When ILAST = 0 the end of the data has been reached.

3. CONCLUSIONS AND RECOMMENDATIONS

This document has described the new capabilities which have been added to the RAMP code. In addition to the basic capabilities of the RAMP code, which allow it to perform detailed two-phase flow calculations for supersonic nozzle/plume flows, the following improvements have been made:

- A nozzle exit plane start line can be punched or put on tape which will directly interface with the JANNAF Standard Plume Flowfield Code (SPF). This start line can include any or all of the following phenomena: two-phase flow effects, ideal, equilibrium or finite rate chemistry, variable O/F distribution, nozzle wall boundary layer, shock waves and transonic effects.
- A nozzle boundary layer solution can be performed with little or no additional input requirements.
- The effect of the nozzle boundary layer on particles which enter the boundary layer can be considered.
- A finite difference shock capturing numerical operator has been added. This option has been checked out for single phase ideal gas solutions only.
- A variable O/F transonic solution module has been incorporated into the code. This module will treat the transonic portion of nozzles for ideal and equilibrium chemistry for constant as well as variable O/F flows.
- An improved two-phase transonic solution has been added which allows the treatment of small throat radii of curvature. At the present time this transonic calculations domain does not extend far enough downstream to generate a normal start line so that the throat radius of curvature must be greater than 1.5. This deficiency will be corrected and code modifications will be forwarded to the users.
- The code will generate an exit plane start line which includes the nozzle wall boundary layer. The subsonic portion of the boundary layer is expanded to Mach = 1.01 via the Seubold method so that a plume solution is possible.

The updated version of the RAMP code has considerably more capability than the original version. It will allow users to generate an exit plane viscous start line with little effort unlike the numerous hand calculations and computer runs which were necessary in the past.

Additional work in the area of rarefied flows is necessary to make the plume calculations more applicable in the back flow regions of the plume.

In its present form, the code has the capability of producing data for the following applications:

- Gas/Gas-Particle Impingement (Heat-Transfer-Loads)
- Rocket Nozzle Performance (Thrust, I_{sp})
- IR Signatures (Radiating Species)
- RF Attenuation (Electron Densities)
- Plume Radiation (Radiative Heat Transfer Gas/Particles)
- Vehicle Base Pressure
- Base Heating (Convection-Recirculation)

4. REFERENCES

1. Penny, M. M. et al., "Supersonic Flow of Chemically Reacting Gas-Particle Mixtures – Volume I – A Theoretical Analysis and Development of the Numerical Solution," LMSC-HREC TR 476555-I, Lockheed Missiles & Space Company, Huntsville, Ala., January 1976.
2. Penny, M. M. et al., "Supersonic Flow of Chemically Reacting Gas-Particle Mixtures – Volume II – RAMP, a Computer for Analysis of Chemically Reacting Gas-Particle Flows," LMSC-HREC TR 496555, Lockheed Missiles & Space Company, Huntsville, Ala., January 1976.
3. Dash, S. M., H. S. Pergament and R. D. Thorpe, "A Modular Approach for the Coupling of Viscous and Inviscid Processes in Exhaust Plume Flows," 17th Aerospace Sciences Meeting, New Orleans, 15-17 January 1979.
4. Penny, M.M., "Analytical Data for the APS R-1E Engine Plume Impingement Forces and Moments on the S-IVB Protuberances and the OWS Panels (Small Version), LMSC-HREC A148628, TN 54/20-51, Lockheed Missiles & Space Company, Huntsville, Ala., January 1969.
5. Boynton, F. P., "Exhaust Plumes from Nozzles with Wall Boundary Layers," J. Spacecraft Roc., Vol. 5, October 1968, pp. 1143-1147.
6. Simons, G. A., "Effect of Nozzle Boundary Layers on Rocket Exhaust Plumes," AIAA J., Vol. 10, November 1972, pp. 1534-1535.
7. Curtis, J. T. et al., "Plume Interference Prediction (PIP) Code: User's Manual and Test and Evaluation Report – Vols. I and II," KC-5900-A-6, Calspan Corp., Buffalo, N. Y., April 1977.
8. Spradley, L. W., and M. L. Pearson, "GIM Code User's Manual for the STAR-100 Computer," NASA CR-3157, November 1979.
9. Evans, R. M., "BLIMP-J User's Manual," UM-75-64, Aerotherm, Mountain View, Calif., July 1975.
10. Smith, S. D., "Definition of Solid Particle Plume Flow Fields of the Space Shuttle Interim Upper Stage (IUS, SSUS-A, SSUS-D) Solid Booster Motors," LMSC-HREC TN D568087, Lockheed Missiles & Space Company, Huntsville, Ala., November 1977.
11. Smith, S. D., and A. W. Ratliff, "User's Manual – Variable O/F Ratio Method of Characteristics Program for Nozzle and Plume Analysis," LMSC-HREC D162220-IV, Lockheed Missiles & Space Company, Huntsville, Ala., June 1971.
12. Seubold, J. G., and R. H. Edwards, "A Simple Method for Calculating Expansion of a Rocket Engine Nozzle Boundary Layer into a Vacuum," Seventh JANNAF Plume Technology Conference, April 1973, pp. 35-44.

