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CHEMICALLY REACTING ONE-DIMENSIONAL GAS-PARTICLE FLOWS

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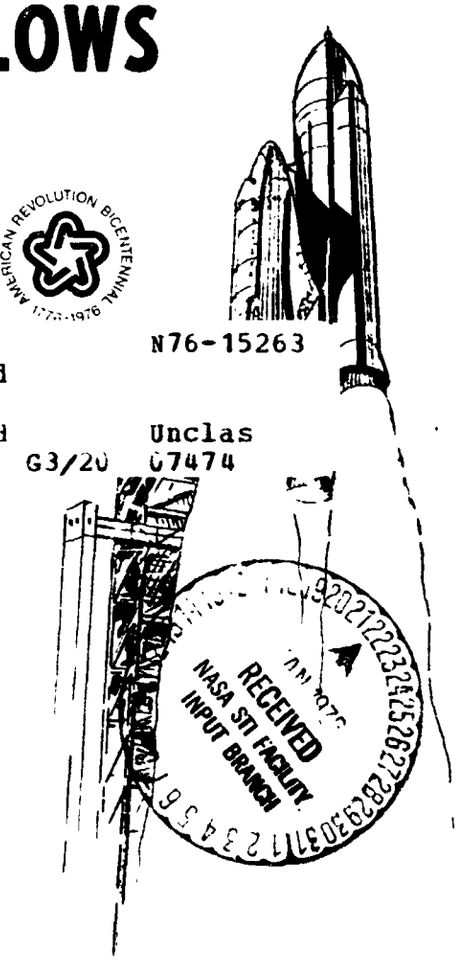

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FOREWORD

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

NOMENCLATURE

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

Symbol	Description
x	axial coordinate
∇	ratio of j^{th} particle mass flow rate to total particle mass flow rate
Greek	
γ	viscosity
ρ	density
Subscripts	
P	particle
m	mixture
g	gas
r	radial component
x	axial component
Superscripts	
j	j^{th} particle
np	number of particles

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 design 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 then 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.
5. 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

$$\rho u \frac{du}{dx} + \sum_{j=1}^{np} \rho^j u^j \frac{du^j}{dx} + \frac{dP}{dx} = 0 \qquad (1)$$

The one-dimensional energy equation for the mixture is given by

$$H = \dot{w}\left[h + \frac{u^2}{2}\right] + \sum_{j=1}^{np} \rho^j u^j A\left[h^j + \frac{u^{j\,2}}{2}\right] \qquad (2)$$

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

$$\dot{w}_m = \rho u A + \sum_{j=1}^{np} \rho^j u^j A \qquad (3)$$

Thermodynamic relations used in the solution of gas phase properties include

$$TdS = dh - \frac{dP}{\rho} \qquad (4)$$

and pressure as a function of density and entropy

$$dP = v^2\, d\rho + \frac{P}{C_P - R}\, dS \qquad (5)$$

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 $C_D/C_{D_{Stokes}}$ 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

$$C_D^j = \left(\frac{C_D}{C_{D_{Stokes}}}\right)^j \frac{Re^j\left[(1+9.45\bar{\tau}^j)(1+2.52\bar{\tau}^j) + 3.03\bar{\tau}^{j2}\right]}{\left[(1+9.45\bar{\tau}^j)(1+3.78\bar{\tau}^j) + (.911)(4. + 11.34\bar{\tau}^j)\right]\bar{\tau}^{j\,2}} \qquad (6)$$

where the parameter, $\bar{c}$, is calculated as follows

$$\bar{c}^{j} = \frac{(u - u_p^{j})}{Re^{j}\sqrt{RT}} \tag{7}$$

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

$$C_{D_{Stokes}}^{j} = \frac{24}{Re^{j}} \tag{8}$$

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

$$a^{j} = 4.5\, \nu^{j} C_D^{j} m_p^{j} r_p^{j2} \tag{9}$$

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

$$du^{j} = \frac{a^{j}(u - u^{j})dx}{u^{j}} \tag{10}$$

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

$$c^{j} = \frac{c_p^{j}(1 + 0.2295\, Re^{j(0.55\, Pr^{j\,0.33})})}{Pr^{j} C_D^{j}} \tag{11}$$

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, ν, as a function of gas velocity. Change in particle enthalpy with respect to change in axial coordinate is calculated by

$$dh^j = -\frac{2}{3}\,\frac{a^j c^j \Delta T^j\, dx}{u^j} \qquad (12)$$

where the thermal lag, ΔT^j is defined by

$$\Delta T^j = T_p^{\,j} - T \qquad (13)$$

As can be observed, the particle size, r_p^j, enters the calculation of both du^j and dh^j 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 specie 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

$$dP = v^2 d\rho + \frac{P}{c_p - R} dS \tag{14}$$

Solving for dS, Eq. (14) becomes

$$dS = \frac{c_p - R}{P} (dP - v^2 d\rho)$$

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

$$TdS = \frac{1}{\rho R} (c_p - R) (dP - v^2 d\rho)$$

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

$$dh - \frac{dP}{\rho} = \frac{1}{\rho R} (c_p - R) (dP - v^2 d\rho)$$

Dividing through by dx and rearranging terms the expression becomes

$$\frac{dh}{dx} - \frac{dP}{\rho dx} = \frac{1}{\rho R} (c_p - R) \left(\frac{dP}{dx} - v^2 \frac{d\rho}{dx}\right) \tag{15}$$

The energy equation for a gas-particle mixture is

$$H = \left(h + \frac{u^2}{2}\right) + \frac{\dot{w}^j}{\dot{w}} \left(h^j + \frac{u^{j2}}{2}\right) \tag{16}$$

Differentiating and dividing through by dx, the energy equation becomes

$$\frac{dh}{dx} + u\frac{du}{dx} + \frac{\dot{w}^j}{\dot{w}}\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx}\right) = 0 \qquad (17)$$

The momentum equation for a gas-particle mixture is

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

Rearranging terms, the momentum equation becomes

$$u\frac{du}{dx} = -\frac{1}{\rho}\frac{dP}{dx} - \frac{\rho^j}{\rho}u^j\frac{du^j}{dx} \qquad (19)$$

The ratio of particle to gas mass flow is written

$$\frac{\rho^j u^j A}{\rho u A} \qquad \frac{\dot{w}^j}{\dot{w}}$$

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

$$\frac{\rho^j}{\rho} = \frac{u}{u^j}\frac{\dot{w}^j}{\dot{w}} \qquad (20)$$

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

$$u\frac{du}{dx} = -\frac{1}{\rho}\frac{dP}{dx} - \frac{u}{u^j}\frac{\dot{w}^j}{\dot{w}}u^j\frac{du^j}{dx} \qquad (21)$$

Simplifying momentum Eq. (21) and substituting Eq. (21) in Eq. (17), the energy equation becomes

$$\frac{dh}{dx} - \frac{1}{\rho}\frac{dP}{dx} - \frac{\dot{w}^j}{\dot{w}} u \frac{du^j}{dx} + \frac{\dot{w}^j}{\dot{w}}\left(\frac{dh^j}{dx} + u^j \frac{du^j}{dx}\right) = 0 \qquad (22)$$

Collecting terms and simplifying, the equation is written

$$\frac{dh}{dx} - \frac{1}{\rho}\frac{dP}{dx} + \frac{\dot{w}^j}{\dot{w}}\left(\frac{dh^j}{dx} + u^j \frac{du^j}{dx} - u \frac{du^j}{dx}\right) = 0 \qquad (23)$$

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

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

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

$$\frac{1}{\rho}\frac{dP}{dx} - \frac{v^2 d\rho}{\rho dx} + \left(\frac{R}{c_p - R}\right)\frac{\dot{w}^j}{\dot{w}}\left(\frac{dh^j}{dx} + u^j \frac{du^j}{dx} - u \frac{du^j}{dx}\right) = 0 \qquad (24)$$

Introduce the conservation of mass relationship for the gas

$$\rho u A = \dot{w}$$

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

$$\frac{1}{\rho}\frac{d\rho}{dx} = -\left(\frac{1}{u}\frac{du}{dx} + \frac{1}{A}\frac{dA}{dx}\right) \qquad (25)$$

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

$$\frac{1}{\rho}\frac{dP}{dx} - v^2\left(-\frac{1}{u}\frac{du}{dx} - \frac{1}{A}\frac{dA}{dx}\right) + \left(\frac{R}{c_p - R}\right)\left(\frac{\dot{w}^j}{\dot{w}}\right)\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx} - u\frac{du^j}{dx}\right) = 0$$

Solving for $dP/\rho dx$, the expression is

$$\frac{1}{\rho}\frac{dP}{dx} = -\frac{v^2}{u}\frac{du}{dx} - \frac{v^2}{A}\frac{dA}{dx} - \left(\frac{R}{c_p - R}\right)\left(\frac{\dot{w}^j}{\dot{w}}\right)\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx} - u\frac{du^j}{dx}\right) \qquad (26)$$

From Eq. (21) the expression for $dP/\rho dx$ is substituted in Eq. (26)

$$-u\frac{du}{dx} - \frac{u}{u^j}\frac{\dot{w}^j}{\dot{w}}u^j\frac{du^j}{dx} = -\frac{v^2}{u}\frac{du}{dx} - \frac{v^2}{A}\frac{dA}{dx} - \left(\frac{R}{c_p - R}\right)\left(\frac{\dot{w}^j}{\dot{w}}\right)\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx} - u\frac{du^j}{dx}\right)$$

Collecting terms and rearranging, the relationship is

$$u\frac{du}{dx} - \frac{v^2}{u^2}u\frac{du}{dx} - \frac{v^2u^2}{Au^2}\frac{dA}{dx} - \frac{\dot{w}^j}{\dot{w}}\left[\left(\frac{R}{c_p - R}\right)\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx} - u\frac{du^j}{dx}\right) - u\frac{du^j}{dx}\right] = 0$$

