SN 63

ENGINEERING AND PROGRAMMING MANUAL

TWO-DIMENSIONAL KINETIC REFERENCE COMPUTER PROGRAM

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TDK

Final Report
Contract No. NAS8-35931

April 1985

By: G. R. Nickerson
L. D. Dang
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Prepared For
George C. Marshall Space Flight Center
Marshall Space Flight Center, Al. 35812

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FOREWORD

This report contains an engineering and programming description for the revised April/85 version of the Two-Dimensional Kinetic Thrust Chamber Analysis Computer Program, TDK, developed by Software and Engineering Associates, Inc., Carson City, Nevada. Revision of the TDK Computer Program was performed under Contract Numbers NAS8-34974, NAS8-35046, and NAS8-35931. The work performed was monitored by Mr. Klaus Gross and Mr. A. Krebsbach of the NASA George C. Marshall Space Flight Center, Huntsville, Alabama.

The TDK Computer Program consists of the following computational modules:

MCM	Master Control Module
ODE	One-Dimensional Equilibrium Nozzle Analysis Module
ODK	One-Dimensional Kinetic Nozzle Analysis Module
TRANS	Transonic Analysis Module
MOC	Method of Characteristics Module for Equilibrium, Kinetic, or Frozen Nozzle Flow
BLM	Boundary Layer Module

The reference procedure which utilizes the above computer programs is given in the JANNAF Rocket Engine Performance Prediction and Calculation Manual, CPIA246, Reference 1.

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NOMENCLATURE

a	Nozzle area ratio, also reaction rate parameter
a_{ki}	Gram atoms of the k^{th} element in the i^{th} species
A	Adiabatic heat addition term linking fluid dynamic and relaxation processes, also total mass reactant in ODE
b	Reaction rate parameter
B	Energy exchange term linking fluid dynamic and relaxation processes
c	Species mass fraction
c_F	Thrust coefficient
C_p	Frozen heat capacity
C_{pe}	Equilibrium heat capacity
C^*	Characteristic exhaust velocity
$\mathcal{C}_i$	Heat capacity per mole of i^{th} species/R
f	Derivative
F	Free energy, also function defined by Equation (2.5-5)
$\mathcal{F}_i$	Free energy per mole of i^{th} species/R
G	Function defined by Equation (2.5-6)
h	Enthalpy, also integration increment
H	Total enthalpy, also function defined by Equation (2.5-7)
ΔH_F	Heat of formation
$\mathcal{H}_i$	Enthalpy per mole of i^{th} species/RT
I_{sp}	Specific impulse
k	Variable increment, also reaction rate parameter
K	Equilibrium constant
m	Reaction rate ratio
Mw	Molecular weight
M	Mach number, also third body reaction term
n	Reaction rate parameter, also summation or iteration index
n_i	Moles of i^{th} species
N_e	Average equilibrium pressure expansion coefficient
P	Pressure

NOMENCLATURE (continued)

r	Radial distance coordinate, from axis
r^*	Nozzle throat radius
R	Gas constant
R^*	Nozzle wall radius of curvature at throat
$\mathcal{R}$	Universal gas constant
S	Entropy, also summation term
$\mathcal{S}_i$	Entropy per mole of i^{th} species/R
T	Temperature
u	Velocity in x-direction
v	Velocity in r-direction
V	Velocity
x	Axial distance coordinate, from throat
y	Dependent variable
Y_i	Slipline height
α	Mach angle, angle between streamline and Mach line characteristics
α_i	Partial derivative, $\partial f_i/\partial x$
$\beta_{i,j}$	Partial derivative, $\partial f_i/\partial y_j$
γ	Frozen heat capacity ratio
γ_e	Equilibrium heat capacity ratio
δ_i	Incremental error
$\delta_{i,j}$	Kronecker delta
ϵ	Area ratio
ρ	Density
θ	Nozzle cone angle
ω_i	Net species production rate

Subscripts:

c	Refers to chamber conditions
i	Refers to i^{th} species or equation
j	Refers to j^{th} reaction or variable
o	Refers to reference conditions

Superscript:

*	Refers to throat conditions or sonic conditions.

ABBREVIATIONS

BLIMP	Boundary Layer Integral Matrix Procedure, JANNAF computer program
BLM	Boundary Layer Module, computer program
JANNAF	Joint Army-Navy-NASA-Air Force
M0C	Method of Characteristics, module of SPP and TDK
0DE	One-Dimensional Equilibrium, module of SPP and TDK
ODK	One-Dimensional Kinetics, module of SPP and TDK
OTV	Orbit Transfer Vehicle
PSS	Performance Standardization Subcommittee of JANNAF
SEA	Software and Engineering Associates, Inc.
SPP	Solid Performance Program, JANNAF computer program
TDE	Two-Dimensional Equilibrium, module of TDK
TDK	Two-Dimensional Kinetics, JANNAF computer program

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1. INTRODUCTION

The Two-Dimensional Kinetics (TDK) computer program is a primary tool in applying the JANNAF liquid rocket thrust chamber performance prediction methodology.[1] This computer program and the performance prediction methodology were originally developed under the auspices of the Performance Standardization Subcommittee (PSS) of the JANNAF. The goal of the PSS is the development of a methodology that includes all aspects of rocket engine performance from analytical calculation to test measurements, that is physically accurate and consistent, and that serves as an industry and government reference.

Recent interest in rocket engines that operate at high expansion ratio, such as most Orbit Transfer Vehicle (OTV) engine designs, has required an extension of the analytical methods used by the TDK computer program. Thus, the version of TDK that is described in this manual is in many respects different from the 1973 version of the program that is described in Reference 2. Although much material from the 1973 document is included in this manual, other material is entirely new. This new material reflects the new capabilities of the TDK computer program, the most important of which are described below.

Ref. 2: Nickerson, G. R., Coats, D. E., and Bartz, J. L., "The Two-Dimensional Kinetic (TDK) Reference Computer Program", Engineering and Programming Manual, Ultrasystems, Inc., December 1973, prepared for Contract No. NAS9-12652, NASA JSC.

a) A Boundary Layer Module (BLM) has been included within the TDK program. The BLM can be used to automatically calculate the wall boundary layer after execution of the Method of Characteristics (MOC). The resulting wall displacement and the heat transferred through the wall are computed. The ODE-ODK-TRANS-MOC series of calculations can then be automatically repeated with the appropriate parameters (wall contour and propellant enthalpy) updated. This feature allows the "rigorous analytical procedure" of the JANNAF rocket engine performance prediction methodology[1] to be carried out with a single computer run for a regeneratively cooled engine.

b) The ODE module of TDK has been modified so that it will compute transport properties for the nozzle exhaust composition. This information is required by the BLM.

c) The ODE module of TDK has been modified so that it will provide tables of gas properties versus temperature for the stream tube mixture ratio adjacent to the nozzle wall. This information is required by the BLM.

d) New nozzle wall geometry options have been added to the program.

e) The ODK and MOC modules can contain condensed phases that are in thermal and velocity equilibrium with the gas.

f) The transonic flow module (TRANS) has been modified to analyze flow with variable mixture ratio.

g) The MOC module has been rewritten to allow for the presence of a shock wave in the flow. The shock can be either attached to the nozzle wall, or induced by the nozzle wall curvature. Regular reflections from the nozzle axis and the nozzle wall can be computed. The shock option can be used for flows with gas properties along streamlines that are either:

   1) constant,

   2) chemically frozen (i.e., fixed composition, but properties varying with temperature), or

   3) governed by finite rate kinetics.

h) The thermodynamic data and kinetic rate data (see Appendix A) for the program have been updated.

The TDK Computer Program is designed for engineering use and is specified and programmed in a straight forward manner to facilitate its application. The FORTRAN IV programming language has been used in an attempt to make the computer program as machine independent as possible. A complete engineering and programming description of the TDK Computer Program is contained in this report.

Section 2 of this report contains a description of the methods of analysis used in the computer program.

Section 3 contains a description of the numerical methods used to integrate the fluid dynamic and chemical relaxation equations in the computer program.

Section 4 contains a description of the program structure.

Section 5 contains a detailed engineering and programming description of the program subroutines.

Section 6 contains a program user's manual describing the use of the computer program with an explanation of the program input and output.

Section 7 contains input and output for a sample case using the TDK option of the program.

Section 8 contains a discussion of program usage and error diagnostics.

2. ANALYSIS

The TDK Computer Program has been written for the purpose of evaluating two-dimensional effects on the performance of liquid propellant exhaust nozzles. An important feature of the TDK program is its ability to consider nonequilibrium chemical processes. The basic method of analysis used by TDK is the method of characteristics. The program constructs a finite-difference mesh by tracing gas streamlines and characteristic surfaces. The mesh points are located at the intersections of these surfaces. Systems of large size can be considered by the program as is indicated by Table 2-1 which gives maximum dimensions for the program.

The method of characteristics calculation is capable of considering either continuous mixture ratio variation, or flow striations. Striated regions are separated by slipline conditions, i.e., adjacent streamlines with matched pressure and gas streamline angle, but at different mixture ratio, temperature, etc. Mixing between striated zones, is not considered. The initial data line required to start the method of characteristics is calculated using a transonic analysis provided for this purpose. The characteristic equations governing the fluid dynamic variables are integrated using a second order (modified Euler) explicit integration method while the chemical relaxation equations are integrated using a first order implicit integration method to insure numerical stability in near equilibrium flows.

In order to start the method of characteristics calculation, it is necessary to approximate an initial data line across the nozzle throat. This initial data line must be supersonic and

TABLE 2-1 MAXIMUM DIMENSIONS FOR TDK

Number of defined elements provided	102
Number of possible species per case	40
Number of species in the Master Thermodynamic Data File	1000
Number of possible reactions	150
Number of possible reactions with implied third body	50
Number of reactants per reaction	10
Number of products per reaction	10
Maximum stoichiometric coefficient total	600
Number of possible third body efficiencies to be considered	2000
Maximum number of streamlines (i.e. mesh points per left running characteristic)	275
Maximum number of zones (i.e. striations)	50

must be compatible with the mesh construction methods used by TDK. The calculations performed by TDK to generate this initial data line are carried out in two stages. First chemical information is computed by use of the ODK module as described in Section 2.1. Chemical and fluid properties, obtained from this calculation are retained in the form of tables. The second stage of the calculation makes use of this information and employs a perturbation method to estimate two dimensional effects in the transonic region of the nozzle throat. Variable mixture ratio flows and striated flows are treated by means of a straight forward extension of the procedure described above.

The description given above is shown schematically in Figure 2-1a. The TDK Computer Program is divided into modules as shown in the figure. The modules are illustrated in the master flow chart presented in Figure 2-1b. For a description of the analysis used by ODE, Reference 3 should be used.

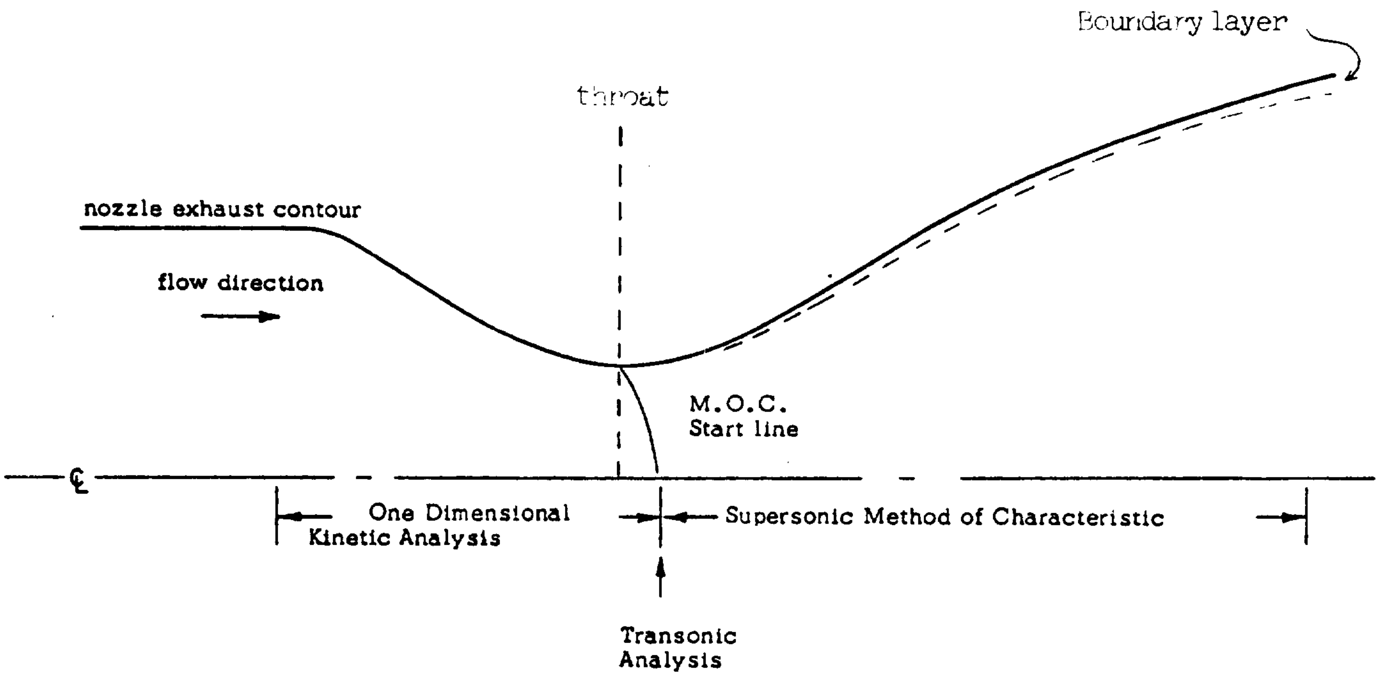

Figure 2-1a. Schematic for TDK Analysis

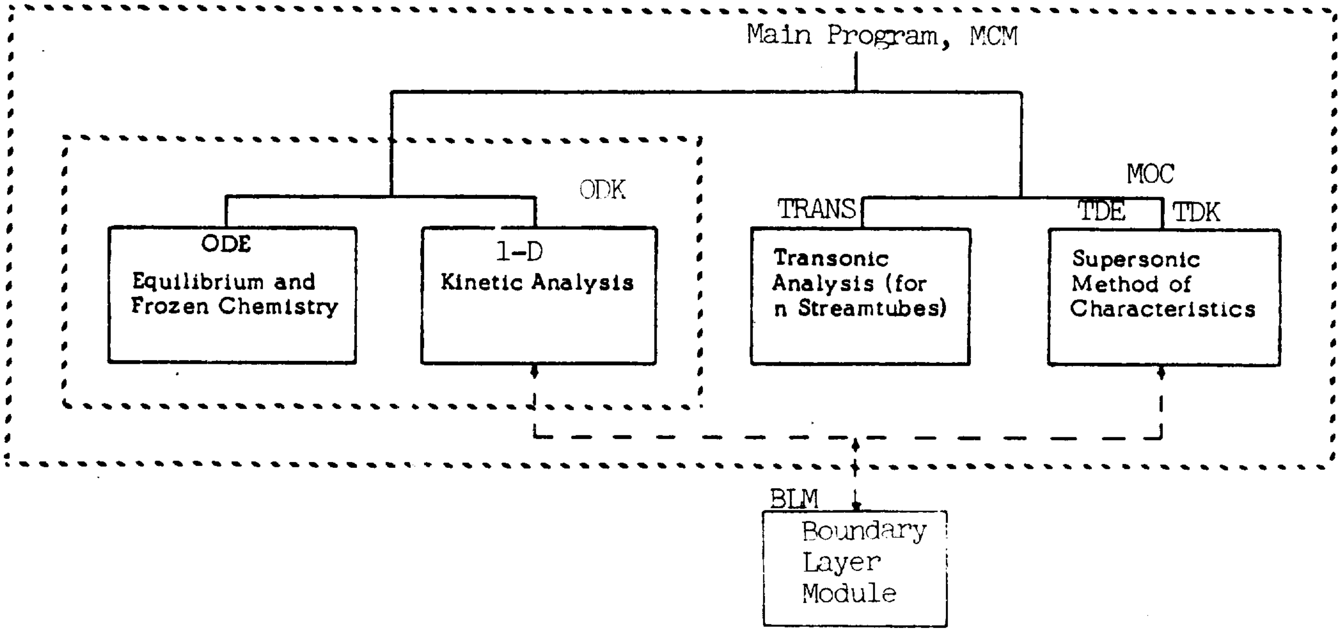

Figure 2-1b. Master Flow Chart for TDK

In Section 2.1 of this report the analysis for the ODK computer program is given. In Section 2.2 a discussion of the finite rate chemistry used by both ODK and TDK is presented. In Section 2.3 the conservation equations governing two dimensional axisymmetric inviscid flow are presented. In Section 2.4 the transonic flow method used to construct an initial data line for the method of characteristics solution is presented. The method of characteristics relations are presented in Section 2.5. The boundary layer solution is presented in Section 2.6.

PERFORMANCE PREDICTION METHODOLOGY

The JANNAF thrust chamber performance prediction methodology is defined in Reference 1. In this methodology the predicted delivery specific impulse for the thrust chamber can be expressed as:

$$I_{sp_{deliv}} = \eta_{DER} \; I_{sp_{TDK'}} - \Delta F_{BLM} / \dot{M}_{TDK'}$$

The factor η_{DER} in the above expression represents the distributed energy release of the combustion process. The terms

$I_{sp_{TDK'}}$, $\dot{M}_{TDK'}$, and ΔF_{BLM} represent the values predicted by TDK for nozzle specific impulse and mass flow, and by the BLM for boundary layer thrust deficit. The prime denotes that these quantities have been corrected using the Prandtl procedure. Thus, a second TDK calculation has been made with the nozzle wall displaced inwards a distance equal to the boundary layer displacement thickness. Also, in this calculation the heat picked up by the regen cooling circuits has been returned to the thrust chamber as increased propellant enthalpy. Care is taken in the procedure to assure that a complete energy balance is maintained.

The boundary layer thrust deficit is evaluated by integrating across the boundary layer at the nozzle exit for momentum thickness, θ, and displacement thickness, δ^*, and applying the results as follows:

$$F_{BLM} = 2\pi r_e \cos \alpha_e \ \rho_e U_e^2 \theta_{BLM}$$
$$- 2\pi r_e \cos \alpha_e (P_e - P_{BLM}) \ \delta^*_{BLM}$$

The first term in the above expression represents the momentum deficit in the boundary layer and includes the effects of wall skin friction and heat transfer. The second term represents the pressure force acting on the annular portion of the nozzle exit plane that is between the real wall and the invisid edge of the boundary layer. The quantities r_e, ρ_e, P_e, and U_e, are boundary layer edge properties obtained from the second TDK calculation.

2.1 ANALYSIS FOR THE 0DK COMPUTER PROGRAM

The One Dimensional Kinetic nozzle analysis computer program (0DK) described in this section has been developed for performing reference liquid propellant thrust chamber performance calculations. The ODK computer program calculates the inviscid one dimensional equilibrium, frozen and nonequilibrium nozzle expansion of gaseous propellant exhaust mixtures. The 0DK program is also used as a subprogram by TDK. The 0DE computer program, which is described in Reference 3, is used to perform the equilibrium composition computations. The 0DE program computations are based on the assumption that species compositions at any pressure and enthalpy point will be distributed such that the free energy of the system is minimized. Solid and liquid phases can be included in 0DE computations, and to a certain extent in the 0DK and TDK computations.

The ODK one dimensional nonequilibrium calculation is performed beginning at the converging section of the nozzle and ending at an axial station located beyond the throat plane. In this calculation pressure defined relations are used to integrate the differential equations for a one dimensional streamtube until the flow becomes supersonic. This pressure profile is obtained by computing an average value of expansion coefficient based on a chemical equilibrium gas composition at the nozzle chamber and throat. These parameters are supplied automatically by ODE. Pressure and its axial derivative are then obtained for the exact prescribed inlet geometry from the relations for isentropic expansion. Once the pressure profile has been determined the one dimensional nonequilibrium flow relations are integrated starting with an equilibrium calculation obtained at the thrust chamber contraction ratio. The advantage of using the pressure defined boundary condition is that the differential equations are not singular at Mach one so that no difficulties are encountered when integrating through the nozzle throat region. The throat (minimum area) occurs when the product of density and velocity maximizes and thus determines the mass flux corresponding to the choke flow condition. Using this mass flux, the nozzle area profile can then be determined. Experience has shown good agreement between this area profile and the original input geometry. Once supersonic conditions are reached the program automatically changes over to area defined differential equations.

2.1.1 Conservation Equations for One Dimensional Kinetic Expansions

The conservation equations governing the inviscid one dimensional flow of reacting gas mixtures have been given by Hirschfelder, Curtiss and Byrd,[4] Penner[5] and others. The basic assumptions made in the derivation of these equations are:

- There are no mass or energy losses from the system
- The gas is inviscid
- Each component of the gas is a perfect gas
- The internal degrees of freedom (translational, rotational and vibrational) of each component of the gas are in equilibrium.