13. Bird, G. A., "The Nozzle Lip Problem," Rarefied Gas Dynamics: Proceedings of the 9th International Symposium, Vol. 1, 1974, pp. A.22-1-A.22-8.

14. Wiernbaum, S., "Rapid Expansion of a Supersonic Boundary Layer and Its Application to the Near Wake," AIAA J., Vol. 4, No. 2, 1966, pp. 217-226.

15. Baum, E., "An Interaction Model of a Supersonic Laminar Boundary Layer on Sharp and Backward Facing Steps," AIAA J., Vol. 6, No. 3, March 1966, pp. 440-447.

16. Cooper, B. P., "Nozzle Boundary Layer Model Including the Subsonic Sublayer Usable for Determining Boundary Layer Effects on Plume Flow Fields," JANNAF 11th Plume Technology Meeting, Huntsville, Ala., May 1979.

17. Prozan, R. J., "Striated Combustion Solution," LMSC-HREC A791356, Lockheed Missiles & Space Company, Huntsville, Ala., May 1968

18. Combs, L. P., "Liquid Rocket Performance Computer Model with Distributed Energy Release," NASA CR-11462, 10 June 1972.

19. Ring, L. R., "Evaluation of Combustion/Nozzle Gasdynamic Models for Liquid Rocket Engine Applications," AFRPL-TR-77-46, Air Force Rocket Propulsion Laboratory, Edwards, Calif., July 1977.

20. Stephens, J. T., and A. W. Ratliff, "Studies of Rocket Engine Combustion Chamber Geometry Using an Equilibrium Reacting Gas Transonic Flow Program," LMSC-HREC A784898, Lockheed Missiles & Space Company, Huntsville, Ala., November 1967.

21. Ratliff, A. W. et al., "Analysis of Exhaust Plumes from Skylab-Configuration R-4D Attitude Control Motors," LMSC-HREC D162171, Lockheed Missiles & Space Company, Huntsville, Ala., March 1970.

22. Ring, L. R. et al., "Analysis and Correpation of High Altitude Rocket Exhaust Plume Experimental Data," JANNAF 7th Plume Technology Meeting, Huntsville, Ala., April 1973.

23. Nickerson, G. R. et al., "Solid Rocket Motor Performance Predictions Using the Improved SPP Computer Model," 16th JANNAF Combustion Meeting, Monterey, Calif., September 1979.

24. Svehla, Roger, A., and B. J. McBride, "FORTRAN IV Computer Program for Calculation of Thermodynamic and Transport Properties of Complex Chemical Systems," NASA TN D-7056, Lewis Research Center, Cleveland, Ohio, 1973.

25. Gordon, Sanford, and Bonnie J. McBride, "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouget Detonations," NASA SP-273, Lewis Research Center, Cleveland, Ohio, 1968.

26. Penny, M. M., and C. J. Wojciechowski, "User's Manual and Description of a Computer Program for Calculating Heating Rates, Forces and Moments Acting on Bodies Immersed in Rocket Exhaust Plumes," LMSC-HREC D162867-II, Lockheed Missiles & Space Company, Huntsville, Ala., March 1971.

