CHEMICALLY REACTING
ONE-DIMENSIONAL
GAS-PARTICLE FLOWS

October 1975

Contract NAS9-14517

(NASA-CR-147388) CHEMICALLY REACTING
ONE-DIMENSIONAL GAS-PARTICLE FLOWS (Lockheed
Missiles and Space Co.) 77 p HC $4.50

Prepared for
National Aeronautics and Space Administration
Aerodynamic Systems Analysis Section
Johnson Space Center, Houston, TX 77058

by
James A. Tevepaugh
Morris M. Penny

Lockheed Missiles & Space Company, Inc.
Huntsville Research & Engineering Center
4800 Bradford Drive, Huntsville, AL 35807
FOREWORD

This document presents the results of work performed by personnel of the Advanced Technology Systems Section of Lockheed's Huntsville Research & Engineering Center. This document was prepared for the Aerodynamic Systems Analysis Section of the NASA-Johnson Space Center, Houston, Texas under Contract NAS9-14517, Barney B. Roberts, technical monitor.
SUMMARY

The governing equations for the one-dimensional flow of a gas-particle system are discussed. Gas-particle effects are coupled via the system momentum and energy equations with the gas assumed to be chemically frozen or in chemical equilibrium. A computer code for calculating the one-dimensional flow of a gas-particle system is discussed and a user's input guide presented.

The computer code provides for the expansion of the gas-particle system from a specified starting velocity and nozzle inlet geometry. Though general in nature, the final output of the code is a startline for initiating the solution of a supersonic gas-particle system in rocket nozzles. The startline includes gasdynamic data defining gaseous startline points from the nozzle centerline to the nozzle wall and particle properties at points along the gaseous startline.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOREWORD</td>
<td>ii</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>iii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>v</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2 TECHNICAL DISCUSSION</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Equations Defining the One-Dimensional Flow of a Gas-Particle System</td>
<td>4</td>
</tr>
<tr>
<td>2.2 Equations Defining the Calculation of Particle Limiting Streamlines</td>
<td>17</td>
</tr>
<tr>
<td>2.3 Results of Analytical Comparisons</td>
<td>19</td>
</tr>
<tr>
<td>3 CONCLUDING REMARKS</td>
<td>21</td>
</tr>
<tr>
<td>4 REFERENCES</td>
<td>22</td>
</tr>
</tbody>
</table>

### Appendixes

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>DIFFERENCE EQUATIONS FOR CALCULATING THE FLOW OF A ONE-DIMENSIONAL GAS-PARTICLE SYSTEM</td>
</tr>
<tr>
<td>B</td>
<td>ODPART-A ONE-DIMENSIONAL GAS-PARTICLE COMPUTER CODE</td>
</tr>
</tbody>
</table>
# NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>local area</td>
</tr>
<tr>
<td>a</td>
<td>drag parameter</td>
</tr>
<tr>
<td>c</td>
<td>heat transfer coefficient</td>
</tr>
<tr>
<td>( \bar{c} )</td>
<td>slip flow velocity factor</td>
</tr>
<tr>
<td>( C_D )</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>( c_P )</td>
<td>specific heat at constant pressure</td>
</tr>
<tr>
<td>H</td>
<td>total enthalpy</td>
</tr>
<tr>
<td>h</td>
<td>static enthalpy</td>
</tr>
<tr>
<td>m</td>
<td>mass</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
</tr>
<tr>
<td>( Pr )</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>r</td>
<td>radius</td>
</tr>
<tr>
<td>R</td>
<td>gas constant</td>
</tr>
<tr>
<td>( Re )</td>
<td>Reynolds's number</td>
</tr>
<tr>
<td>S</td>
<td>entropy</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
</tr>
<tr>
<td>u</td>
<td>velocity</td>
</tr>
<tr>
<td>v</td>
<td>velocity of sound</td>
</tr>
<tr>
<td>( \dot{w} )</td>
<td>mass flow rate</td>
</tr>
<tr>
<td>X</td>
<td>ratio of total particle mass flow rate to total gas mass flow rate</td>
</tr>
</tbody>
</table>

LOCKHEED·HUNTSVILLE RESEARCH & ENGINEERING CENTER
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>axial coordinate</td>
</tr>
<tr>
<td>∇</td>
<td>ratio of (j)th particle mass flow rate to total particle mass flow rate</td>
</tr>
</tbody>
</table>

**Greek**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>viscosity</td>
</tr>
<tr>
<td>(\rho)</td>
<td>density</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P)</td>
<td>particle</td>
</tr>
<tr>
<td>(m)</td>
<td>mixture</td>
</tr>
<tr>
<td>(g)</td>
<td>gas</td>
</tr>
<tr>
<td>(r)</td>
<td>radial component</td>
</tr>
<tr>
<td>(x)</td>
<td>axial component</td>
</tr>
</tbody>
</table>

**Superscripts**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(j)</td>
<td>(j)th particle</td>
</tr>
<tr>
<td>(np)</td>
<td>number of particles</td>
</tr>
</tbody>
</table>
Section 1
INTRODUCTION

Solid propellant formulations are used in the Space Shuttle booster and stage separation motors. Interaction of the solid propellant exhaust plumes with the external surroundings can result in a hostile environment which must be considered in the sign process. The solid propellant boost motor exhaust significantly affects the vehicle base environment. During the separation of the orbiter and booster motors the exhaust plumes from the separation motors impinge on the orbiter. Particle impingement results in erosion of the surfaces as well as high heating rates and forces acting on the surfaces. Consequently, gas-particle flows in nozzle exhaust plumes have received considerable attention.

A recent formulation (Ref. 1) has extended the supersonic two-dimensional axisymmetric calculation (Ref. 2) to include the treatment of chemically reacting flows. A computer code was subsequently developed which treated chemical equilibrium (Ref. 3) or chemical kinetics (Ref. 4) in the gas phase. Calculations are initiated along some data surface which must be everywhere supersonic. Gas data (velocity, flow deflection angle, pressure, etc.) and particle data (velocity, density, streamline location, etc.) are required to initiate the solution.

Originally, a computer code developed by Kliegel (Ref. 2) was used to calculate a startline to initiate a supersonic method-of-characteristics solution. The Kliegel code utilizes a Sauer (Ref. 4) approximation to the transonic solution. One-dimensional particle lags (velocity and temperature) which are assumed constant from the chamber are determined. Particle limiting streamline trajectories are then traced from some starting location upstream of the startline to determine their intersections with the startline. The location of the startline is specified by input data. These data are then utilized in the
transonic approximation to obtain the gas-particle startline conditions. This calculation procedure was incorporated into the gas-particle reacting gas code (Ref. 5) to provide startline information. The Kliegel calculation assumes constant thermodynamic properties in the gas and particle phases. Combining the transonic data with chemical equilibrium thermodynamics (Ref. 3) results in a mismatch of thermodynamic properties and at least one state variable. To minimize the mismatch, the gas velocity, pressure and temperature from the transonic approximation and chemical equilibrium thermodynamic data are used to initiate the supersonic flow solution. The supersonic computer code calculates the change in entropy and total enthalpy levels.

Solutions to the transonic approximation become difficult for throat radius of curvature ratios less than 1.5. This difficulty, coupled with the constant thermodynamic property assumption, prompted the development of a reacting gas code (Appendix B) to provide startline data for the RAMP code (Ref. 5). The solution is one-dimensional and is intended for interim use until a fully coupled transonic solution for two-dimensional chemically reacting flows is developed.

The one-dimensional gas-particle solution is fully coupled through the mixture momentum and energy equations. Particle distributions are represented as a series of discrete sizes and/or chemical species. The gas is assumed to be either in chemical equilibrium, or frozen or to have constant thermodynamic and transport properties. The solution is initiated at a starting condition specified geometrically and gasdynamically. Analytical functions are used to describe the geometry from which the variation in area ratio is obtained. The work performed by the gas in accelerating the particles and the heat given up by the particles are a function of the relative distance over which the expansion occurs. The gas-particle flow is defined at specified area ratios and axial stations relative to the initial data plane. At each axial station the mixture properties are solved iteratively. The solution is continued until a gas Mach number specified by the user is reached. Particle trajectories are then traced through the region of interest by numerically integrating the particle equations.
of motion. The complete solution consists of the one-dimensional gas-particle properties and particle limiting streamline locations at a specified data line.

The following sections describe the flow assumptions, present a development of the governing equations and outlines the user's guide for a computer code (ODPART) to calculate one-dimensional, chemically reacting gas-particle flows.
Section 2
TECHNICAL DISCUSSION

The one-dimensional gas-particle solution is fully coupled via the momentum and energy equations. Particle distributions are represented as a series of discrete sizes and/or chemical species. The gas is assumed to be in chemical equilibrium, frozen or to have constant thermodynamic and transport properties with no mass exchanged between the phases. The solution is initiated at a specified condition. Analytical functions are used to describe the geometry from which the variation in area ratio is obtained. The work performed by the gas in accelerating the particles and the heat given up by the particles are a function of the relative distance over which the expansion occurs. Thus the gas-particle flow is defined at specified area ratios and axial stations relative to the initial data plane. At each axial station the mixture properties are solved iteratively. The solution is continued until a gas Mach number specified by the user is reached. Particle trajectories are then traced through the region of interest by numerically integrating the particle equation of motion. The complete solution consists of the one-dimensional gas-particle properties and particle limiting streamline locations at a specified data surface.

The following subsections describe the flow assumptions, present a development of the governing equations and discuss a comparison of analytical calculations generated with start lines from the Kliegel transonic analysis and the ODPART computer code.

2.1 EQUATIONS DEFINING THE ONE-DIMENSIONAL FLOW OF A GAS-PARTICLE MIXTURE

The flow of a gas-particle mixture is described by the equations for conservation of momentum, conservation of energy and conservation of mass.
Development of the equations defining the gas and particle phases and their coupling in the conservation 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.
4. The gas obeys the perfect gas law and is either frozen or in chemical equilibrium.
5. The forces acting on the control volume are the pressure of the gas and the drag of the particles.
6. The gas is inviscid except for the drag it exerts on the particles.
7. There are no particle interactions, i.e., no collisions and no exchange of thermal energy.
8. The volume occupied by the particles is negligible.
9. There is no mass exchange between the phases.
10. The particles are inert.
11. A discrete number of particles, each of different size or chemical species, are chosen to represent the actual continuous particle distribution.