The conservation equations are presented here in the form used in the present analysis.

For each component of the gas the continuity equation is

$$\frac{d}{dx}(\rho_i V\bar{a}) = \omega_i r^*\bar{a}$$

where the axial coordinate (x) has been normalized with the throat radius. Summing over all components of the mixture, the overall continuity equation is obtained

$$\frac{d}{dx}(\rho V\bar{a}) = 0$$

Combining the above two equations gives

$$\frac{dc_i}{dx} = \frac{\omega_i r^*}{\rho V}$$

The momentum equation is

$$\rho V \frac{dV}{dx} + \frac{dP}{dx} = 0$$

The energy equation is

$$h + \frac{1}{2} V^2 = H_c$$

where

$$h = \sum_{i=1} c_i h_i$$

and

$$h_i = \int_o^T C_{pi} dT + h_{io}$$

For each component of the gas, the equation of state is

$$P_i = \rho_i R_i T$$

Summing over all components of the mixture, the overall equation of state is obtained

$$P = \rho R T$$

where

$$R = \sum_{i=1} c_i R_i$$

Since the expansion through a nozzle can be specified either by the expansion process or by the nozzle geometry, two forms of the above equations are of interest.

If the expansion process is specified and the pressure is known as a function of distance through the nozzle, the above equations become

$$\frac{dc_i}{dx} = \frac{\omega_i r^*}{\rho V}$$

$$\frac{dV}{dx} = -\frac{1}{\rho V}\frac{dP}{dx}$$

$$\frac{d\rho}{dx} = \left[\frac{1}{\gamma P}\frac{dP}{dx} - A\right]\rho$$

$$\frac{dT}{dx} = \left[\frac{\gamma - 1}{\gamma}\frac{1}{P}\frac{dP}{dx} - B\right]T$$

while if the nozzle geometry is specified, the above equations become

$$\frac{dc_i}{dx} = \frac{\omega_i r^*}{\rho V}$$

$$\frac{dV}{dx} = \left[\frac{1}{\bar{a}}\frac{d\bar{a}}{dx} - A\right]\frac{V}{M^2 - 1}$$

$$\frac{d\rho}{dx} = -\left\{\left[\frac{1}{\bar{a}}\frac{d\bar{a}}{dx} - A\right]\frac{M^2}{M^2 - 1} + A\right\}\rho$$

$$\frac{dT}{dx} = -\left\{\left[\frac{1}{\bar{a}}\frac{d\bar{a}}{dx} - A\right]\frac{(\gamma - 1)M^2}{M^2 - 1} + B\right\}T$$

$$P = \rho R T$$

where

$$A = \frac{r^*}{PV}\left[\sum_{i=1} \omega_i R_i T - \frac{\gamma - 1}{\gamma} \sum_{i=1} \omega_i h_i\right]$$

$$B = \frac{\gamma - 1}{\gamma} \frac{r^*}{PV} \sum_{i=1} \omega_i h_i$$

$$M = \frac{V}{\sqrt{\gamma R T}}$$

$$\gamma = \frac{C_p}{C_p - R}$$

and

$$C_p = \sum_{i=1} c_i C_{pi}.$$

The first set of equations is completely specified at the sonic point while the second set of equations is singular. Thus, if the expansion through the nozzle is specified by the pressure distribution, the equations governing the expansion can be directly integrated through the sonic point without mathematical difficulty.

The expansion from the chamber through the sonic point is specified by the pressure distribution in the present program in order to eliminate numerical difficulties at the sonic point. In the expansion section downstream of the sonic point, however, the area variation is specified and the second set of equations is integrated through the supersonic expansion section.

In specifying the nozzle pressure distribution from the chamber through the sonic point, rather than the known area distribution, a question naturally arises regarding how accurately the calculation represents the flow through a specified nozzle geometry. It has been shown by Bray [6] and others that the pressure distribution through a nozzle is essentially identical with the equilibrium pressure distribution up to the freeze point which generally occurs downstream of the throat (or sonic point). Thus, the difference in the expansion and predicted performance caused by utilizing the equilibrium pressure distribution rather than the nozzle geometry to specify the expansion from the chamber to the sonic point is negligible. If a case does arise in which the equilibrium pressure distribution is not an adequate representation of the expansion, the pressure distribution can be iterated to obtain the correct pressure distribution. Experience has shown that this is rarely if ever required.

In the above analysis the chemistry is brought into the conservation equations through the net species production rates, ω_i. The analysis pertaining to the chemistry is given in the following section.

2.2 CHEMISTRY

The method by which the net species production rate, $\dot{\omega}_i$, required by the preceeding analysis is determined is described below.

A chemical reaction can be written in terms of its stoichiometric coefficients (ν_{ij} and ν'_{ij}) as

$$\sum_{i=1} \nu_{ij} \; \bar{M}_i \rightleftarrows \sum_{i=1} \nu'_{ij} \; \bar{M}_i$$

where $\bar{M}_i$ represents the i^{th} chemical species name and j represents the j^{th} reaction.

Given a system of chemical reactions, the net species production rate ω_i for each species (component) is calculated from

$$\omega_i = m_{w_i} \sum_{j=1} \rho^{\sum_{\ell=1} \nu_{\ell j}} (\nu'_{ij} - \nu_{ij}) \; X_j$$

where

$$X_j = [K_j \prod_{i=1} \bar{c}_i^{\;\nu_{ij}} - \rho^{\lambda_j} \prod_{i=1} \bar{c}_i^{\;\nu'_{ij}}] \; k_j \, M_j \qquad (2.2\text{-}1)$$

The reaction rate, k_j, is from right to left (reverse) in the above equation and is represented by the Arrhenius form

$$k_j = a_j T^{-n_j} e^{(-b_j/\Re T)}$$

where

a_j	is the pre-exponential coefficient
n_j	is the temperature dependence of the pre-exponential factor
b_j	is the activation energy

The term M_j is provided so that the reaction rate can be modified for reactions involving a third body, i.e.

$$M_j = \sum_{i=1} m_{j,i} \, \bar{c}_i \qquad \text{for reactions requiring a third body}$$

$$M_j = 1 \qquad \text{for all other reactions}$$

where the constants $m_{j,i}$ are specified, and

$$\bar{c}_i = c_i / Mw_i$$

The integer, λ_j, is determined for a given reaction from the stoichiometric coefficients

$$\lambda_j = \sum_{i=1} (\nu'_{ij} - \nu_{ij})$$

The equilibrium constant, K_j, is*

$$K_j = e^{-\Delta F/\mathcal{R}T} \quad (\mathcal{R}T)^{-\lambda_j}$$

where

$$\Delta F = \sum_{i=1} f_i \nu_{ij} - \sum_{i=1} f_i \nu'_{ij}$$

Reactions involving a third body have a distinct reaction rate for each particular third body, so that the net production rate should be calculated from

$$X_j = \sum_{k=1} \left[K_j \prod_{i=1} \bar{c}_i^{\nu_{ij}} - \rho^{\lambda_j} \prod_{i=1} \bar{c}_i^{\nu'_{ij}} \right] \bar{c}_k \, k_{kj} \qquad (2.2\text{-}2)$$

rather than Equation (2.2-1). Benson and Fueno [7] have shown theoretically that the temperature dependence of recombination rates is approximately independent of the third body. Available experimental recombination rate data also indicates that the temperature dependence of recombination rates is independent of the third body within the experimental accuracy of the measurements. Assuming that the temperature dependence of recombination rates is independent of the third body, the recombination rate associated with the kth species (third body) can be represented as

$$k_{kj} = a_{kj} T^{-n_j} e^{(-b_j/\mathcal{R}T)} \qquad (2.2\text{-}3)$$

where only the constant a_{kj} is different for different species (third bodies). From Equation (2.2-2) it can be shown that

$$X_j = \left[K_j \prod_{i=1} \bar{c}_i^{\nu_{ij}} - \rho^{\lambda_j} \prod_{i=1} \bar{c}_i^{\nu'_{ij}} \right] \sum_{k=1} a_{kj} \bar{c}_k \, T^{-n_j} e^{-b_j/\mathcal{R}T}$$

$$= \left[K_j \prod_{i=1} \bar{c}_i^{\nu_{ij}} - \rho^{\lambda_j} \prod_{i=1} \bar{c}_i^{\nu'_{ij}} \right] \left[\sum_{i=1} \frac{a_{ij}}{a_{kj}} \bar{c}_i \right] a_{kj} \, T^{-n_j} e^{-b_j/\mathcal{R}T}$$

---

*K_j is also the ratio of the forward to reverse reaction rates.

Thus the recombination rates associated with each third body can be considered as in Equation (2.2-1) by calculating the general third body term (M_j) as

$$M_j = \sum_{i=1} m_{j,i} \bar{c}_i$$

where $m_{j,i}$ is the ratio $\left(\frac{a_{ij}}{a_{kj}}\right)$ of the recombination rate associated with the i^{th} species (third body) to the recombination rate associated with the k^{th} species (third body) which is the reference species (third body) whose rate in the form of Equation (2.2-3) is specified in the program input.

Chemical kinetic rate data is discussed in Appendix A.

2.3 CONSERVATION EQUATIONS FOR TWO DIMENSIONAL KINETIC EXPANSIONS

The conservation equations governing the axisymmetric inviscid flow of reacting gas mixtures have been given by Hirschfelder, Curtiss and Bird[4] Penner[5] and others. The basic assumptions made in the derivation of these equations are:

- There are no mass or energy losses from the system
- The gas is inviscid
- Each component of the gas is a perfect gas
- The internal degrees of freedom (translational, rotational, and vibrational) of each component of the gas are in equilibrium.

The conservation equations are presented here in the form used in the present analysis.

For each component of the gas, the continuity equation is

$$\left(\rho_i u\right)_x + \frac{1}{r}\left(r\rho_i v\right)_r = \omega_i r^* \tag{2.3-1}$$

where the coordinates (r,x) have been normalized with the throat radius. Summing over all components of the mixture, the overall continuity equation is obtained

$$(\rho u)_x + \frac{1}{r}(r\rho v)_r = 0 \tag{2.3-2}$$

Combining the above two equations gives

$$u\left(c_i\right)_x + v\left(c_i\right)_r = \frac{\omega_i r^*}{\rho} \tag{2.3-3}$$

The momentum equations are

$$\rho(uu_x + vu_r) + P_x = 0 \tag{2.3-4}$$

$$\rho(uv_x + vv_r) + P_r = 0 \tag{2.3-5}$$

The energy equation is

$$h + \frac{1}{2}(u^2 + v^2) = H_c \tag{2.3-6}$$

where

$$h = \sum_{i=1} c_i h_i \tag{2.3-7}$$

and

$$h_i = \int_o^T C_{pi}\, dT + h_{io} \tag{2.3-8}$$

For each component of the gas, the equation of state is

$$P_i = \rho_i R_i T \tag{2.3-9}$$

Summing over all components of the mixture, the overall equation of state is obtained

$$P = \rho RT \tag{2.3-10}$$

where

$$R = \sum_{i=1} c_i R_i \tag{2.3-11}$$

2.4 INITIAL LINE CONSTRUCTION

The solution to equations 2.3-1 through 2.3-11 becomes highly complex in the subsonic-transonic domain. Because of the elliptic character of the partial differential equations for the case of steady-state, choked flow in a rocket nozzle, the known boundary conditions are improperly set. Thus, it is necessary to construct by approximate means an initial data line suitable for the calculation by method of characteristics of the flow field in the supersonic domain. The method used by the TDK Computer Program in constructing this initial line is summarized below.

2.4.1 Uniform Expansions

For the purpose of calculating a transonic solution in the region of the nozzle throat, an average expansion coefficient is determined. To accomplish this, a one-dimensional calculation is performed from the chamber to throat for the propellant system and nozzle geometry specified using the ODK subprogram.

Tables of flow properties (ρ, V, T, c_i) are constructed as a function of pressure. These tables span the nozzle throat region. An average expansion coefficient is computed using these tables as*

$$\gamma = \frac{\ln(P_\ell / P_1)}{\ln(\rho_\ell / \rho_1)}$$

where the subscripts 1 and ℓ refer to the first and last table entries, respectively.

Using the above expansion coefficient and the throat wall geometry, the transonic flow field is constructed using the method of Sauer in a somewhat modified form as described in section 2.4.3. The initial line calculated by this method is an approximation to the constant pressure surface emanating from the throat minimum point. Along a constant property line it is a reasonable assumption that a constant value for expansion coefficient can be used.

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* $\gamma \equiv \dfrac{d\,\ell nP}{d\,\ell n\rho} \doteq \dfrac{\ell n\,P_\ell - \ell n\,P_1}{\ell n\,\rho_\ell - \ell n\,\rho_1} = \dfrac{\ell n(P_\ell / P_1)}{\ell n(\rho_\ell / \rho_1)}$

The TDK transonic analysis computes the pressure value at the throat minimum point, the location of the corresponding isobar, and the variation of streamline flow angle along this isobar. This particular surface has been chosen because it is advantageous from the standpoint of the assumptions made in the transonic analysis. It satisfies boundary conditions exactly at the wall, as well as at the axis and will yield a constant Mach number which is usually slightly greater than unity. If supersonic, this surface will be upstream of its characteristics, both left and right running. Should this surface be subsonic due to nonequilibrium effects, a provision exists for displacing the initial line downstream. Once the pressure surface described above has been calculated, all of the other gas dynamic properties are obtained by interpolation from the tables constructed by ODK.

2.4.2 Zoned Expansions

Many rocket thrust chambers are designed to operate with a cool (fuel rich) barrier zone near the wall to help shield the wall from excessive heat transfer. In addition thrust chamber and injector design usually result in a mal-distribution of the fuel/oxidizer ratio so that the resultant flow is striated into numerous zones of varying mixture ratio. In order to obtain an estimate of the effect of these phenomena on engine performance, a zoned expansion capability is included in the TDK computer program. Each zone is assumed to have a distinct mixture ratio and to contain a specified fraction of the total nozzle mass flow rate. The zones are assumed to be axially symmetric and are distributed radially from the nozzle axis to the nozzle wall.

The procedure used in constructing an initial line for zoned expansions is analogous to that described above for uniform expansions. For the purpose of calculating a transonic solution in the region of the nozzle throat, an average expansion coefficient is determined for each zone. To accomplish this, a one dimensional calculation is performed from the chamber to throat for the propellant system and nozzle geometry specified using the ODK Computer Program. One such calculation is performed for each zone (i.e. for each mixture ratio).

Tables of flow properties (ρ, V, T, c_i) are constructed as a function of pressure for each zone. These tables span the nozzle throat region. An average expansion coefficient, $\bar{\gamma}_n$, is computed for each of N zones using these tables as

$$\bar{\gamma}_n = \frac{\ln(P_\ell / P_1)_n}{\ln(\rho_\ell / \rho_1)_n} \qquad n = 1, \ldots, N$$

where the subscripts 1 and ℓ refer to the first and last table entries, respectively.

Using the above expansion coefficient vector and the throat wall geometry, the transonic flow field is constructed using the method described in section 2.4.3. The initial line calculated by this method is an approximation to the constant pressure surface emanating from the throat minimum point. Along this line each zone is separated by a double point defining the properties on either side of the contact discontinuity.

These points, which have equal pressure and gas streamline angle, become dividing streamline points in the method of characteristics calculation (see subroutine DSPT, Section 5). Properties other than pressure and flow angle are discontinuous across a dividing streamline and these discontinuities may be large. Within a given zone only the gas streamline angle will vary with location (r,x) along the start line. Properties other than pressure and flow angle are obtained by interpolation on pressure from the tables constructed as described above by use of the ODK subprogram.

2.4.3 Transonic Analysis

The basic assumptions made in carrying out the transonic analysis are summarized below (see Reference 9 for a more complete discussion):

- The flow is inviscid and compressible
- The flow is near the sonic speed and directed nearly along the nozzle axis
- The flow is axially symmetric
- The flow is divided into annular zones, each of which is characterized by a single adiabatic expansion coefficient, γ.
- In the nozzle throat region the flow is dependent only on the local wall geometry

With the above assumptions equations 2.3-1 through 2.3-11 reduce to the equations governing the irrotational flow of a perfect gas, i.e.:

$$\frac{\partial v}{\partial x} - \frac{\partial u}{\partial r} = 0$$

and

$$(a^2 - u^2) \frac{\partial u}{\partial x} - 2uv \frac{\partial u}{\partial r} + (a^2 - v^2) \frac{\partial v}{\partial r} + \frac{a^2 v}{r} = 0$$

The method of analysis used to approximate a transonic solution to these equations is a small perturbation technique. For a one zone expansion the method reduces to that given by Sauer.[8] The method consists of normalizing the velocity to the critical speed of sound

$$\tilde{u} = \frac{u}{a^*}$$

$$\tilde{v} = \frac{v}{a^*}$$

Perturbation variables u' and v' (both of which are assumed of small magnitude with respect to unity) are then introduced.

$$\tilde{u} = 1 + u'$$

$$\tilde{v} = v'$$

It can be shown that substituting these relations into the governing equations and retaining only terms through first order gives*

$$\frac{\partial v'}{\partial x} - \frac{\partial u'}{\partial r} = 0$$

$$(\gamma + 1)\, u' \frac{\partial u'}{\partial x} - \frac{\partial v'}{\partial r} - v'/r = 0$$

An exact solution for the above equations can be constructed and is found to be

$$u' = \frac{1}{4} (\gamma + 1)\, B_1^2\, r^2 + C_1 \ln r + B_0 + B_1\, x$$

$$\begin{aligned} v' = \frac{1}{16} (\gamma + 1)^2 B_1^3\, r^3 + \frac{1}{2} (\gamma + 1)\, B_1\, C_1\, r \left(\ln r - \frac{1}{2}\right) \\ + \frac{1}{2} (\gamma + 1)\, B_1\, B_0\, r + C_2/r \\ + \left[\frac{1}{2} (\gamma + 1)\, B_1^2\, r + C_1/r\right] x \end{aligned}$$

where B_0, B_1, C_1, and C_2 are constant coefficients which must be determined from boundary conditions. For the case of a nozzle throat with constant radius of curvature, R, (i.e. a circular arc, see Figure 2-2) these coefficients are found to be

$$B_0 = - \frac{1}{4R}$$

$$B_1 = + \left(\frac{2}{(\gamma + 1) R}\right)^{\frac{1}{2}}$$

$$C_1 = C_2 = 0$$

which is the classical solution given by Sauer.[8]

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*A complete derivation of the material presented here is given in Reference 9.

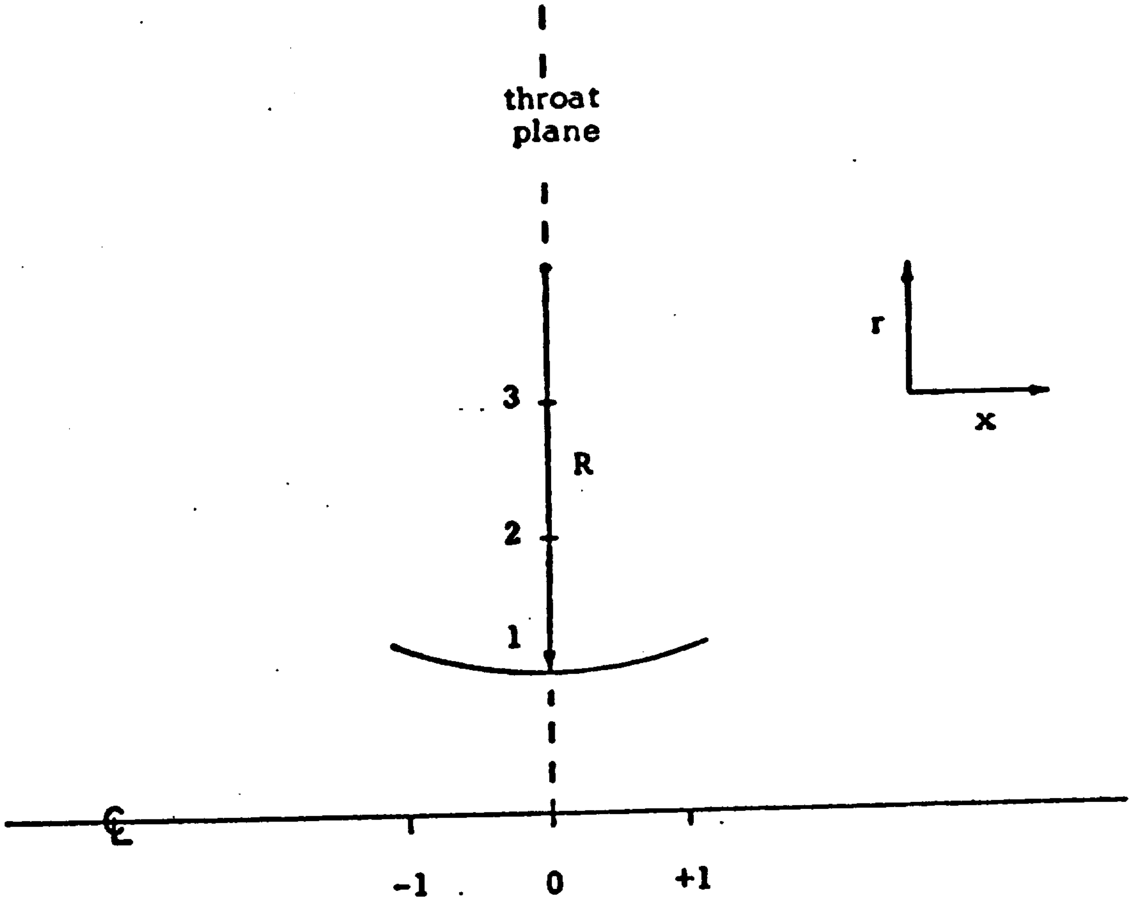

Figure 2-2 Nozzle Throat Geometry

Nearly all exhaust nozzles for engines using liquid propellants are constructed with a radius of curvature smaller than appropriate to the small perturbation methods of analysis. Fortunately a simple modification to the method yields results which compare favorably both with experimental measurement and with the results of other analysis when applied to throat geometries such as occur in rocket exhaust nozzles of practical interest. The basis for this modification is to bound the method such that the computed pressure proceeds to a physically reasonable limit for a zero radius of curvature throat. The bound is applied at the wall boundary condition and is chosen such that the ratio of pressure to sonic pressure be zero at this limit. This assumption leads to the result that

$$P/P^* \Big|_{\text{throat}} = 1 - (\gamma/4) \,/\, (R + \gamma/4)$$

rather than the usual result

$$P/P^* \Big|_{\text{throat}} = 1 - (\gamma/4) \,/\, R$$

which is divergent for $R = 0$. Results obtained from the transonic analysis (see Reference 8) have been found to compare favorably to both available experimental data and to the results of other, more complex, analytical methods.