27. JANAF Thermochemical Tables, Second Edition, U. S. Dept. of Commerce, National Bureau of Standards, NSRDS-NBS 37, Washington, D. C., June 1971.

28. Kliegel, J. R., and G. R. Nickerson, "Axisymmetric Two-Phase Perfect Gas Performance Program – Vol. I," NASA CR 92069, April 1967.

29. Crowe, C. J., "Drag Coefficient of Particles in a Rocket Nozzle," AIAA J., No. 5, May 1967

Appendix A
EMPIRICAL INPUT DATA AND INPUT DATA SUGGESTIONS

Appendix A

The results obtained from the Reacting and Multiphase Computer Program (RAMP) are very sensitive to data which are input. For two-phase cases the mean particle size, distribution of sizes, specific heats, mass density, particle melting temperature, chemistry assumptions and boundary equations are the primary input variables which determine the results. Each of these variables will be discussed in some detail and suggestions will be made as to what values can be used for aluminized propellants. It should be noted, however, that the data presented is not necessarily the best available

Mean Particle Size

Several different methods have been employed for obtaining mean particle size. Included are techniques which correlate mean size to throat diameter (Ref. A-1), mean motor L^* (Ref. A-2) (chamber volume/throat area), chamber pressure, residence time, particle loading, maximum stable droplet size as well as combinations of each of these parameters. As a simple estimate of mean particle size the correlation of Delaney (Ref. A-1) based on throat diameter can be used:

$$D_m = 4\, D_t^{.3} \qquad (A.1)$$

where D_m is the mean particle diameter in microns and D_t is the throat diameter in inches.

Particle Size Distribution

For nozzle calculations in which no particle impingement on the wall is anticipated, one particle size at the mean size can be used. However, for plume calculations a knowledge of the particle size distribution is necessary.

Delaney in Ref. A-1 showed that the distribution of particles for smaller motors ($D_t \lesssim 3.5$ in.) followed a log normal distribution (Fig. A-1). For the large motors ($D_t > 3.5$ in.) the data indicate that the size distribution follows a normal distribution (Fig. A-2). To use these distributions· move the curves up or down to the mean size at the 50% coordinate, then divide the curve into 5 or 6 sections and determine the mean size that goes with each of these sections. Table A-1 gives an example of the size distribution (for 6 discrete sizes) which was determined from the curve in Fig. C-1.

Particle Specific Heats, Enthalpies and Melting Temperature

The values for particle specific heats, enthalpies and melting temperature which the authors use are shown in Table A-2. The specific heats shown are used for the ideal approximation of particle enthalpy verses temperature (i.e., the specific heat for liquid and solid phases of the aluminum oxide are constant). The user may find the tables of temperature verses enthalpy in the JANAF Thermochemical Tables (Ref. A-3).

Particle Mass Density

The mass density for aluminum oxide is different for the solid and liquid phases. Reference A-4 shows the mass density of liquid aluminum oxide (Al_2O_3) to be 188 lbm/ft^3. The mass density of solid Al_2O_3 is 250 lbm/ft^3. For cases where the particle temperatures will be higher than the melting temperature for most of the flow field, the liquid mass density should be used. In cases where the particle temperature will be below the melting temperature (i.e , plumes) the solid mass density should be used.

Chemistry Assumptions

There are numerous chemistry assumptions which can be employed by the RAMP code. The various assumptions are: (1) ideal gas (constant specific heat ratio and molecular weight); (2) equilibrium; (3) frozen (constant molecular weight, varying specific heat ratio); (4) equilibrium/frozen (equilibrium with the molecular weight constant below a specified pressure) or (5) finite-rate chemistry.