Substitutions are made using the definition of Mach number, $M = u/v$

$$u\frac{du}{dx}\left(1 - \frac{1}{M^2}\right) - \frac{u^2}{AM^2}\frac{dA}{dx} - \frac{\dot{w}^j}{\dot{w}}\left[\left(\frac{R}{c_p - R}\right)\left(\frac{dh^j}{dx} + u^j\frac{du^j}{dx} - u\frac{du^j}{dx}\right) - u\frac{du^j}{dx}\right] = 0$$

Substituting the basic relations for changes in particle velocity, du^j, the relationship is written

$$u\frac{du}{dx}\left(\frac{M^2 - 1}{M^2}\right) - \frac{u^2}{AM^2}\frac{dA}{dx} - \frac{\dot{w}^j}{\dot{w}}\left[\left(\frac{R}{c_p - R}\right)\left(-\frac{2}{3}a^jc^j\frac{(T^j - \cdot)}{u^{\cdot}} + u^ja^j\frac{(u - u^j)}{u^j}\right.\right.$$

$$\left.\left. - u\,a^j\frac{(u - u^j)}{u^j}\right) - u\,a^j\frac{(u - u^j)}{u^j}\right] \qquad (27)$$

Define a parameter, B^j,

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

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

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

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

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

Solving for du,

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

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

$$\rho u du + \rho \cdot u^j du^j + dP = 0$$

Multiplying through by A, the momentum equation is

$$\rho u A du + A\rho^j u^j du^j + A dP = 0 \qquad (29)$$

Multiply differentials of the conservation of mass equations for the gas and particle phases by u and u^j respectively

$$ud(\rho uA) = 0 \tag{30}$$

$$u^j d(\rho^j u^j A) = 0 \tag{31}$$

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

$$\rho uAdu + ud(\rho uA) + \rho^j u^j Adu^j + u^j d(\rho^j u^j A) + AdP = 0$$

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

$$\rho uAdu + u^2 Ad\rho + \rho uAdu + \rho u^2 dA + \rho^j u^j Adu^j + u^{j2} Ad\rho^j + \rho^j u^j Adu^j + \rho^j u^{j2} dA + AdP = 0$$

Rearranging and collecting terms the expression is

$$2\rho uAdu + u^2 Ad\rho + \rho u^2 dA + 2\rho^j u^j Adu^j + u^{j2} Ad\rho + u^{j2} \rho^j dA + AdP = 0 \tag{32}$$

The differential of the product PA is written

$$d(PA) = PdA + AdP$$

Solving this expression for AdP, the relation is written

$$AdP = d(PA) - PdA \tag{33}$$

The differential of $\rho u^2 A$ is written

$$d(\rho u^2 A) = u^2 A d\rho + 2\rho u A du + \rho u^2 dA \tag{34}$$

and the differential of $\rho^j u^{j2} A$ is written

$$d(\rho^j u^{j2} A) = u^{j2} A d\rho + 2\rho^j u^j A du^j + \rho^j u^{j2} dA \tag{35}$$

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

$$d(\rho u^2 A) + d(\rho^j u^{j2} A) + d(PA) - PdA = 0$$

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

$$d(\rho u^2 A) + d\frac{(u\rho \dot{w}^j u^{j2} A)}{u^j \dot{w}} + d(PA) - PdA = 0 \tag{36}$$

Using the relationship, $\sum_{j=1}^{np} \dot{w}^j / \dot{w} = X$ and $\dot{w}^j / \sum_{j=1}^{np} \dot{w}^j = \nabla^j$ Eq. (36) becomes

$$d(\rho u^2 A) + X \sum_{j=1}^{np} \nabla^j (\rho u^{j2} A) + d(PA) - PdA = 0$$

The equation used to calculate gas pressure is then written

$$d(PA) = PdA - d(\rho u^2 A) - X \sum_{j=1}^{np} \nabla^j (\rho u u^j A) \tag{37}$$

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

$$dh = TdS + \frac{dP}{\rho} \tag{41}$$

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

$$H = h + \frac{u^2}{2} \tag{42}$$

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

$$dr^j = dx^j \frac{u^j_r}{u^j_x} \tag{43}$$

A change in particle axial velocity as a function of x is given by

$$du_x^j = dx^j a^j \frac{(u_x - u_x^j)}{u_x} \tag{44}$$

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

$$du_r^j = dx^j a^j \frac{(u_r - u_r^j)}{u_x^j} \tag{45}$$

Change in particle enthalpy is given by

$$dh^j = dx^j \left[-\frac{2}{3} a^j c^j \frac{(T^j - T)}{u^j} \right] \tag{46}$$

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.

Section 3
CONCLUDING REMARKS

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

1. Penny, M. M., S. D. Smith, P. G. Anderson, P. R. Sulyma and M. L. Pearson, "Supersonic Flow of Chemically Reacting Gas-Particle Mixtures – Vol. I – A Theoretical Analysis and Development of the Numeric Solution," LMSC-HREC TM D496555-I, Lockheed Missiles & Space Company, Huntsville, Ala. (to be published January 1976).

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8. Svekla, 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.

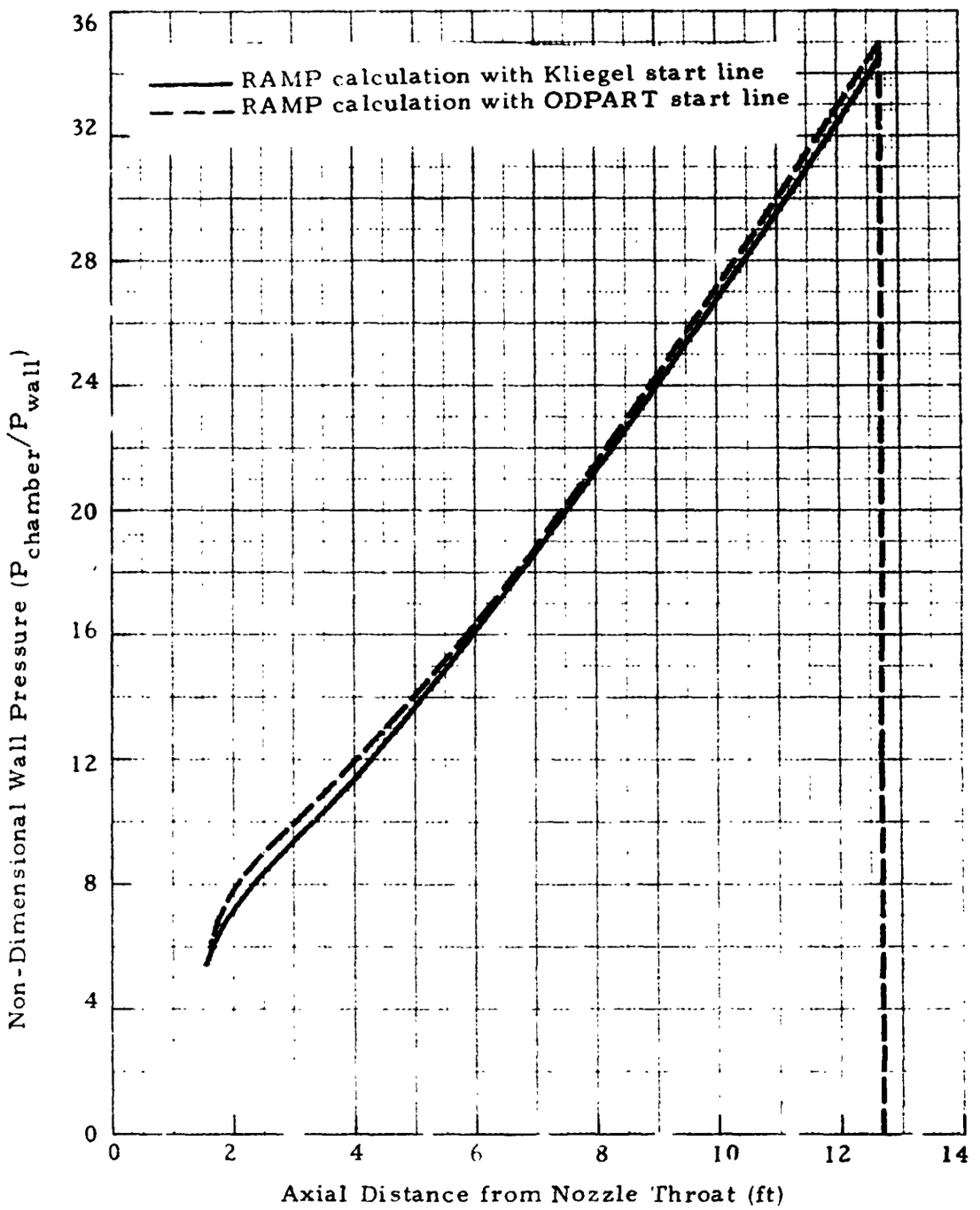

Fig. 1 - Non-Dimensional Nozzle Wall Pressure Distributions for Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry

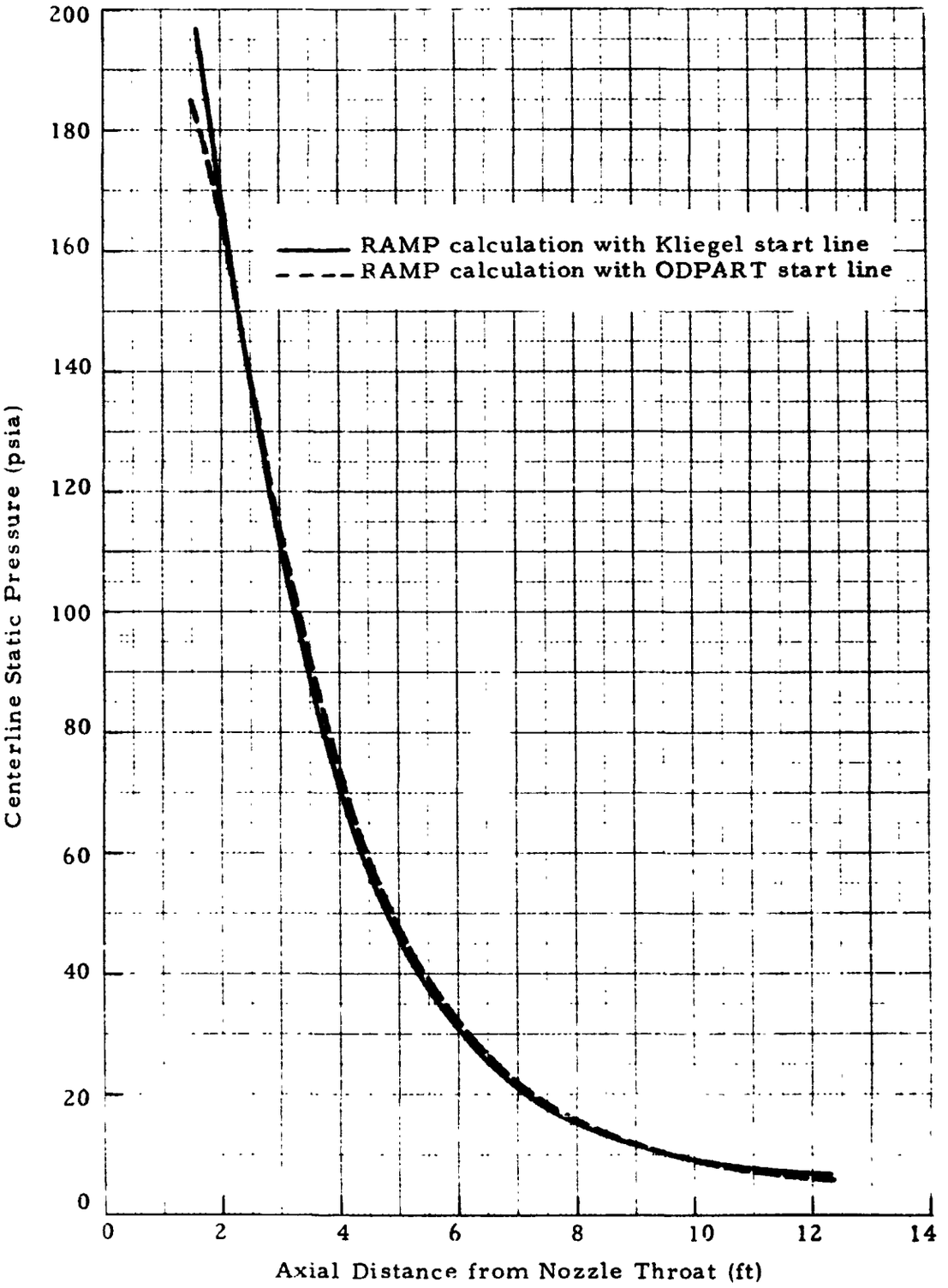

Fig. 2 - Centerline Static Pressure Distributions for Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry

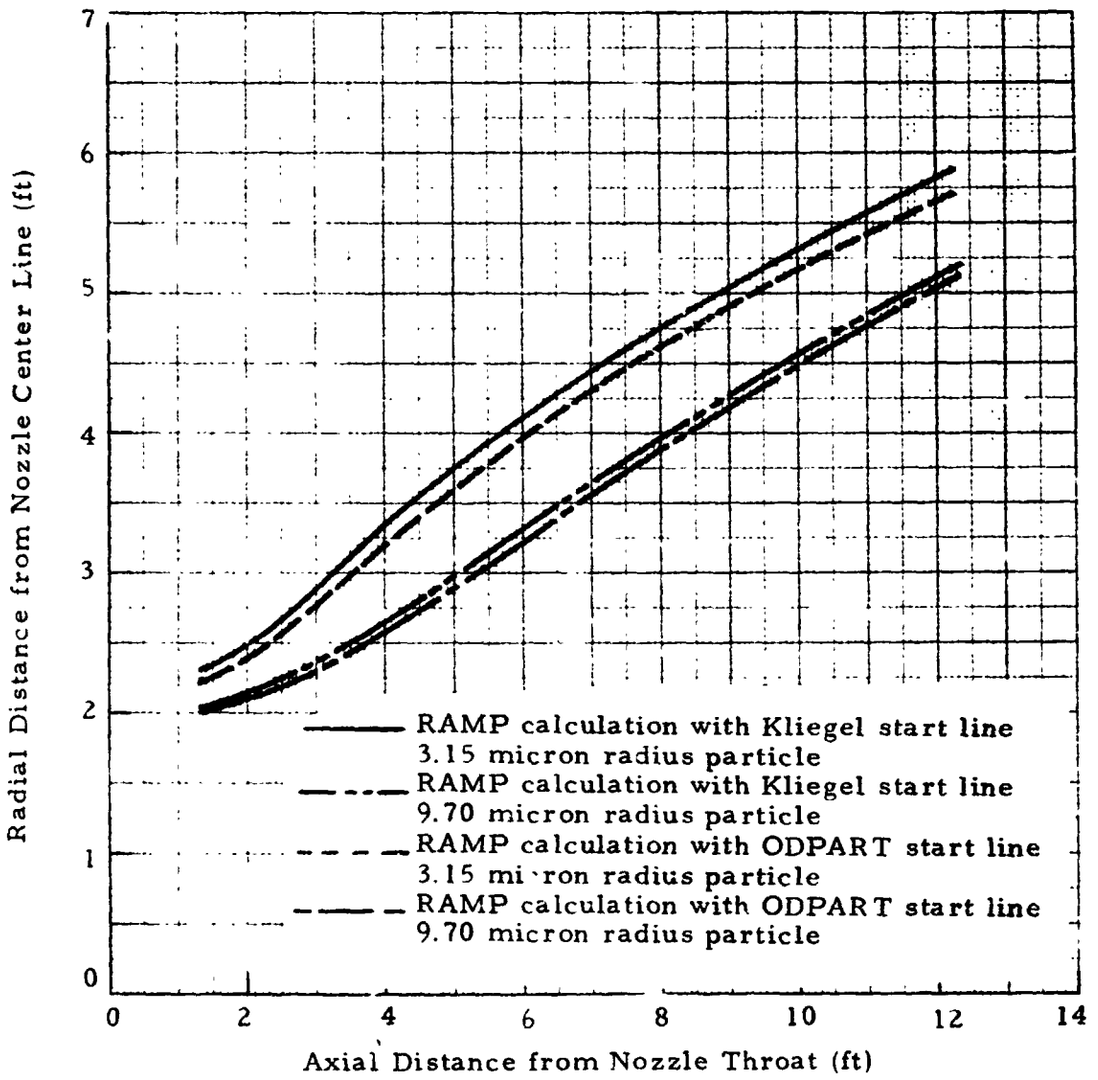

Fig. 3 - Particle Limiting Streamlines for Particles of Radii 3.15 and 9.70 Microns, Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry

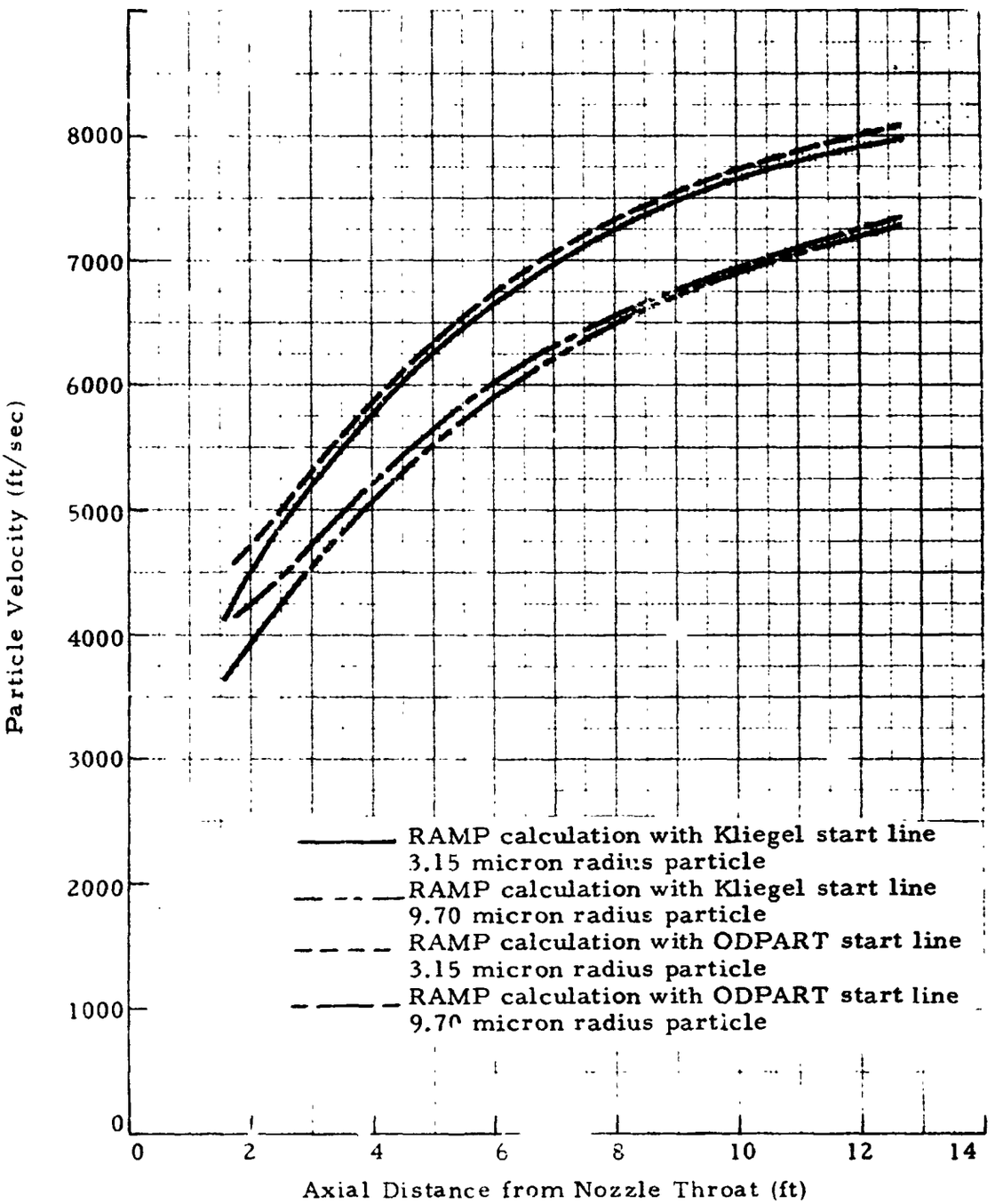

Fig. 4 - Particle Velocity as a Function of Axial Distance Along the Nozzle Center Line for Particle Radii of 3.15 and 9.70 Microns, Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry

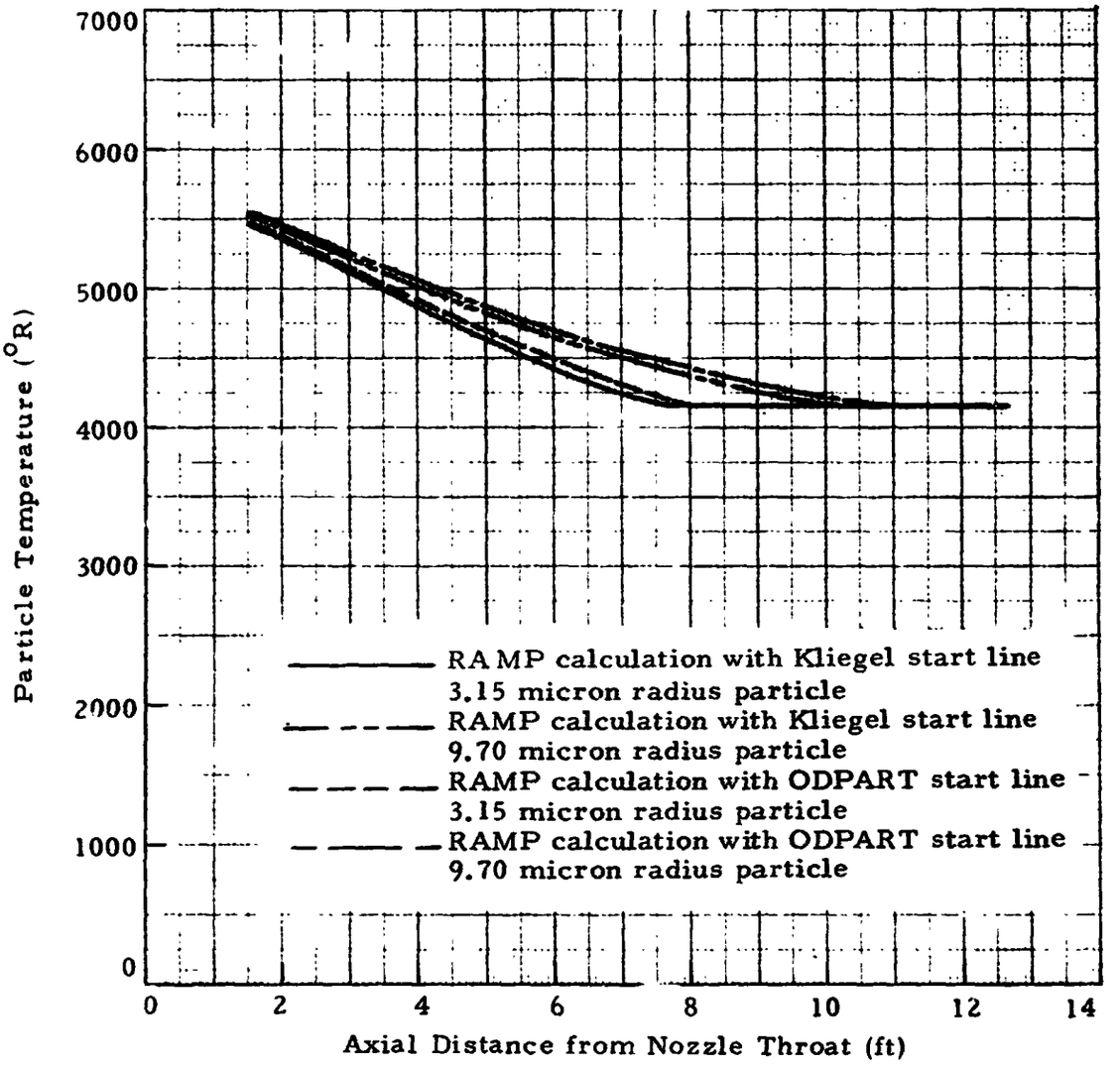

Fig. 5 - Particle Temperature as a Function of Axial Distance Along the Nozzle Center Line for Particle Radii of 3.15 and 9.70 Microns, Real Gas Thermodynamics, a $P_{chamber}$ of 500 psia and SRM Nozzle Geometry

Appendix A

DIFFERENCE EQUATIONS FOR CALCULATING THE FLOW OF A ONE-DIMENSIONAL GAS-PARTICLE MIXTURE

Appendix A

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:

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

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:

$$\Delta S = \frac{1}{T} \left(\Delta h - \frac{\Delta P}{\rho} \right)$$

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:

$$\Delta r^j = \frac{\Delta x^j u_r^j}{u_x^j}$$

$$\Delta u_x^j = \frac{\Delta x^j a^j (u_x - u_x^j)}{u_x^j}$$

$$\Delta u_r^j = \frac{\Delta x^j a^j (u_r - u_r^j)}{u_x^j}$$

$$\Delta h^j = \Delta x^j \left[-\frac{2}{3} \frac{a^j c^j (T^j - T)}{u^j} \right]$$

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 themodynamic 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 thermodyanmic 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 polynominal 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 charcteristics 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

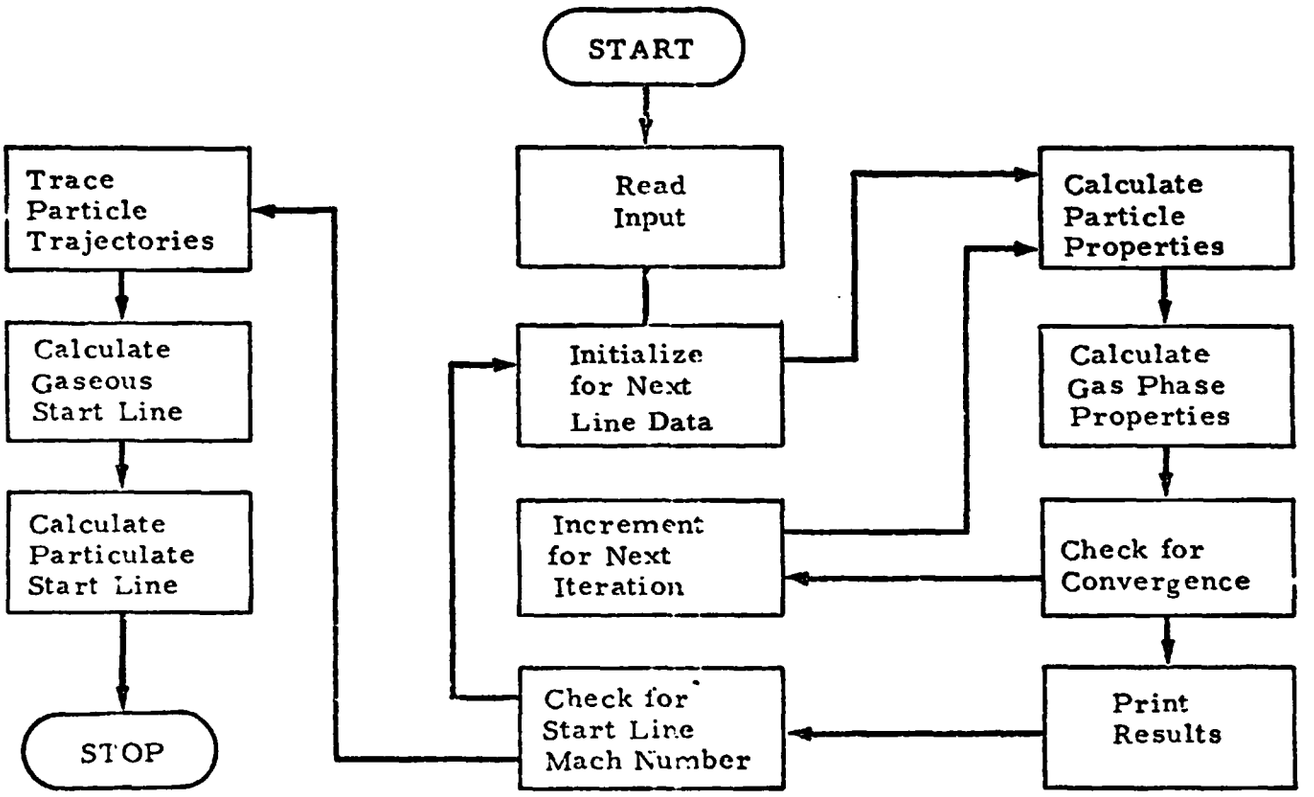

Fig. B-1 - Schematic of One-Dimensional Gas-Particle Solution

B.2.1 Detailed Guide for Input Data

Card 1 - Program control flags — Format: 16I5

Column	Parameter	Description
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
16-20	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 — Format: 16I5

1-5	ISPECS	Number of particle species (maximum of 6)
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)

Column	Parameter	Description
11-15	IDEL	Interval at which properties of data surfaces are printed
16-20	ISAV	Interval at which properties of data surfaces are stored for use in particle limiting streamline calculations

Card 3 - Initial conditions and problem limits Format: 7E10.6

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

Card 4 - Gas-particle equilibrium thermodynamic table (only one table required) Format: I5, 5X, E10.6, A3

1-5	IVEQ	Number of Mach numbers in the gas-particle equilibrium thermo table
11-20	HC	Chamber enthalpy
21-30	UNITS	ENG Input gas data with English units MKS Input gas data with Metric units