To apply the small perturbation analysis to striated flow the analysis assumes that the nozzle flow is divided into N axially symmetric zones, each of which is characterized by a constant (i.e. average) specific heat ratio. These N zones are bounded by N-1 sliplines, i.e. dividing streamlines, such that pressure and streamline angle are matched but other properties such as velocity, temperature, and Mach number are discontinuous. A first order method is used to determine the radial coordinate location, Y_n, of each slipline. Once these locations are known, boundary conditions are applied at the wall, axis, and each slipline to complete the solution.

The indices n = 0, 1, . . . N identifying each zone and slipline boundary are taken numbered from nozzle axis to wall as shown in Figure 2-3. The sliplines are located at

$$Y_n \; ; n = 0, 1, \ldots, N$$

The total mass flow rate for the nozzle is

$$\dot{M}$$

and for each zone the partial mass flow rate is

$$\dot{m}_n = \frac{\text{mass flow rate, zone n}}{\dot{M}} \qquad , n = 1, 2, \ldots N$$

so that

$$\sum_{n=1}^{N} \dot{m}_n = 1 = \dot{m}_1 + \dot{m}_2 + \ldots + \dot{m}_n$$

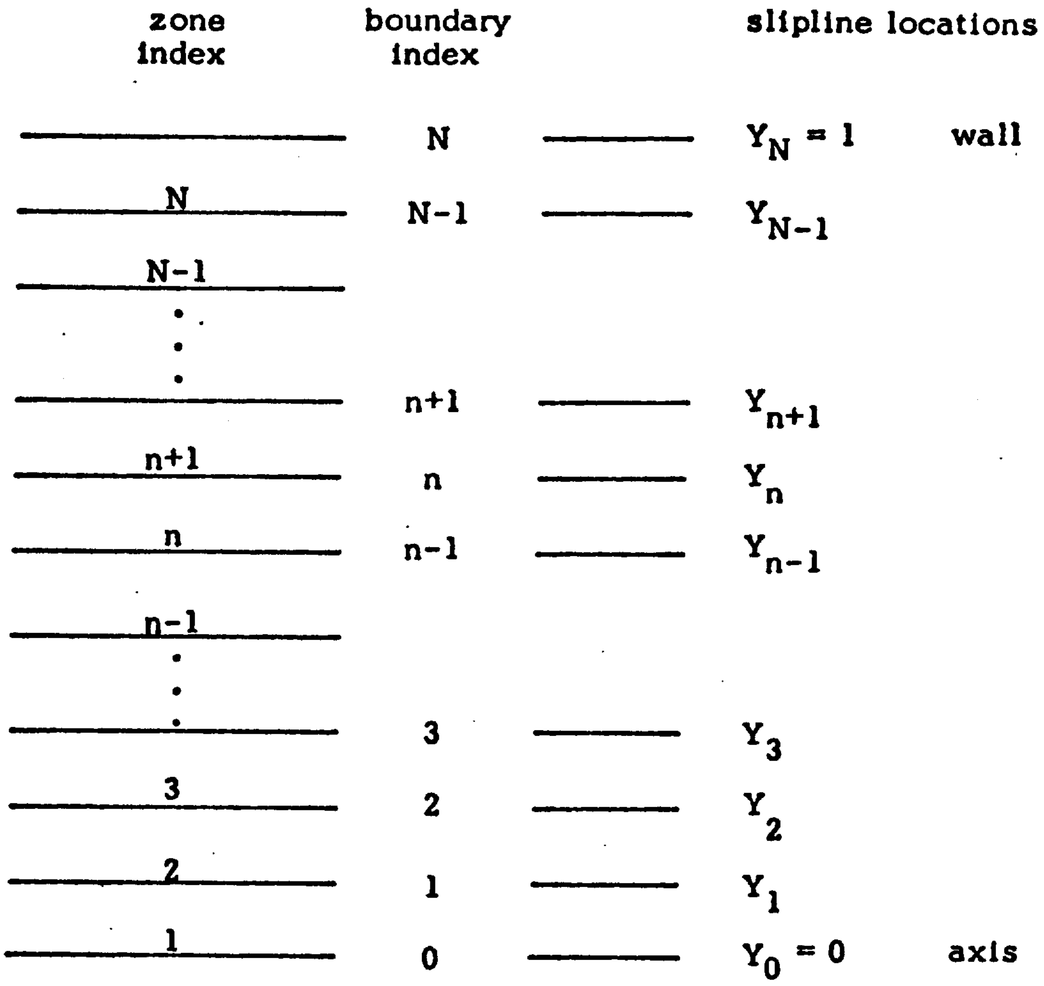

Figure 2-3 Nomenclature for the Numbering of Zones

Applying the continuity relation it can be shown that to first order the Y_n^2 are solutions to the tridiagonal system shown below.

$$\begin{bmatrix} (1 + A_1K_1) \, , & -1 & & & \\ -A_2K_2 \, , & (1 + A_2K_2) \, , & -1 & & \\ & \cdot & \cdot & & \\ & & \cdot & \cdot & \\ & & & -A_{N-1}K_{N-1} \, , & (1 + A_{N-1}K_{N-1}) \end{bmatrix} \begin{bmatrix} Y_1^2 \\ Y_2^2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ Y_{N-1}^2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ 1 \end{bmatrix}$$

where

$$K_n = \frac{\dot{m}_{n+1}}{\dot{m}_n} \qquad n = 1, 2, \ldots N-1.$$

$$A_n = \frac{\rho^*_n \; a^*_n}{\rho^*_{n+1} \; a^*_{n+1}} \qquad n = 1, 2, \ldots N-1$$

Once the slipline locations Y_n, are known it is necessary to apply boundary conditions sufficient to determine the constant coefficients B_{0_n}, B_{1_n}, C_{1_n}, C_{2_n}. The conditions applied are:

at the axis;

the radial velocity component is zero.

at the sliplines;

the gas pressure and streamline angle match through first order.

at the wall;

the gas streamline follows the wall streamline through first order. These conditions require that the following relations be satisfied by the constant coefficients:

at the axis (for n-1);

$$C_{1_1} = C_{2_1} = 0$$

at the sliplines (for n=2, . . ., N=1);

$$\begin{aligned}
&\frac{1}{16}(\gamma_n+1)^2 B_{1_n}^3 Y_n^3 + \frac{1}{2}(\gamma_n+1) B_{1_n} C_{1_n} Y_n (\ln Y_n - \tfrac{1}{2}) \\
&\qquad + \frac{1}{2}(\gamma_n+1) B_{1_n} B_{0_n} Y_n + C_{2_n} Y_n^{-1} = \\
&\frac{1}{16}(\gamma_{n+1}+1)^2 B_{1_{n+1}}^3 Y_n^3 + \frac{1}{2}(\gamma_{n+1}+1) B_{1_{n+1}} C_{1_{n+1}} Y_n (\ln Y_n - \tfrac{1}{2}) \\
&\qquad + \frac{1}{2}(\gamma_{n+1}+1) B_{1_{n+1}} B_{0_{n+1}} Y_n + C_{2_{n+1}} Y_n^{-1}
\end{aligned}$$

and

$$\frac{1}{2}(\gamma_n+1) B_{1_n}^2 Y_n + C_{1_n} Y_n^{-1} = \frac{1}{2}(\gamma_{n+1}+1) B_{1_{n+1}}^2 Y_n + C_{1_{n+1}} Y_n^{-1}$$

and

$$\begin{aligned}
&P_n^* \left\{ 1-\gamma_n \left[\frac{1}{4}(\gamma_n+1) B_{1_n}^2 Y_n^2 + C_{1_n} \ln Y_n + B_{0_n} \right] \right\} = \\
&P_{n+1}^* \left\{ 1-\gamma_{n+1} \left[\frac{1}{4}(\gamma_{n+1}+1) B_{1_{n+1}}^2 Y_n^2 + C_{1_{n+1}} \ln Y_n + B_{0_{n+1}} \right] \right\}
\end{aligned}$$

and

$$P_n^* \gamma_n B_{1_n} = P_{n+1}^* \gamma_{n+1} B_{1_{n+1}} .$$

at the wall (n = N);

$$\frac{1}{16}(\gamma_N+1)^2 B_{1_N}^3 - \frac{1}{4}(\gamma_N+1)\, B_{1_N} C_{1_N}$$

$$+\frac{1}{2}(\gamma_N+1)\, B_{1_N} B_{0_N} + C_{2_N} = 0$$

and

$$\frac{1}{2}(\gamma_N+1)\, B_{1_N}^2 + C_{1_N} = 1/R$$

The above equations form a system of 4N non-linear equations in 4N unknowns $(B_{0_n}, B_{1_n}, C_{1_n}, C_{2_n})$. For given values of R and of the vectors $\dot{m}_n$, A_n, γ_n, and Y_n the above system of equations can be used to determine the 4N unknown coefficients by employing standard numerical technique.

To apply a numerical method (such as the Newton method) to obtain a solution to the above system of equations requires an estimate for the solution vector $(B_{0_n}, B_{1_n}, C_{1_n}, C_{2_n})$. The TDK program uses the one zone solution to provide a first estimate. A good estimate is obtained since if

$$\gamma_n = \gamma_{n+1} \qquad n = 1, 2, \ldots, N-1$$

the one zone solution satisfies the above system identically. The program also takes advantage of the banded property of the Jacobian, J, for the above system in using Newton's Method, $x^{(k+1)} = x^{(k)} - J^{(k)^{-1}} f^{(k)}$, to obtain solutions.

The method described above has also been bounded so as to give reasonable answers for nozzle geometries where R is small.

2.4.4 Transonic Model with Mixture Ratio Variation

The transonic model used by TDK which is described in the preceding section divides the flow into regions of constant mixture ratio that are separated by sliplines. Each region contains a specified fraction of the total mass flow. This method, which is called the striated flow option, has been modified so that flows with continuous mixture ratio variation can be analyzed. This variable mixture ratio option is described below.

When the variable mixture ratio option is used, there are no sliplines in the flow. Instead, the flow mixture ratio ,r, will vary from the axis ($\Psi=0$) to the wall ($\Psi=1$) as specified by an input table of r versus Ψ. The streamline function ,Ψ, represents the mass flow between the streamline and the axis, divided by the total nozzle mass flow. An ODK calculation is done for each entry in the above table. Values along the initial data line for the MOC are obtained by interpolation in the ODK results using pressure and radial coordinate position ,Y, as independent variables. The transonic analysis is used to provide a table of Ψ versus Y. The method used is described below.

The ODK program constructs tables of flow properties (ρ, V, T, and c_1) as a function of pressure. These tables span the nozzle throat region. An average expansion coefficient is computed using these tables as

$$\bar{\gamma} = \ln (P_\ell/P_1)/\ln (\rho_\ell/\rho_1)$$

where the subscripts 1 and ℓ refer to the first and last table entries, respectively. Values of Y are found from $\bar{Y}$ and from input to the transonic analysis

$$Y_n = (\bar{Y}_n + \bar{Y}_{n-1})/2 \qquad n = 1,2,\ldots N$$

and also

$$P_{c_n} = (\bar{P}_{c_n} + \bar{P}_{c_{n-1}})/2$$

$$\xi_n = \Psi_n - \Psi_{n-1}$$

Using these values, the transonic analysis calculates

$$Y_0 = 0,\ Y_1,\ Y_2,\ \ldots Y_N = Y_{wall}.$$

The above Y_n values represent the radial location at which the input mixture ratios

$$r_0,\ r_1,\ r_2, \ldots . r_N$$

are located. In this way the input table of r versus Ψ is converted to a table of r versus Y.

Next, the transonic analysis is used to compute the coefficients (B_{0_n}, B_{1_n}, C_{1_n}, C_{2_n}). These are used to compute $P(X,Y)$ and $\theta\ (X,Y)$ in the transonic region (see Reference 9, pp.2-20) at points $n=0,1\ldots N$. Using each of these $N + 1$ values of P as an independent variable, the corresponding values for ρ, V, T, and c_i are obtained by linear interpolation from the corresponding table that was computed by ODK. These tables are then used to linearly interpolate for P, ρ, V, θ, T, and c_i at each MOC initial line point using ψ as the independent variable.

The program will not function properly if the spacing in the mixture ratio table, r_n, is too large. The required spacing depends on the chemcial system. As a rule each entry must differ no more than 4 or 5% from its adjacent values, depending on the stoichiometry of the system.

The average engine mixture ratio, r_{ave}, is also calculated:

$$r_{ave} = \int_0^{Y_{wall}} \left(\frac{r}{r+1}\right) d\dot{m} \Big/ \int_0^{Y_{wall}} \left(\frac{1}{r+1}\right) d\dot{m}$$

where

r is the mixture ratio at position Y, and

$$d\dot{m} = \rho V \frac{\sin(\phi-\theta)}{\sin\phi} YdY.$$

2.5 METHOD OF CHARACTERISTICS FOR KINETIC EXPANSIONS

By standard methods the characteristic relationships for the conservation equations 2.3-1 through 2.3-11 can be shown to be (see Volume 2, Section 18-3, Zucrow and Hoffman[10]).

$$\frac{dr}{dx} = \tan\theta$$

$$d\,\frac{V^2}{2} + \frac{dP}{\rho} = 0$$

$$\frac{dP}{\gamma P} - \frac{d\rho}{\rho} = \frac{A}{\cos\theta}\,dx$$

$$\frac{\gamma - 1}{\gamma}\,\frac{dP}{P} - \frac{dT}{T} = \frac{B\,dx}{\cos\theta}$$

$$dc_i = \frac{\omega_i r^*}{\rho V \cos\theta}\,dx$$

along streamlines,

$$\frac{dx}{dr} = \cot(\theta + a) \qquad (2.5\text{-}1)$$

$$\frac{dP}{P} = G\left[\left(A - \frac{\sin\theta}{r}\right)F\,dr - d\theta\right] \qquad (2.5\text{-}2)$$

along left running characteristics, and

$$\frac{dr}{dx} = \tan(\theta - a) \qquad (2.5\text{-}3)$$

$$\frac{dP}{P} = -G\left[\left(A - \frac{\sin\theta}{r}\right)H\,dx - d\theta\right] \qquad (2.5\text{-}4)$$

along right running characteristics, where

$$A = \frac{r^*}{PV}\left(\sum_{i=1} \omega_i R_i T - \frac{\gamma - 1}{\gamma} \sum_{i=1} \omega_i h_i\right)$$

$$B = \frac{r^*}{PV} \frac{\gamma - 1}{\gamma} \sum_{i=1} \omega_i h_i$$

$$V = \left(u^2 + v^2\right)^{1/2}$$

$$\theta = \tan^{-1}\left(\frac{v}{u}\right)$$

$$\alpha = \sin^{-1}\left(\frac{1}{M}\right)$$

$$M = \frac{V}{(\gamma R T)^{1/2}}$$

$$\gamma = \frac{C_p}{C_p - R}$$

$$C_p = \sum_{i=1} c_i C_{pi} .$$

$$F = \cos\theta - \sin\theta \cot(\theta + \alpha) \tag{2.5-5}$$

$$G = \frac{\gamma}{\sin\alpha \cos\alpha} \tag{2.5-6}$$

$$H = \cos\theta \tan(\theta - \alpha) - \sin\theta \tag{2.5-7}$$

The above form of the characteristic relationships remains determinant when the streamline is horizontal, when the left running characteristic is vertical, or when the right running characteristic is horizontal. Rarely (if ever) will the inverse of the three situations occur in nozzle flow field calculations.

In the analysis above the chemistry is brought into the conservation equations through the net species production rates, ω_i. The analysis pertaining to the chemistry is identical to that used by the ODK program as presented in Section 2.2.

2.5.1 Method of Characteristics for Frozen Expansions (TDF)

The methods developed in the preceding section for kinetic expansions apply with the exception that

$$\dot{\omega}_i = 0$$

so that

$$A = B = 0$$

and

$$dc_i/dx = 0$$

Ordinarily the TDF expansion assumes the chemical composition to be frozen at the equilibrium values at the chamber contraction ratio (ECRAT). However, initial species compositions and flow conditions can be input. This is the procedure that must be followed when analyzing hydrazine monopropellant thrusters.

2.5.2 Method of Characteristics for Equilibrium Expansions (TDE)

The supersonic expansion can be analyzed using the method of characteristics assuming that the process is in a state of shifting chemical equilibrium. This option is called a TDE analysis. It can be used both for striated flow, and flow with streamline to streamline mixture ratio variation. Like the TDF analysis, it is very much faster than a TDK analysis. The methods used by TDE are described below.

The conservation equations to be solved are:

continuity:

$$(\rho u)_x + \frac{1}{r}(r\rho v)_r = 0$$

momentum:

$$\rho\,(uu_x + vu_r) + P_x = 0$$

$$\rho\,(uv_x + vv_r) + P_r = 0$$

energy: The energy equation is not used explicitly. Instead, property distributions are provided in the form of tables by a separate equilibrium computation. The energy equation is then satisfied in an implicit manner as*

$$V = (2h_o - 2h)^{1/2}$$

where

$$h = h(P)$$

is supplied by the chemical equilibrium module, ODE, in the form of a table.

---

*Entropy is a constant for the expansion so that a function of only one variable, P, is required.

state: The state equation is also satisfied in an implicit manner as

$$\rho = \frac{PM_w}{RT}$$

where $T = T(P)$

and $M_w = M_w(P)$

are supplied by the chemical equilibrium module, ODE, in the form of tables.

The above conservation equations have been transformed to the characteristic form and are solved numerically in the same manner as by TDK. For convenience tables of specific heat ratio and Mach number are also tabulated. The complete set of tables used are:

h	vs	$\log(P)$	enthalpy
M	vs	$\log(P)$	Mach number
M_w	vs	$\log(P)$	molecular weight
T	vs	$\log(P)$	temperature
γ	vs	$\log(P)$	ratio of specific heats

where each of the above tables has been constructed for each zone (i.e., region of constant mixture ratio) of the expansion. The above choice of curve fit form (i.e., vs P or log P) was made after investigating the graphical form of the above functions for typical equilibrium expansions. A spline fit method is used to interpolate in the above tables.

2.5.3 METHOD OF CHARACTERISTICS FOR APPROXIMATE KINETIC EXPANSION (TTDK)

The supersonic expansion can be analyzed using the method of characteristics assuming that the gas properties are defined by a set of tables prepared by the ODK module. The procedures and tables are the same as presented in the preceding subsection describing TDE expansions, except that ODK is used to prepare the tables, not ODE.

An expression for the kinetic variable, A, is also required. It is found as (see the third equation in Section 2.5):

$$A = \left(\frac{1}{\gamma P} \frac{dP}{dX} - \frac{1}{\rho} \frac{d\rho}{dX} \right) \cos \theta$$

where dP/dX and $d\rho/dX$ are found by numerical differencing.

The kinetic variable, B, is not required, since the gas temperature is found as a tabular function of the logarithm of the pressure.

A significant advantage of this option is that it gives an order of magnitude reduction in computer time for a given case. Although exact results can be obtained in the frozen and equilibrium limits, error can be introduced when the expansion is in chemical nonequilibrium.