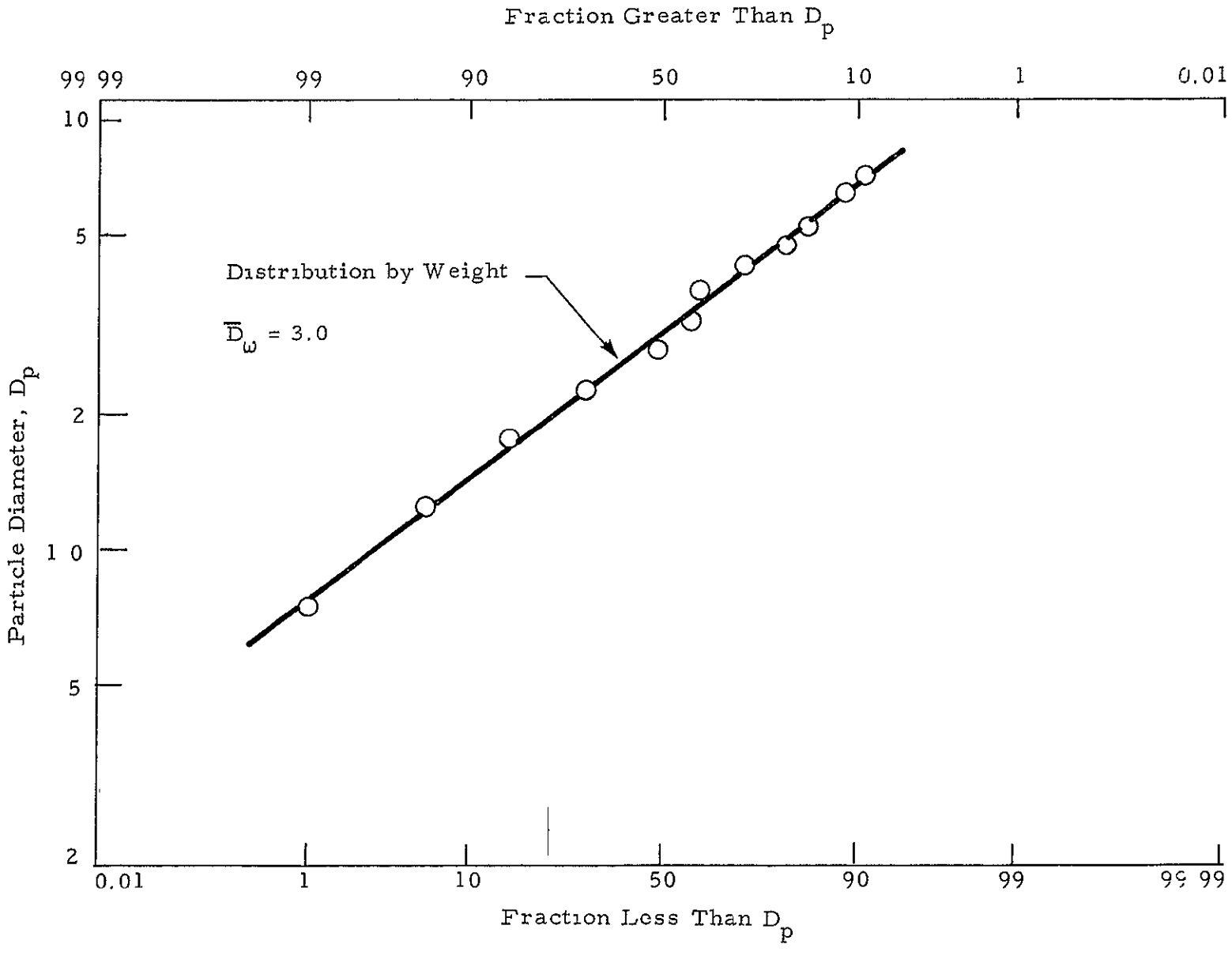


Fig A-1 - Log Normal Particle Size Distribution from HI 5 PC Motor (Ref A-1)