In a gas-particle flow, the coupling between the particles and gas is important and must be properly treated in order to construct an accurate model. Particles in the flow gain motion from the drag forces exerted by the combustion gases and, transfer heat to the gas primarily by convection. Losses in a gas-particle flow result from the difference between particle and gas velocity, and from the difference between particle and gas temperature. Coupling between the gas and particle phases in this analysis is accomplished through the momentum and energy equations. The one-dimensional momentum equation for the gas-particle mixture is

\[ \rho^u \frac{du}{dx} + \sum_{j=1}^{np} \rho^j u^j \frac{d u^j}{dx} + \frac{dP}{dx} = 0 \] (1)
The one-dimensional energy equation for the mixture is given by

\[ H = \dot{w} \left[ h + \frac{u^2}{2} \right] + \sum_{j=1}^{np} \rho_j u_j A \left[ h_j + \frac{u_j^2}{2} \right] \]  

(2)

The remaining equation used to define the mixture properties is the conservation of mass equation for a gas-particle flow

\[ \dot{w}_m = \rho u A + \sum_{j=1}^{np} \rho_j u_j A \]  

(3)

Thermodynamic relations used in the solution of gas phase properties include

\[ TdS = dh - \frac{dP}{\rho} \]  

(4)

and pressure as a function of density and entropy

\[ dP = v^2 d\rho + \frac{P}{C_P - R} dS \]  

(5)

For accurate modeling of gas-particle flows, particle properties must be known as well as gas phase and mixture properties. To obtain a particle drag coefficient, \( C_D \), a table look-up is done to obtain the ratio \( C_D/C_{D\text{Stokes}} \) as a function of local Reynolds number. The resulting ratio is then used to calculate the particle drag coefficient using the following relationship to correct for slip flow

\[ C_D^j = \left( \frac{C_D}{C_{D\text{Stokes}}} \right)^j \frac{Re^j[(1+9.45\tau^j)(1+2.52\tau^j) + 3.03\tau^j]}{[(1+9.45\tau^j)(1+3.78\tau^j) + 0.911(4. + 1.34\tau^j)]\tau^j} \]  

(6)
where the parameter, $\tau$, is calculated as follows

$$
\tau^j = \frac{(u - u_p^j)}{Re^j \sqrt{RT}}
$$

In Eq. (6), the Stokes drag coefficient is used as a reference drag coefficient calculated by

$$
C_{D_{Stokes}}^j = \frac{24}{Re^j}
$$

The particle drag coefficient enters the calculation of particle properties through the drag parameter, $a$, which is defined as

$$
a^j = 4.5 \nu^j C_D^j \frac{m_p^j r_p^j}{2}
$$

Change in particle velocity with respect to change in axial coordinate is determined by

$$
du^j = \frac{a^j (u - u^j) dx}{u^j}
$$

Heat energy exchange between the particle and gas phases is established by the particle heat transfer coefficient, $c$, defined by

$$
c^j = \frac{c_p^j (1 + 0.2295 Re^j (0.55 Pr^j 0.33)^{0.5})}{Pr^j C_D^j}
$$

This relationship assumes that heat energy exchange between the gas and particles occurs only by convection. A table look-up is performed for Prandtl number $Pr$, specific heat at constant pressure, $c_p$, and viscosity, $\nu$, as a function of gas velocity. Change in particle enthalpy with respect to change in axial coordinate is calculated by
where the thermal lag, $\Delta T^j$, is defined by

$$\Delta T^j = T_p^j - T$$  \hspace{1cm} (13)

As can be observed, the particle size, $r_p^j$, enters the calculation of both $d u_j^p$ and $d h_j^p$ in Eqs. (10) and (12), respectively. The particle size then appears in the mixture momentum and energy equations (Eqs. (1) and (2)) through the particle velocity and enthalpy terms. Particle size thus has a significant effect on the coupling between the gas and particle phases and the resulting performance of a particular nozzle-propellant combination.

From the basic equations defining the gas-particle mixture, the gas phase properties and the particle properties, expressions were derived to calculate gas and particle properties at successive axial locations in a rocket nozzle. The expressions were derived in differential form in order to be compatible with the forward marching integration technique used in the computer solution of the equations.

In the following derivations (to simplify the equations), it is assumed that there is only one particle species present thus eliminating the need for the summation symbolism, $\sum_{j=1}^{np}$, on all particle properties. Complete symbolism for multiple particle species is used for the basic governing Eqs. (1) through (12), and for the difference form of the derived expressions presented in Appendix A.

Beginning with the gas phase thermodynamic relationship defined by Eq. (5), an expression was derived for calculating gas velocity.
Pressure may be written as a function of density and entropy as follows

\[ dP = \nu^2 d\rho + \frac{P}{c_p} dS \]  \hspace{1cm} (14)

Solving for \( dS \), Eq. (14) becomes

\[ dS = \frac{c_p - R}{P} (dP - \nu^2 d\rho) \]

Multiplying through by temperature, \( T \), and using the perfect gas law, \( P = \rho RT \), the relation becomes

\[ TdS = \frac{1}{\rho R} (c_p - R) (dP - \nu^2 d\rho) \]

Substituting for \( TdS \) using the basic thermodynamic relation \( TdS = dh - dP/\rho \), the equation is

\[ \frac{dh}{\rho} - \frac{dP}{\rho} = \frac{1}{\rho R} (c_p - R) (\frac{dP}{dx} - \nu^2 \frac{d\rho}{dx}) \]

Dividing through by \( dx \) and rearranging terms the expression becomes

\[ \frac{dh}{dx} - \frac{dP}{\rho dx} = \frac{1}{\rho R} (c_p - R) (\frac{dP}{dx} - \nu^2 \frac{d\rho}{dx}) \]  \hspace{1cm} (15)

The energy equation for a gas-particle mixture is

\[ H = (h + \frac{u^2}{2}) + \frac{w_j}{W} (v_j + \frac{u_j^2}{2}) \]  \hspace{1cm} (16)
Differentiating and dividing through by \( \text{dx} \), the energy equation becomes

\[
\frac{dh}{dx} + u \frac{du}{dx} + \frac{\psi^j}{\psi} \left( \frac{dh^j}{dx} + u^j \frac{du^j}{dx} \right) = 0
\] (17)

The momentum equation for a gas-particle mixture is

\[
\rho u \frac{du}{dx} + \rho^j u^j \frac{du^j}{dx} + \frac{dp}{dx} = 0
\] (18)

Rearranging terms, the momentum equation becomes

\[
u \frac{du}{dx} = \frac{1}{\rho} \frac{dp}{dx} - \frac{\rho^j}{\rho} u^j \frac{du^j}{dx}
\] (19)

The ratio of particle to gas mass flow is written

\[
\frac{\rho^j u^j A}{\rho u A} = \frac{\psi^j}{\psi
\]

Rearranging terms and solving for the ratio of densities, the relation is

\[
\frac{\rho^j}{\rho} = \frac{u \psi^j}{u^j \psi}
\] (20)

Substituting Eq. (20) in Eq. (19), the momentum equation becomes

\[
u \frac{du}{dx} = - \frac{1}{\rho} \frac{dp}{dx} - \frac{u \psi^j}{u^j \psi} u^j \frac{du^j}{dx}
\] (21)
Simplifying momentum Eq. (21) and substituting Eq. (21) in Eq. (17), the energy equation becomes

\[
\frac{dh}{dx} - \frac{1}{\rho} \frac{dP}{dx} - \frac{\dot{\omega}^j}{\dot{\omega}} u \frac{du^j}{dx} + \frac{\dot{\omega}^j}{\dot{\omega}} \left( \frac{dh^j}{dx} + u^j \frac{du^j}{dx} \right) = 0
\]  

(22)

Collecting terms and simplifying, the equation is written

\[
\frac{dh}{dx} - \frac{1}{\rho} \frac{dP}{dx} + \frac{\dot{\omega}^j}{\dot{\omega}} \left( \frac{dh^j}{dx} + u^j \frac{du^j}{dx} - u \frac{du^j}{dx} \right) = 0
\]  

(23)

Substituting Eq. (15) in Eq. (23), the energy equation becomes

\[
\frac{1}{\rho R} \left( c_p - R \right) \left( \frac{dP}{dx} - v^2 \frac{d\rho}{dx} \right) + \frac{\dot{\omega}^j}{\dot{\omega}} \left( \frac{dh^j}{dx} + u^j \frac{du^j}{dx} - u \frac{du^j}{dx} \right) = 0
\]

Collecting terms and multiplying through by \( R/(c_p - R) \) the relation is written

\[
\frac{1}{\rho} \frac{dP}{dx} - \frac{v^2}{\rho} \frac{d\rho}{dx} + \left( \frac{R}{c_p - R} \right) \frac{\dot{\omega}^j}{\dot{\omega}} \left( \frac{dh^j}{dx} + u^j \frac{du^j}{dx} - u \frac{du^j}{dx} \right) = 0
\]  

(24)

Introduce the conservation of mass relationship for the gas

\[
\rho u A = \dot{\omega}
\]

and implicitly differentiate the equation

\[
u A d\rho + \rho A du + \rho u dA = 0
\]

Dividing through by \( \rho u A dx \) and rearranging terms, the expression becomes

\[
\frac{1}{\rho} \frac{d\rho}{dx} = - \left( \frac{1}{u} \frac{du}{dx} + \frac{1}{A} \frac{dA}{dx} \right)
\]  

(25)
Substituting Eq. (25) in Eq. (24), the energy equation is defined by

\[ \frac{1}{\rho} \frac{dP}{dx} - \nu^2 \left( -\frac{1}{u} \frac{du}{dx} - \frac{1}{A} \frac{dA}{dx} \right) + \left( \frac{R}{c_p - R} \right) \left( \frac{\nabla_j}{w} \right) \left( \frac{dh_j}{dx} + \frac{u_j}{x} \frac{u_j}{dx} - \frac{u_j}{dx} \right) = 0 \]

Solving for \( \frac{dP}{\rho dx} \), the expression is

\[ \frac{1}{\rho} \frac{dP}{dx} = -\frac{\nu^2}{u} \frac{du}{dx} - \frac{\nu^2}{A} \frac{dA}{dx} - \left( \frac{R}{c_p - R} \right) \left( \frac{\psi_j}{w} \right) \left( \frac{dh_j}{dx} + \frac{u_j}{dx} \frac{du_j}{dx} - \frac{u_j}{dx} \right) \]  

From Eq. (21) the expression for \( \frac{dP}{\rho dx} \) is substituted in Eq. (26)

\[ -\frac{u}{u_j} \frac{du}{dx} \frac{\psi_j}{w} u_j \frac{du_j}{dx} = -\frac{\nu^2}{u} \frac{du}{dx} - \frac{\nu^2}{A} \frac{dA}{dx} - \left( \frac{R}{c_p - R} \right) \left( \frac{\psi_j}{w} \right) \left( \frac{dh_j}{dx} + \frac{u_j}{dx} \frac{du_j}{dx} - \frac{u_j}{dx} \right) \]

Collecting terms and rearranging, the relationship is

\[ u \frac{du}{dx} - \frac{\nu^2}{u} \frac{du}{dx} - \frac{\nu^2}{A} \frac{dA}{dx} - \frac{\psi_j}{w} \left( \left( \frac{R}{c_p - R} \right) \left( \frac{dh_j}{dx} + \frac{u_j}{dx} \frac{du_j}{dx} - \frac{u_j}{dx} \right) - \frac{u_j}{dx} \right) = 0 \]

Substitutions are made using the definition of Mach number, \( M = \frac{u}{v} \)

\[ u \frac{du}{dx} \left( 1 - \frac{1}{M^2} \right) - \frac{\nu^2}{AM^2} \frac{dA}{dx} - \frac{\psi_j}{w} \left[ \left( \frac{R}{c_p - R} \right) \left( \frac{dh_j}{dx} + \frac{u_j}{dx} \frac{du_j}{dx} - \frac{u_j}{dx} \right) - \frac{u_j}{dx} \right] = 0 \]

Substituting the basic relations for changes in particle velocity, \( du_j \), the relationship is written

\[ u \frac{du}{dx} \left( \frac{M^2 - 1}{M^2} \right) - \frac{\nu^2}{AM^2} \frac{dA}{dx} - \frac{\psi_j}{w} \left[ \left( \frac{R}{c_p - R} \right) \left( -\frac{2}{3} a_j \frac{\nabla_j (T^j - 1)}{u^j} + u_j a_j \frac{(u - u_j)}{u^j} \right) - u a_j \frac{(u - u_j)}{u^j} \right] \]

\[ \frac{u_j}{u^j} \left( u_j - u^j \right) - u_j a_j \left( \frac{u - u^j}{u^j} \right) \]

(27)
Define a parameter, $B^j$,

$$B^j = \left( \frac{\dot{w}^j}{w} \right) \left[ \frac{a^j_j}{u^j_j} \right] \left[ \left( \frac{R}{c_p - R} \right) \left( \frac{2}{3} c^j (T^j - T) - u^j_j (u - u^j_j) + u(u - u^j_j) + u(u - u^j_j) \right) \right]$$

Substituting $B^j$ is Eq. (27) and multiplying through by $M^2$, the equation becomes

$$u \frac{du}{dx} (M^2 - 1) - \frac{M^2 u^2}{A M^2} \frac{dA}{dx} + B^j M^2 = 0$$

Dividing through by $u$ and multiplying through by $dx$, the relation is defined by

$$du(M^2 - 1) - \frac{u}{A} \frac{dA}{dx} + \frac{B^j M^2 dx}{u} = 0$$

Solving for $du$,

$$du = \left( \frac{u}{A} \frac{dA}{dx} - \frac{B^j M^2 dx}{u} \right) \frac{1}{M^2 - 1} \quad (28)$$

an equation is developed from which gas velocity is calculated for the gas-particle mixture.