2.5.4 SUPERSONIC FLOW WITH SHOCK WAVES

For the case of continuous variation (or no variation) in mixture ratio, the TDK computer program can calculate the effects of a single shock wave that is caused by the nozzle wall. The shock can either be attached to the wall, or induced by the wall. The latter case is the more difficult to treat. The program logic utilizes a series six of point calculation procedures to locate and compute the shock. These procedures are illustrated in Figures 2-4a through f. The flow direction

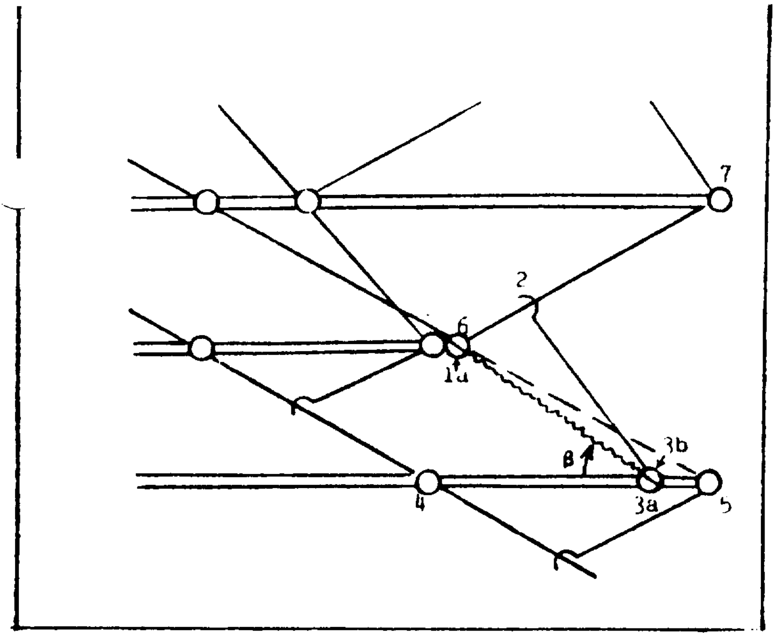

Fig. 2-4a: Right-Running Shock Point

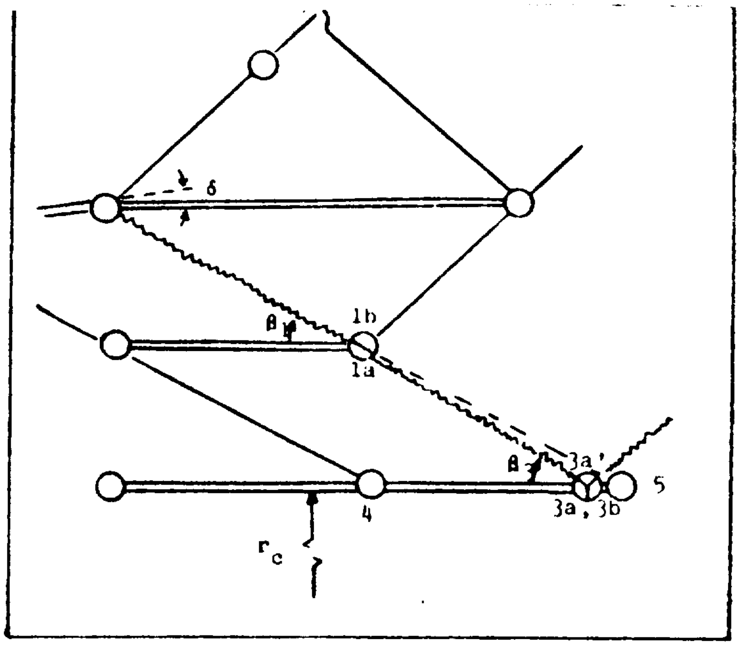

Fig. 2-4b: Shock Reflection Point at the Axis

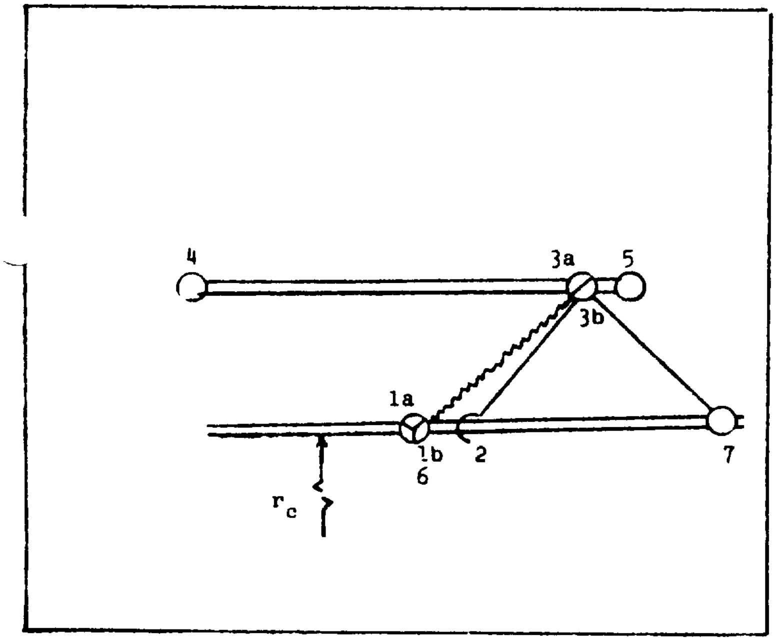

Fig. 2-4c: Left-Running Shock Point at the Axis

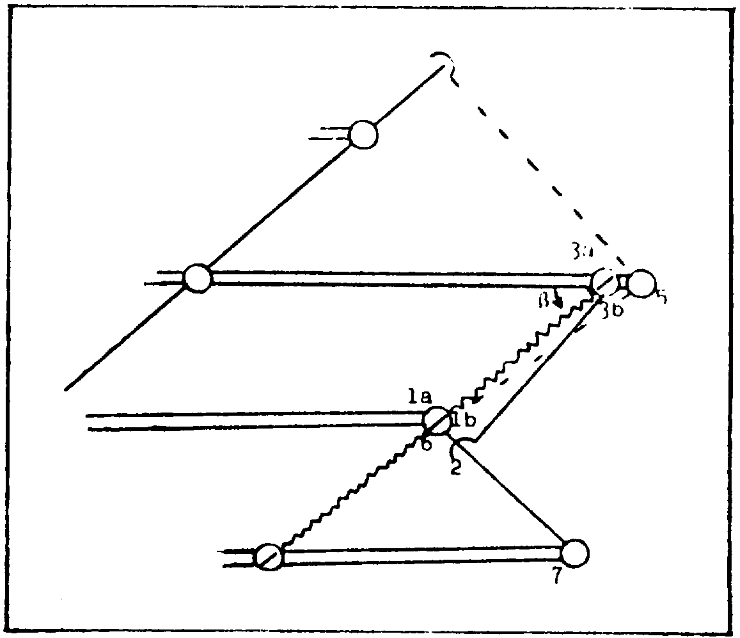

Fig. 2-4d: Left-Running Shock Point

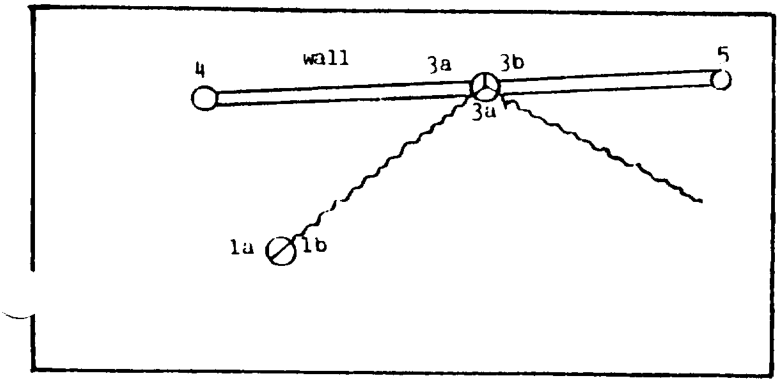

Fig. 2-4e: Shock Reflection Point at the Wall

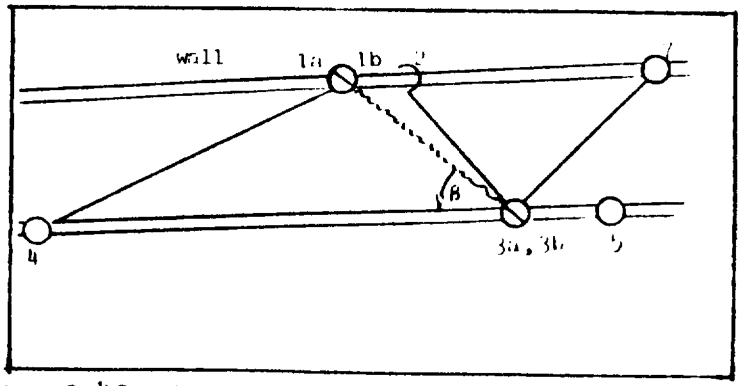

Fig. 2-4f: Right-Running Shock Point at the Wall

is left to right with streamlines shown as double lines. As shown in Fig. 2-4a the shock is initiated by a crossing of right-running characteristics. A shock point, labeled 3a (front) and 3b (back) is computed by iteration of the streamline, characteristic, and shock relations. When completed, the point location and the front and back side properties satisfy all of these relations. This right running shock is traced to the flow axis and reflected as a left running shock. The procedure for calculating the reflection is shown in Fig. 2-4b. If at any point in the shock tracing it is found that regular reflection is not possible, then a right regular cylinder of radius, r_c, is inserted centered along the flow axis. The shock is reflected from this cylinder, which is located so that regular reflection is still possible. In this way Mach shocks are removed from the flow. The first point off the axis (or cylinder) behind the shock reflection is calculated by the special procedure shown in Fig. 2-4c. Next, the shock is traced as a left running shock using the point calculation procedure shown in Fig. 2-4d. This procedure is the inverse of the right running shock point procedure shown in Fig. 2-4a. When the shock reaches the wall, it is reflected using the procedure shown in Fig. 2-4e. A special point calculation procedure is then required for the first point behind this reflection as shown in Fig. 2-4f. The resultant right running shock is then traced as before, etc. Thus, multiple reflections are allowed from the axis and the wall. In general the shock strengthens as it travels towards the axis (right running), and weakens as it travels away from the axis and towards the wall (left running).

The shock option is not applicable to the TDE and TTDK options.

2.6 THE BOUNDARY LAYER MODULE (BLM)

The purpose of the Boundary Layer Module (BLM) is to provide a method for computing compressible laminar and turbulent wall boundary layers in axisymmetric nozzles. The BLM can also be used to calculate two-dimensional and axisymmetric external flows. The method utilizes an efficient two-point finite difference method developed by Keller and Cebeci[11]. Turbulence modeling is achieved through the use of Cebeci-Smith eddy-viscosity formulation[12] which has been tested for a large class of flows with various boundary conditions.

In this section the method is described and the relavant equations, turbulence model, fluid properties and solution procedure are presented. Description of the numerical procedure is not presented, since it has already been described in several sources, for example Reference 13.

The computer program on which the BLM is based was developed for SEA, Inc. by CBC Enterprises, Inc.

Ref. 11 Keller, H. B., and Cebeci, T.: Accurate Numerical Methods for Boundary Layer Flows, Pt. 2, Two-Dimensional Turbulent Flows. AIAA J., 10, 1972, pg. 1193.

Ref. 12 Cebeci, T., and Smith, A. M. O.: Analysis of Turbulent Boundary Layers, Academic Press, N.Y., 1974.

Ref. 13 Bradshaw, P., Cebeci, T., and Whitelaw, J. H.: Engineering Calculation Methods for Turbulent Flows. Academic Press, London, 1981.

2.6.1 Boundary-Layer Equations

For a compressible boundary-layer flow in a symmetric nozzle, the governing equations are well known and can be written as

Continuity

$$\frac{\partial}{\partial x}(\rho u r^k) + \frac{\partial}{\partial y}(\overline{\rho v} r^k) = 0 \tag{2.6-1}$$

Momentum

$$\rho u \frac{\partial u}{\partial x} + \overline{\rho v}\frac{\partial u}{\partial y} = \rho_e u_e \frac{du_e}{dx} + \frac{1}{r^k}\frac{\partial}{\partial y}\left[r^k\left(\mu\frac{\partial u}{\partial y} - \rho\overline{u'v'}\right)\right] \tag{2.6-2}$$

Energy

$$\rho u \frac{\partial H}{\partial x} + \overline{\rho v}\frac{\partial H}{\partial y} = \frac{1}{r^k}\frac{\partial}{\partial y}\left\{r^k\left[\frac{\mu}{Pr}\frac{\partial H}{\partial y} + \mu\left(1 - \frac{1}{Pr}\right) u \frac{\partial u}{\partial y} - \rho\overline{H'v'}\right]\right\} \tag{2.6-3}$$

where k denotes the flow index which is zero for a two-dimensional flow and is unity for an axisymmetric flow, and

$$\overline{\rho v} = \rho v + \overline{\rho' v'}$$

$$r = r_o - y \cos\phi$$

The boundary conditions for Eqs. (7-1) to (7-3) are

$$\text{at} \quad y = 0, \quad u = 0, \quad v = v_w(x),$$

$$T = T_w(x) \quad \text{or} \quad \dot{q}_w(x) \text{ (heat transfer specified)} \tag{2.6-4a}$$

$$\text{at} \quad y = \delta, \quad u = u_e, \quad H = H_e \tag{2.6-4b}$$

The above equations require initial conditions and a turbulence model for Reynolds shear stress and heat flux terms, $-\rho\overline{u'v'}$ and $-\rho\overline{H'v'}$, respectively. Here we use the concepts of eddy viscosity and turbulent Prandtl number and define

$$-\rho\overline{u'v'} = \rho\varepsilon_m \frac{\partial u}{\partial y}, \qquad -\rho\overline{H'v'} = \rho \frac{\varepsilon_m}{Pr_t}\frac{\partial H}{\partial y} \tag{2.6-5}$$

We also use transformed variables to provide the initial conditions for a stagnation point flow and to reduce the sensitivity of the solutions to the Δx-spacing. They are defined by

$$d\xi = \left(\frac{r_o}{L}\right)^{2k} dx \tag{2.6-6a}$$

$$d\eta = \left(\frac{u_e}{\rho_e\mu_e\xi}\right)^{1/2} \rho\left(\frac{r}{L}\right)^k dy \tag{2.6-6b}$$

We also use a dimensionless stream function $f(\xi,\eta)$ defined by

$$\psi = (u_e\rho_e\mu_e\xi)^{\frac{1}{2}}\ L^k f(\xi,\eta) \tag{2.6-7}$$

where

$$\rho u r^k = \frac{\partial\psi}{\partial y}, \qquad \overline{\rho v} r^k = (\rho v)_w r_o^k - \frac{\partial\psi}{\partial x} \tag{2.6-8}$$

With these transformations and with the definition of the relations given by Eqs (2.6-6 to 8) . it can be shown that the momentum and energy equations can be written as

$$(bf'')' + m_1 ff'' + m_2[c - (f')^2] - m_3 f'' = \xi\left(f'\frac{\partial f'}{\partial\xi} - f''\frac{\partial f}{\partial\xi}\right) \tag{2.6-9}$$

$$(eg')' + (df'f'')' + m_1 fg' - m_3 g' = \xi\left(f'\frac{\partial g}{\partial\xi} - g'\frac{\partial f}{\partial\xi}\right) \tag{2.6-10}$$

Here primes denote differentiation with respect to η and

$$f' = u/u_e, \qquad g = H/H_e \tag{2.6-11}$$

The parameters b,e,d denote parameters defined by

$$b = (1 + \varepsilon_m^+)C(1 - t)^{2k}, \qquad e = \frac{C}{Pr}\left(1 + \varepsilon_m^+\frac{Pr}{Pr_t}\right)(1 - t)^{2k} \tag{2.6-12}$$

$$d = \frac{Cu_e^2}{H_e}\left(1 - \frac{1}{Pr}\right)(1 - t)^{2k}$$

where

$$C = \frac{\rho\mu}{\rho_e\mu_e}, \qquad c = \frac{\rho_e}{\rho}$$

The parameters below denote dimensionless pressure gradients

$$m_1 = \frac{1 + m_2 + m_4}{2}, \quad m_2 = \frac{\xi}{u_e}\frac{du_e}{d\xi}, \quad m_4 = \frac{\xi}{\rho_e\mu_e}\frac{d}{d\xi}(\rho_e\mu_e) \tag{2.6-13}$$

and m_3 denotes dimensionless mass transfer parameter

$$m_3 = \frac{(\rho v)_w}{\rho_e u_e} R_\xi^{1/2} \left(\frac{L}{r_0}\right)^k \tag{2.6-14}$$

The boundary conditions given by (2.6-4) can be written in the following form

$$\text{at} \quad \eta = 0, \qquad f = f' = 0, \qquad g = g_w(\xi) \text{ given}$$

or

$$g'_w(\xi) = \text{given} \tag{2.6-15a}$$

$$\text{at} \quad \eta = \eta_e, \qquad f' = 1, \qquad g = 1 \tag{2.6-15b}$$

Note that the wall mass transfer quantity $(\rho v)_w$ does not appear in the above boundary conditions, instead it appears in the differential equations through m_3. This is a useful convenient form when dealing with mass transfer (suction or blowing) problems.

2.6.2 Turbulence Model

Here we use the eddy-viscosity formulation due to Cebeci and Smith to model the Reynolds shear stress term. We assume a constant turbulent Prandtl number and take it equal to 0.9.

According to the Cebeci and Smith eddy-viscosity formulation, the dimensionless eddy-viscosity ϵ_m^+ is defined by two separate formulas: in the inner region of the boundary layer, ϵ_m^+ is defined by a modified mixing-length expression and in the outer region by an expression based on the velocity defect. This formulation is defined by the following expressions:

$$\epsilon_m^+ = \begin{cases} \frac{L^2}{\nu}\frac{\partial u}{\partial y}\ \gamma\gamma_{tr} & y \le y_c \quad \text{,inner} \\ \frac{0.0168}{\nu}\int_0^\infty |(u_e - u)|dy\ \gamma\gamma_{tr} & y > y_c \quad \text{,outer} \end{cases} \tag{2.6-16}$$

Here y_c is obtained from the continuity of eddy-viscosity expression. The definition of L is:

$$L = 0.4y[1 - \exp(-y/A)] \tag{2.6-17}$$

where

$$A = 26(\frac{\rho}{\rho_w})^{1/2}\frac{\nu}{N}u_\tau^{-1} \qquad u_\tau = (\frac{\tau_w}{\rho_w})^{1/2}$$

$$N^2 = \frac{\mu}{\mu_e}(\frac{\rho_e}{\rho_w})^2\frac{p^+}{v_w^+}[1 - \exp(11.8\frac{\mu_w}{\mu}v_w^+)] + \exp(11.8\frac{\mu_w}{\mu}v_w^+) \tag{2.6-18}$$

$$p^+ = \frac{\nu_e u_e}{u_\tau^3}\frac{du_e}{dx}, \quad v_w^+ = \frac{v_w}{u_\tau}, \quad R_\xi = \frac{u_e\xi}{\nu_e}, \quad \frac{\mu}{\mu_e}(\frac{\rho_e}{\rho_w})^2 = Cc_w^2$$

When there is no mass transfer,

$$N^2 = 1 - 11.8\frac{\mu_w}{\mu_e}(\frac{\rho_e}{\rho_w})^2 p^+ = 1 - 11.8C_w c_w^3 p^+$$

The parameter γ is an intermittency term defined by

$$\gamma = \frac{1}{1 + 5.5(y/\delta)^6} \tag{2.6-19a}$$

and γ_{tr} is a parameter which accounts for the transitional region which exists between a laminar and turbulent flow. At high Reynolds number flows, though the transition region is small and γ_{tr} has negligible effect on the results, this expression is still useful because it avoids a jump from laminar to turbulent flow calculations by allowing ϵ_m^+ to change gradually. It is given by:

$$\gamma_{tr} = 1 - \exp[-Gr_0^k(x_{tr})(\int_{x_{tr}}^{x}\frac{dx}{r_0^k})(\int_{x_{tr}}^{x}\frac{dx}{u_e})] \tag{2.6-19b}$$

where G is a spot-formation-rate parameter

$$G = (3/C_1^2)(u_e^3/\nu_e^2)R_{\xi_{tr}}^{-1.34}$$

$$C_1 = 60 + 4.86M_e^{1.92}$$

In terms of transformed variables, the eddy-viscosity formulas become:

$$\varepsilon_m^+ = \begin{cases} \varphi_1 f'' & 0 < \eta < \eta_c \\ \varphi_2 \left| \int_0^{\eta_e} \frac{c}{(1 - t)^k} (1 - f')d\eta \right| & \eta_c \leq \eta < \eta_e \end{cases} \tag{2.6-20}$$

Here

$$\varphi_1 = \frac{0.16}{c^2} (\frac{L}{r_o})^k (1 - t)^k \frac{\mu_e}{\mu} R_\xi^{1/2} I_1^2 [1 - \exp(-y/A)]^2 \gamma\gamma_{tr}$$

$$\varphi_2 = \frac{0.0168}{c} \frac{\mu_e}{\mu} (\frac{L}{r_o})^k R_\xi^{1/2} \gamma\gamma_{tr}$$

(2.6-21)

$$\frac{y}{A} = \frac{N}{26} c^{-3/2} (\frac{L}{r_o})^{k/2} \frac{C_w^{1/2}}{C} R_\xi^{1/4} I_1 (f_w'')^{1/2}, \qquad I_1 = \int_0^\eta \frac{c}{(1 - t)^k} d\eta$$

$$p^+ = (\frac{u_e}{u_\tau})^3 \frac{m_2}{R_\xi} (\frac{r_o}{L})^{2k}, \qquad u_\tau = \frac{u_e}{R_\xi^{1/4}} \sqrt{c_w f_w'' C_w (r_o/L)^k}$$

2.6.3 Fluid Properties

Values of specific heat at constant pressure, C_p, and ratio of specific heats, γ, static enthalpy, h, and the gas constant R, are required by BLM. These properties are evaluated along the wall streamline as a function of temperature using the ODE module. The tables are prepared using a series of (T,S) equilibrium calculations, where T varies from 600^oR to 7000^oR at 200^oR increments. The chamber entropy value is used for S. Values at 100^oR are then extrapolated and added to the table. The table is printed with the BLM output. An example of this output is presented in Figure 2-5.