Card 4 - Gas-particle equilibrium thermodynamic data (repeat Card 4 IVEQ times in order of increasing Mach number) Format: BE10.6

1-10	EQUIL(J, 1)	Gas-particle equilibrium Mach number
11-20	EQUIL(J, 2)	Gas-particle equilibrium molecular weight

Card 4 - (Con't)

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

Card 5 - Control flags for gas phase thermodynamic tables Format: 2I5

1-5	IHC	Number of enthalpy tables (maximum of 10)
6-10	ISA	Number of entropy cuts for each enthalpy table (maximum of 2)

Card 6 - Total enthalpy of table Format: E10.6

1-10	DELHC(M)	Enthalpy from which gas was expanded

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

1-10	STAB(M, I)	Entropy at which gas was expanded
19-20	IVTAB(M, I)	Number of Mach numbers in thermodynamic table

Card 8 - Gas phase thermodynamic data

1-10	GAS(J, 1)	Gas phase Mach number
11-20	GAS(J, 2)	Gas phase molecular weight
21-30	GAS(J, 3)	Gas phase ratio of specific heats

Card 8 - (Con't)

Column	Parameter	Description
31-40	DUM	Not currently used
41-50	DUM	Not currently used
51-60	GAS(J, 4)	Gas phase Prandtl number
61-70	GAS(J, 5)	Gas phase viscosity
71-80	GAS(J, 6)	Gas phase C_p

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 — Format: I1, 3X, I1, 5X, 6E10.6

1	IWALL(K, 2)	1 Conic Equation $R = A[(B + CX + DX^2)^{1/2} + E]$ 2 Polynomial Equation $R = AX^4 + BX^3 + CX^2 + DX + E$
5	ITRAN (K, 2)	Not presently used
11-20	WALLCO (K, 1, 2)	Coefficient A
21-30	WALLCO (K, 2, 2)	Coefficient B
31-40	WALLCO (K, 3, 2)	Coefficient C
41-50	WALLCO (K, 4, 2)	Coefficient D
51-60	WALLCO (K, 5, 2)	Coefficient E
61-70	WALLCO (K, 6, 2)	Maximum value of X applicable to equation

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

Card 10

Column	Parameter	Description
1-10	XMASSP	Ratio of particle total mass flowrate to gas mass flowrate

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
•	•	•
•	•	•
•	•	•
	PERTG (ISPECS)	

Card 12 — Radius of each particle — Format: 6E10.6

1-10	PSP(2, 1)	Radius of particle 1, microns
•	•	•
•	•	•
•	•	•
	PSP(2, 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
•	•	•
•	•	•
•	•	•
	PSP(1, 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 ($C_D/C_{D\ Stokes}$)

Card 14 – (Con't)

Column	Parameter	Description
21-30	AREY(2)	
31-40	BREY(2)	
•	•	
•	•	
•	•	

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

Card 15 – Particle data control variables Format: 4A6, I3, A6

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 Format: 10I2

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

Card 17 – Number data points in particle thermodynamic table Format: I3

1-3	NPTM(I)	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

Column	Parameter	Description
1-10	TM(I)	Melting point temperature of particle I
11-20	H_S(I)	Enthalpy of solid phase of particle I at melting point temperature
21-30	HM(I)	Enthalpy of liquid phase of particle I at melting point temperature

If NPTM (I) = 1, use the following format

31-40	APHO(1, 1, I)	Heat capacity of liquid phase of particle I (Btu/lbm-^{o}R or cal/gm-^{o}K)
41-50	APHO(1, 2, I)	Heat capacity of solid phase of particle 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 I (^{o}R or ^{o}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 (^{o}R or ^{o}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, . . . NPTM(I).

B.2.2 Input FORTRAN Symbols

Symbol	Description	Units
ICON(1)	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.	N/A
ICON(2)	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.	N/A

Symbol	Description	Units
ICON(3)	ICON(3) is the number of start line points to be generated. A maximum of 50 is permitted.	N/A
ICON(4)	ICON(4) is the number of upper boundary equations defining the nozzle geometry.	N/A
ICON(9)	ICON(9) specifies the units to be used. If ICON(9) = 0, English units are used. If ICON(9) = 1, Mks units are used.	N/A
ICON(10)	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.	N/A
ISPECS	Number of particle species to be input. A maximum of 10 is permitted.	N/A
IDRAG	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.	N/A
IDEL	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.	N/A
ISAV	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.	N/A
XM1	Axial coordinate of nozzle throat	in or ft
XI	Axial coordinate of initial data surface	in or ft
DX	Integration step between successive data surface calculations	in or ft
DXJ	Radius of the nozzle throat	in or ft
UG	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.	ft/sec
UP	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.	ft/sec

Symbol	Description	Units
XSTART	XSTART is the axial location of the initial data surface if internal calculation of initial gas and particle velocities is desired.	in or ft
EMOUT	This is the Mach number at which the integration of the gas-particle equations is to stop and a start line calculated and punched.	N/A
IVEQ	This flag designates the number of Mach number entries in the gas-particle equilibrium thermodynamic table. A maximum of 13 is permitted.	N/A
HC	This is the chamber enthalpy in units consistent with the thermodynamic tables.	ft^2/sec^2 or M^2/sec^2
EQUIL(J, 1)	Mach number entry in the gas-particle equilibrium thermodynamic table.	N/A
EQUIL(J, 2)	Molecular weight entry in the gas-particle equilibrium thermodynamic table	lbm./lbm. mole or gm./gm. mole
EQUIL(J, 3)	Ratio of specific heats entry in the gas-particle equilibrium thermodynamic table	N/A
EQUIL(J, 4)	Temperature entry in the gas-particle equilibrium thermodynamic table	^oR or ^oK
EQUIL(J, 5)	Pressure entry in the gas-particle equilibrium thermodynamic table	atm.
EQUIL(J, 6)	Prandtl number entry in the gas-particle equilibrium thermodynamic table	N/A
EQUIL(J, 7)	Viscosity entry in the gas-particle equilibrium thermodynamic table	$\frac{lbf.\ sec}{ft^2}$ or $\frac{Kg.\ m}{sec}$
EQUIL(J, 8)	Gas specific heat at constant pressure entry in the gas-particle equilibrium thermodynamic table	$\frac{ft^2}{sec^2 .\ ^oR}$
IHC	Number of enthalpy tables in the gas phase thermodynamic data A maximum of 10 is permitted.	N/A
ISA	Number of entropy cuts for each enthalpy table. A maximum of 2 is permitted.	N/A

Symbol	Description	Units
DELHC(M)	This variable is the total enthalpy from which the gas was expanded.	Btu/lbm or cal/gm
STAB(M, I)	This variable is the entropy at which the gas was expanded	Btu/lbm - ^{o}R or cal/gm - ^{o}K
IVTAB(M, I)	This flag designates the number of Mach number entries in the gas phase thermodynamic table. A maximum of 13 is permitted.	N/A
GAS(J, 1)	Mach number entry in the gas phase thermodynamic table.	N/A
GAS(J, 2)	Molecular weight entry in the gas phase thermodynamic table	lbm/lbm. mole or gm/gm. mole
GAS(J, 3)	Ratio of specific heats in the gas phase thermodynamic table.	N/A
GAS(J, 7)	Temperature entry in the gas phase thermodynamic table.	^{o}R or ^{o}K
GAS(J, 4)	Prandtl number entry in the gas phase thermodynamic table.	N/A
GAS(J, 5)	Viscosity entry in the gas phase thermodynamic table.	$\frac{lbf.\ sec}{ft^2}$ or $\frac{kg.\ M}{sec}$
GAS(J, 6)	Gas specific heat at constant pressure entry in the gas phase thermodynamic table. For ideal gas thermodynamics it is the non-dimensional temperature exponent.	$\frac{ft^2\ ft^2}{sec^2 - {}^{o}R}$ or $\frac{M^2}{sec^2 - {}^{o}K}$
IWAL(K, 2)	This flag designates the type of equation defining the nozzle geometry. If IWALL(K, 2) = 1, a conic equation of the form, $R = A[(B + CX + DX^2)^{1/2} + E]$ is input. If IWALL(K, 2) = 2, a polynomial equation of the form, $R = AX^4 + BX^3 + CX^2 + DX + E$ is input.	N/A

Symbol	Description	Units
ITRAN(K, 2)	Not presently used.	N/A
WALLCO(K,1,2)	This variable corresponds to the coefficient A in the conic or polynomial nozzle equations.	Equation coefficients in the WALLCO array should be developed in units consistent with ICON ICON(10)
WALLCO(K, 2, 2)	This variable corresponds to the coefficient B in the conic or polynomial nozzle equations.	
WALLCO(K, 3, 2)	This variable corresponds to the coefficient C in the conic or polynomial nozzle equations.	———
WALLCO(K, 4, 2)	This variable corresponds to the coefficient D in the conic or polynomial nozzle equations.	———
WALLCO(K, 5, 2)	This variable corresponds to the coefficient E in the conic or polynomial nozzle equations.	———
WALLCO(K, 6, 2)	Maximum axial coordinate for which a particular nozzle equation is applicable.	———
XMASSP	XMASSP is the ratio of total particle mass flow rate to gas mass flow rate	N/A
PERTG(J)	This is the ratio of the Jth particle mass flow rate to total particle mass flow rate	N/A
PSP(2, J)	PSP(2, J) is the radius of the Jth particle	Microns
PSP(1, J)	PSP(1, J) is the mass density of the Jth particle	lbm/ft^3 or gm/cm^3
ALPHA	ALPHA is the particle specie name is used for printout purposes.	N/A
NOCUTS	Not presently used	N/A
UNIT	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.	N/A
JTEM(J)	JTEM(J) specifies the temperature-enthalpy table to be used for the Jth particle	N/A
NPTM(J)	Number of entries in temperature-enthalpy table for a particular particle. If NPTM(J) = 1, input the liquid and solid heat capacities.	N/A

Symbol	Description	Units
TM(J)	Melting point temperature of Jth particle	^{o}R or ^{o}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.	see 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(z, 1, J)	Second temperature entry in the Jth particle temperature-enthalpy table if NPTM(J) > 1.	^{o}R or ^{o}K
APH(z, z, 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 B-32) which correspond to numbered comments listed below.