Starting with the momentum equation an expression was derived for calculating gas pressure for the gas-particle mixture

$$\rho(u + j du) + \dot{d} + dP = 0$$

Multiplying through by $A$, the momentum equation is

$$\rho u A du + A \rho u^j du^j + AdP = 0 \quad (29)$$
Multiply differentials of the conservation of mass equations for the gas and particle phases by $u$ and $u^j$ respectively

$$ud(\rho uA) = 0 \quad (30)$$

$$u^j d(\rho^j u^j A) = 0 \quad (31)$$

Equations (29), (30) and (31) are added to obtain

$$\rho u \text{Ad}u + ud(\rho uA) + \rho^j u^j \text{Ad}u^j + u^j d(\rho^j u^j A) + AdP = 0$$

Expanding the derivatives, $d(\rho uA)$ and $d(\rho^j u^j A)$ the equation becomes

$$\rho u \text{Ad}u + u^2 \text{Ad}\rho + \rho u \text{Ad}u + \rho u^2 \text{dA} + \rho^j u^j \text{Ad}u^j + u^j \rho \text{Ad}u^j + \rho^j u^j \rho \text{dA} + AdP = 0$$

Rearranging and collecting terms the expression is

$$2\rho u \text{Ad}u + u^2 \text{Ad}\rho + \rho u^2 \text{dA} + 2\rho^j u^j \text{Ad}u^j + u^j \rho \text{Ad}u^j + u^j \rho \rho \text{dA} + AdP = 0 \quad (32)$$

The differential of the product $PA$ is written

$$d(PA) = P\text{dA} + AdP$$

Solving this expression for $AdP$, the relation is written

$$AdP = d(PA) - P\text{dA} \quad (33)$$
The differential of \( \rho u^2 A \) is written

\[
d(\rho u^2 A) = u^2 A d\rho + 2\rho u A du + \rho u^2 dA
\]  
(34)

and the differential of \( \rho^j u^j A \) is written

\[
d(\rho^j u^j A) = u^j A d\rho + 2\rho^j u^j du + \rho^j u^j dA
\]  
(35)

Substituting Eqs. (33), (34) and (35) in Eq. (32), Eq. (32) becomes

\[
d(\rho u^2 A) + d(\rho^j u^j A) + d(\mathcal{P}A) - P dA = 0
\]

From the conservation of mass relationship the expression \( \rho^j = \rho u \dot{\psi}^j / u \dot{\psi} \) is obtained and substituted in the previous equation

\[
d(\rho u^2 A) + d \left( \frac{u \rho \dot{\psi}^j u^j A}{u \dot{\psi}^j} \right) + d(\mathcal{P}A) - P dA = 0
\]  
(36)

Using the relationship, \( \sum_{j=1}^{np} \dot{\psi}^j / \dot{\psi} = X \) and \( \dot{\psi}^j / \dot{\psi} \sum_{j=1}^{np} \dot{\psi}^j = \mathcal{V}^j \) Eq. (36) becomes

\[
d(\rho u^2 A) + X \sum_{j=1}^{np} \mathcal{V}^j (\rho u \dot{\psi}^j A) + d(\mathcal{P}A) - P dA = 0
\]

The equation used to calculate gas pressure is then written

\[
d(\mathcal{P}A) = P dA - d(\rho u^2 A) - \sum_{j=1}^{np} \mathcal{V}^j (\rho u \dot{\psi}^j A)
\]  
(37)
A relationship to calculate gas density was derived as follows from the conservation of mass equation for the gas

\[ \rho u A = \dot{w} \]

Differentiating implicitly and dividing through by \( \rho u A \), the conservation equation becomes

\[ \frac{d\rho}{\rho} + \frac{du}{u} + \frac{dA}{A} = 0 \]

Solving for the change in density, a relationship is obtained for calculating gas density at successive integration steps

\[ d\rho = -\rho \left( \frac{du}{u} + \frac{dA}{A} \right) \tag{38} \]

Gas temperature is calculated from the perfect gas law using the previously calculated values of density and pressure

\[ T = \frac{P}{\rho R} \tag{39} \]

Entropy is calculated using the basic thermodynamic relationship defined by Eq. (5)

\[ dP = v^2 d\rho + \frac{P}{c_p - R} dS \]

Solving for \( dS \), an equation is obtained for calculating entropy at successive integration steps

\[ dS = \frac{c_p - R}{P} (dP - v^2 d\rho) \tag{40} \]
Gas static enthalpy is calculated using the thermodynamic relationship defined by Eq. (4)

\[ TdS = dh - \frac{dP}{\rho} \]

Solving for \( dh \), an equation is obtained for calculating gas static enthalpy from previously calculated values of pressure, density, temperature and entropy

\[ dh = TdS + \frac{dP}{\rho} \quad (41) \]

The gas total enthalpy is calculated by adding the gas static enthalpy to the gas velocity contribution

\[ H = h + \frac{u^2}{2} \quad (42) \]

2.2 EQUATIONS DEFINING THE CALCULATION OF PARTICLE LIMITING STREAMLINES

If the user of the ODPART computer code flags the appropriate option, particle limiting streamline calculations are performed after the one-dimensional gas-particle calculations. The equations governing the particle limiting streamline calculations were obtained from the derivations of Ref. 1. The following equations define compatibility relations along particle limiting streamlines. Change in particle radial location along a limiting streamline is calculated as a function of \( x \) using the following relationship

\[ dr^j = dx^j \frac{u^j_r}{u^j_x} \quad (43) \]
A change in particle axial velocity as a function of $x$ is given by

$$\frac{du_j}{dx} = a_j \frac{(u_x - u_j^x)}{u_x}$$

(44)

The change in particle radial velocity along a limiting streamline as a function of $x$ is

$$\frac{du_j}{dx} = a_j \frac{(u_r - u_j^r)}{u_j}$$

(45)

Change in particle enthalpy is given by

$$dh_j = dx_j \left[ -\frac{2}{3} a_j c_j \frac{(T_j - T)}{u_j} \right]$$

(46)

The difference form of equations (43) and (46) used in the one-dimensional computer code are presented in Appendix A. The particle equations of motion defined in Eqs. (43) through (46) are integrated from the initial data line to the calculated startline. The equations are solved iteratively at each axial location stored during the one-dimensional gas-particle mixture calculations.

The particle limiting streamline concept implies that there is a streamline above which particles larger than a certain size cannot flow. The concept of a nozzle flowing full implies that particles of all sizes are distributed from the nozzle centerline to the nozzle wall. Both concepts of particle distributions in two-phase flows are incorporated in the one-dimensional computer code presented in Appendix B. The user of the code may select the particle distribution scheme appropriate to a given application.
2.3 RESULTS OF ANALYTICAL COMPARISONS

To confirm the validity of the one-dimensional, chemically reacting gas-particle calculations, an analysis was conducted to compare results obtained from the RAMP supersonic code using startlines generated with the Kliegel and ODPART computer codes. Three problem cases were analyzed with RAMP supersonic nozzle calculations generated with Kliegel and ODPART startlines for each case. The first case comparison used full-scale Space Shuttle solid rocket motor (SRM) geometry, ideal gas (constant property) thermodynamics, a chamber pressure of 500 psia and an aluminum propellant loading of 16%. The second case comparison used full-scale SRM geometry, real gas (chemically reacting) thermodynamics, a chamber pressure of 500 psia and an aluminum propellant loading of 16%. The final case comparison used a subscale nozzle, real gas thermodynamics, a chamber pressure of 1000 psia and an aluminum propellant loading of 2%. In each case, aluminum oxide was the particle species represented by a six particle size distribution. A detailed report of the analysis is presented in Ref. 6.

For ease of reference, the results of one case comparison are presented in Figs. 1 through 5. The results presented were calculated for full scale SRM nozzle geometry, real gas thermodynamics, a chamber pressure of 500 psia and a 16% aluminum propellant loading. The aluminum oxide particle species was represented by a six-particle size distribution with sizes ranging from a radius of 3.15 microns to 9.70 microns.

In Fig. 1 the non-dimensional nozzle wall static pressure distributions for the RAMP nozzle calculations are compared. The RAMP calculation initiated with an ODPART startline demonstrates good agreement with the RAMP calculation initiated with a Kliegel startline. The nozzle centerline static pressure distributions for the RAMP calculations are in excellent agreement in Fig. 2. Location of particle limiting streamlines for the largest (9.70 micron radius) and smallest (3.15 micron radius) particles are compared in Fig. 3. Particle velocity and temperature distributions along the nozzle centerline are compared in Figs. 4 and 5, respectively. Agreement of particle properties between RAMP
Calculations initiated with Kliegel and ODPART startlines is acceptable. Based
on these comparisons it was concluded that the one-dimensional gas-particle
calculations produce acceptable agreement with current analytical techniques.
An analytical technique has been developed for calculating the one-dimensional flow of a gas-particle system. The technique employs a fully coupled solution with particle effects entering the calculations via the system momentum and energy equations. The one-dimensional equations are not restricted by nozzle throat radius of curvature ratio as are current two-dimensional transonic calculations. The gas may be assumed to be chemically reacting, thus eliminating the problem of combining thermodynamic data from chemically frozen transonic calculations with chemically reacting supersonic flow solutions. Particle lags (velocity and temperature) are allowed to vary, thus eliminating the constant lag assumption present in currently used transonic calculations.

The computer code (Appendix B) developed using this analytical approach expands a gas-particle system from a specified starting velocity and inlet geometry. Although the code may be used to calculate the general one-dimensional flow of a gas-particle system, the final output of the code is a startline for initiating the solution of a supersonic gas-particle flow. The startline includes gasdynamic data defining gaseous startline points from the nozzle centerline to the nozzle wall and particle properties at points along the gaseous startline.