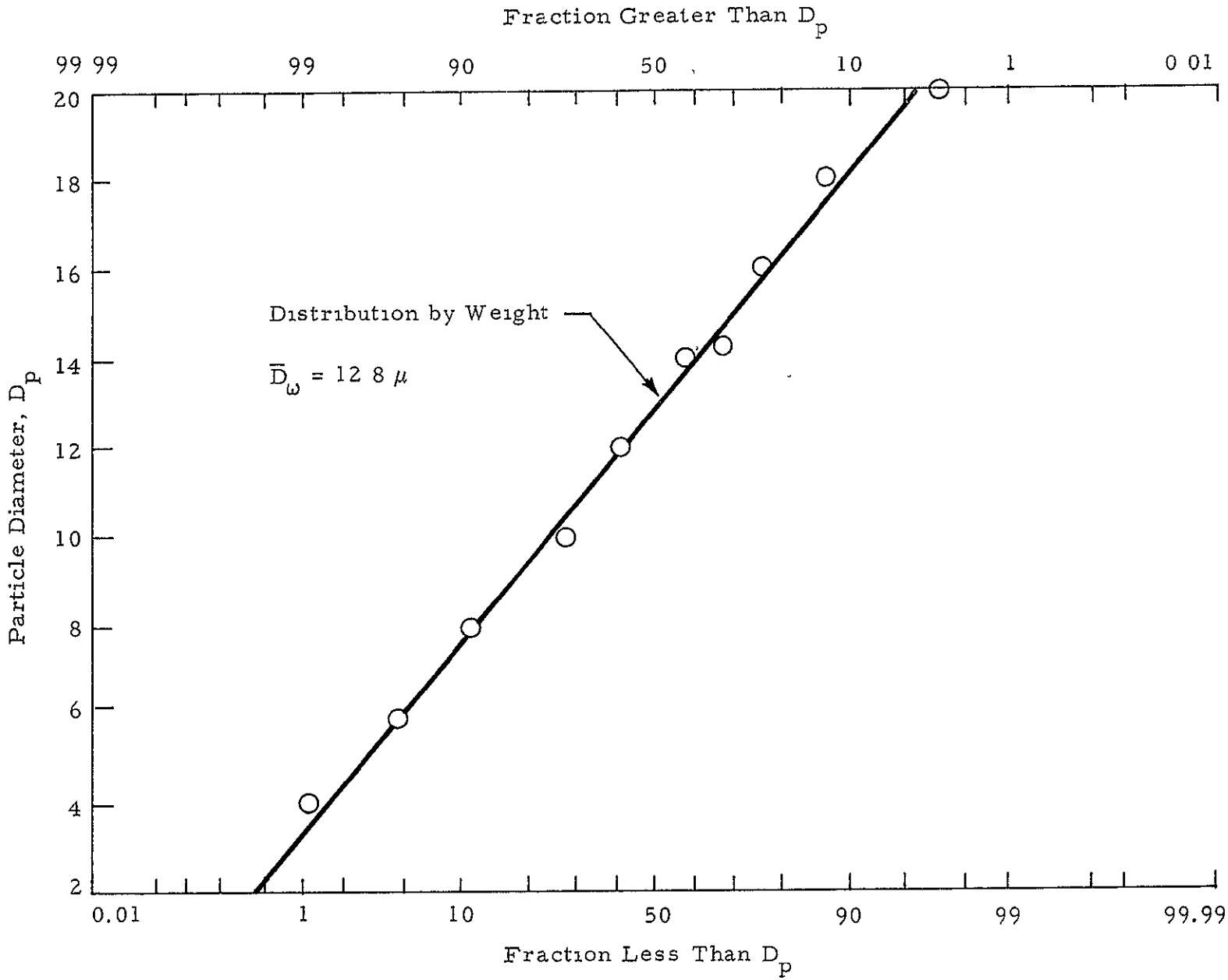


Fig A-2 - Normal Particle Size Distribution from AGC 260-2 Motor (Ref. A-1)

Table A-1

LOG NORMAL PARTICLE SIZE DISTRIBUTION
FOR HI 5 PC MOTOR

Particle Diameter	Percent Total Particle Mass Flow
1.2	10
1.9	20
2.65	20
3.5	20
5.0	20
8.0	10

Table A-2

Al_2O_3 THERMODYNAMIC DATA

Liquid Al_2O_3 Specific Heat (C_{p_l})	–	.34 Btu/lbm°R
Solid Al_2O_3 Specific Heat (C_{p_s})	–	.32 Btu/lbm°R
Enthalpy of Solid Phase of Al_2O_3 at Melting Temperature	–	1358.9 Btu/lbm
Enthalpy of Liquid Phase of Al_2O_3 at Melting Temperature	–	1858.7 Btu/lbm
Melting Temperature	–	4188°R

The type of chemistry assumption is very case dependent and also depends on the use of the flow field. Table A-3 presents various cases and applications, along with suggestions as to the type of chemistry assumptions to be used.