Since the ODE module did not contain a (T,S) option, it was added using the following procedure. Using known values of P_a, T_a, and γ_a, and the given value of temperature, T, a first estimate for pressure $P^{(1)}$ was found as

$$P^{(1)} = P_a \ (T/T_a).^{\gamma_a/(\gamma_a-1)}$$

The (T,P) option of ODE is used to obtain $S^{(i)}$ as a function of $P^{(i)}$. The procedure is iterated using the secant method (subroutine ITER plus a driver) to find $P^{(i)}$ such that

$$|(S^{(i)}-S_c)/S_c| < 5\ E\text{-}5$$

where S_c is the chamber entropy. The procedure is repeated for each temperature in these tables. The procedure is internal to the program and not callable through the ODE input.

If the chemical system contains a condensed phase, then equilibrium solutions made during phase change can yield values for γ that are unacceptable to BLM, e.g., values of $\gamma < 1$.

Figure 2-5: Tables of h, μ, k, C_p, γ, and R versus T^oR for use by the BLM

```
GAS PROPERTIES TABLES

     T            HS            MU              K              CP            GAMMA          RGAS
   DEG R       FT2/SEC2     LBM/FT-SEC   LBM-FT/S3-DEGR  FT2/SEC2-DEGR               LBF-FT/LBM-DEGR

 1.0000E+02   -1.4650E+08   2.1240E-06    4.5618E-02     1.3210E+04     1.3391E+00     1.0396E+02
 6.0000E+02   -1.3989E+08   9.3635E-06    2.0110E-01     1.3210E+04     1.3391E+00     1.0396E+02
 8.0000E+02   -1.3722E+08   1.1882E-05    2.6108E-01     1.3514E+04     1.3289E+00     1.0396E+02
 1.0000E+03   -1.3448E+08   1.4293E-05    3.2270E-01     1.3887E+04     1.3173E+00     1.0396E+02
 1.2000E+03   -1.3167E+08   1.6622E-05    3.8664E-01     1.4307E+04     1.3052E+00     1.0396E+02
 1.4000E+03   -1.2876E+08   1.8885E-05    4.5315E-01     1.4759E+04     1.2931E+00     1.0396E+02
 1.6000E+03   -1.2576E+08   2.1092E-05    5.2228E-01     1.5230E+04     1.2815E+00     1.0396E+02
 1.8000E+03   -1.2267E+08   2.3253E-05    5.9399E-01     1.5711E+04     1.2705E+00     1.0396E+02
 2.0000E+03   -1.1947E+08   2.5372E-05    6.6906E-01     1.6219E+04     1.2598E+00     1.0396E+02
 2.2000E+03   -1.1618E+08   2.7456E-05    7.4517E-01     1.6693E+04     1.2506E+00     1.0396E+02
 2.4000E+03   -1.1280E+08   2.9506E-05    8.2215E-01     1.7137E+04     1.2425E+00     1.0396E+02
 2.6000E+03   -1.0933E+08   3.1528E-05    8.9997E-01     1.7557E+04     1.2354E+00     1.0397E+02
 2.8000E+03   -1.0578E+08   3.3523E-05    9.7888E-01     1.7960E+04     1.2290E+00     1.0397E+02
 3.0000E+03   -1.0215E+08   3.5494E-05    1.0596E+00     1.8361E+04     1.2231E+00     1.0397E+02
 3.2000E+03   -9.8436E+07   3.7442E-05    1.1435E+00     1.8783E+04     1.2174E+00     1.0397E+02
 3.4000E+03   -9.4642E+07   3.9370E-05    1.2327E+00     1.9258E+04     1.2118E+00     1.0399E+02
 3.6000E+03   -9.0754E+07   4.1277E-05    1.3304E+00     1.9824E+04     1.2058E+00     1.0401E+02
 3.8000E+03   -8.6755E+07   4.3167E-05    1.4409E+00     2.0530E+04     1.1995E+00     1.0405E+02
 4.0000E+03   -8.2623E+07   4.5040E-05    1.5692E+00     2.1429E+04     1.1926E+00     1.0411E+02
 4.2000E+03   -7.8330E+07   4.6897E-05    1.7215E+00     2.2578E+04     1.1853E+00     1.0420E+02
 4.4000E+03   -7.3842E+07   4.8738E-05    1.9036E+00     2.4023E+04     1.1777E+00     1.0433E+02
 4.6000E+03   -6.9128E+07   5.0565E-05    2.1210E+00     2.5799E+04     1.1703E+00     1.0452E+02
 4.8000E+03   -6.4157E+07   5.2379E-05    2.3775E+00     2.7917E+04     1.1632E+00     1.0476E+02
 5.0000E+03   -5.8909E+07   5.4180E-05    2.6735E+00     3.0350E+04     1.1569E+00     1.0507E+02
 5.2000E+03   -5.3376E+07   5.5968E-05    3.0056E+00     3.3030E+04     1.1516E+00     1.0544E+02
 5.4000E+03   -4.7567E+07   5.7744E-05    3.3664E+00     3.5857E+04     1.1475E+00     1.0589E+02
 5.6000E+03   -4.1503E+07   5.9509E-05    3.7456E+00     3.8712E+04     1.1445E+00     1.0639E+02
 5.8000E+03   -3.5216E+07   6.1264E-05    4.1324E+00     4.1487E+04     1.1425E+00     1.0694E+02
 6.0000E+03   -2.8754E+07   6.3008E-05    4.5145E+00     4.4068E+04     1.1414E+00     1.0754E+02
 6.2000E+03   -2.2138E+07   6.4742E-05    4.8870E+00     4.6427E+04     1.1410E+00     1.0817E+02
 6.4000E+03   -1.5411E+07   6.6466E-05    5.2427E+00     4.8514E+04     1.1411E+00     1.0883E+02
 6.6000E+03   -8.6044E+06   6.8181E-05    5.5780E+00     5.0319E+04     1.1417E+00     1.0950E+02
 6.8000E+03   -1.7450E+06   6.9888E-05    5.8911E+00     5.1845E+04     1.1427E+00     1.1019E+02
 7.0000E+03    5.1455E+06   7.1585E-05    6.1813E+00     5.3109E+04     1.1439E+00     1.1087E+02
```

Since condensation is an isothermal process, using (T,S) solutions avoid this problem. It also avoids the "temperature out of range" problem that can occur had other, existing options been used.

The fluid properties shown in Fig. 2-5 are h, μ, κ, C_p, γ, and R versus T^oR. The values of μ and κ are prepared as described in Section 2.6.4. The values for h, C_p, γ, and R are prepared as described above, i.e., they are equilibrium properties including condensed phases (no gas particle lag). The gas constant, R, is the universal gas constant divided by the molecular weight of the equilibrium mixture.

If the invisid core flow is frozen, it is more appropriate to use gas properties prepared using a frozen expansion of the chemical species. The program will prepare frozen tables that are analogous to the equilibrium tables described above when the TDF option is used, or if requested.

2.6.4 Near Wall Gas Transport Properties.

Values of gas viscosity, μ, gas conductivity, κ, Prandtl number, Pr, are required by BLM. These transport properties are evaluated along the wall streamline as a function of temperature using the ODE module. It is assummed that the expansion is in equilibrium, including condensed species. In the model these properties are then computed as "frozen" properties using the local gas composition with condensed phases included.

The viscosity and thermal conductivity of the individual gaseous species are calculated from formulas given in Reference 14 as follows:

$$\mu_i = \frac{4.15822 \times 10^{-8} \sqrt{M_{w_i} T}}{\sigma_i^2 \;\; \Omega_i}$$

$$\kappa_i = \frac{\mu_i R}{M_{w_i}} (.45 + 1.32 \frac{C_{p_i}}{(R/M_{w_i})})$$

The required Lennard Jones parameters, (σ_i, Ω_i) are internally stored in the computer program for 206 gas phase species. (See Subroutine MUK in Section 5 of this report, for a list of the species.) The viscosity of the mixture is calculated from Wilke's semi-empirical formula[15].

$$\mu = \sum_{i=1}^{N} \left[\mu_i \left(1 + \sum_{\substack{j=1 \\ j \neq 1}}^{N} \Phi_{ij} \frac{x_j}{X_i} \right)^{-1} \right]$$

where N is the number of species, x_i the mole fraction of species i, and Φ_{ij} is defined by:

Ref. 14. Svehla, R. A., "Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures," NASA TR-132, 1962.

Ref. 15. Bird, R. B., Stewart, U. E., and Lightfoot, E. N., Transport Phenomena, John Wiley & Sons, 1960.

$$\Phi_{ij} = \frac{1}{2^{3/2}} \left[1 + \frac{M_i}{M_j} \right]^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_j}{M_i}\right)^{1/4} \right]^2$$

The thermal conductivity, κ, is based on the equation given by Mason and Saxena[16] which is a slight modification of Eucken's relation,

$$\kappa = \sum_{i=1}^{N} \kappa_i \left[1 + 1.065 \sum_{\substack{j=1 \\ j \neq 1}}^{N} \Phi_{ij} \frac{x_j}{x_i} \right]^{-1}$$

The results calculated as described above are used to provide the BLM with properties using the following procedure.

The viscosity at the nozzle throat, μ^*, and the corresponding temperature, T^*, are calculated. Using these values, an exponent, ω, is computed such that the expression

$$\mu = \mu^* \, (T/T^*)^{\omega}$$

provides a best fit in a least square manner to the chamber and exit values for viscosity. Next, a constant value for Prandtl number is computed as

$$Pr^* = \left(\frac{\mu \, C_p}{\kappa} \right)^*$$

where μ, κ, and C_p are evaluated at the nozzle throat. The "frozen" C_p value is used. The values transmitted to BLM are then μ^*, T^*, ω, and Pr^*. Actually, BLM only uses the ratio Pr/μ, and does not require κ or the frozen C_p versus T.

Ref. 16. Mason, E. A., and Saxena, S. C., Physics of Fluids, Vol. 1, No. 5, pp. 361-369, 1958.

2.6.5 Use of Boundary Conditions and Gas Properties by BLM

In general, the flow properties at the boundary layer edge as computed by TDK are not isentropic. The TDK expansion is isentropic only if the flow is in a state of equilibrium, or if the flow is frozen in composition. When the TDK expansion is not isentropic, there are inconsistencies between TDK and BLM with respect to edge values and gas properties. Thus it is important to describe the methods by which these parameters are treated.

TDK supplies BLM with tables of V, and P vs X. Corresponding values of static enthalpy, h, are computed from the relation:

$$h = H_t - V^2/2$$

i.e., the BLM is given the condition that total enthalpy at the boundary layer edge is constant. In BLM enthalpy profiles and velocity profiles at constant pressure are used as state variables. Temperature and the gas constant, R, are obtained as a function of h by interpolation in the gas properties tables that were computed by the ODE module (see Section 2.6.3). Temperature is not a state variable, but together with the gas constant, it is used to obtain the gas density from the equation of state, i.e.,

$$\rho = P/RT.$$

Thus, in general the gas density used by BLM at the boundary layer edge does not match the TDK value, although the values of P, V, and h do match.

The only other gas properties required by BLM are the Prandtl number, P_r, and the viscosity, μ. A constant value is input for P_r and the viscosity, μ, is computed (see Section 2.6.4) as

$$\mu = \mu^* (T/T^*)^\omega$$

where the reference values μ^* and T^* are taken at the nozzle throat.

Values for $C_p(T)$, $\gamma(T)$, and $k(T)$ are made available to BLM for auxillary calculations, but are not used in the boundary layer solution procedure.

2.6.6 Solution Procedure

The solution procedure uses the numerical method described in Bradshaw et.al., Reference 13, to solve the governing equations presented in Section 2.6.1. This is an efficient two-point finite-difference method developed by Keller and Cebeci and extensively used by Cebeci for two-dimensional and three-dimensional flows. A detailed description is presented in Reference 13, and is not repeated here.

One of the advantages of this numerical method is that nonuniform net spacings can be used in the x-direction as well as across the boundary layer. In the latter case, the nonuniform grid is a geometric progression with the property that the ratio of lengths of any two adjacent intervals is a constant; that is, $\Delta\eta_j = K\Delta\eta_{j-1}$. The distance to the j-th line is given by the following formula:

$$\eta_j = \Delta\eta_1(K^j - 1)/(K - 1) \qquad\qquad K > 1$$

There are two parameters in the above equation: 1) $\Delta\eta_1$, the length of the first step, and: 2) K, the ratio of two successive steps. The total number of points, J, can be calculated from the following formula:

$$J = \frac{\ln[1 + (K - 1)(\eta_e/\Delta\eta_1)]}{\ln K} + 1$$

Default values used by the computer program for $\Delta\eta_1$ and K are 0.01 and 1.14, respectively.

NOMENCLATURE FOR SECTION 2.6, BLM

Alphabetic Symbol	Definition
A	damping length
c	density ratio, ρ_e/ρ
C	dimensionless density-viscosity ratio
c_f	local skin-friction coefficient, $\tau_w/(1/2)\rho_e u_e^2$
c_p	specific heat at constant pressure
f	dimensionless stream function
g	total emthalpy ratio, H/H_e
h	static enthalpy
H	total enthalpy
k	flow index, 0 for two dimensional flow, 1 for axisymmetric flow
L	reference length
M	Mach number
M_w	molecular weight
P	static pressure
Pr	molecular Prandtl number
Pr_t	turbulent Prandtl number
q	heat-transfer rate
r	radial distance from axis of revolution
r_o	local radius of body of revolution
R	gas constant
R_ξ	local Reynolds number, $u_e\xi/\nu_e$
S	entropy
t	transverse curvature term, $y \cos\phi/r_o$
T	static temperature
u,v	x and y components of velocity, respectively
u_e	velocity at the edge of the boundary layer
u_τ	friction velocity $(\tau_w \rho_w)^{1/2}$
x	surface distance
X	axial distance
y	distance normal to the surface of the body

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NOMENCLATURE (Continued)

Greek Symbol	Definition
γ	ratio of specific heats, C_p/C_v
δ	boundary-layer thickness
δ^*	displacement thickness
ε_m^+	eddy viscosity
η	similarity variable
θ	momentum thickness
κ	gas conductivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress
ϕ	angle of body slope, $\tan^{-1}(dr_o/dX)$
ψ	stream function

Subscripts	Definition
c	chamber (stagnation) conditions
e	edge of the boundary layer
r	reference conditions
tr	transition
w	evaluated at the wall
x	x-direction

Superscripts	Definition
*	nozzle throat conditions

Primes designate differentiation with respect to η

3. NUMERICAL METHODS

In this Section numerical methods used by the ODK and TDK programs are discussed. The ODK subprogram integrates the system of differential equations presented in Section 2.1.1. Standard integration methods, such as Runge-Kutta, are impractical when applied to these differential equations because of the very small step sizes often required for stability. Consequently a fully stable integration method has been developed and applied as described in Section 3.1.

Solution of the characteristic differential equations presented in Section 2.5 also requires a numerically stable integration method. A highly stable implicit finite difference method is presented in Section 3.2 for integration of these characteristic relationships.

3.1 ODK NUMERICAL INTEGRATION METHOD

It has been shown by Tyson[17] that in the numerical integration of relaxation equations in near equilibrium flow regions (such as the chamber and nozzle inlet in rocket engines), explicit integration methods are unstable unless the integration step size is of the order of the characteristic relaxation distance of the relaxation equations. Since the characteristic relaxation distance is orders of magnitude smaller than the characteristic physical dimensions of the system of interest (such as the nozzle throat diameter and length) in near equilibrium flow regions, the use of explicit methods to integrate relaxation equations in these regions results in excessively long computation times. Implicit integration methods were shown to be inherently stable in integrating relaxation equations in all flow situations (whether near equilibrium or frozen) and can thus be used to integrate with step sizes of the order of the physical dimensions of the system of interest throughout the integration reducing the computation time per case several orders of magnitude. Since it has been demonstrated that there are significant advantages in using implicit rather than explicit integration of the relaxation equations, a second order implicit integration method has been chosen for use in the ODK computer program.

3.1.1 Stability Considerations

The numerical considerations leading to the above conclusions can be illustrated by considering the simple relaxation equation

$$\frac{dy}{dx} = - \frac{y - y_e}{\tau} \tag{3.1-1}$$

which represents the relaxation toward equilibrium of chemical reactions, gas particle lags, etc. In this equation y_e is the equilibrium condition and τ is the characteristic relaxation distance of the equation. In the equilibrium limit, τ is very small compared to the physical dimensions of the system of interest while in the frozen limit, τ, is very large compared to the physical dimensions of the system of interest. The mathematical behavior of solutions to the above equation can be found by considering the simple case where τ is constant and

$$y_e = y_{eo} + a(x - x_o)$$

which is equivalent to terminating the Taylor series for y_e after the first term. The exact solution for this case can be shown to be

$$y(x_o + h) = y(x_o) + \left[y_{eo} - y(x_o) - a\tau\right] \left[1 - e^{-h/\tau}\right] + ah$$

where $y(x_o)$ is the initial value of y and h is the integration step.

It is seen that the solution consists of two parts, a term which varies slowly with x and a term which exponentially decays with a relaxation length of τ, the characteristic relaxation length of Equation (3.1-1). Thus after a few relaxation lengths

$$y(x) \simeq y_{eo} + ah, \quad h >> \tau$$

which is independent of $y(x_o)$ the initial condition. Since explicit integration methods construct the solution of Equation (3.1-1) as a Taylor series about the initial condition $y(x_o)$, the above example indicated that explicit integration methods should be limited to step sizes of the order of a few relaxation lengths.

That this is indeed the case can be shown by explicitly integrating Equation (3.1-1) using Euler's method. The explicit finite difference form is

$$\frac{y(x_o + h) - y(x_o)}{h} = - \frac{y(x_o) - y_{eo}}{\tau}$$

which yields the truncated Taylor series

$$y(x_o + h) = y(x_o) \ (1 - \frac{h}{\tau}) + y_{eo} \frac{h}{\tau}$$

when solved for $y(x_o + h)$. After n integration steps, it is found that

$$y(x_o + nh) = y(x_o) \left[1 - \frac{h}{\tau}\right]^n + \sum_{i=1}^{n} \left[y_{oo} + (i - 1)\, ah\right] \left[1 - \frac{h}{\tau}\right]^{n-i} \frac{h}{\tau}$$

Examination of this equation shows that the independence on the initial condition $y(x_o)$ will decay only if $|1 - h/\tau| < 1$, otherwise $y(x_o + nh)$ will oscillate with rapidly increasing amplitude. Hence the calculation will be stable only if $h/\tau < 2$. Similar results are obtained for other explicit integration methods. (The stable step size for Runge-Kutta integrations is $h/\tau < 5.6$.) Thus the stable step size for explicit integration of relaxation equations is of the order of the relaxation distance which explains the large computation times associated with explicit integration of relaxation equations in near equilibrium flow regions. As shown below, the use of implicit integration methods allows the integration of relaxation equations on a step size which is independent of the relaxation length.

Implicitly integrating Equation (3.1-1) using Euler's method, the finite difference form of Equation (3.1-1) is

$$\frac{y(x_o + h) - y(x_o)}{h} = - \frac{y(x_o + h) - y_{eo} - ah}{\tau}$$

which yields

$$y(x_o + h) = \frac{y(x_o) + (y_{eo} + ah)\frac{h}{\tau}}{1 + \frac{h}{\tau}}$$

when solved for $y(x_o + h)$. After n integration steps it is found that

$$y(x_o + nh) = \frac{y(x_o)}{\left[1 + \frac{h}{\tau}\right]^n} + \sum_{i=1}^{n} \frac{y_{eo} + iah}{\left[1 + \frac{h}{\tau}\right]^{n+1-i}} \frac{h}{\tau} \tag{3.1-2}$$

Examination of this equation shows that the dependence on the initial condition $y(x_o)$ always decays, regardless of the step size. Hence the implicit calculation will always be stable. As an extreme example, consider one integration step, $h = x - x_o$. From Equation (3.1-2), it is seen that

$$y(x) \simeq y_{eo} + ah \quad , \quad h >> \tau$$

when the step size is large compared to the relaxation length and

$$y(x) = y(x_o) \; (1 - \frac{h}{\tau}) + y_{eo} \frac{h}{\tau} + \; . \; . \; . \; , \; h >> \tau$$

when the step size is small compared to the relaxation length.