Results of supersonic nozzle calculations initiated with startlines from the ODPART code compare favorably with those initiated with startlines from the Kliegel transonic approximation. Based on these analytical comparisons (Ref. 6), it was concluded that the one-dimensional chemically reacting gas-particle solution produces a valid and useful solution to two-phase flows in the inlet and throat regions of rocket nozzles.
Section 4

REFERENCES


Fig. 1 - Non-Dimensional Nozzle Wall Pressure Distributions for Real Gas Thermodynamics, a $P_{\text{chamber}}$ of 500 psia and SRM Nozzle Geometry.
Fig. 2 - Centerline Static Pressure Distributions for Real Gas
Thermodynamics, a P\textsubscript{chamber} of 500 psia and SRM
Nozzle Geometry
Fig. 3 - Particle Limiting Streamlines for Particles of Radii 3.15 and 9.70 Microns, Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry
Fig. 4 - Particle Velocity as a Function of Axial Distance Along the Nozzle Center Line for Particle Radii of 3.15 and 9.70 Microns. Real Gas Thermodynamics, a Pchamber of 500 psia and SRM Nozzle Geometry
Fig. 5 - Particle Temperature as a Function of Axial Distance Along the Nozzle Center Line for Particle Radii of 3.15 and 9.70 Microns, Real Gas Thermodynamics, a Pchamber of 500 psia and SRM Nozzle Geometry
Appendix A

DIFFERENCE EQUATIONS FOR CALCULATING THE FLOW OF A ONE-DIMENSIONAL GAS-PARTICLE MIXTURE
The following equations are the difference form of particle Eqs. (10) and (12) presented in the main text of this report and of gas Eqs. (28), (37), (38), (40) and (41) derived in the text. The following equations are coded in the ODPART Computer code to calculate gas and particle properties at successive integration steps.

**Gas Velocity:**

\[
\Delta u = \left[ \frac{u}{A} \frac{\Delta A}{\Delta x} - \frac{M^2}{u} \sum_{j=1}^{np} B^j \right] \frac{1}{M^2 - 1}
\]

**Gas Pressure:**

\[
\Delta P = -\rho u \left[ \Delta u + X \sum_{j=1}^{np} \nabla^j a^j \frac{(u - u^j)}{u^j} \right]
\]

**Gas Density:**

\[
\Delta \rho = -\rho \left[ \frac{\Delta u}{u} + \frac{\Delta A}{A} \right]
\]

**Gas Static Enthalpy:**

\[
\Delta h = -u \Delta u + \Delta x X \sum_{j=1}^{np} \frac{\nabla^j A}{u^j} \left[ \frac{2}{3} c^j (T^j - T) - u^j (u - u^j) \right]
\]
Gas Entropy:

\[ \Delta S = \frac{1}{T} (\Delta h - \frac{\Delta P}{\rho}) \]

Particle Velocity:

\[ \Delta u_j = a_j \frac{(u - u_j)}{u_j} \Delta x \]

Particle Enthalpy:

\[ \Delta h_j = -\frac{2}{3} a_j c_j \frac{(T_j - T)}{u_j} \Delta x \]

Particle Limiting Trajectories:

\[ \Delta r_j = \frac{\Delta x_j u_j}{u_j} \]

\[ \Delta u_j = \frac{\Delta x_j a_j (u_j - u_j)}{u_j} \]

\[ \Delta u_j = \frac{\Delta x_j a_j (u_j - u_j)}{u_j} \]

\[ \Delta h_j = \Delta x_j \left[ -\frac{2}{3} a_j c_j (T_j - T) \right] \]
Appendix B

ODPART — A ONE DIMENSIONAL GAS-PARTICLE COMPUTER CODE
Appendix B

B.1 DESCRIPTION OF THE COMPUTER CODE

ODPART is a computer code written in FORTRAN V language which performs one-dimensional calculations of gas-particle flows. The code was written for use on the Univac 1108 Executive VIII multiprocessor system but is easily adapted for use on other systems.

Program Operation

A schematic diagram of the ODPART solution is presented in Fig. A-1. The input data are read from cards and the gas and particle properties on the initial data line calculated. The gas and particles are assumed to be in dynamic and thermal equilibrium on the initial data line. A forward marching integration scheme is employed for integrating the fully coupled equations defining the gas-particle system. Solution of the equations is accomplished at successive axial stations at intervals equal to the input parameter, DX. At each new axial station, the first iteration is initialized with the properties of the previous data line. The particle and gas properties are calculated and a check is made for convergence of the properties. If the solution has not converged, the program iterates the solution and recalculates the particle and gas properties based on the data from the previous iteration. If a solution at an axial station is not reached in 100 iterations, an error message is printed and the run is terminated. When the solution at an axial station converges, the converged values of the gas and particle properties are stored and output on a line printer. A check is made to determine whether or not the solution has progressed to the terminating Mach number specified by the programer. If the specified Mach number has not been reached, the solution is initialized for the next axial station. When the specified Mach number is reached, the one-dimensional flow field calculations are terminated. By the appropriate choice of input flags, the user may instruct the program to calculate particle trajectories through the
flow field or distribute the particles along a gaseous start line from the nozzle centerline to the nozzle wall. If ICON(1) is set at 1, the program omits the particle trajectory tracing calculations and the nozzle is assumed to be flowing full.

A gaseous start line is constructed based on the value of ICON(12). If ICON(12) is 0, the program distributes gas points on the start line by a sine distribution. If ICON(12) is 1, the gas points are distributed at even radial increments. With ICON(1) as 1, particle start line data points are calculated for each gas point. The angle of the particle trajectory at each point is set equal to the gas flow angle. The gas and particle start line points are arranged in order and output in units compatible with the RAMP code input. If ICON(11) is 0, the gas and particle start line points are output on a line printer and a card punch. If ICON(11) is 1, the start line points are output on the line printer only.

When ICON(1) is 0, the flowfield calculations are followed by particle trajectory tracing calculations. Particle trajectories are traced through the one-dimensional flowfield data previously calculated and stored. Particle trajectory calculations are performed from the initial axial station to the final axial station. The intersection of the particle trajectories with the line defining the final axial station provide the necessary data points to construct a start line of particle properties. As outlined previously a gaseous start line is constructed with gas data points either distributed at even radial increments or with a sine distribution. Each gaseous start line point consists of a radial co-ordinate, axial co-ordinate, Mach number, flow angle, entropy, Mach angle and total enthalpy arranged in the necessary order and output with the proper units to be compatible with the input of the RAMP computer code. The intersections of the particle trajectories with the gaseous start line determine the location of particle limiting streamline points on the start line. If a particle limiting streamline intersects the start line between gas points, a new gas point is calculated at the intersection by interpolating between the two existing gas points. The new gas point is added to the gaseous start line. For the particle start line data points up to the limiting streamline intersections, particle properties are calculated at the axial and radial location of each gas point. Particle start line properties output for the equilibrium version of the RAMP code are axial and radial velocity.
components, particle trajectory angle and particle density. Properties output for the finite rate version of the RAMP code are particle enthalpy and density, ratio of particle velocity to gas velocity and particle trajectory angle. As outlined previously the gas and particle start line data points are output on a line printer or a line printer and card punch depending on the value of ICON(11).

- Program Input Data

Input data required for the calculations include program control flags and starting parameters, problem geometry, gas and mixture thermodynamics, and particle properties. Program control flags control the input to be read, the interval at which calculations are printed and stored, the axial distance between stations, and the type of start line which is output. The input starting parameters determine the axial location of the initial data line relative to the nozzle throat and the gas and particle velocities on the initial data line.

The input thermodynamic data consist of thermodynamic and transport property data as a function of Mach number for the gas-particle mixture and for the gas phase. The gas-particle mixture thermodynamics includes Mach number, molecular weight, ratio of specific heats, temperature, pressure, Prandtl number, viscosity and specific heat at constant pressure. Gas phase thermodynamics includes Mach number, gas constant, ratio of specific heats, Prandtl number, viscosity and specific heat at constant pressure. The user may chose to use either ideal gas thermodynamic relationships or real gas thermodynamic data. When ideal gas thermodynamics is specified, a temperature exponent is input in place of the specific heat at constant pressure in the gas phase thermodynamics. For ideal gas thermodynamics, only one entry is made in the gas-particle mixture and gas phase thermodynamic tables. Thermodynamic properties in each table are input for a Mach number of 0.0. If real gas thermodynamics are used, one table of Mach numbers and corresponding properties is input for the gas-particle mixture thermodynamics and one or more tables are input for the gas phase thermodynamics. A maximum of 13 Mach number entries is permitted in each table.
The work required to accelerate the particles combined with the heat exchanged between the particle and gas phase is a non isentropic process. In gas-particle nozzle expansions, the gas total enthalpy and entropy vary. To account for this variance analytically, tables of these variables may be generated by expanding the gaseous products from various reference conditions (total enthalpy and entropy). The ODPART code has the capability to interpolate for gas constant, ratio of specific heats and transport properties between thermodynamic tables of data expanded from different chamber enthalpies and entropies. A maximum of ten tables with different total enthalpies may be input for the gas phase thermodynamics. For each total enthalpy, a maximum of two tables with different values of entropy are permitted. ODPART was written to accept the real gas thermodynamic card output of the CEC computer code (Ref. 8). ODPART does not read a magnetic tape for thermodynamic data.

The geometry defining a given problem establishes the boundary of the one-dimensional flow field. Geometry is input to the program in the form of equation coefficients. ODPART is equipped for conic and polynomial equations (see B2.1, Detailed Guide for Input Data). During a one-dimensional calculation the local radius from the nozzle centerline to the nozzle wall is calculated as a function of axial coordinate using the input equation coefficients. Program logic automatically switches from one equation to another as the maximum axial coordinate is reached for which a given equation is applicable. A maximum of 10 sets of equation coefficients may be input to define the nozzle boundary.

Data must be input to define individual particle sizes, particle mass densities and the percentage of the total particle mass comprised by each particle. The total particle mass relative to the gas must also be input. These properties define the physical characteristics of the particle phase. A maximum of six different particle species may be input. To define the particle thermodynamics, the user may input either a temperature-enthalpy table or thermodynamic properties for each particle species. A temperature-enthalpy table consists of tabulated values of particle temperature and the particle enthalpy at each temperature. The temperature range should include the temperature at which
the particle species changes phase from solid to liquid. A maximum of 10 temperature-enthalpy points may be input for each particle species. If the user chooses to input thermodynamic and phase change properties, particle temperature and enthalpy will be calculated using ideal gas relationships. The thermodynamic and phase data required for input are melting temperature, the enthalpy of the solid and liquid phases at the melting temperature and the specific heat at constant pressure for the solid and liquid phases.

To define the drag characteristics of the particle species, a table of Reynolds number and corresponding drag coefficients must be input. A maximum of 50 Reynolds number-drag coefficients points may be input. The user may input a particle drag table or use a drag table contained in the program. If the program control flag, IDRAG, is set to 0, the program will use the particle drag table contained internally (Kliegel drag data, see Ref. 7). If IDRAG is set to 1, the user must input a drag table.

The numerous calculational and input options of the ODPART computer code are outlined in greater detail in Section B-2.