1		Program title
2		Control flags input by user
3	THROAT X COORDINATE	Axial coordinate of nozzle throat, ft or in

4	AXIAL COORDINATE AT THE THROAT ENTRANCE	Axial coordinate of nozzle inlet, ft or in
5	DELTA X	Axial integration step, ft or in
6	R^*	Nozzle throat radius, ft or in
7	MIXTURE VELOCITY AT	Velocity at nozzle inlet input by user, ft/sec
8	CHAMBER ENTHALPY	Chamber enthalpy for which gas-particle thermodynamics were calculated, ft^2/sec^2 or M^2/sec^2
9	VELOCITY	Velocity for which gas-particle thermodynamics were calculated, ft/sec
10	R	Gas constant, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
11	GAMMA	Ratio of specific heats
12	TEMPERATURE	Static temperature, ^oR or ^oK
13	PRESSURE	Static pressure, psfa
14	PRANDTL NUMBER	Prandtl number
15	VISCOSITY	Viscosity, poise
16	CP	Specific heat at constant pressure, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
17	ENTHALPY	Chamber enthalpy for which gas phase thermodynamics were calculated, ft^2/sec^2 or M^2/sec^2
18	ENTROPY	Chamber entropy for which gas phase thermodynamics were calculated, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
19	VELOCITY	Velocity for which gas-particle thermodynamics were calculated.
20	R	Gas constant, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
21	GAMMA	Ratio of specific heats
22	PRANDTL NUMBER	Prandtl number
23	VISCOSITY	Viscosity, poise
24	EXPONENT	Viscosity exponent
25	TYPE	Type of nozzle boundary equation

26	ITRANS	Gas dynamic condition existing at the end of the current nozzle boundary equations (not currently used)
27	A	Nozzle boundary equation coefficient
28	B	Nozzle boundary equation coefficient
29	C	Nozzle boundary equation coefficient
30	D	Nozzle boundary equation coefficient
31	E	Nozzle boundary equation coefficient
32	MAX	Maximum axial coordinate for which nozzle boundary equation is appicable
33	TOTAL PARTICLE WEIGHT RELATIVE TO THE GAS IS	Ratio of total particle mass flow rate to gas mass flow rate
34	I	Particle number
35	RADIUS	Particle radius, microns
36	PERCENT	Ratio of Jth particle mass flow rate to total particle mass flow rate
37	DENSITY	Particle mass density, lbm/ft^3
38	VELOCITY	Particle velocity at first axial station, ft/sec
39	TMELT	Melting temperature of particle species, ^oR or ^oK
40	HSOLID	Enthalpy of solid particle at melting temperature, ft^2/sec^2 or M^2/sec^2
41	HLIQUID	Enthalpy of liquid particle at melting temperature, ft^2/sec^2 or M^2/sec^2
42	CPMELT	Heat capacity of liquid particle at melting temperature, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
43	CPSOLID	Heat capacity of solid particle at melting temperature, $ft^2/sec^2 - {}^oR$ or $M^2/sec^2 - {}^oK$
44	I	Point number
45	RE	Reynolds number
46	DRAG COEF	Drag Coefficient ($C_D/C_{D_{Stokes}}$)

47	AXIAL STATION X	Axial coordinate of data line, ft or in
48	AREA RATIO A/A^*	Area ratio at the axial location of the data line
49	VELOCITY	Gas velocity, ft/sec
50	R	Gas constant, $ft^2/sec^2 - {}^oR$
51	ENTHALPY	Gas static enthalpy, ft^2/sec^2
52	GAMMA	Ratio of specific heats
53	TEMPERATURE	Gas static temperature, ^oR
54	PRANDTL NUMBER	Prandtl number
55	MACH NUMBER	Mach number
56	VISCOSITY	Viscosity, poise
57	PRESSURE	Gas static pressure, psia
58	CP	Specific heat at constant pressure, $ft^2/sec^2 - {}^oR$
59	DENSITY	Gas density, $slugs/ft^3$
60	TOTAL ENTHALPY	Gas total enthalpy, ft^2/sec^2
61	ENTROPY	Entropy, $ft^2/sec^2 - {}^oR$
62	PARTICLE	Particle number
63	VELOCITY	Particle velocity, ft/sec
64	ENTHALPY	Particle enthalpy, ft^2/sec^2
65	TEMPERATURE	Particle temperature, ^oR
66	MIXTURE MASS FLOW	Percent change in mass flow from the initial data line to the calculated start line
67	GAS MOMENTUM	Percent change in gas momentum from the initial data line to the calculated start line
68	PARTICLE MOMENTUM	Percent change in particle momentum from the initial data line to the calculated start line
69	MIXTURE MOMENTUM	Percent change in mixture momentum from the initial data line to the calculated start line

70	TOTAL ENTHALPY	Percent change in total enthalpy from the initial data line to the calculated start line
71	FXG	Integral of force parallel to the nozzle centerline due to the gas, lbf
72	FXP	Integral of force parallel to the nozzle centerline due to the particles, lbf
73	FXM	Total integral of force parallel to the nozzle centerline, lbf
74	ISP	One-dimensional ISP, sec
75	_	Particle number
76	RADIAL COORDINATE	Radial distance from nozzle centerline, ft
77	AXIAL COORDINATE	Axial location, ft
78	AXIAL VELOCITY	Particle axial velocity, ft/sec
79	RADIAL VELOCITY	Particle radial velocity, ft/sec
80	ANGLE	Angle from the horizontal of the particle trajectory, degrees
81	ENTHALPY	Particle enthalpy, ft^2/sec^2
82	NOZZLE RADIUS	Nozzle radius, ft
83	_	Particle number
84	RADIAL COORDINATE	Radial coordinate of particle limiting streamline intersection with calculated start line, ft
85	AXIAL COORDINATE	Axial coordinate of particle limiting streamline intersection with calculated start line, ft
86	AXIAL VELOCITY	Particle axial velocity at intersection of particle limiting streamline with calculated start line, ft/sec
87	RADIAL VELOCITY	Particle radial velocity at intersection of particle limiting streamline with calculated start line, ft/sec
88	ANGLE	Angle from the horizontal of the particle trajectory at intersection of particle limiting streamline with calculated start line, degrees
89	ENTHALPY	Particle enthalpy at intersection of particle limiting streamline with calculated start line, ft^2/sec^2

90	NOZZLE RADIUS	Nozzle radius, ft
91	R	Radial coordinate of start line point, ft
92	X	Axial coordinate of start line point, ft
93	MACH NUMBER	Mach number at start line point
94	THETA	Gas flow angle at start line point, degrees
95	ENTROPY	Entropy at start line point, $ft^2/sec^2 - {}^oR$
96	MACH ANGLE	Mach angle at start line point, degrees
97	TOTAL ENTHALPY	Total enthalpy at start line point, ft^2/sec^2
98	PARTICLE	Particle number
99	I	Start line point number
100	AXIAL VELOCITY	Particle axial velocity at start line point, ft/sec
101	RADIAL VELOCITY	Particle radial velocity at start line point, ft/sec
102	THETA	Angle from the horizontal of the particle trajectory at the start line point, degrees
103	ENTHALPY	Particle enthalpy at the start line point, ft^2/sec^2
104	DENSITY	Particle denisty at the start line point, lbm/ft^3

Note: These cards were input to a Univac 1108 multiprocessor system to generate the sample output which follows.

```
*RUN
*ASG,T  ONED,T,29794
*REWIND ONED
*ASG,N
*COPIN ONED,TAPE5,,
*FREE ONED
*XQT A
                21      5     0          1     1
     6     0  200      5
  .0         -1.567     0.0012     0.25       0.0000     0.0        -1.567     1.100
     1       81.0       MKS
   .0000       .2517+02   .1173+01   .3072+04   .6805+02   .3837+00   .8698-03   .6568+00
     1     1
81.0
  .0                    1
   .0000       .2050+02   .1208+01   .3072+04   .6805+02   .3837+00   .8698-03   .6568+00
2    0       0.0        0.0        0.0        -0.577350  0.0995303  -0.500
1    0       -1.0       1.0        0.0        -1.0       -1.250     0.258819
2    1       0.0        0.0        0.0        0.267949   0.2145097  1.8360
  .2275
  .1         0.2        0.2        0.2        0.2        0.1
  .4         0.8        1.125      1.500      2.15       3.5
250.0       250.0      250.00     250.0      250.0      250.0
ALPHA                          .ENG
  1  0  0  2  0  0  0  0  0  0
   !
4170.0      1112.8     1612.1     0.3395     0.2676
*FIN
*FIN
```

(2) RUN CONTROL PARAMETERS

ICON(1)	ICON(2)	ICON(3)	ICON(4)	ICON(9)	ICON(10)	ICON(11)	ICON(12)
0	0	21	3	0	0	1	1

ISPECS	IDRAG	IDEL	ISAV
6	0	200	5

INPUT DATA FOR SUBSONIC GAS-PARTICLE CALCULATIONS

(3) THROAT X COORDINATE .00000 (4) AXIAL COORDINATE AT THE THROAT ENTRANCE= -.15670+01

(5) DELTA X= .12000-02 R= .25000+00 MIXTURE VELOCITY AT THE THROAT ENTRANCE= .00000

THERE ARE 1 (6) ENTRIES IN THE GAS-PARTICLE (7) THERMODYNAMIC AND TRANSPORT PROPERTY TABLES

(8) CHAMBER ENTHALPY= .74045+08

(9) VELOCITY (FT/SEC)	(10) P	(11) GAMMA	(12) TEMPERATURE (R)	(13) PRESSURE (PSFA)	(14) PRANDTL NUMBER	(15) VISCOSITY (POISE)	(16) CP (FT2/SEC2-R)
.00000	.19749+04	.11730+01	.55296+04	.14401+06	.38370+00	.12473-05	.16441+05