It is seen that in the equilibrium limit (τ small, h/τ large) the exact solution and the implicit integration of the relaxation equation go to the same limit which is independent of the relaxation distance and depends only on the rate of change of the equilibrium condition. In the frozen case (τ large and h/τ small) the implicit and explicit methods are essentially the same (terminated Taylor series). Thus, implicit numerical integration methods can be used to integrate relaxation equations using step sizes of the order of the physical dimensions of the system of interest in all flow situations whether near equilibrium or near frozen. For a complete discussion of the numerical integration of relaxation equations, see Reference 17.

In choosing a numerical integration method, the primary items of concern are the stability, accuracy and simplicity of the method. As shown by Tyson[21] and discussed above, implicit methods are to be preferred for numerically integrating relaxation equations due to their inherent stability. Having chosen the basic integration method for stability reasons, the order of the integration method is determined by accuracy and simplicity considerations. In general, the higher the order of the integration method, the more complex the method becomes requiring more information in the form of past value or past derivatives of the function being integrated.

Second order methods (accurate to h^2 with error of order h^3) have the advantage of simplicity and flexibility since they require only one past value of the function while retaining sufficient accuracy to allow the use of reasonably economical step sizes. For these reasons, a second order implicit numerical integration method was chosen for use in the present program. A complete derivation of this numerical integration method is given in the following section.

3.1.2 Derivation of the ODK Numerical Integration Method

Consider the coupled set of first order simultaneous differential equations.

$$\frac{dy_i}{dx} = f_i(x, y_1, \ldots, y_N) \quad , \quad i = 1, 2, \ldots, N$$

It will be assumed that the equations are not singluar and that a solution exists which may be developed as a Taylor series about the forward point

$$k_{i,n+1} = \left.\frac{dy_i}{dx}\right|_{x_n+h} h - \left.\frac{d^2y_i}{dx^2}\right|_{x_n+h} \frac{h^2}{2} + \left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^3}{6} - \left.\frac{d^4y_i}{dx^4}\right|_{x_n+h} \frac{h^4}{24} + \cdots$$

where $k_{i,n+1}$ is the increment in y_i and h is sufficiently small. For equal integration steps

$$k_{i,n+1} + k_{i,n} = 2\left.\frac{dy_i}{dx}\right|_{x_n+h} h - 4\left.\frac{d^2y_i}{dx^2}\right|_{x_n+h} \frac{h^2}{2} + 8\left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^3}{6}$$

$$- 16\left.\frac{d^4y_i}{dx^4}\right|_{x_n+h} \frac{h^4}{24} + \cdots$$

Solving these equations for the derivative at the forward point, it is found that

$$\left.\frac{dy_i}{dx}\right|_{x_n+h} = \frac{3k_{i,n+1} - k_{i,n}}{2h} + \left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^2}{3} - \cdots$$

Expanding the function $f_i(x, y, \ldots, y_N)$ as a Taylor's series about the back point (x_n), it is found that

$$\left.\frac{dy_i}{dx}\right|_{x_n+h} = f_{i,n} + \alpha_{i,n} h + \sum_{j=1}^{N} \beta_{i,j,n} k_{j,n+1} + \left.\frac{d^3y_i}{dx^3}\right|_{x_n} \frac{h^2}{2} + \cdots$$

where

$$f_i = f_i(x, y_1 \,.\,.\,.\,, y_N).$$

$$\alpha_i = \frac{\partial f_i}{\partial x}$$

$$\beta_{i,j} = \frac{\partial f_i}{\partial y_j}$$

and the subscript n refers to the functions f_i, α_i and $\beta_{i,j}$ evaluated at the point x_n. Since

$$\left.\frac{d^3y}{dx^3}\right|_{x_n} = \left.\frac{d^3y}{dx^3}\right|_{x_n+h} - \left.\frac{d^4y}{dx^4}\right|_{x_n+h} h + \cdots$$

and

$$\left.\frac{d^4y}{dx^4}\right|_{x_n} = \left.\frac{d^4y}{dx^4}\right|_{x_n+h} \cdots\cdot,$$

Thus the formula for Taylor Series expansion about the back point can be written as

$$\left.\frac{dy_i}{dx}\right|_{x_n+h} = f_{i,n} + \alpha_{i,n}h + \sum_{j=1}^{N} \beta_{i,j,n}k_{j,n+1} + \left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^2}{2} \cdots\cdot$$

Equating the expressions for the derivative at the forward point and back point, it is found that

$$\frac{3k_{i,n+1} - k_{i,n}}{2h} = f_{i,n} + \alpha_{i,n}h + \sum_{j=1}^{N} \beta_{i,j,n}\, k_{j,n+1} + \left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^2}{6} + \cdots$$

or

$$k_{i,n+1} = \frac{1}{3}\left[k_{i,n} + 2\left(f_{i,n} + \alpha_{i,n}h + \sum_{j=1}^{N} \beta_{i,j,n}k_{j,n+1}\right)h\right] + \left.\frac{d^3y_i}{dx^3}\right|_{x_n+h} \frac{h^3}{9} + \cdots$$

Neglecting the third order derivative term and solving the set of N linear nonhomogeneous algebraic equations

$$\left(1 - \frac{2}{3}\beta_{i,i,n}h\right)k_{i,n+1} - \sum_{j=1}^{N}(1 - \delta_{i,j})\beta_{i,j,n}k_{j,n+1} = \frac{1}{3}\left[k_{i,n} + 2(f_{i,n} + \alpha_{i,n}h)h\right]$$

where $\delta_{i,j}$ is the Kronecker delta thus yields a second order implicit solution of the above coupled first order simultaneous differential equations.

For unequal step sizes, it can be similarly shown that solving the set of N linear nonhomogeneous algebraic equations

$$\left(1 - \frac{h_{n+1} + h_n}{2h_{n+1} + h_n}\beta_{i,i,n}h_{n+1}\right)k_{i,n+1} - \frac{h^2_{n+1}}{(2h_{n+1} + h_n)h_n}\sum_{j=1}^{N}(1 - \delta_{i,j})\beta_{i,j,n}k_{j,n+1}$$

$$= \frac{h^2_{n+1}}{(2h_{n+1} + h_n)h_n}\left[k_{i,n} + (f_{i,n} + \alpha_{i,n}h_{n+1})\frac{h_n}{h_{n+1}}(h_{n+1} + h_n)\right]$$

yields a second order implicit solution of the above set of coupled first order simultaneous differential equations.

3.2 TDK NUMERICAL INTEGRATION METHOD

The reacting gas characteristic relationships given in Section 2.5 are usually integrated using second order explicit methods. It has been shown, however , that implicit integration methods are superior to explicit methods for integrating chemical relaxation equations[17]. Thus, in the present program the fluid dynamic equations are integrated using an explicit Euler method while the chemical relaxation equations are integrated using a first order implicit integration method.

In numerically calculating flow fields using the method of characteristics, only two (previously calculated) known points are directly usable in calculating a forward point. In equilibrium flows, only two known points are required to calculate a forward point and the calculation is straightforward and unambigous. In nonequilibrium flows, however, more than two known points are required to calculate a forward point so that a choice must be made as to which points in the flow field will be used directly and which will be interpolated. Since even small interpolation errors in species concentrations are known to cause serious stability and accuracy problems in the numerical integration of the chemical relaxation equations, the back streamline point and one characteristic point were chosen as the known points. This choice avoids interpolation for the species concentrations in that only fluid dynamic properties (velocity, pressure, etc.) and the kinetic coupling terms (A and B) need be interpolated at one of the back characteristic points. Since these quantities are all slowly varying across the characteristics mesh, they can be accurately interpolated. Experience has shown that this choice of numerical integration methods and known data points is satisfactory for reacting gas characteristics calculations. A derivation of the numerical integration methods used in the program are given in Sections 3.2.1 and 3.2.2 below.

3.2.1 Integration of the Fluid Dynamic Equations

Consider the flow field shown in Figure 3-1, below:

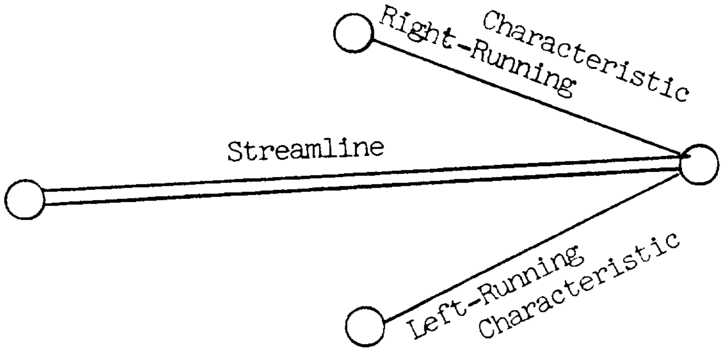


Figure 3-1. Flow Field Interior Point Calculation

Between points 3 and 4 the streamline characteristic relationships are integrated as:

$$r_3 = r_4 + (x_3 - x_4)\tan\theta_{34} \qquad (3.2\text{-}1)$$

$$V_3 = \{V_4^2 - 4(P_3 - P_4)/(\rho_3 + \rho_4)\}^{1/2} \qquad (3.2.2a)$$

or

$$V_3 = \{2(H_T - \sum c_i h_i)\}^{1/2} \qquad (3.2.2b)$$

$$\rho_3 = \rho_4 \left(\frac{P_3}{P_4}\right)^{\left(\frac{1}{\gamma}\right)_{43}} \exp\left\{-\left(\frac{A}{\cos\theta_{43}}\right)(x_3 - x_4)\right\} \qquad (3.2\text{-}3)$$

$$T_3 = T_4 \left(\frac{P_3}{P_4}\right)^{\left(\frac{\gamma-1}{\gamma}\right)_{43}} \exp\left\{-\left(\frac{B}{\cos\theta_{43}}\right)(x_3 - x_4)\right\} \qquad (3.2\text{-}4)$$

where the double subscripts imply averaged values, e.g.:

$$\theta_{34} = (\theta_3+\theta_4)/2 \ ,$$

$$(\frac{1}{\gamma})_{43} = (1/\gamma_4 + 1/\gamma_3)/2 \ , \text{etc.}$$

The integration formula (3.2-1) relating the coordinates of points 3 and 4 is exact if the streamline is a circular arc between points 3 and 4. Equation (3.2-2a) is the Bernoulli Equation and is used to obtain a first estimate for V_3. Successive estimates are made using the energy equation directly, i.e., equation 3.2-2b, so that energy is conserved exactly along streamlines. In integrating the energy equation and the perfect gas relationship to obtain Equations (3.2-3) and (3.2-4), the coefficients γ^{-1}, $A/\cos\theta$, $(\gamma-1)/\gamma$, and $B/\cos\theta$ appearing in these equations were assumed to be equal to their average value between points 3 and 4.

Between points 1 and 3 the right running characteristics relationships are integrated as:

$$r_3 = r_1 + (x_3-x_1)\tan(\theta-\alpha)_{31} \qquad (3.2\text{-}5)$$

$$P_3 = P_1 + P_{13}\{[-(AGH)_{13}+(GH)_{13}\frac{\sin\theta_{13}}{r_{13}}](x_3-x_1) + G_{13}(\theta_3-\theta_1)\} \qquad (3.2\text{-}6)$$

The above equations are a finite difference form of equations (2.5-3) and (2.5-4), respectively.

If point 3 is an axis point then r_3 and θ_3 are zero and the indeterminate quantity $(\sin\theta_3)/r_3$ appearing in Equation (3.2-9) can be approximated by using the value obtained at point 1.

Between points 2 and 3 the left running characteristics relationships are integrated as:

$$x_3 = x_2 + (r_3 - r_2)/\tan(\theta + \alpha)_{32} \qquad (3.2\text{-}7)$$

$$P_3 = P_2 + P_{23}\{[\ (AGF)_{23} - (GF)_{23}\frac{\sin\theta_{23}}{r_{23}}\ ]$$
$$(r_3 - r_2) - G_{23}\ (\theta_3 - \theta_2)\} \qquad (3.2\text{-}8)$$

The above equations (3.2-7) and (3.2-8) are a finite difference form of equations (2.5-1) and (2.5-2), respectively.

If point 2 is an axis point, then r_2 and θ_2 are zero and the indeterminate quantity $(\sin\theta_2)/r_2$ appearing in Equation (3.2-8) can be approximated using the values estimated for point 3.

Equations (3.2-6) and (3.2-8) can be combined to yield:

$$\theta_3 = \{P_2 - P_1 + P_{23}[+(AGF)_{23} - (GF)_{23}\ \frac{\sin\theta_{23}}{r_{23}}](r_3 - r_2)$$
$$-P_{13}[-(AGH)_{13} + (GH)_{13}\ \frac{\sin\theta_{13}}{r_{13}}](x_3 - x_1)$$
$$+P_{23}G_{23}\theta_2 + P_{13}G_{13}\theta_1\}/\{P_{23}G_{23} + P_{13}G_{13}\} \qquad (3.2\text{-}9)$$

The modified Euler iteration method is used by TDK to solve the above equations in the various point calculations. The implicit method used by TDK to integrate the chemical relaxation equations is presented next in Section 3.2.2.

3.2.2 Derivation of the TDK Numerical Integration Method

The chemical relaxation equations are a coupled set of first order simultaneous differential equations of the form

$$\frac{dc_i}{dx} = f_i(c_1, c_2, \cdots, c_N, y_1, y_2, y_3, y_4) \qquad i = 1, 2, \cdots, N$$

along the streamline where y_1, y_2, y_3, and y_4 refer to the fluid dynamic variables V, ρ, T, and θ, respectively. Assuming that the equations are not singular and that a solution exists which may be developed as a Taylor series about the forward point, one obtains

$$k_i = \left.\frac{dc_i}{dx}\right|_{x_{n+h}} h$$

where k_i is the increment in c_i and h is sufficiently small. The first coefficient of the Taylor series may be calculated as

$$\frac{dc_i}{dx} = f_i(c_1, c_2, \cdots, c_N, y_1, y_2, y_3, y_4)$$

Expanding as a Taylor series about the point x_n, it is found that

$$\left.\frac{dc_i}{dx}\right|_{x_{n+h}} = f_{i,n} + \sum_{j=1}^{N} \beta_{i,j,n} k_j + \sum_{j=1}^{4} \phi_{i,j,n} \Delta y_j + 0\left[h^2\right]$$

where

$$\beta_{i,j} = \frac{\partial f_i}{\partial c_j}$$

$$\phi_{i,j} = \frac{\partial f_i}{\partial y_j}$$

and the subscript n refers to the functions f_i, $\beta_{i,j}$, and $\Phi_{i,j}$ evaluated at the point x_n.

Thus neglecting the second order error and derivative terms yields the integration formula for the increment k_i

$$k_i = \left[f_{i,n} + \sum_{j=1}^{N} \beta_{i,j,n} \; k_j + \sum_{j=1}^{4} \phi_{i,j,n} \; \Delta y_j \right] h$$

3.3 SUMMARY OF THE TDK COMPUTATIONAL PROCEDURE

The steps below summarize the computational procedure used by the TDK Computer Program (ODE-ODK-TDK input option):

Step 1. (Zone 1, inner zone O/F ratio)

1.1 ODE is used to compute:

1.1.1 P,H solution at stagnation (chamber V=0) condition

1.1.2 P,S solution at throat (ρV maximum) condition. Entropy, S, is computed in step 1.1.1 above.

1.1.3 ϵ_c,S solution at input contraction ratio.

1.2 An average expansion coefficient, N_e, is computed by Subroutine SUBNE . This expansion coefficient is the perfect gas expansion coefficient which would yield the throat pressure ratio computed in step 1.1.2.

1.3 A pressure table P(x) and its derivative dP(x)/dx are computed using the perfect gas relations, N_e, and the input thrust chamber geometry.

1.4 The ODK Computer Program is used to integrate the finite rate equations for one dimensional flow. The integration begins at ϵ_c. So that the flow will not be singular at the throat, P(x) and dP(x)/dx are used until the flow is supersonic ($M \leq 1.02$). For supersonic flow the area defined relations are used.

Step 2.

The sequence described in Step 1, above, is repeated for zones 2 through $N \leq 50$, the outer zone.

The following throat property tables are constructed during each of the above calculations:

ρ, V, T, c_1 vs. P.

These tables begin at the ODK determined throat (ρV maximum) and end when the flow attains a Mach number of 1.5.

Step 3.

An average expansion coefficient, γ_n, is computed for each zone using the tables constructed in Step 2.

$$\gamma_n = \frac{\ln (P_\ell/P_1)}{\ln (\rho_\ell/\rho_1)} \qquad n = 1, \ldots N \leq 50$$

The subscripts 1 and ℓ refer to the first and last table entries (at the ODK throat and at M=1.5). Thus if the flow through the throat is in equilibrium γ will attain the equilibrium value and if the flow is frozen γ will attain the frozen value.

Step 4.

4.1 Using the above values of γ_n and the upstream radius of curvature at the nozzle throat, R_u, a two dimensional (axially symmetric) initial data line is constructed using a small perturbation method. The location of the initial data line across the nozzle throat region is determined. The location of the slipline positions is also determined by the small perturbation method (from the continuity relation). Pressure and flow angle are matched (through a first order of approximation) at the sliplines.

4.2 Flow properties of ρ, V, T, and c_i are interpolated from the tables constructed in Step 2 using the pressure determined in Step 4.1.

Step 5.

A method of characteristics solution is computed for the nozzle. Boundary conditions are the initial data line and nozzle wall with a symmetry condition used along the nozzle axis and slip conditions (matched pressure and flow angle) used along the streamlines dividing zones of different O/F. The finite difference mesh is constructed at gas streamline and left running characteristic intersections.

4. PROGRAM STRUCTURE

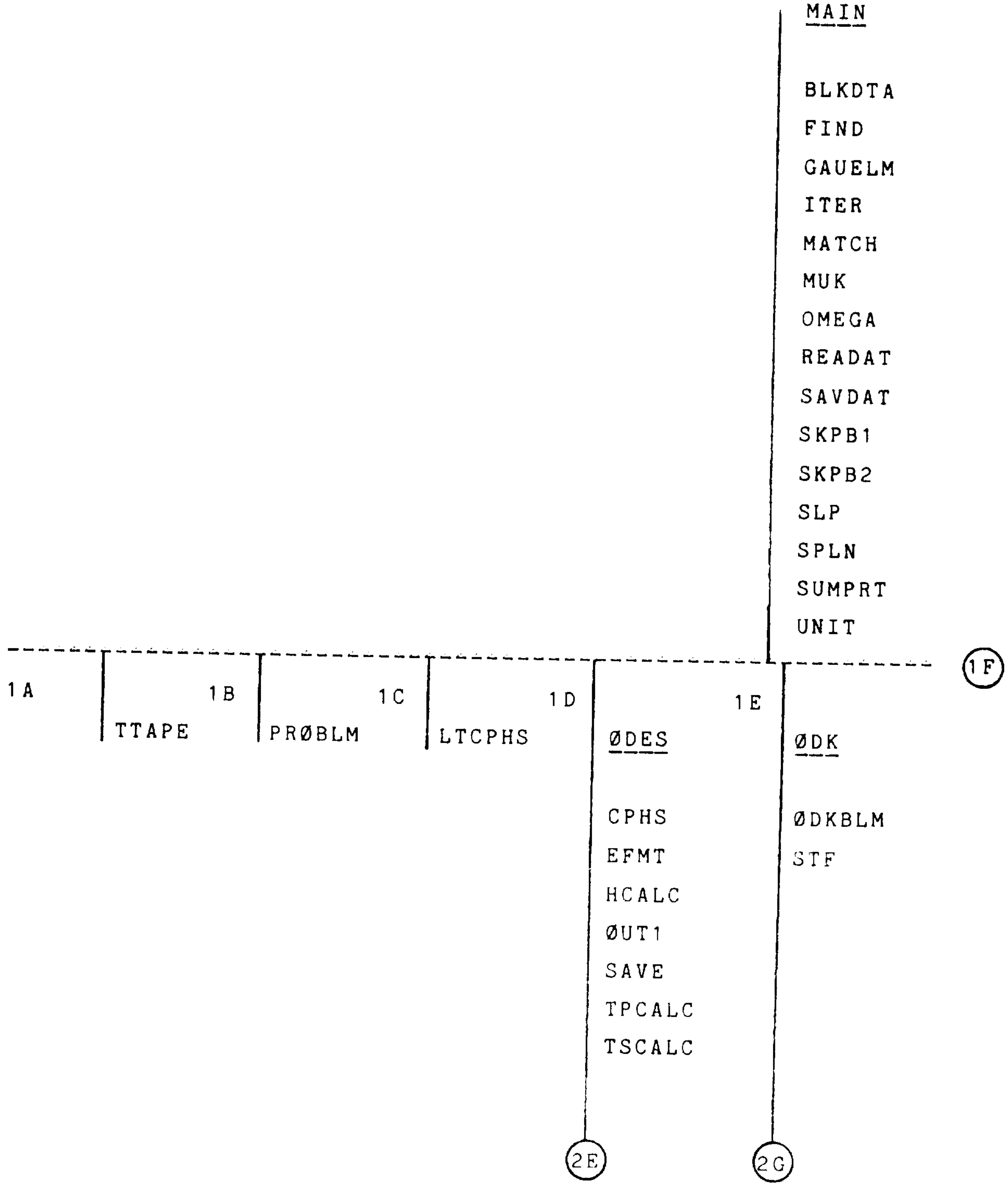
This section contains an over-all description of the structure of the TDK computer program. TDK consists of a master control module (MCM) and five major computational modules, as follows: ODE, ODK, TRAN, MOC, and BLM. Each module is described briefly in Figure 4-1. The computational modules have been combined with the MCM so that they can be run together automatically. The extensive use of internal communication between the modules has eliminated the need for redundant inputs by the user.