B.2 DESCRIPTION OF PROGRAM INPUT

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

- Detailed input guide
- Detailed description of the input FORTRAN symbols
Fig. B-1 - Schematic of One-Dimensional Gas-Particle Solution
**B.2.1 Detailed Guide for Input Data**

**Card 1 - Program control flags**

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1-5    | ICON(1)   | 0 Particle limiting streamlines will be calculated  
1 Particles will be distributed on start line for a nozzle flowing full |
| 6-10   | ICON(2)   | 0 Straight start line (constant axial coordinate) 
1 Normal start line (points calculated at intersection of source streamlines with curved line at start line position) |
| 11-15  | ICON(3)   | Number of start line points |
| 1b-20  | ICON(4)   | Number of upper boundary equations (maximum of 10) |
| 21-25  | ICON(9)   | 0 Use English units for nozzle geometry |
| 26-30  | ICON(10)  | 0 Geometry input in inches 
1 Geometry input in feet |
| 31-35  | ICON(11)  | 0 Punch start line points 
1 Do not punch start line points |
| 36-40  | ICON(12)  | 0 Points distributed on start line with sine function 
1 Points distributed on start line at even radial increments |
| 41-45  | ICON(13)  | 0 Start line calculated for input to RAMP equilibrium code 
1 Start line calculated for input to RAMP finite rate code |

**Card 2 - Calculational control parameters**

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>ISPECS</td>
<td>Number of particle species (maximum of 6)</td>
</tr>
</tbody>
</table>
| 6-10   | IDRAG     | 0 Use drag table coded in program * 
N Number of points to be input for new drag table |

* Kliegel drag data (Ref. 7)
Card 2 - (Con't)

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-15</td>
<td>IDEL</td>
<td>Interval at which properties of data surfaces are printed</td>
</tr>
<tr>
<td>16-20</td>
<td>ISAV</td>
<td>Interval at which properties of data surfaces are stored for use in particle limiting streamline calculations</td>
</tr>
</tbody>
</table>

Card 3 - Initial conditions and problem limits

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Axial location of initial data surface if internal calculation of initial gas and particle velocities is desired</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>XM1</td>
<td>Axial coordinate of throat</td>
</tr>
<tr>
<td>11-20</td>
<td>XI</td>
<td>Axial coordinate of initial data surface</td>
</tr>
<tr>
<td>21-30</td>
<td>DX</td>
<td>Axial integration step</td>
</tr>
<tr>
<td>31-40</td>
<td>DXJ</td>
<td>Throat radius</td>
</tr>
<tr>
<td>H-50</td>
<td>UG</td>
<td>Gas velocity on initial data surface. IF XSTART &gt; 0, UG = 0</td>
</tr>
<tr>
<td>51-60</td>
<td>UP</td>
<td>Particle velocity on initial data surface. IF XSTART &gt; 0, UP = 0</td>
</tr>
<tr>
<td>61-70</td>
<td>XSTART</td>
<td>Axial location of initial data surface if internal calculation of initial gas and particle velocities is desired</td>
</tr>
<tr>
<td>T1-80</td>
<td>EMOUT</td>
<td>Mach number at which calculations are to stop and start line to be punched</td>
</tr>
</tbody>
</table>

Card 4 - Gas-particle equilibrium thermodynamic data (only one table required)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Number of Mach numbers in the gas-particle equilibrium thermo table</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>IVEQ</td>
<td>Chamber enthalpy</td>
</tr>
<tr>
<td>11-20</td>
<td>HC</td>
<td>ENG Input gas data with English units</td>
</tr>
<tr>
<td>21-30</td>
<td>UNITS</td>
<td>MKS Input gas data with Metric units</td>
</tr>
</tbody>
</table>

Card 4 - Gas-particle equilibrium thermodynamic data (repeat Card 4 IVEQ times in order of increasing Mach number)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Gas-particle equilibrium Mach number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>EQUIL(J, 1)</td>
<td>Gas-particle equilibrium molecular weight</td>
</tr>
</tbody>
</table>
### Card 4 - (Con't)

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-30</td>
<td>EQUIL(J, 3)</td>
<td>Gas-particle equilibrium ratio of specific heats</td>
</tr>
<tr>
<td>31-40</td>
<td>EQUIL(J, 4)</td>
<td>Gas-particle equilibrium temperature</td>
</tr>
<tr>
<td>41-50</td>
<td>EQUIL(J, 5)</td>
<td>Gas-particle equilibrium pressure</td>
</tr>
<tr>
<td>51-60</td>
<td>EQUIL(J, 6)</td>
<td>Gas-particle equilibrium Prandtl number</td>
</tr>
<tr>
<td>61-70</td>
<td>EQUIL(J, 7)</td>
<td>Gas-particle equilibrium viscosity</td>
</tr>
<tr>
<td>71-80</td>
<td>EQUIL(J, 8)</td>
<td>Gas-particle equilibrium specific heat at constant pressure</td>
</tr>
</tbody>
</table>

### Card 5 - Control flags for gas phase thermodynamic tables

Format: 2I5

<table>
<thead>
<tr>
<th>1-5</th>
<th>IHC</th>
<th>Number of enthalpy tables (maximum of 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-10</td>
<td>ISA</td>
<td>Number of entropy cuts for each enthalpy table (maximum of 2)</td>
</tr>
</tbody>
</table>

### Card 6 - Total enthalpy of table

Format: E10.6

<table>
<thead>
<tr>
<th>1-10</th>
<th>DELHC(M)</th>
<th>Enthalpy from which gas was expanded</th>
</tr>
</thead>
</table>

### Card 7 - Entropy of table and no. Mach numbers at this entropy

<table>
<thead>
<tr>
<th>1-10</th>
<th>STAB(M, I)</th>
<th>Entropy at which gas was expanded</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-20</td>
<td>IVTAB(M, I)</td>
<td>Number of Mach numbers in thermodynamic table</td>
</tr>
</tbody>
</table>

### Card 8 - Gas phase thermodynamic data

<table>
<thead>
<tr>
<th>1-10</th>
<th>GAS(J, 1)</th>
<th>Gas phase Mach number</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-20</td>
<td>GAS(J, 2)</td>
<td>Gas phase molecular weight</td>
</tr>
<tr>
<td>21-30</td>
<td>GAS(J, 3)</td>
<td>Gas phase ratio of specific heats</td>
</tr>
</tbody>
</table>

B-9

LOCKHEED · HUNTSVILLE RESEARCH & ENGINEERING CENTER
Card 8 - (Cont't)

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-40</td>
<td>DUM</td>
<td>Not currently used</td>
</tr>
<tr>
<td>41-50</td>
<td>DUM</td>
<td>Not currently used</td>
</tr>
<tr>
<td>51-60</td>
<td>GAS(J, 4)</td>
<td>Gas phase Prandtl number</td>
</tr>
<tr>
<td>61-70</td>
<td>GAS(J, 5)</td>
<td>Gas phase viscosity</td>
</tr>
<tr>
<td>71-80</td>
<td>GAS(J, 6)</td>
<td>Gas phase C_p</td>
</tr>
</tbody>
</table>

Note: Repeat Cards 6, 7 and 8 IHC times in order of increasing total enthalpy, DELHC(M)

Card 9 - Coefficients of equations defining nozzle geometry

<table>
<thead>
<tr>
<th>Format: 11, 3X, 11, 5X, 6E10.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 IWALL(K, 2)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>2 Polynomial Equation</td>
</tr>
<tr>
<td>R = AX^4 + BX^3 + CX^2 + DX + E</td>
</tr>
<tr>
<td>5 ITRAN(K, 2)</td>
</tr>
<tr>
<td>11-20 WALLCO</td>
</tr>
<tr>
<td>(K, 1, 2)</td>
</tr>
<tr>
<td>21-30 WALLCO</td>
</tr>
<tr>
<td>(K, 2, 2)</td>
</tr>
<tr>
<td>31-40 WALLCO</td>
</tr>
<tr>
<td>(K, 3, 2)</td>
</tr>
<tr>
<td>41-50 WALLCO</td>
</tr>
<tr>
<td>(K, 4, 2)</td>
</tr>
<tr>
<td>51-60 WALLCO</td>
</tr>
<tr>
<td>(K, 5, 2)</td>
</tr>
<tr>
<td>61-70 WALLCO</td>
</tr>
<tr>
<td>(K, 6, 2)</td>
</tr>
</tbody>
</table>

Note: Repeat Card 9 sufficient number of times to define the nozzle inlet, throat and divergent exit
Card 10

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>XMASSP</td>
<td>Ratio of particle total mass flowrate to gas mass flowrate</td>
</tr>
</tbody>
</table>

Card 11 - Percentage of particle mass flow contributed by each particle

Format: 6E10.6

| 1-10 | PERTG(1) | Ratio of particle 1 mass flowrate to total particle mass flowrate |
| 11-20| PERTG(2) | Ratio of particle 2 mass flowrate to total particle mass flowrate |

Card 12 - Radius of each particle

Format: 6E10.6

| 1-10 | PSP(2, 1) | Radius of particle 1, microns |
| 11-20| PERTG(ISPECS) | Radius of particle ISPECS, microns |

Card 13 - Mass density of each particle

Format: 6E10.6

| 1-10 | PSP(1, 1) | Mass density of particle 1 |
| 11-20| PERTG(ISPECS) | Mass density of particle ISPECS |

Card 14 - Particle drag data (Use only if IDRAG>0)

Format: 8E10.6

| 1-10 | AREY(1) | Reynolds number used as independent variable in drag table |
| 11-20| BREY(1) | Drag coefficient corresponding to above Reynolds number (CD/C_D Stokes) |
Card 14 — (Cont'd)

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-30</td>
<td>AREY(2)</td>
<td></td>
</tr>
<tr>
<td>31-40</td>
<td>BREY(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Use as many cards as necessary to input all necessary drag data (50 max entries)

Card 15 — Particle data control variables

1-24
ALPHA  
Particle name

25-27
NOCUTS  
Not used

28-33
UNIT  
ENG  Data input in English units
MKS  Data input in Metric units (left adjusted)

Card 16 — Thermodynamic table to be used by each particle species

1-2
JTEM(l)  
Temperature-enthalpy table to be used for particle l

JTEM(ISPECS)  
Temperature-enthalpy table to be used for particle ISPECS

Card 17 — Number data points in particle thermodynamic table

1-3
NPTM(l)  
Number of temperature-enthalpy data points for this particle. If equal to 1, input liquid and solid heat capacities.
## Card 18 - Particle thermodynamic data

**Format:** 7E10.6

<table>
<thead>
<tr>
<th>Column</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>TM(I)</td>
<td>Melting point temperature of particle I</td>
</tr>
<tr>
<td>11-20</td>
<td>Hs(I)</td>
<td>Enthalpy of solid phase of particle I at melting point temperature</td>
</tr>
<tr>
<td>21-30</td>
<td>HM(I)</td>
<td>Enthalpy of liquid phase of particle I at melting point temperature</td>
</tr>
</tbody>
</table>

If \( NPTk(I) = 1 \), use the following format

| 31-40  | APHO(1, 1, I) | Heat capacity of liquid phase of particle I (Btu/lbm \( \cdot \) R or cal/gm \( \cdot \) K) |
| 41-50  | APHO(1, 2, I) | Heat capacity of solid phase of particle I (Btu/lbm \( \cdot \) R or cal/gm \( \cdot \) K) |

If \( NPTM(I) > 1 \), use following format

| 31-40  | APHO(1, 1, I) | Temperature for T-H table for particle I (\( ^{\circ} \) R or \( ^{0} \) K) |
| 41-50  | APHO(1, 2, I) | Enthalpy for T-H table for particle I (Btu/lbm or cal/gm) |
| 51-60  | APHO(2, 1, I) | Second temperature in T-H table for particle I (\( ^{\circ} \) R or \( ^{0} \) K) |
| 61-70  | APHO(2, 2, I) | Second enthalpy in T-H table for particle I (Btu/lbm or cal/gm) |