Finite rate cases can generally be started at the nozzle throat assuming the species distribution is in chemical equilibrium since this is valid for most propellant systems. Tables A-4 through A-6 present some reaction mechanisms which may be used for applicable propellant systems. These reaction mechanisms were obtained from data presented in Ref. A-5.

Boundary Equations

The boundary equations which are input to the code should be smooth and not contain discontinuities in either the slopes or coordinates where no discontinuities are physically present. Fictitious discontinuities can result in undesirable mass flow errors showing up during a solution. In Fig. A-3 a description of the boundary equations for the nozzle throat and free boundary are presented.

More complex nozzle contours may be input with discrete points which define the wall as a function of radial position and flow angle versus axial position.

Table A-3

SUGGESTED CHEMISTRY ASSUMPTIONS
FOR VARIOUS APPLICATIONS

Application	Ideal Gas	Equilibrium	Equilibrium/Frozen	Finite Rate
Nozzle Performance		x		
Plume Radiation				x
Plume Impingement			x	
Base Pressure (Initial Plume Expansion)	x*			
Electron Density				x
Contamination				x

*Use specific heat ratio which exists at lip.

Table A-4

REACTION MECHANISM FOR SPACE SHUTTLE SRM PROPELLANT

H	+OH	+M1	=H2O	+M1	22	6.10-26	2.0	0.0
O	+H	+M1	=OH	+M1	21	2.00-32	0.0	0.0
O	+O	+M1	=O2	+M1	24	3.80-30	1.0	-340.0
H	+H	+M2	=H2	+M2	22	2.80-30	1.0	0.0
OH	+H		=H2	+O	14	1.40-14-1.0		-7000.0
OH	+O		=H	+O2	11	4.00-11	0.0	0.0
OH	+H2		=H2O	+H	14	1.00-17-2.0		-2900.0
OH	+OH		=H2O	+O	13	1.00-11	0.0	-1100.0
CO	+O	+M3	=CO2	+M3	23	2.00-33	0.0	-4000.0
OH	+CO		=CO2	+H	14	1.10-19-2.0		1600.0
CL	+CL	+M1	=CL2	+M1	24	4.30-31	1.0	1250.0
H	+CL	+M4	=HCL	+M4	22	3.00-30	1.0	0.0
OH	+HCL		=H2O	+CL	14	1.00-14-1.0		-1000.0
O	+HCL		=OH	+CL	13	2.00-12	0.0	-4500.0
H	+CL2		=HCL	+CL	13	2.00-10	0.0	-2400.0
CL	+H2		=HCL	+H	13	8.00-11	0.0	-5260.0

Catalytic Species

M_1 = 3 H_2O, 2 CO_2; All others: 1.0

M_2 = 20 H, 10 H_2O, 3 CO_2, 2.5 H_2; All others: 1.0

M_3 = 20 O_2, 10 H_2O, 3 CO_2, 1.5 CO; All others: 1.0

M_4 = 10 H_2O, 5 $HC\ell$, 5 $C\ell$, 5 H, 3 $C\ell_2$, 3 CO_2; All others: 1.0

Table A-5

REACTION MECHANISM FOR H_2-O_2 PROPELLANT SYSTEM

H	+OH	+M1	=H2O	+M1	22	6.10-26	2.0	0.0
O	+H	+M1	=OH	+M1	21	2.00-32	0.0	0.0
O	+O	+M1	=O2	+M1	24	3.80-30	1.0	-340.0
H	+H	+M2	=H2	+M2	22	2.80-30	1.0	0.0
OH	+H		=H2	+O	14	1.40-14	-1.0	-7000.0
OH	+O		=H	+O2	11	4.00-11	0.0	0.0
OH	+H2		=H2O	+H	14	1.00-17	-2.0	-2900.0
OH	+OH		=H2O	+O	13	1.00-11	0.0	-1100.0