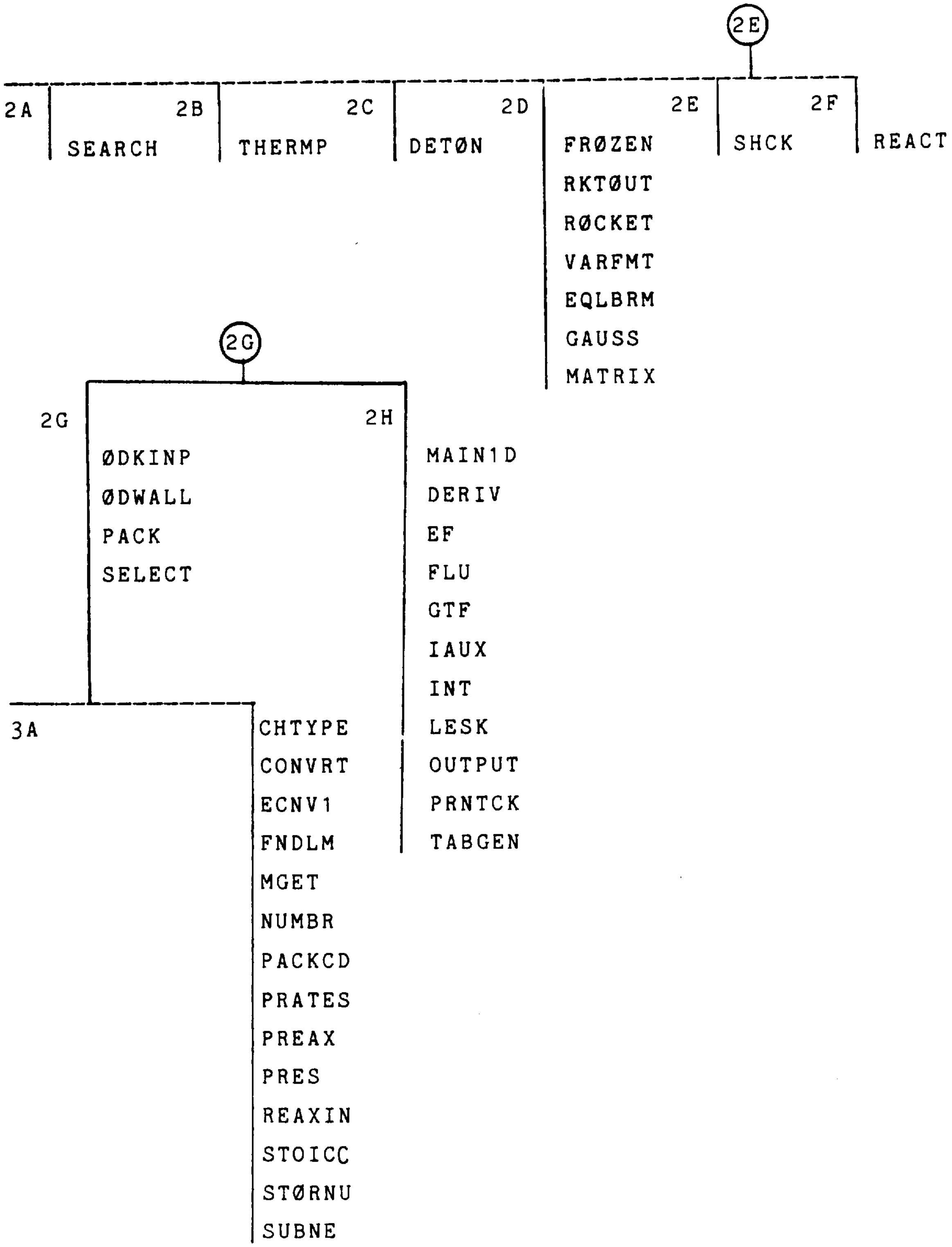
A schematic of an overlay structure for TDK is presented in Figure 4-2. This figure should prove useful to programmers who wish to convert TDK to a computer, such as CDC or Univac, on which an overlay structure is mandatory. TDK has been developed for the DEC 11/780 Virtual Address Extension (VAX) computer for which no overlay structure is required.

Figure 4-1: BASIC MODULES OF TDK

MODULE	DESCRIPTION
MCM	The Master Control Module is used to control the execution of TDK by selecting the computation modules to be exercised. The MCM is also used to process output files for the purpose of creating printed and plotted output.
ODE	The One-Dimensional Equilibrium module is used to calculate ideal engine performance. Engine performance can also be calculated assumming that the chemical composition is frozen at chamber (stagnation) conditions.
ODK	The One-Dimensional Kinetics module is used to calculate the loss in nozzle performance caused by finite-rate chemistry of the expansion products.
TRANS	The Transonic Flow module is used to calculate two-dimensional flow conditions in the throat region of the nozzle. It is used to obtain an initial data line for the MOC module.
MOC	The Method of Characteristics module is used to calculate the loss in nozzle performance caused by flow divergence, including the effects of chemistry and mixture ratio variation.
BLM	The Boundary Layer Module is used to calculate the loss in nozzle performance due to a viscous boundary layer and its interaction with the nozzle wall. The effects of both drag and heat transfer are included.

FIGURE 4-2: SUGGESTED OVERLAY STRUCTURE TDK, VERSION 4.0
APRIL 1985

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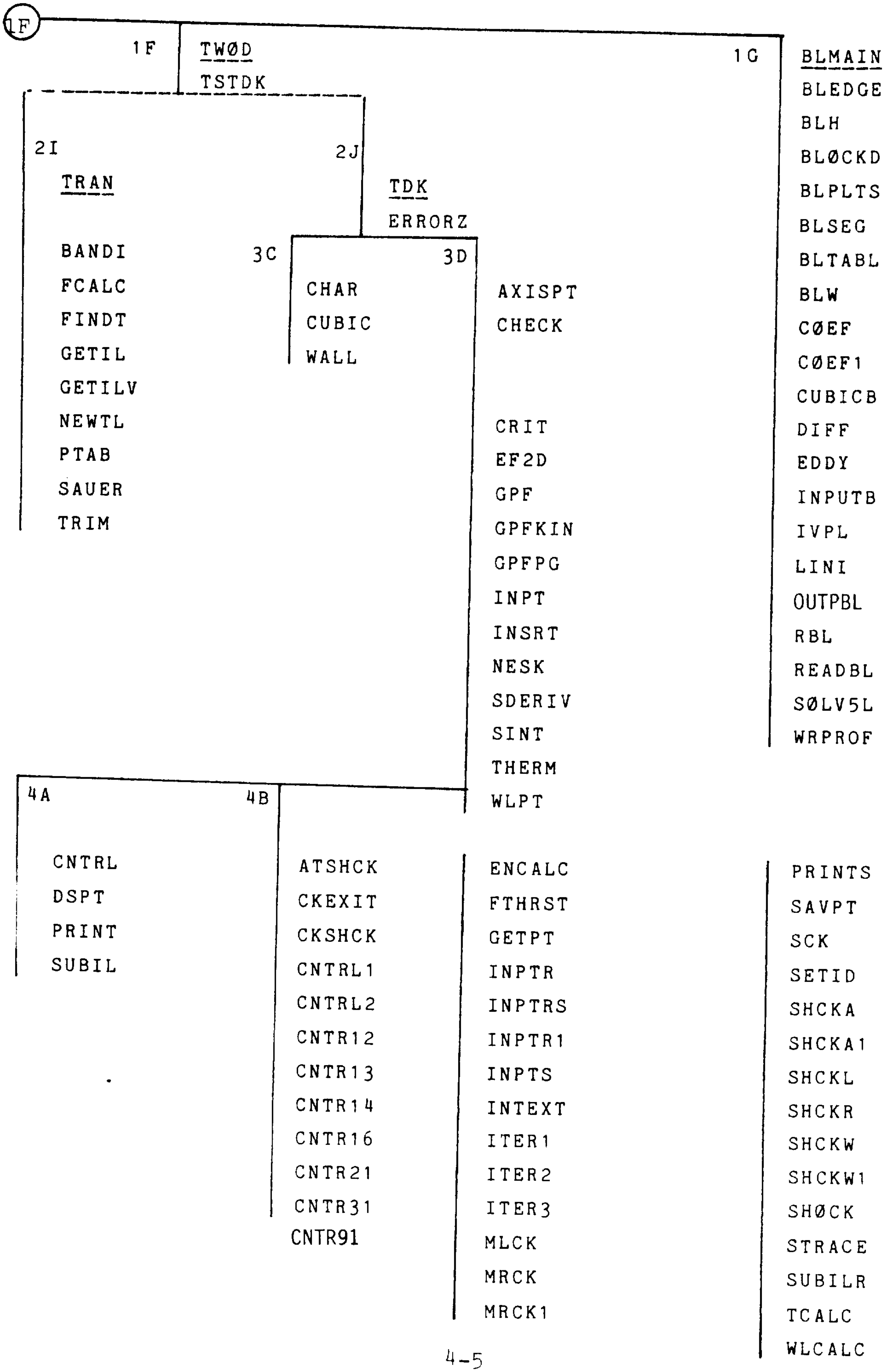
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FCALC
FINDT
GETIL
GETILV
NEWTL
PTAB
SAUER
TRIM
2J
TDK
ERRORZ
3C
CHAR
CUBIC
WALL
3D
AXISPT
CHECK
CRIT
EF2D
GPF
GPFKIN
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CNTR21
CNTR31
CNTR91
ENCALC
FTHRST
GETPT
INPTR
INPTRS
INPTR1
INPTS
INTEXT
ITER1
ITER2
ITER3
MLCK
MRCK
MRCK1
PRINTS
SAVPT
SCK
SETID
SHCKA
SHCKA1
SHCKL
SHCKR
SHCKW
SHCKW1
SH0CK
STRACE
SUBILR
TCALC
WLCALC

4.1 PROGRAM FILES

The files used by TDK are listed in Table 4-1. For those files referred to by a Fortran variable name, the name is listed. The description of the file includes the name of the labeled common block in which the file name is communicated. Subroutines using the file are also listed.

The type of file is indicated by the following codes:

B	binary
F	formated
MS	mass storage (saved)
DA	direct access
TMS	temporary mass storage

For Univac machines, write statements to unit 50 must be replaced by PUNCH statements.

Table 4-1: Files Used by TDK

Logical Unit	Fortran Variable Name	Type	Description
5	MUN	F	Data input stream COMMON/NUCM30/
6	-	F	Printed output stream
8	IPUNIT	F,TMS	Initial Data Line file, $LINE, COMMON/PCHILF, Subroutine CHAR
10	LU	F,TMS	Temporary input, COMMON/NUCM 30/, Subroutines MAIN, SAVDAT,CHAR, LTCPHS, ODES, OKDINP, REACT, REAXIN, TDK, TTAPE
11*	LUBLM	F,TMS,MS	TDK-BLM interface data, COMMON/BLM2/,Subroutines BLKDTA, ODES, PRINT, PRINTS, PTAB, READAT, READBL
12	LU0UT	F,TMS,MS	BLM-TDK interface data, Subroutines BLMAIN, BLW, RBL
13	NUPLT	B,TMS	BLM plots Subroutine BLMAIN
14	NUPR0F	B,TMS	BLM plots Subroutine WRPR0F

15*	-	B,TMS,MS	TDK restart Subroutines READAT, SAVDAT, MAIN
16	-	DA	Direct access file for variable mixture ratio option (1st pass) Subroutines FINDT, GETILV, GETIL
17	-	DA	Direct access file for shock option (1st pass) Subroutines GETPT, SAVPT
18	-	DA	Direct access file for shock option (2nd pass) Subroutine CNTR91
19	-	DA	Same as 16, (2nd pass)
20	IRRED	B,TMS	Scratch data, Common/NTAPE/, Subroutines BLKDTA, 0DKINP
21	KREX	B,TMS	Initial line data, COMMON/NTAPE/, Subroutines BLKDTA, CHAR, GETIL, GETILV, 0DKINP, PACK, SUBIL, TRAN, TSTDK
23	JTABLE	B,TMS	TDE unit, COMMON/NTAPE1/, Subroutines BLKDTA, 0DES, OUTPUT, TDK, TRAN
25	JANAF	F,TMS,MS	Thermodynamic data, COMMON/CUTIL/, Subroutines MAIN, TTAPE, 0DK, PACK, SEARCH

26	KREAX	B,TMS	Scratch data, COMMON/CUTIL/, Subroutines MAIN, ODKINP, REAXIN
27	KSTF	F,TMS	Scratch data, COMMON/CUTIL/, Subroutines MAIN, PACK, SEARCH
28	IRREAD	B,TMS	Scratch data, COMMON/CUTIL/, Subroutines MAIN, 0DKINP, REAXIN
29*	ITSTAB	B,TMS,MS	Transonic data, COMMON/CUTIL/, Subroutines MAIN, GETIL, GETILV, MAIN1D,TW0D
50	-	F,TMS,MS	Boundary layer edge data computed by TDK, TDE, or TDF. Subroutines PRINT, PRINTS, PTAB

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* Files 11, 15, and 29 must be saved if the restart option, IRSTRT = 1, is to be used on later runs.

4.2 SUBROUTINE AND COMMON BLOCK CROSS-REFERENCES

This section provides tables that contain cross-references for subroutines and common blocks. Referal to these tables, or their equivalent, is usually necessary if the program is to be modified.

Table 4-2 lists in alphanumeric order each TDK subroutine. All modules are included. Opposite each subroutine name are the names of all subroutines that call the subroutine.

Table 4-3 lists in alphanumeric order each TDK common block. Again, all modules are included. Opposite each common block name are the names of all subroutines that contain the common block.

Tables 4-2 and 4-3 do not contain the names of system supplied subroutines, such as SIN, COS, or the I/0 subroutines.

TABLE 4-2 SUBROUTINE ENTRY POINT CROSS-REFERENCES

SUBROUTINE	REFERRED BY ...			
ATSHCK	CNTR16	CNTR21	CNTR31	CNTR41
AXIS	BLPLTS			
AXISPT	CNTR14	CNTRL	CNTRL1	SHCKA1
BANDI	NEWT			
BLEDGE	BLMAIN			
BLH	MAIN			
BLKDTA				
BLMAIN	MAIN			
BLOCKD				
BLPLTS	BLMAIN			
BLSEG	BLMAIN			
BLTABL	BLEDGE	INPUTB		
BLW	MAIN			
CHAR	TDK			
CHECK	ATSHCK	AXISPT	DSPT	INPT
	INPTR	INPTR1	INPTRS	INPTS
	WLPT			
CHTYPE	PREAX			
CKEXIT	CNTR21	CNTR31	CNTR41	CNTRL1
	CNTRL2			
CKSHCK	CNTRL1			
CNTR12	CNTR91			
CNTR13	CNTR91			
CNTR14	CNTR91			
CNTR16	CNTR91			
CNTR21	CNTR91			
CNTR31	CNTR91			
CNTR41	CNTR91	(SUBROUTINE NOT USED)		
CNTR91	TDK			
CNTRL	TDK			
CNTRL1	CNTR13	CNTR21	CNTR31	CNTR41
CNTRL2	CNTR12	CNTR14	CNTR16	CNTR41
COEF	BLSEG	IVPL		
COEF1	BLSEG			
CONVRT	PACK			
CPHS	EQLBRM	FROZEN	HCALC	OUT1
	ROCKET	SHCK		
CRIT	CHECK	DSPT	SHCKA1	SHCKL
	SHCKR	SHCKW1		
CUBIC	WALL			
CUBICB	BLTABL			
DERIV	IAUX	INT	MAIN1D	
DETON	ODES			
DIFF	BLEDGE			
DSPT	CNTRL			
ECNV1	MGET	PRATES	REAXIN	
EDDY	BLSEG			
EF	DERIV			
EF2D	SDERIV			
EFMT	OUT1			
ENCALC	SHOCK	TCALC		
EQLBRM	DETON	ROCKET	SHCK	THERMP
	TPCALC			
ERRORZ	CHAR	CNTRL	TDK	
FCALC	TRAN			

SUBROUTINE	REFERRED BY ...			
FIND	CHAR	CPHS	ENCALC	GPFPG
	IAUX	MAIN1D	MUK	PACK
	PRES	PTAB	STF	THERM
FINDT	GETIL	GETILV		
FLU	DERIV			
FNDLM	MGET	PRATES	REAXIN	
FROZEN	ROCKET			
FTHRST	CNTR12	CNTR13	CNTR14	CNTR16
	CNTR21	CNTR31	CNTR41	CNTRL2
GAUELM	SKPB1			
GAUSS	EQLBRM			
GETIL	TRAN			
GETILV	TRAN			
GETPT	CNTR12	CNTR13	CNTR14	CNTR16
	CNTR41	INPTRS	INPTS	SUBILR
GPF	ATSHCK	AXISPT	DSPT	INPT
	INPTR	INPTR1	INPTRS	INPTS
	INSRT	SHCKA	SHCKA1	SHCKL
	SHCKR	SHCKW	SHCKW1	SUBIL
	SUBILR	WLPT		
GPFKIN	GPF	SUBIL		
GPFPG	GPF			
GTF	DERIV	MAIN1D		
HCALC	DETON	SAVE	SHCK	
IAUX	INT	MAIN1D		
INPT	CNTRL	CNTRL2		
INPTR	CNTRL1			
INPTR1	CNTR16			
INPTRS	CNTR14			
INPTS	CNTR13			
INPUTB	BLMAIN			
INSRT	CNTRL	CNTRL1	CNTRL2	WLCALC
INT	MAIN1D			
INTEXT	CNTR12	CNTR14	CNTR16	CNTR21
	CNTR31	CNTR41		
ITER	PRINT	PRINTS	TCALC	TRAN
	TSCALC			
ITER1	ENCALC			
ITER2	SHOCK			
ITER3	ATSHCK			
IVPL	BLMAIN			
LESK	IAUX			
LINE	BLPLTS			
LINI	BLEDGE	BLTABL	INPUTB	OUTPBL
	WRPROF			
LTCPHS	MAIN			
MAIN				
MAIN1D	ODK			
MATCH	ODKBLM	ROCKET		
MATRIX	EQLBRM			
MGET	REAXIN			
MLCK	CNTR12	CNTR14	CNTR16	CNTR41
MRCK	CNTR13	CNTR21	CNTR31	CNTR41
MRCK1	CNTRL1			
MUK	ODKBLM	ROCKET		

SUBROUTINE	REFERRED BY ...			
NESK	SINT			
NEWOF	DETON	ROCKET	SHCK	THERMP
NEWT	TRAN			
NUMBER	BLPLTS			
ODES	MAIN			
ODK	MAIN			
ODKBLM	ODK			
ODKINP	ODK			
ODWALL	ODKINP			
OMEGA	ODKBLM	ROCKET		
OUT1	DETON	RKTOUT	SHCK	THERMP
OUT2	DETON	RKTOUT	SHCK	THERMP
OUT3	DETON	RKTOUT	SHCK	THERMP
OUTPBL	BLMAIN	BLSEG		
OUTPUT	INT	MAIN1D	PRNTCK	
PACK	ODK			
PACKCD	REAXIN			
PLOT	BLPLTS			
PLOTS	BLPLTS			
PRATES	REAXIN			
PREAX	REAXIN			
PRES	PACK			
PRINT	CNTRL			
PRINTS	CNTR12	CNTR13	CNTR14	CNTR16
	CNTR21	CNTR31	CNTR41	CNTRL1
	CNTRL2			
PRNTCK	INT	MAIN1D		
PROBLM	MAIN			
PTAB	TRAN			
RBL	BLH	BLW		
REACT	ODES			
READAT	MAIN			
READBL	INPUTB			
REAXIN	ODKINP			
RKTOUT	ROCKET			
ROCKET	ODES			
SAUER	TRAN			
SAVDAT	MAIN			
SAVE	DETON	ROCKET	SHCK	THERMP
SAVPT	CNTR12	CNTR13	CNTR14	CNTR16
	CNTR31	CNTR41	CNTRL1	CNTRL2
	SUBILR	WLCALC		
SCALE	BLPLTS			
SCK	CNTR12	CNTR14		
SDERIV	GPFKIN	SINT		
SEARCH	ODES			
SELECT	ODKINP			
SETID	CNTR12	CNTR13	CNTR14	CNTR16
	CNTR21	CNTR31	CNTR41	CNTRL1
	CNTRL2	SUBILR	WLCALC	
SHCK	ODES			
SHCKA	CNTR12	CNTR14		
SHCKA1	CNTR13			
SHCKL	CNTR13	SHCKW		
SHCKR	CNTR12	CNTR14	CNTR16	