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

### B.2.2 Input FORTRAN Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICON(1)</td>
<td>This flag designates type of particulate start line to be calculated and punched. If ICON(1) = 0, particle trajectories and their intersection with the gas start line are calculated. If ICON(1) = 1, the particles are evenly distributed across the gas start line.</td>
<td>N/A</td>
</tr>
<tr>
<td>ICON(2)</td>
<td>This flag designates type of gas start line to be calculated and punched. If ICON(2) = 0, a straight start line is calculated. If ICON(2) = 1, a normal start line is calculated.</td>
<td>N/A</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>ICON(3)</td>
<td>ICON(3) is the number of start line points to be generated. A maximum of 50 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>ICON(4)</td>
<td>ICON(4) is the number of upper boundary equations defining the nozzle geometry.</td>
<td>N/A</td>
</tr>
<tr>
<td>ICON(9)</td>
<td>ICON(9) specifies the units to be used. If ICON(9) = 0, English units are used. If ICON(9) = 1, Mks units are used.</td>
<td>N/A</td>
</tr>
<tr>
<td>ICON(10)</td>
<td>This flag designates the dimensions of the input geometry and geometric control parameters if English units are used. If ICON(10) = 0, geometry is input in inches. If ICON(10) = 1, geometry is input in feet.</td>
<td>N/A</td>
</tr>
<tr>
<td>ISPECS</td>
<td>Number of particle species to be input. A maximum of 10 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>IDRAG</td>
<td>IDRAG controls which particle drag data is used. If IDRAG = 0, the particle drag table coded in the program will be used. If a drag table is input, IDRAG is number of points to be read.</td>
<td>N/A</td>
</tr>
<tr>
<td>IDEL</td>
<td>IDEL is the interval at which properties of data surfaces are printed. If IDEL = 1, the properties of each data surface are printed. If IDEL = 10, the properties of every tenth data surface are printed, etc.</td>
<td>N/A</td>
</tr>
<tr>
<td>ISAV</td>
<td>ISAV is the interval at which properties of data surfaces are stored for use in particle trajectory calculations. A maximum of 300 data surfaces may be stored.</td>
<td>N/A</td>
</tr>
<tr>
<td>XM1</td>
<td>Axial coordinate of nozzle throat</td>
<td>in or ft</td>
</tr>
<tr>
<td>XI</td>
<td>Axial coordinate of initial data surface</td>
<td>in or ft</td>
</tr>
<tr>
<td>DX</td>
<td>Integration step between successive data surface calculations</td>
<td>in or ft</td>
</tr>
<tr>
<td>DXJ</td>
<td>Radius of the nozzle throat</td>
<td>in or ft</td>
</tr>
<tr>
<td>UG</td>
<td>This variable is the gas velocity on the initial data surface. If the velocity is unknown, UG should be set equal to zero and the program will calculate an initial guess for UG.</td>
<td>ft/sec</td>
</tr>
<tr>
<td>UP</td>
<td>This variable is the particle velocity on the initial data surface. If UP is set equal to zero, the program will set UP = UG and assume the gas and particles are in equilibrium on the initial data surface.</td>
<td>ft/sec</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>XSTART</td>
<td>XSTART is the axial location of the initial data surface if internal calculation of initial gas and particle velocities is desired.</td>
<td>in or ft</td>
</tr>
<tr>
<td>EMOUT</td>
<td>This is the Mach number at which the integration of the gas-particle equations is to stop and a start line calculated and punched.</td>
<td>N/A</td>
</tr>
<tr>
<td>IVEQ</td>
<td>This flag designates the number of Mach number entries in the gas-particle equilibrium thermodynamic table. A maximum of 13 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>HC</td>
<td>This is the chamber enthalpy in units consistent with the thermodynamic tables.</td>
<td>ft²/sec² or M²/sec²</td>
</tr>
<tr>
<td>EQUIL(J, 1)</td>
<td>Mach number entry in the gas-particle equilibrium thermodynamic table.</td>
<td>N/A</td>
</tr>
<tr>
<td>EQUIL(J, 2)</td>
<td>Molecular weight entry in the gas-particle equilibrium thermodynamic table</td>
<td>lbm./lbm. mole or gm./gm. mole</td>
</tr>
<tr>
<td>EQUIL(J, 3)</td>
<td>Ratio of specific heats entry in the gas-particle equilibrium thermodynamic table</td>
<td>N/A</td>
</tr>
<tr>
<td>EQUIL(J, 4)</td>
<td>Temperature entry in the gas-particle equilibrium thermodynamic table</td>
<td>°R or °K</td>
</tr>
<tr>
<td>EQUIL(J, 5)</td>
<td>Pressure entry in the gas-particle equilibrium thermodynamic table</td>
<td>atm.</td>
</tr>
<tr>
<td>EQUIL(J, 6)</td>
<td>Prandtl number entry in the gas-particle equilibrium thermodynamic table</td>
<td>N/A</td>
</tr>
<tr>
<td>EQUIL(J, 7)</td>
<td>Viscosity entry in the gas-particle equilibrium thermodynamic table</td>
<td>lbf. sec/ft² or Kg. m/sec</td>
</tr>
<tr>
<td>EQUIL(J, 8)</td>
<td>Gas specific heat at constant pressure entry in the gas-particle equilibrium thermodynamic table</td>
<td>ft²/sec² °R</td>
</tr>
<tr>
<td>IHC</td>
<td>Number of enthalpy tables in the gas phase thermodynamic data A maximum of 10 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>ISA</td>
<td>Number of entropy cuts for each enthalpy table. A maximum of 2 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>DELHC(M)</td>
<td>This variable is the total enthalpy from which the gas was expanded.</td>
<td>Btu/lbm or cal/gm</td>
</tr>
<tr>
<td>STAB(M, I)</td>
<td>This variable is the entropy at which the gas was expanded</td>
<td>Btu/lbm - °R or cal/gm - °K</td>
</tr>
<tr>
<td>IVTAB(M, I)</td>
<td>This flag designates the number of Mach number entries in the gas phase thermodynamic table. A maximum of 13 is permitted.</td>
<td>N/A</td>
</tr>
<tr>
<td>GAS(J, 1)</td>
<td>Mach number entry in the gas phase thermodynamic table.</td>
<td>N/A</td>
</tr>
<tr>
<td>GAS(J, 2)</td>
<td>Molecular weight entry in the gas phase thermodynamic table</td>
<td>lbm/lbm, mole or gm/gm, mole</td>
</tr>
<tr>
<td>GAS(J, 3)</td>
<td>Ratio of specific heats in the gas phase thermodynamic table.</td>
<td>N/A</td>
</tr>
<tr>
<td>GAS(J, 7)</td>
<td>Temperature entry in the gas phase thermodynamic table.</td>
<td>°R or °K</td>
</tr>
<tr>
<td>GAS(J, 4)</td>
<td>Prandtl number entry in the gas phase thermodynamic table.</td>
<td>N/A</td>
</tr>
<tr>
<td>GAS(J, 5)</td>
<td>Viscosity entry in the gas phase thermodynamic table.</td>
<td>lbm/sec ft² or kg·M/sec</td>
</tr>
<tr>
<td>GAS(J, 6)</td>
<td>Gas specific heat at constant pressure entry in the gas phase thermodynamic table. For ideal gas thermodynamics it is the non-dimensional temperature exponent.</td>
<td>ft²·ft²/°R or M²/sec² - °K</td>
</tr>
<tr>
<td>IWAL(K, 2)</td>
<td>This flag designates the type of equation defining the nozzle geometry.</td>
<td>N/A</td>
</tr>
</tbody>
</table>

If $\text{IWALL}(K, 2) = 1$, a conic equation of the form, $R = A[(B + CX + DX^2)^{1/2} + E]$ is input. If $\text{IWALL}(K, 2) = 2$, a polynomial equation of the form, $R = AX^4 + BX^3 + CX^2 + DX + E$ is input.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITRAN(K, 2)</td>
<td>Not presently used.</td>
<td>N/A</td>
</tr>
<tr>
<td>WALLCO(K, 1, 2)</td>
<td>This variable corresponds to the coefficient A in the conic or polynomial nozzle equations.</td>
<td>Equation coefficients in the WALLCO array should be developed in units consistent with ICON ICON(10)</td>
</tr>
<tr>
<td>WALLCO(K, 2, 2)</td>
<td>This variable corresponds to the coefficient B in the conic or polynomial nozzle equations.</td>
<td></td>
</tr>
<tr>
<td>WALLCO(K, 3, 2)</td>
<td>This variable corresponds to the coefficient C in the conic or polynomial nozzle equations.</td>
<td></td>
</tr>
<tr>
<td>WALLCO(K, 4, 2)</td>
<td>This variable corresponds to the coefficient D in the conic or polynomial nozzle equations.</td>
<td></td>
</tr>
<tr>
<td>WALLCO(K, 5, 2)</td>
<td>This variable corresponds to the coefficient E in the conic or polynomial nozzle equations.</td>
<td></td>
</tr>
<tr>
<td>WALLCO(K, 6, 2)</td>
<td>Maximum axial coordinate for which a particular nozzle equation is applicable.</td>
<td></td>
</tr>
<tr>
<td>XMASSP</td>
<td>XMASSP is the ratio of total particle mass flow rate to gas mass flow rate</td>
<td>N/A</td>
</tr>
<tr>
<td>PERTG(J)</td>
<td>This is the ratio of the Jth particle mass flow rate to total particle mass flow rate</td>
<td>N/A</td>
</tr>
<tr>
<td>PSP(2, J)</td>
<td>PSP(2, J) is the radius of the Jth particle</td>
<td>Microns</td>
</tr>
<tr>
<td>PSP(1, J)</td>
<td>PSP(1, J) is the mass density of the Jth particle</td>
<td>lbm/ft$^3$ or gm/cm$^3$</td>
</tr>
<tr>
<td>ALPHA</td>
<td>ALPHA is the particle specie name is used for printout purposes.</td>
<td>N/A</td>
</tr>
<tr>
<td>NOCUTS</td>
<td>Not presently used</td>
<td>N/A</td>
</tr>
<tr>
<td>UNIT</td>
<td>UNIT specifies the units in which the particle temperature and enthalpy data will be input. If UNIT = ENG, data will be input in English units. If UNIT = MKS, data will be input in MKS units.</td>
<td>N/A</td>
</tr>
<tr>
<td>JTEM(J)</td>
<td>JTEM(J) specifies the temperature-enthalpy table to be used for the Jth particle</td>
<td>N/A</td>
</tr>
<tr>
<td>NPTM(J)</td>
<td>Number of entries in temperature-enthalpy table for a particular particle. If NPTM(J) = 1, input the liquid and solid heat capacities.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Symbol | Description | Units
--- | --- | ---
TM(J) | Melting point temperature of Jth particle | $^\circ R$ or $^\circ K$
HS(J) | Enthalpy of solid phase of Jth particle at the melting point temperature | Btu/lbm or cal/gm
HM(J) | Enthalpy of liquid phase of Jth particle at the melting point temperature | Btu/lbm or cal/gm
APHO(1, 1, J) | Heat capacity of the liquid phase of the Jth particle if $NPTM(J) = 1$. First temperature entry in the Jth particle temperature-enthalpy table if $NPTM(J) > 1$. | sec detailed input guide
APHO(1, 2, J) | Heat capacity of the solid phase of the Jth particle if $NPTM(J) = 1$. First enthalpy entry in the Jth particle temperature-enthalpy table if $NPTM(J) > 1$. | see detailed input guide
APHO(2, 1, J) | Second temperature entry in the Jth particle temperature-enthalpy table if $NPTM(J) > 1$. | $^\circ R$ or $^\circ K$
APHO(2, 2, J) | Second enthalpy entry in the Jth particle temperature-enthalpy table if $NPTM(J) > 1$. | Btu/lbm or cal/gm

**B.3 DESCRIPTION OF PROGRAM OUTPUT**

This subsection contains a description of the output scheme utilized by the program and a description of the error messages printed out by the program.