Catalytic Species

M_1 = 3 H_2O; All others: 1.0

M_2 = 20 H, 10 H_2O, 2.5 H_2; All others: 1.0

Table A-6

REACTION MECHANISM FOR LOX-RP1 PROPELLANT SYSTEM

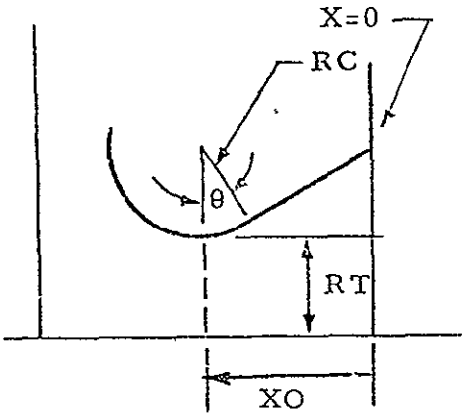
H	+OH	+M1	=H2O	+M1	22	6.10-26	2.0	0.0
O	+H	+M1	=OH	+M1	21	2.00-32	0.0	0.0
O	+O	+M1	=O2	+M1	24	3.80-30	1.0	-340.0
H	+H	+M2	=H2	+M2	22	2.80-30	1.0	0.0
OH	+H		=H2	+O	14	1.40-14	-1.0	-7000.0
OH	+O		=H	+O2	11	4.00-11	0.0	0.0
OH	+H2		=H2O	+H	14	1.00-17	-2.0	-2900.0
OH	+OH		=H2O	+O	13	1.00-11	0.0	-1100.0
CO	+O	+M3	=CO2	+M3	23	2.00-33	0.0	-4000.0
OH	+CO		=CO2	+H	14	1.10-19	-2.0	1600.0

Catalytic Species

M_1 = 3 H_2O, 2 CO_2; All others: 1.0

M_2 = 20 H, 10 H_2O, 3 CO_2, 2.5 H_2; All others: 1.0

M_3 = 20 O_2, 10 H_2O, 3 CO_2, 1.5 CO; All others: 1.0



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 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)

$B = RC^2 - XO^2$

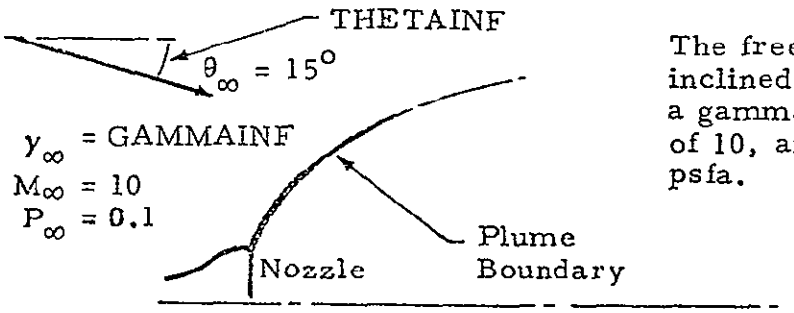
$C = 2XO$

$D = -1$

$E = -(RC + RT)$

$Xmax = RC \sin\theta + XO$

An example of a free boundary is shown in the sketch below.



The freestream approach flow is inclined at 15 deg to the plume with a gamma (γ) of 1.4, a Mach number 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°

Fig. A-3 - Sample of Boundary Equations

REFERENCES

A-1. Delaney, L. J., "Particle Characteristics in Two-Phase Plumes," Rocket Plume Phenomena Specialists Meeting, Aerospace Corp., San Bernadino, Calif., July 1968.

A-2. Coats, D.E. et al, "A Computer Program for the Prediction of Solid Propellant Rocket Motor Performance," Vol.I, AFRPL-TR-75-36, July 1975.

A-3. JANAF Thermochemical Tables, Second Edition, H.S. Dept. of Commerce, National Bureau of Standards, NSRDS-NBS37, Washington, D.C., June 1971.

A-4. Rasmussen, J. J., and R.P. Nelson, "Surface Tension of Molten Al_2O_3," Vol. 54, No. 8, J. American Ceramic Soc.

A-5. Ring, L.R., "Analysis and Correlation of the Gasdynamic and Radiative Exhaust Plume Properties Obtained in the Emitted Radiation from Special Engines Test Program," LMSC-HREC L511027, Lockheed Missiles & Space Company, Huntsville, Ala., December 1975.