(17) ENTHALPY= .74045D+08 (18) ENTROPY= .000000

THERE ARE 1 ENTRIES IN THE GAS PHASE THERMODYNAMIC AND TRANSPORT PROPERTY TABLES

(19) VELOCITY (FT/SEC)	(20) P	(21) GAMMA	(22) PRANDTL NUMBER	(23) VISCOSITY (POISE)	(24) EXPONENT
.00000	.24248+04	.12080+01	.38370+00	.17473-05	.65680+00

EQUATIONS DEFINING NOZZLE GEOMETRY

(25) TYPE	(26) ITRANS	(27) A	(28) B	(29) C	(30) D	(31) E	(32) MAX
2	0	.000000	.000000	.000000	-.577350+00	.953030-01	.600000+00
1	0	-.100000+01	.100000+01	.000000	-.100000+01	-.125000+01	.258819+00
2	0	.000000	.000000	.000000	.267949+00	.214510+00	.181800+01

PARTICLE DATA

(33) TOTAL PARTICLE WEIGHT RELATIVE TO THE GAS IS .22750+00

PARTICLE DISTRIBUTION DATA

(34) J	(35) RADIUS	(36) PERCENT	(37) DENSITY	(38) VELOCITY
1	.40000+00	.10000+00	.25000+01	.13290+01
2	.80000+00	.20000+00	.25000+01	.13290+01
3	.11250+01	.20000+00	.25000+01	.13290+01
4	.15000+01	.20000+00	.25000+01	.13290+01
5	.21500+01	.20000+00	.25000+01	.13290+01
6	.35000+01	.10000+00	.25000+01	.13290+01

THE PARTICLE TEMPERATURE-ENTHALPY TABLE WILL BE READ IN WITH ENGLISH UNITS

PARTICLE TEMPERATURE-ENTHALPY TABLE

(39) (40) (41)

PHASE CHANGE DATA ... TMELT= .417000+04 HSOLID= .278514+08 HLIQUID= .403481+08

CPMELT= .8197+04 CPSOLID= .4824+04

(42) (43)

PARTICLE DRAG TABLE

(44) I	(45) RE	(46) DRAG COFF
1	.00000	.10000+01
2	.12500+01	.10000+01
3	.12550+01	.10000+01
4	.12600+01	.10010+01
5	.12650+01	.10020+01
6	.15820+01	.10630+01
7	.19950+01	.11410+01
8	.25100+01	.12240+01
9	.31600+01	.13150+01
10	.39800+01	.14120+01
11	.50100+01	.15170+01
12	.63100+01	.16250+01
13	.79500+01	.17450+01
14	.10000+02	.18740+01
15	.12600+02	.20260+01
16	.15820+02	.21860+01
17	.19950+02	.23640+01
18	.25100+02	.25550+01
19	.31600+02	.27600+01
20	.39800+02	.30000+01
21	.50100+02	.32520+01
22	.63100+02	.32520+01
23	.79500+02	.38250+01
24	.10000+03	.41550+01
25	.31600+03	.79000+01
26	.10000+04	.20000+02
27	.10010+04	.20020+02
28	.10000+06	.20000+04

VELOCITY (FT/SEC)	ENTHALPY (FT2/SEC2)	TEMPERATURE (R)	MACH NUMBER	PRESSURE (PSIA)	DENSITY (SLUGS/FT3)	TOTAL ENTHALPY (FT2/SEC2)	ENTROPY (FT2/SEC2-R)
R	GAMMA	PRANDTL NUMBER	VISCOSITY	CP			

(47) AXIAL STATION X= -.159922+01 (48) AREA RATIO A/A*= .165823+02

(49)	(51)	(53)	(55)	(57)	(59)	(60)	(61)
.132899+03	.740362+08	.552894+04	.330238-01	.999255+03	.107329-01	.740450+08	.000000
(50) .242482+04	(52) .120800+01	(54) .383700+00	(56) .174717-05	(58) .140826+05			

PARTICLE (62)	(63)	(64)	(65)
1	.132899+03	.518951+08	.552894+04
2	.132899+03	.518951+08	.552894+04
3	.132899+03	.518951+08	.552894+04
4	.132899+03	.518951+08	.552894+04
5	.132899+03	.518951+08	.552894+04
6	.132899+03	.518951+08	.552894+04

AXIAL STATION X= -.135822+01 AREA RATIO A/A*= .123754+02 WDOA= .234609+01

	.178168+03	.740309+08	.552837+04	.442750-01	.998636+03	.107274-01	.740450+08	.182814+00
	.242482+04	.120800+01	.383700+00	.174706-05	.140826+05			

PARTICLE			
1	.177312+03	.518904+08	.552837+04
2	.174932+03	.518905+08	.552838+04
3	.172124+03	.518907+08	.552840+04
4	.168232+03	.518908+08	.552842+04
5	.161124+03	.518912+08	.552845+04
6	.152025+03	.518919+08	.552854+04

AXIAL STATION X= -.111821+01 AREA RATIO A/A*= .878302+01 WDOA= .330569+01

	.251390+03	.740187+08	.552717+04	.624650-01	.997237+03	.107147-01	.740450+08	.405178+00
	.242482+04	.120800+01	.383700+00	.174682-05	.140826+05			

PARTICLE			
1	.249335+03	.518804+08	.552722+04
2	.243966+03	.518807+08	.552726+04
3	.237947+03	.518810+08	.552728+04
4	.230015+03	.518814+08	.552733+04
5	.219484+03	.518822+08	.552742+04
6	.201528+03	.518838+08	.552761+04

VELOCITY (FT/SEC) R	ENTHALPY (FT2/SEC2) GAMMA	TEMPERATURE (R) PRANDTL NUMBER	MACH NUMBER VISCOSITY	PRESSURE (PSIA) CP	DENSITY (SLUGS/FT3)	TOTAL ENTHALPY (FT2/SEC2)	ENTROPY (FT2/SEC2*R)

AXIAL STATION X= -.158215+00 AREA RATIO A/A*= .110330+01 WDOA= .263156+02

.254229+04	.713823+08	.529500+04	.645534+00	.751883+03	.843271-02	.740997+08	.892078+02
.242482+04	.120800+01	.383700+00	.169684-05	.140826+05			

PARTICLE

1	.232682+04	.500700+08	.531415+04
2	.210334+04	.502674+08	.533738+04
3	.195115+04	.504028+08	.535332+04
4	.180211+04	.505308+08	.536838+04
5	.158381+04	.506979+08	.538804+04
6	.131137+04	.509288+08	.541522+04

THE MIXTURE START CONDITION OCCURRED BEFORE THE FOLLOWING AXIAL STATION

AXIAL STATION X= .685852-01 AREA RATIO A/A*= .101893+01 WDOA= .284947+02

.418145+04	.664920+08	.491207+04	.110236+01	.459196+03	.555157-02	.740438+08	.218761+03
.242482+04	.120800+01	.383700+00	.160891-05	.140826+05			

PARTICLE

1	.376420+04	.472288+08	.498200+04
2	.337218+04	.478029+08	.504929+04
3	.311208+04	.481713+08	.509246+04
4	.286260+04	.485083+08	.513196+04
5	.250759+04	.489295+08	.518133+04
6	.206763+04	.495189+08	.525042+04

PERCENT CHANGE IN MASS, MOMENTUM AND ENERGY RELATIVE TO THE STARTING CONDITIONS

(66) PERCENT CHANGE IN MIXTURE MASS FLOW WAS , .722216-03 PERCENT
PERCENT CHANGE IN GAS MOMENTUM WAS -.930404+02 PERCENT (67)
(68) PERCENT CHANGE IN PARTICLE MOMENTUM WAS .212281+04 PERCENT
PERCENT CHANGE IN MIXTURE MOMENTUM WAS -.923274+02 PERCENT (69)
(70) PERCENT CHANGE IN TOTAL ENTHALPY WAS -.164359-02 PERCENT

MOMENTUM INTEGRATION RESULTS

(71) FXG= .226728+03 FXP= .216748+02 FXM= .248403+03 ISP= .195019+03
(72) (73) (74)