**B.3.1 Description of Program Data Output**

The following guide consists of numbered flags on sample printout sheets (pages B-25 through P-32) which respond to numbered comments listed below:

1
Program title

2
Control flags input by user

3
THROAT X COORDINATE
Axial coordinate of r-zle throat, ft or in
<table>
<thead>
<tr>
<th></th>
<th>AXIAL COORDINATE AT THE THROAT ENTRANCE</th>
<th>Axial coordinate of nozzle inlet, ft or in</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>DELTA X</td>
<td>Axial integration step, ft or in</td>
</tr>
<tr>
<td>6</td>
<td>R*</td>
<td>Nozzle throat radius, ft or in</td>
</tr>
<tr>
<td>7</td>
<td>M\text{\textit{I}}TURE VELOCITY AT</td>
<td>Velocity at nozzle inlet, ft/sec</td>
</tr>
<tr>
<td>8</td>
<td>CHAMBER ENTHALPY</td>
<td>Chamber enthalpy for which gas-particle thermodynamics were calculated, ft$^2$/sec$^2$ or M$^2$/sec$^2$</td>
</tr>
<tr>
<td>9</td>
<td>VELOCITY</td>
<td>Velocity for which gas-particle thermodynamics were calculated, ft/sec</td>
</tr>
<tr>
<td>10</td>
<td>R</td>
<td>Gas constant, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>11</td>
<td>GAMMA</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>12</td>
<td>TEMPERATURE</td>
<td>Static temperature, °R or °K</td>
</tr>
<tr>
<td>13</td>
<td>PRESSURE</td>
<td>Static pressure, psf</td>
</tr>
<tr>
<td>14</td>
<td>PRANDTL NUMBER</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>15</td>
<td>VISCOSITY</td>
<td>Viscosity, poise</td>
</tr>
<tr>
<td>16</td>
<td>CP</td>
<td>Specific heat at constant pressure, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>17</td>
<td>ENTHALPY</td>
<td>Chamber enthalpy for which gas phase thermodynamics were calculated, ft$^2$/sec$^2$ or M$^2$/sec$^2$</td>
</tr>
<tr>
<td>18</td>
<td>ENTROPY</td>
<td>Chamber entropy for which gas phase thermodynamics were calculated, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>19</td>
<td>VELOCITY</td>
<td>Velocity for which gas-particle thermodynamics were calculated.</td>
</tr>
<tr>
<td>20</td>
<td>R</td>
<td>Gas constant, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>21</td>
<td>GAMMA</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>22</td>
<td>PRANDTL NUMBER</td>
<td>Prandtl number</td>
</tr>
<tr>
<td>23</td>
<td>VISCOSITY</td>
<td>Viscosity, poise</td>
</tr>
<tr>
<td>24</td>
<td>EXPONENT</td>
<td>Viscosity exponent</td>
</tr>
<tr>
<td>25</td>
<td>TYPE</td>
<td>Type of nozzle boundary equation</td>
</tr>
</tbody>
</table>

**B-19**
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>ITRANS</td>
<td>Gas dynamic condition existing at the end of the current nozzle boundary equations (not currently used)</td>
</tr>
<tr>
<td>27</td>
<td>A</td>
<td>Nozzle boundary equation coefficient</td>
</tr>
<tr>
<td>28</td>
<td>B</td>
<td>Nozzle boundary equation coefficient</td>
</tr>
<tr>
<td>29</td>
<td>C</td>
<td>Nozzle boundary equation coefficient</td>
</tr>
<tr>
<td>30</td>
<td>D</td>
<td>Nozzle boundary equation coefficient</td>
</tr>
<tr>
<td>31</td>
<td>E</td>
<td>Nozzle boundary equation coefficient</td>
</tr>
<tr>
<td>32</td>
<td>MAX</td>
<td>Maximum axial coordinate for which nozzle boundary equation is applicable</td>
</tr>
<tr>
<td>33</td>
<td>TOTAL PARTICLE WEIGHT RELATIVE TO THE GAS IS</td>
<td>Ratio of total particle mass flow rate to gas mass flow rate</td>
</tr>
<tr>
<td>34</td>
<td>I</td>
<td>Particle number</td>
</tr>
<tr>
<td>35</td>
<td>RADIUS</td>
<td>Particle radius, microns</td>
</tr>
<tr>
<td>36</td>
<td>PERCENT</td>
<td>Ratio of jth particle mass flow rate to total particle mass flow rate</td>
</tr>
<tr>
<td>37</td>
<td>DENSITY</td>
<td>Particle mass density, lbm/ft$^3$</td>
</tr>
<tr>
<td>38</td>
<td>VELOCITY</td>
<td>Particle velocity at first axial station, ft/sec</td>
</tr>
<tr>
<td>39</td>
<td>TMELT</td>
<td>Melting temperature of particle species, °R or °K</td>
</tr>
<tr>
<td>40</td>
<td>HSOLID</td>
<td>Enthalpy of solid particle at melting temperature, ft$^2$/sec$^2$ or M$^2$/sec$^2$</td>
</tr>
<tr>
<td>41</td>
<td>HLIQUID</td>
<td>Enthalpy of liquid particle at melting temperature, ft$^2$/sec$^2$ or M$^2$/sec$^2$</td>
</tr>
<tr>
<td>42</td>
<td>CPMELT</td>
<td>Heat capacity of liquid particle at melting temperature, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>43</td>
<td>CPSOLID</td>
<td>Heat capacity of solid particle at melting temperature, ft$^2$/sec$^2$ - °R or M$^2$/sec$^2$ - °K</td>
</tr>
<tr>
<td>44</td>
<td>I</td>
<td>Point number</td>
</tr>
<tr>
<td>45</td>
<td>RE</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>46</td>
<td>DRAG COEF</td>
<td>Drag Coefficient ($C_D/C_D^{Stokes}$)</td>
</tr>
<tr>
<td>Column Number</td>
<td>Description</td>
<td>Unit or Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>47</td>
<td><strong>AXIAL STATION X</strong></td>
<td>Axial coordinate of data line, ft or in</td>
</tr>
<tr>
<td>48</td>
<td><strong>AREA RATIO A/A⁺</strong></td>
<td>Area ratio at the axial location of the data line</td>
</tr>
<tr>
<td>49</td>
<td><strong>VELOCITY</strong></td>
<td>Gas velocity, ft/sec</td>
</tr>
<tr>
<td>50</td>
<td><strong>R</strong></td>
<td>Gas constant, ft²/sec² - °R</td>
</tr>
<tr>
<td>51</td>
<td><strong>ENTHALPY</strong></td>
<td>Gas static enthalpy, ft²/sec²</td>
</tr>
<tr>
<td>52</td>
<td><strong>GAMMA</strong></td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>53</td>
<td><strong>TEMPERATURE</strong></td>
<td>Gas static temperature, °R</td>
</tr>
<tr>
<td>54</td>
<td><strong>PRANDTL NUMBER</strong></td>
<td>Prandtl number</td>
</tr>
<tr>
<td>55</td>
<td><strong>MACH NUMBER</strong></td>
<td>Mach number</td>
</tr>
<tr>
<td>56</td>
<td><strong>VISCOSITY</strong></td>
<td>Viscosity, poise</td>
</tr>
<tr>
<td>57</td>
<td><strong>PRESSURE</strong></td>
<td>Gas static pressure, psia</td>
</tr>
<tr>
<td>58</td>
<td><strong>CP</strong></td>
<td>Specific heat at constant pressure, ft²/sec² - °R</td>
</tr>
<tr>
<td>59</td>
<td><strong>DENSITY</strong></td>
<td>Gas density, slugs/ft³</td>
</tr>
<tr>
<td>60</td>
<td><strong>TOTAL ENTHALPY</strong></td>
<td>Gas total enthalpy, ft²/sec²</td>
</tr>
<tr>
<td>61</td>
<td><strong>ENTROPY</strong></td>
<td>Entropy, ft²/sec² - °R</td>
</tr>
<tr>
<td>62</td>
<td><strong>PARTICLE</strong></td>
<td>Particle number</td>
</tr>
<tr>
<td>63</td>
<td><strong>VELOCITY</strong></td>
<td>Particle velocity, ft/sec</td>
</tr>
<tr>
<td>64</td>
<td><strong>ENTHALPY</strong></td>
<td>Particle enthalpy, ft²/sec²</td>
</tr>
<tr>
<td>65</td>
<td><strong>TEMPERATURE</strong></td>
<td>Particle temperature, °R</td>
</tr>
<tr>
<td>66</td>
<td><strong>MIXTURE MASS FLOW</strong></td>
<td>Percent change in mass flow from the initial data line to the calculated start line</td>
</tr>
<tr>
<td>67</td>
<td><strong>GAS MOMENTUM</strong></td>
<td>Percent change in gas momentum from the initial data line to the calculated start line</td>
</tr>
<tr>
<td>58</td>
<td><strong>PARTICLE MOMENTUM</strong></td>
<td>Percent change in particle momentum from the initial data line to the calculated start line</td>
</tr>
<tr>
<td>69</td>
<td><strong>MIXTURE MOMENTUM</strong></td>
<td>Percent change in mixture momentum from the initial data line to the calculated start line</td>
</tr>
<tr>
<td>Column</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>TOTAL ENTHALPY</td>
<td>Percent change in total enthalpy from the initial data line to the calculated start line</td>
</tr>
<tr>
<td>71</td>
<td>FXG</td>
<td>Integral of force parallel to the nozzle centerline due to the gas, lbf</td>
</tr>
<tr>
<td>72</td>
<td>FXP</td>
<td>Integral of force parallel to the nozzle centerline due to the particles, lbf</td>
</tr>
<tr>
<td>73</td>
<td>FXM</td>
<td>Total integral of force parallel to the nozzle centerline, lbf</td>
</tr>
<tr>
<td>74</td>
<td>ISP</td>
<td>One-dimensional ISP, sec</td>
</tr>
<tr>
<td>75</td>
<td>-</td>
<td>Particle number</td>
</tr>
<tr>
<td>76</td>
<td>RADIAL COORDINATE</td>
<td>Radial distance from nozzle centerline, ft</td>
</tr>
<tr>
<td>77</td>
<td>AXIAL COORDINATE</td>
<td>Axial location, ft</td>
</tr>
<tr>
<td>78</td>
<td>AXIAL VELOCITY</td>
<td>Particle axial velocity, ft/sec</td>
</tr>
<tr>
<td>79</td>
<td>RADIAL VELOCITY</td>
<td>Particle radial velocity, ft/sec</td>
</tr>
<tr>
<td>80</td>
<td>ANGLE</td>
<td>Angle from the horizontal of the particle trajectory, degrees</td>
</tr>
<tr>
<td>81</td>
<td>ENTHALPY</td>
<td>Particle enthalpy, ft$^2$/sec$^2$</td>
</tr>
<tr>
<td>82</td>
<td>NOZZLE RADIUS</td>
<td>Nozzle radius, ft</td>
</tr>
<tr>
<td>83</td>
<td>-</td>
<td>Particle number</td>
</tr>
<tr>
<td>84</td>
<td>RADIAL COORDINATE</td>
<td>Radial coordinate of particle limiting streamline intersection with calculated start line, ft</td>
</tr>
<tr>
<td>85</td>
<td>AXIAL COORDINATE</td>
<td>Axial coordinate of particle limiting streamline intersection with calculated start line, ft</td>
</tr>
<tr>
<td>86</td>
<td>AXIAL VELOCITY</td>
<td>Particle axial velocity at intersection of particle limiting streamline with calculated start line, ft/sec</td>
</tr>
<tr>
<td>87</td>
<td>RADIAL VELOCITY</td>
<td>Particle radial velocity at intersection of particle limiting streamline with calculated start line, ft/sec</td>
</tr>
<tr>
<td>88</td>
<td>ANGLE</td>
<td>Angle from the horizontal of the particle trajectory at intersection of particle limiting streamline with calculated start line, degrees</td>
</tr>
<tr>
<td>89</td>
<td>ENTHALPY</td>
<td>Particle enthalpy at intersection of particle limiting streamline with calculated start line, ft$^2$/sec$^2$</td>
</tr>
<tr>
<td>Column</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>NOZZLE RADIUS</td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>MACH NUMBER</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>THETA</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>ENTROPY</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>MACH ANGLE</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>TOTAL ENTHALPY</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>PARTICLE</td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>AXIAL VELOCITY</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>RADIAL VELOCITY</td>
<td></td>
</tr>
<tr>
<td>102</td>
<td>THETA</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>ENTHALPY</td>
<td></td>
</tr>
<tr>
<td>104</td>
<td>DENSITY</td>
<td></td>
</tr>
</tbody>
</table>

- **NOZZLE RADIUS**
  - Nozzle radius, ft

- **R**
  - Radial coordinate of start line point, ft

- **X**
  - Axial coordinate of start line point, ft

- **MACH NUMBER**
  - Mach number at start line point

- **THETA**
  - Gas flow angle at start line point, degrees

- **ENTROPY**
  - Entropy at start line point, \( \text{ft}^2/\text{sec}^2 \) or \( \circ R \)

- **MACH ANGLE**
  - Mach angle at start line point, degrees

- **TOTAL ENTHALPY**
  - Total enthalpy at start line point, \( \text{ft}^2/\text{sec}^2 \)

- **PARTICLE**
  - Particle number

- **I**
  - Start line point number

- **AXIAL VELOCITY**
  - Particle axial velocity at start line point, ft/sec

- **RADIAL VELOCITY**
  - Particle radial velocity at start line point, ft/sec

- **THETA**
  - Angle from the horizontal of the particle trajectory at the start line point, degrees

- **ENTHALPY**
  - Particle enthalpy at the start line point, \( \text{ft}^2/\text{sec}^2 \)

- **DENSITY**
  - Particle density at the start line point, \( \text{lbm}/\text{ft}^3 \)
Note: These cards were input to a Univac 1108 multiprocessor system to generate the sample output which follows.

```
*RUN
*ANG T= 0.001 T= 0.001794
*REWIND UNED
*EDISON Q=0.0
*CUPIN UNED TPF *
*FREE UNED
*XUT A

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>-1.567</td>
<td>0.0012</td>
<td>0.025</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>81.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>2.5</td>
<td>1.92</td>
<td>1.07</td>
<td>0.595</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.675</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
<td>250.0</td>
</tr>
</tbody>
</table>
```

ALPHABET : ENG

```
1174.0
1112.0
1012.1
0.3395
0.2676
```

*FIN
*FIN
### Run Control Parameters

<table>
<thead>
<tr>
<th>ICON11</th>
<th>ICON12</th>
<th>ICON13</th>
<th>ICON14</th>
<th>ICON15</th>
<th>ICON16</th>
<th>ICON17</th>
<th>ICON18</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ISPECs</th>
<th>IDRAG</th>
<th>IDEL</th>
<th>ISAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

### Input Data for Subsonic Gas-Particle Calculations

3. Throat A Coordinate: 0.0000
4. Axial Coordinate at the Throat Entrance: -1.5676E+01

5. Delta K: +12000*03, t = 25000*00 Mixture Velocity at the Throat Entrance: -1.0000

There are 1 entries in the gas-particle thermodynamic and transport property tables

6. Chamber Enthalpy: 7.0495E+06

7. Velocity (m/s):
   - Gamma: 1.04
   - Temperature (K):
   - Pressure (Pa):
   - Prandtl Number (PSF): 1.04
   - Viscosity (Pas):
   - Exponent:

8. Enthalpy: 7.0495E+08
   - Entropy: 1.0000

There are 1 entries in the gas phase thermodynamic and transport property tables

9. Velocity (m/s):
   - Gamma:
   - Prandtl Number (PSF):
   - Viscosity:
   - Exponent:

10. Type:
    - Trans A
     - Trans B

11. Max:
    - A
     - B

12. Particle Data
    - Total Particle Weight Relative to the Gas is 1.2275E+00

<table>
<thead>
<tr>
<th>J</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RADIUS</td>
<td>PERCENT</td>
<td>DENSITY</td>
<td>VELOCITY</td>
</tr>
<tr>
<td>1</td>
<td>40000*00</td>
<td>10000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
<tr>
<td>2</td>
<td>80000*00</td>
<td>20000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
<tr>
<td>3</td>
<td>11250*01</td>
<td>20000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
<tr>
<td>4</td>
<td>15000*01</td>
<td>20000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
<tr>
<td>5</td>
<td>21500*01</td>
<td>20000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
<tr>
<td>6</td>
<td>15000*01</td>
<td>10000*00</td>
<td>25000*01</td>
<td>13290*03</td>
</tr>
</tbody>
</table>

---

**B-26**

**RENDIVIAL PAGE**
### Table: Axial Station 1

<table>
<thead>
<tr>
<th>VELOCITY (FT/SEC)</th>
<th>ENTHALPY (FT^2/SEC^2)</th>
<th>TEMPERATURE (R)</th>
<th>MACH NUMBER (PRANDTL NUMBER)</th>
<th>PRESSURE (PSI)</th>
<th>DENSITY (SLU./FT^3)</th>
<th>TOTAL ENTHALPY (FT^2/SEC^2)</th>
<th>ENTRPY</th>
</tr>
</thead>
<tbody>
<tr>
<td>25423+0</td>
<td>.71323+0</td>
<td>5.29300+0</td>
<td>.01035+01</td>
<td>.243156+02</td>
<td>.843271-02</td>
<td>.740497+08</td>
<td>.802078+02</td>
</tr>
<tr>
<td>242482+00</td>
<td>1205700+00</td>
<td>2387900+00</td>
<td>146989-05</td>
<td>149026+05</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Particle 1**
- 232482+04
- 15033+04
- 1194+04
- 18021+04
- 159381+04
- 151137+04

**Particle 2**
- 191450+04
- 649200+08
- 119270+09
- 110234+01
- 459176+03
- 140891+05

**Particle 3**
- 376420+04
- 472284+08
- 498200+09
- 80173+08
- 509794+04
- 85083+04

**Particle 4**
- 25075+04
- 49589+08
- 5183+04
- 20583+04

### The Mixture Start Condition Occurred Before the Following Axial Station

**Axial Station 2**
- 685852+01
- 101893+01
- 284997+02

**Particle 1**
- 419450+04
- 64920+08
- 11023+01
- 455152+02
- 179493+00
- 12187+03

**Particle 2**
- 120900+01
- 140891+05

**Percent Change in Mass, Momentum and Energy Relative to the Starting Conditions**

- Percent change in mixture mass flow was +722214+03 percent
- Percent change in gas momentum was +930904+02 percent
- Percent change in particle momentum was +212201+04 percent
- Percent change in mixture momentum was +933714+02 percent
- Percent change in total enthalpy was +164359+02 percent

**Momentum Integration Results**

- FDF = .724728+03
- FDF = .216749+02
- FDF = .248053+03
- FDF = .195019+03
### PARTICLE TRAJECTORY CALCULATIONS

<table>
<thead>
<tr>
<th>Radial Co-ordinate</th>
<th>Axial Co-ordinate</th>
<th>Axial Velocity</th>
<th>Radial Velocity</th>
<th>Angle</th>
<th>Enthalpy</th>
<th>Nozzle Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>(FT)</td>
<td>(FT)</td>
<td>(FT/SEC)</td>
<td>(FT/SEC)</td>
<td>(DEG)</td>
<td>(FT²/SEC²)</td>
<td>(FT)</td>
</tr>
<tr>
<td>4</td>
<td>531593-02</td>
<td>1970810-09</td>
<td>10622900-03</td>
<td>477287-01</td>
<td>940576-08</td>
<td>20722-01</td>
</tr>
<tr>
<td>1</td>
<td>192869-01</td>
<td>531593-02</td>
<td>3723610-04</td>
<td>467267-02</td>
<td>716958-00</td>
<td>973090-01</td>
</tr>
<tr>
<td>2</td>
<td>175371-01</td>
<td>531593-02</td>
<td>3101270-09</td>
<td>368572-03</td>
<td>167610-01</td>
<td>978689-01</td>
</tr>
<tr>
<td>3</td>
<td>179144-01</td>
<td>531593-02</td>
<td>3039020-09</td>
<td>467797-03</td>
<td>314037-01</td>
<td>982312-09</td>
</tr>
<tr>
<td>4</td>
<td>162227-01</td>
<td>531593-02</td>
<td>2783150-09</td>
<td>520700-03</td>
<td>353399-01</td>
<td>986578-09</td>
</tr>
<tr>
<td>5</td>
<td>152121-01</td>
<td>531593-02</td>
<td>2718490-03</td>
<td>383191-01</td>
<td>489777-06</td>
<td>210030-01</td>
</tr>
<tr>
<td>6</td>
<td>140596-01</td>
<td>531593-03</td>
<td>1951100-09</td>
<td>386272-03</td>
<td>485572-09</td>
<td>240030-01</td>
</tr>
</tbody>
</table>

### ONE DIMENSIONAL PARTICLE START LINE

<table>
<thead>
<tr>
<th>Radial Co-ordinate</th>
<th>Axial Co-ordinate</th>
<th>Axial Velocity</th>
<th>Radial Velocity</th>
<th>Angle</th>
<th>Enthalpy</th>
<th>Nozzle Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>(FT)</td>
<td>(FT)</td>
<td>(FT/SEC)</td>
<td>(FT/SEC)</td>
<td>(DEG)</td>
<td>(FT²/SEC²)</td>
<td>(FT)</td>
</tr>
<tr>
<td>5</td>
<td>571593-02</td>
<td>375580-09</td>
<td>6211860-02</td>
<td>716958-00</td>
<td>973090-01</td>
<td>210259-01</td>
</tr>
<tr>
<td>2</td>
<td>571593-02</td>
<td>333833-04</td>
<td>867418-02</td>
<td>167610-01</td>
<td>978689-01</td>
<td>20722-01</td>
</tr>
<tr>
<td>1</td>
<td>571593-02</td>
<td>306468-04</td>
<td>158804-03</td>
<td>314037-01</td>
<td>982312-09</td>
<td>97029-01</td>
</tr>
<tr>
<td>4</td>
<td>571593-02</td>
<td>286327-09</td>
<td>213365-03</td>
<td>489777-06</td>
<td>980983-09</td>
<td>210259-01</td>
</tr>
<tr>
<td>6</td>
<td>571593-02</td>
<td>200731-09</td>
<td>296167-03</td>
<td>485572-09</td>
<td>945189-08</td>
<td>240030-01</td>
</tr>
</tbody>
</table>
B.3.2 Description of Program Error Message Output

1. **THE MIXTURE START CONDITION WAS NOT FOUND IN 300 STEPS**

   This statement is printed if the program did not reach the desired startline Mach number after 300 axial stations were stored.

2. **THE GAS PARTICLE FLOW SOLUTION AT X= AND A= WILL NOT CONVERGE**

   This statement is printed if the program was unable to converge on a solution after 100 iterations at a particular axial location. The run is terminated following this message.

3. **PARTICLE SOLUTION WILL NOT CONVERGE AT X=**

   This message is printed if the particle trajectory tracing routine is unable to converge on a solution after 50 iterations at a particular axial station. The run is continued and a startline generated for the last axial station at which the solution converged.

4. **ITSUB WNC**

   This message originates in subroutine ITSUB which provides iteration control for a given function. The message indicates that a solution was not obtained after 100 iterations.

5. **CHAMBER ENTHALPY NOT FOUND IN SUBIN**

   This message originates in subroutine SUBIN and indicates that the routine was unable to find a gas phase thermodynamic table expanded from the input chamber enthalpy.