ORIGINAL PAGE IS OF POOR QUALITY

PARTICLE TRAJECTORY CALCULATIONS

(75)	(76) RADIAL CO-ORDINATE (FT)	(77) AXIAL CO-ORDINATE (FT)	(78) AXIAL VELOCITY (FT/SEC)	(79) RADIAL VELOCITY (FT/SEC)	(80) ANGLE (DEG)	(81) ENTHALPY (FT2/SEC2)	(82) NOZZLE RADIUS (FT)
1	.845475-01	-.132685+00	.115882+03	-.669045+02	-.300000+02	.518950+08	.845475-01
PARTICLE INTERSECTION WITH UPPER WALL -- REDO IT YA-LL							
1	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518950+08	.845475-01
2	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518951+08	.845475-01
3	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518951+08	.845475-01
4	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518951+08	.845475-01
5	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518951+08	.845475-01
6	.828627-01	-.132685+00	.116574+03	-.656918+02	-.294022+02	.518951+08	.845475-01
1	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518950+08	.842588-01
2	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518950+08	.842588-01
3	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518950+08	.842588-01
4	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518951+08	.842588-01
5	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518951+08	.842588-01
6	.825810-01	-.132185+00	.117374+03	-.661441+02	-.294026+02	.518951+08	.842588-01
1	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518949+08	.839701-01
2	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518950+08	.839701-01
3	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518950+08	.839701-01
4	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518950+08	.839701-01
5	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518951+08	.839701-01
6	.822992-01	-.131685+00	.118183+03	-.666011+02	-.294030+02	.518951+08	.839701-01
1	.820174-01	-.131185+00	.119001+03	-.670629+02	-.294034+02	.518949+08	.836814-01
2	.820174-01	-.131185+00	.119001+03	-.670629+02	-.294034+02	.518949+08	.836814-01
3	.820174-01	-.131185+00	.119001+03	-.670629+02	-.294034+02	.518949+08	.836814-01
4	.820174-01	-.131185+00	.119001+03	-.670629+02	-.294034+02	.518950+08	.836814-01
5	.820174-01	-.131185+00	.119001+03	-.670629+02	-.294034+02	.518950+08	.836814-01
6	.820174-01	-.131185+00	.118196+03	-.666085+02	-.294030+02	.518951+08	.836814-01
1	.817356-01	-.130685+00	.119827+03	-.675295+02	-.294038+02	.518948+08	.833928-01
2	.817356-01	-.130685+00	.119827+03	-.675295+02	-.294038+02	.518948+08	.833928-01
3	.817356-01	-.130685+00	.119827+03	-.675295+02	-.294038+02	.518949+08	.833928-01
4	.817356-01	-.130685+00	.119827+03	-.675295+02	-.294038+02	.518949+08	.833928-01
5	.817356-01	-.130685+00	.119827+03	-.675295+02	-.294038+02	.518950+08	.833928-01
6	.817356-01	-.130685+00	.118235+03	-.666304+02	-.294030+02	.518950+08	.833928-01
1	.814538-01	-.130185+00	.120661+03	-.680010+02	-.294043+02	.518947+08	.831041-01
2	.814538-01	-.130185+00	.120661+03	-.680010+02	-.294043+02	.518947+08	.831041-01
3	.814538-01	-.130185+00	.120661+03	-.680010+02	-.294043+02	.518948+08	.831041-01
4	.814538-01	-.130185+00	.120661+03	-.680010+02	-.294043+02	.518948+08	.831041-01
5	.814538-01	-.130185+00	.119861+03	-.675488+02	-.294039+02	.518949+08	.831041-01
6	.814539-01	-.130185+00	.118299+03	-.666666+02	-.294031+02	.518950+08	.831041-01
1	.811720-01	-.129685+00	.121505+03	-.684775+02	-.294047+02	.518946+08	.828154-01
2	.811720-01	-.129685+00	.121505+03	-.684775+02	-.294047+02	.518947+08	.828154-01
3	.811720-01	-.129685+00	.121505+03	-.684775+02	-.294047+02	.518947+08	.828154-01
4	.811720-01	-.129685+00	.121505+03	-.684775+02	-.294047+02	.518948+08	.828154-01
5	.811720-01	-.129685+00	.119960+03	-.676049+02	-.294039+02	.518949+08	.828154-01
6	.811721-01	-.129685+00	.118388+03	-.667167+02	-.294031+02	.518950+08	.828154-01
1	.808902-01	-.129185+00	.122357+03	-.689589+02	-.294051+02	.518946+08	.825267-01
2	.808902-01	-.129185+00	.122357+03	-.689589+02	-.294051+02	.518946+08	.825267-01
3	.808902-01	-.129185+00	.122357+03	-.689589+02	-.294051+02	.518946+08	.825267-01

PARTICLE TRAJECTORY CALCULATIONS

	RADIAL CO-ORDINATE (FT)	AXIAL CO-ORDINATE (FT)	AXIAL VELOCITY (FT/SEC)	RADIAL VELOCITY (FT/SEC)	ANGLE (DEG)	ENTHALPY (FT2/SEC2)	NOZZLE RADIUS (FT)
0	.190821-01	.981543-02	.192081+04	-.130423+03	-.827552+01	.494037+08	.209224-01
1	.192844-01	.531543-02	.372361+04	.967287+02	.718985+00	.473040+08	.210030-01
2	.179537-01	.531543-02	.331062+04	-.268572+02	-.167610+01	.478688+08	.210030-01
3	.170914-01	.531543-02	.303902+04	-.167797+03	-.316032+01	.482312+08	.210030-01
4	.162929-01	.531543-02	.278315+04	-.220700+03	-.453399+01	.485628+08	.210030-01
5	.152121-01	.531543-02	.243071+04	-.271849+03	-.638141+01	.489777+08	.210030-01
6	.148059-01	.531543-02	.191104+04	-.289279+03	-.854213+01	.495532+08	.210030-01

ONE DIMENSIONAL PARTICLE START LINE

	(54) RADIAL CO-ORDINATE (FT)	(55) AXIAL CO-ORDINATE (FT)	(56) AXIAL VELOCITY (FT/SEC)	(57) RADIAL VELOCITY (FT/SEC)	(58) ANGLE (DEG)	(59) ENTHALPY (FT2/SEC2)	(60) NOZZLE RADIUS (FT)
(53) 1	.192922-01	.571543-02	.375583+04	-.421184+02	-.718985+00	.472288+08	.210296-01
2	.179427-01	.571543-02	.333833+04	-.857418+02	-.167610+01	.478029+08	.210296-01
3	.170700-01	.571543-02	.306468+04	-.158804+03	-.316032+01	.481713+08	.210296-01
4	.162619-01	.571543-02	.280637+04	-.213365+03	-.453399+01	.485083+08	.210296-01
5	.151646-01	.571543-02	.245081+04	-.266338+03	-.638141+01	.489295+08	.210296-01
6	.137463-01	.571543-02	.200731+04	-.296167+03	-.854213+01	.495189+08	.210296-01

GASEOUS START LINE DATA

(91) R (FT)	(92) X (FT)	(93) MACH NUMBER	(94) THETA (DEG)	(95) ENTROPY (FT2/SEC2-R)	(96) MACH ANGLE (DEG)		(97) TOTAL ENTHALPY (FT2/SEC2)
.000000	.571543-02	.110236+01	.000000	.219685+03	.651142+02	.000000	.778712+08
.105148-02	.571543-02	.110236+01	.196636+00	.219685+03	.651142+02	.000000	.778712+08
.210296-02	.571543-02	.110236+01	.393273+00	.219685+03	.651142+02	.000000	.778712+08
.315443-02	.571543-02	.110236+01	.589909+00	.219685+03	.651142+02	.000000	.778712+08
.420591-02	.571543-02	.110236+01	.786545+00	.219685+03	.651142+02	.000000	.778712+08
.525739-02	.571543-02	.110236+01	.983182+00	.219685+03	.651142+02	.000000	.778712+08
.630887-02	.571543-02	.110236+01	.117982+01	.219685+03	.651142+02	.000000	.778712+08
.736035-02	.571543-02	.110236+01	.137645+01	.219685+03	.651142+02	.000000	.778712+08
.841182-02	.571543-02	.110236+01	.157309+01	.219685+03	.651142+02	.000000	.778712+08
.946330-02	.571543-02	.110236+01	.176973+01	.219685+03	.651142+02	.000000	.778712+08
.105148-01	.571543-02	.110236+01	.196636+01	.219685+03	.651142+02	.000000	.778712+08
.115663-01	.571543-02	.110236+01	.216300+01	.219685+03	.651142+02	.000000	.778712+08
.126177-01	.571543-02	.110236+01	.235964+01	.219685+03	.651142+02	.000000	.778712+08
.136692-01	.571543-02	.110236+01	.255627+01	.219685+03	.651142+02	.000000	.778712+08
.147206-01	.571543-02	.110236+01	.275291+01	.219685+03	.651142+02	.000000	.778712+08
.157721-01	.571543-02	.110236+01	.294954+01	.219685+03	.651142+02	.000000	.778712+08
.168235-01	.571543-02	.110236+01	.314618+01	.219685+03	.651142+02	.000000	.778712+08
.178750-01	.571543-02	.110236+01	.334282+01	.219685+03	.651142+02	.000000	.778712+08
.189264-01	.571543-02	.110236+01	.353945+01	.219685+03	.651142+02	.000000	.778712+08
.199779-01	.571543-02	.110236+01	.373609+01	.219685+03	.651142+02	.000000	.778712+08
.210294-01	.571543-02	.110236+01	.393273+01	.219685+03	.651142+02	.000000	.778712+08

PARTICLE START LINE DATA

(98) PARTICLE	(99) I	(100) AXIAL VELOCITY (FT/SEC)	(101) RADIAL VELOCITY (FT/SEC)	(102) THETA (DEG)	(103) ENTHALPY (FT2/SEC2)	(104) DENSITY (LBM/FT3)
1	1	.3723999+04	.0000000	.0000000	.4730395+08	.1686105-03
2	1	.3311433+04	.0000000	.0000000	.4786882+08	.4376148-03
3	1	.3043648+04	.0000000	.0000000	.4823123+08	.5253678-03
4	1	.2791887+04	.0000000	.0000000	.4856283+08	.6302589-03
5	1	.2445861+04	.0000000	.0000000	.4897723+08	.8252830-03
6	1	.2013519+04	.0000000	.0000000	.4955720+08	.5912931-03
1	2	.3723898+04	.2547674+01	.3919843-01	.4730395+08	.1686105-03
2	2	.3311428+04	-.5673362+01	-.9816289-01	.4786882+08	.4376148-03
3	2	.3043631+04	-.1032819+02	-.1944255+00	.4823123+08	.5253678-03
4	2	.2791850+04	-.1425787+02	-.2926047+00	.4856283+08	.6302589-03
5	2	.2445789+04	-.1882920+02	-.4410897+00	.4897723+08	.8252830-03
6	2	.2013412+04	-.2258912+02	-.6427929+00	.4955720+08	.5912931-03
1	3	.3723895+04	.5095347+01	.7839486-01	.4730395+08	.1686105-03
2	3	.3311914+04	-.1134671+02	-.1963258+00	.4786882+08	.4376148-03
3	3	.3043578+04	-.2065626+02	-.3888509+00	.4823123+08	.5253678-03
4	3	.2791741+04	-.2851536+02	-.5852094+00	.4856283+08	.6302589-03
5	3	.2445571+04	-.3765728+02	-.8821793+00	.4897723+08	.8252830-03
6	3	.2013032+04	-.4517539+02	-.1285586+01	.4955720+08	.5912931-03
1	4	.3723891+04	.7643017+01	.1175953+00	.4730395+08	.1686105-03

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.