SUBROUTINE	REFERRED BY ...			
SHCKW	CNTR13			
SHCKW1	CNTR14	CNTR16		
SHOCK	ATSHCK	SHCKA	SHCKA1	SHCKL
	SHCKR	SHCKW	SHCKW1	
SINT	ATSHCK	AXISPT	DSPT	INPT
	INPTR	INPTR1	INPTRS	INPTS
	SHCKA	SHCKA1	SHCKL	SHCKR
	SHCKW1	SUBIL	SUBILR	WLPT
SKPB1	ODWALL	SKPB2	WALL	
SKPB2	ODWALL	WALL		
SLP	PACK	TDK	WALL	
SOLV5	BLSEG	IVPL		
SPLN	CHAR	CNTRL	CPHS	ENCALC
	FLU	GPFPG	IAUX	MAIN1D
	MUK	PACK	PRES	PTAB
	STF	THERM		
STF	CONVRT	DERIV	MAIN1D	ODKBLM
STOICC	CONVRT	PACK		
STORNU	REAXIN			
SUBIL	CNTRL			
SUBILR	CNTR21	CNTR31	CNTR41	
SUBNE	PRES			
SUMPRT	MAIN			
SUMPRT1	SUMPRT			
SYMBOL	BLPLTS			
TABGEN	IAUX	MAIN1D		
TCALC	SHOCK			
TDK	TWOD			
THERM	ENCALC	SDERIV		
THERMP	ODES			
TIMERX	CHAR	CNTRL	MAIN	MAIN1D
	MLCK	MRCK	TRAN	
TPCALC	TSCALC			
TRAN	TWOD			
TRIM	TRAN			
TSCALC	ODES			
TTAPE	MAIN			
TWOD	MAIN			
UNIT	MAIN			
VARFMT	RKTOUT			
WALL	CHAR			
WLCALC	CNTR21	CNTR31	CNTR41	
WLPT	CNTR13	CNTRL	CNTRL2	SHCKW1
	WLCALC			
WRPROF	BLSEG			

TABLE 4-3 COMMON BLOCK CROSS-REFERENCES

LABELED COMMON	REFERRED BY SUBROUTINE
A	REAXIN STORNU PRATES PREAX
ABMAPS	MAIN TDK FLU
ABOUND	CHAR GPFKIN
AL	BLMAIN INPUTB OUTPBL BLEDGE
ARODE	MAIN BLKDTA ODES PACK REACT SEARCH DETON ODKINP OUT1 OUTPUT
ARPRNT	ODES PROBLM ODKINP
AVGS	REACT SUMPRT TWOD MAIN1D
BCON	BLOCKD INPUTB READBL BLEDGE
BLCO	BLOCKD BLMAIN INPUTB IVPL OUTPBL READBL SOLV5
BLCO	BLEDGE BLSEG COEF COEF1 EDDY WRPROF
BLC1	IVPL OUTPBL SOLV5 BLSEG COEF COEF1 EDDY WRPROF
BLC2	OUTPBL COEF1 EDDY
BLC3	IVPL SOLV5 BLSEG
BLC6	SOLV5 COEF
BLINTP	BLOCKD INPUTB BLEDGE
BLM1	MAIN PROBLM READAT SAVDAT PRINT PTAB PRINTS
BLM2	BLKDTA ODES READAT READBL ODKBLM TDK PRINT PTAB PRINTS
BLM3	ODES

LABELED COMMON	REFERRED BY SUBROUTINE
BLM3	ROCKET
BLM4	ODES OUT1
BLMF	ODK PROBLM SUMPRT
BLMPLT	BLOCKD BLMAIN INPUTB BLEDGE BLSEG WRPROF
BLMSPR	BLH BLW SUMPRT BLSEG
BLPLOT	BLMAIN BLSEG
BLTK	BLMAIN OUTPBL
BLTKPR	PROBLM
CCINT	SINT NESK
CDELHX	MAIN ODES SAVE TWOD MAIN1D
CDELHY	BLH ODES SAVE TWOD MAIN1D
CDINTG	SUMPRT SUMPRT1 TRAN
CINTLN	CHAR
CINT	MAIN1D IAUX INT LESK
CKSHCK	CHAR
CMAXIT	TDK CHAR PRINT PRINTS
CODTDK	MAIN ODK MAIN1D ODKINP TDK FLU
COEFFX	SEARCH CPHS
COM4	MAIN SUMPRT TRAN CHAR
COM6	TRAN GETIL GETILV SAUER
COMCAS	MAIN BLW ODES PACK READAT SAVDAT SUMPRT CONVRT MAIN1D ODKBLM ODKINP OUTPUT PRES REAXIN SELECT STF STORNU

LABELED COMMON	REFERRED BY SUBROUTINE
COMCAS	SUMPRT1
	TRAN
	CHAR
	CNTRL
	DERIV
	DSPT
	EF
	FCALC
	FLU
	GETIL
	GETILV
	GTF
	IAUX
	INPT
	INT
	ODWALL
	PRATES
	PRINT
	PTAB
	SINT
	SUBIL
	WLPT
	AXISPT
	GPFKIN
	INPTR
	INPTR1
	INPTRS
	INPTS
	NESK
	PRINTS
	SDERIV
	SUBILR
	TCALC
	THERM
	ATSHCK
	EF2D
	ENCALC
COMXP	MAIN
	ODES
	SUMPRT
	TRAN
COMY	MAIN
	PACK
	READAT
	SAVDAT
	CONVRT
	MAIN1D
	ODKBLM
COMY	ODKINP
	OUTPUT
	PRES
	REAXIN
	STF
	TRAN
	CHAR
	DERIV
	EF
	FLU
	GTF
	IAUX
	INT
	SDERIV
	EF2D
CONSTS	MAIN
	LTCPHS
	ODES
	SAVE
	SUMPRT
	UNIT
	CONVRT
	EQLBRM
	FROZEN
	MAIN1D
	ODKINP
	OUT1
	OUTPUT
	RKTOUT
	SUMPRT1
	TDK
	TPCALC
	TRAN
	CHAR
	IAUX
	ODWALL
	PRINT
	PTAB
	WALL
	GPFPG
	PRINTS
	ENCALC
COOLC	BLH
	BLW
	INPUTB
CPEES	ROCKET
	CPHS

LABELED COMMON	REFERRED BY SUBROUTINE
CPEES	OUT1
CPRNT	MAIN
	PACK
	MAIN1D
	ODKINP
	INT
	ODWALL
CPUNCH	PRINT
	PRINTS
CSPRXC	MAIN
	PACK
	STOICC
	CONVRT
	REAXIN
	SELECT
	STORNU
CTRBDY	AXISPT
	CNTR14
	CNTRL1
	SHCKA
	SHCKA1
CUTIL	MAIN
	ODES
	ODK
	PACK
	REACT
	READAT
	ROCKET
	SAVDAT
	SEARCH
	SPLN
	TTAPE
	TWOD
	CONVRT
	CPHS
	MAIN1D
	MUK
	ODKBLM
	ODKINP
	OUT1
	OUTPUT
	PRES
	REAXIN
	RKTOUT
	SELECT
CUTIL	STF
	TDK
	TRAN
	CHAR
	CNTRL
	FLU
	GETIL
	GETILV
	IAUX
	PRINT
	SUBIL
	GPFPG
	PRINTS
	SUBILR
	THERM
CWALL	MAIN
	ODES
	PACK
	READAT
	SAVDAT
	MAIN1D
	ODKINP
	PRES
	CHAR
	FLU
	ODWALL
	PTAB
	WALL
CWALL1	PROBLM
	WALL
DASTOI	PACK
	READAT
	SAVDAT
	DERIV
	EF
	SDERIV
	EF2D
DELHN	BLH
	ODES
DFSAV	OUTPBL
	SUMPRT
	COEF1
	SUMPRT1
DIRACC	TDK

LABELED COMMON	REFERRED BY SUBROUTINE
DIRACC	CNTR91
	GETPT
	SAVPT
DOLOOP	MAIN
	READAT
	SAVDAT
	MAIN1D
	OOKINP
	PRNTCK
	DERIV
	EF
	IAUX
	INT
	SDERIV
	EF2D
DOUBLE	ODES
	SHCK
	EQLBRM
	GAUSS
	MATRIX
	OUT1
EDGE	BLOCKD
	BLMAIN
	INPUTB
	OUTPBL
	BLEDGE
	BLSEG
	COEF1
	EDDY
	WRPROF
ENDFLG	CNTR91
	PRINTS
ERR	MAIN
	TTAPE
	TDK
	TRAN
	CHAR
	CNTRL
	DSPT
	GETIL
	GETILV
	INPT
	PRINT
	SUBIL
	WALL
ERR	WLPT
	AXISPT
	CNTR12
	CNTR13
	CNTR14
	CNTR16
	CNTRL1
	CNTRL2
	GPFPG
	INPTR
	INPTR1
	INPTRS
	INPTS
	PRINTS
	SDERIV
	SHCKA
	SHCKA1
	SHCKL
	SHCKR
	SHCKW
	SHCKW1
	SUBILR
	WLCALC
	ATSHCK
	ENCALC
EXTRAP	PACK
FLAGS	CNTR91
	CNTR12
	CNTR13
	CNTR14
	CNTR16
	CNTR21
	CNTR31
	CNTR41
	CNTRL1
	CNTRL2
FLOW2D	PROBLM
	TRAN
	CHAR
	CNTRL
	FTHRST
FNALBT	MAIN1D
	DERIV
	FLU
	IAUX

LABELED COMMON	REFERRED BY SUBROUTINE
GBLK	BLOCKD BLMAIN INPUTB OUTPBL BLEDGE BLSEG COEF1 EDDY WRPROF
GEOM	BLW ODES PROBLM READBL SUMPRT ODKINP RKTOUT TRAN CHAR PRINTS
GEOMN	BLW PROBLM
GRD	BLOCKD BLMAIN INPUTB IVPL OUTPBL SOLV5 BLEDGE BLSEG COEF COEF1 EDDY
HHTCOM	ODES EQLBRM
HTABLE	INPUTB BLEDGE
HTFLX	BLMAIN OUTPBL BLSEG
HTL	ODES PROBLM READAT

LABELED COMMON	REFERRED BY SUBROUTINE
HTL	SAVDAT ODKBLM CHAR GPFKIN GPFPG
HTOTAL	INPUTB READBL BLEDGE
HTPR	BLW PROBLM
ICONT	MAIN
IDIL	SUBILR
IDNO	PROBLM CNTR91 SETID
IHIT	CNTR21 CNTR31 CNTR41 CNTRL1
INDSEG	BLSEG COEF1
INDX	MAIN ODES REACT ROCKET SAVE SEARCH SHCK THERMP CPHS DETON EQLBRM FROZEN GAUSS HCALC MATRIX OUT1 RKTOUT TPCALC
INDXX	ODES REACT

LABELED COMMON	REFERRED BY SUBROUTINE	LABELED COMMON	REFERRED BY SUBROUTINE
INDXX		KINFO	
	ROCKET		MAIN
	SAVE		BLH
	SHCK		ODES
	THERMP		PACK
	CPHS		REACT
	DETON		READAT
	EQLBRM		ROCKET
	FROZEN		SAVDAT
	GAUSS		SUMPRT
	HCALC		TWOD
	MATRIX		FROZEN
	OUT1		MAIN1D
	RKTOUT		ODKINP
	TPCALC		OUT1
INERTS			OUTPUT
	REAXIN		PRES
	SELECT		REAXIN
IOFF			RKTOUT
	PROBLM		SELECT
	READBL		TDK
IRRC			TRAN
	CHAR		CHAR
	INPTR		GETIL
IRSTRT			GETILV
	MAIN		PRINT
	PROBLM		PTAB
	READAT		PRINTS
	SUMPRT	LASTM	
	SUMPRT1		CNTR16
ISPLN			CNTRL2
	PROBLM	LKEQKN	
	SPLN		ROCKET
IUSE		LKMELT	
	MAIN		MAIN1D
	ODES		DERIV
	ROCKET	LOWTH	
	SAVE		MAIN
	SEARCH		LTCPHS
	SHCK		READAT
	THERMP		SAVDAT
	CPHS		CPHS
	DETON		STF
	EQLBRM		THERM
	FROZEN	M1	
	HCALC		READAT
	MATRIX		SAVDAT
	OUT1		SINT
	RKTOUT		GPFKIN
	SELECT		SDERIV

LABELED COMMON	REFERRED BY SUBROUTINE
MACHDR	DERIV
	FLU
MARKET	MAIN
	ODES
	ODK
	PACK
	PROBLM
	READAT
	ROCKET
	TWOD
	CONVRT
	MAIN1D
	ODKINP
	OUTPUT
	REAXIN
	SELECT
	TDK
	TRAN
	CHAR
	FLU
	PRINT
	GPFPG
	PRINTS
MASFLW	MLCK
	MRCK
	MRCK1
	SUBILR
MESHC	TDK
	CHAR
	CNTRL
	PRINT
	SUBIL
	MLCK
	MRCK
	MRCK1
	PRINTS
	SUBILR
MESHCN	CHAR
	INPT
	INPTR
	SHCKL
	SHCKR
MESHCW	CHAR
	WLPT

LABELED COMMON	REFERRED BY SUBROUTINE
MESHCX	CHAR
	CNTRL
	PRINT
	WALL
	WLPT
	PRINTS
	ATSHCK
MISC	MAIN
	BLKDTA
	ODES
	PACK
	REACT
	ROCKET
	SAVE
	SEARCH
	SHCK
	THERMP
	CPHS
	DETON
	EQLBRM
	FROZEN
	HCALC
	MATRIX
	OUT1
	RKTOUT
	TPCALC
MISCT	BLOCKD
	BLH
	BLMAIN
	INPUTB
	OUTPBL
	READBL
	BLEDGE
	BLSEG
	COEF1
	EDDY
	WRPROF
MISCX	ODES
	REACT
	ROCKET
	SAVE
	SHCK
	THERMP
	CPHS
	DETON
	EQLBRM

LABELED COMMON	REFERRED BY SUBROUTINE
MISCX	FROZEN HCALC MATRIX RKTOUT
MOLWTS	ROCKET SEARCH OUT1
MUST	DERIV FLU
NAMBC	TRAN FCALC SAUER
NAME	SUMPRT SUMPRT1 TDK CHAR CNTR91 CNTRL DSPT INPT PRINT SUBIL CNTR12 CNTR13 CNTR14 CNTR16 CNTR21 CNTR31 CNTR41 CNTRL1 CNTRL2 FTHRST INPTR INPTR1 INPTRS INPTS MLCK MRCK MRCK1 PRINTS SHCKA1 SHCKL SHCKR SHCKW1 SUBILR WLCALC
NAMEP	TDK CHAR CNTRL DSPT INPT CNTR12 CNTR13 CNTR14 CNTR16 CNTR21 CNTR31 CNTR41 CNTRL1 CNTRL2 GPFPG INPTR INPTR1 INPTRS INPTS MLCK MRCK MRCK1 SHCKA SHCKA1 SHCKL SHCKR SHCKW1 WLCALC CKSHCK ENCALC
NAMEQ	TDK CHAR CNTR91 CNTRL DSPT INPT INSRT PRINT SINT SUBIL WLPT AXISPT CHECK CNTR12 CNTR13 CNTR14 CNTR16 CNTR21

LABELED COMMON	REFERRED BY SUBROUTINE
NAMEQ	CNTR31
	CNTR41
	CNTRL1
	CNTRL2
	GPFKIN
	GPFPG
	INPTR
	INPTR1
	INPTRS
	INPTS
	MLCK
	MRCK
	PRINTS
	SHCKA
	SHCKA1
	SHCKL
	SHCKR
	SHCKW
	SHCKW1
	SHOCK
	SUBILR
	WLCALC
	ATSHCK
	CKSHCK
NAMEQB	CNTR12
	CNTR13
	CNTR14
	CNTR16
	CNTR21
	CNTR31
	CNTR41
	CNTRL1
	PRINTS
	SHCKA
	SHCKA1
	SHCKL
	SHCKR
	SHCKW
	SHCKW1
	SHOCK
	ATSHCK
NAMES	MAIN
	TRAN
	CHAR
	GETIL
	GETILV
	SUBIL
	SUBILR
NAMEV	TRAN
	FCALC
	GETIL
	GETILV
NAMEW	MAIN
	ODKINP
	TRAN
	CHAR
	CNTRL
	PRINT
	WALL
	WLPT
	CNTR12
	CNTR14
	CNTR16
	CNTR21
	CNTR31
	CNTR41
	CNTRL1
	CNTRL2
	INTEXT
	PRINTS
	SHCKW
	WLCALC
	ATSHCK
	CKEXIT
NAMIN	MAIN
	BLH
	PROBLM
	TWOD
	MAIN1D
	ODKINP
	TDK
	TRAN
	CHAR
	FCALC
	PRINT
	GPFPG
	PRINTS
NC01	CNTRL
	ODWALL
	PRINT
	WALL
	CNTR21
	CNTR31
	CNTRL1

LABELED COMMON	REFERRED BY SUBROUTINE
NCO1	MLCK MRCK PRINTS
NDEBUG	TRAN FCALC
NEWPRT	BLW ODKINP
NODK	ODK ODKINP
NOINST	CNTRL1 INPTR
NRXDIR	PACK CONVRT REAXIN PRATES
NTAPE	BLKDTA PACK ODKINP TRAN CHAR GETIL GETILV SUBIL SUBILR
NTAPE1	BLKDTA ODES OUTPUT TDK TRAN
NUCM30	MAIN INPUTB LTCPHS ODES PROBLM REACT SHCK TTAPE ODKINP REAXIN TRAN CHAR
NUCOM2	ODES ODK PACK PROBLM ROCKET TWOD ODKINP OUTPUT TDK TRAN CHAR DSPT GPF INPT ODWALL PRINT PTAB SUBIL WLPT AXISPT GPFPG INPTR INPTR1 INPTRS INPTS PRINTS SHCKA SHCKA1 SHCKL SHCKR SHCKW1 ATSHCK ENCALC
NUCOM3	MAIN ODES PROBLM READAT SAVDAT PRINT PTAB PRINTS
NUCOM4	BLKDTA PROBLM OUT1 OUTPUT RKTOUT CHAR

LABELED COMMON	REFERRED BY SUBROUTINE
NUCOM4	PRINT
	PRINTS
NUCOM5	MAIN
	ODES
	TDK
	TRAN
	CHAR
NUCOM6	MAIN
	TRAN
	PRINT
	CNTR21
	CNTR31
	CNTR41
	PRINTS
NUCOM7	MAIN
	ODES
	ODKINP
	OUT1
	TRAN
	CHAR
NUCOM8	ODES
	CHAR
NUCOMN	ODES
	ROCKET
	OUT1
NUT	TDK
	GETIL
OAE	ODES
	PROBLM
	ODKINP
	TRAN
ODEOUT	ROCKET
	OUT1
ODERG	ODES
	ROCKET
	OUT1
ODESAV	TWOD
	MAIN1D
	OUT1
	RKTOUT
ODKCOM	MAIN
	ODES
	ODK
	PACK
	READAT
	ROCKET
	SAVDAT
	CONVRT
	MAIN1D
	ODKBLM
	ODKINP
	OUT1
	OUTPUT
	PRES
	PRNTCK
	REAXIN
	RKTOUT
	SELECT
	CHAR
	DERIV
	EF
	FLU
	IAUX
	INT
	PRINT
	PTAB
	SINT
	PRINTS
	SDERIV
	EF2D
ODKRX	MAIN
	PACK
	READAT
	SAVDAT
	CONVRT
	DERIV
	EF
	SDERIV
	EF2D
ODKSP	MAIN
	PACK
	READAT
	SAVDAT
	TWOD
	CONVRT
	MAIN1D
	ODKBLM

LABELED COMMON	REFERRED BY SUBROUTINE
ODKSP	ODKINP OUTPUT REAXIN STF CHAR DERIV EF FLU GTF IAUX PRINT SUBIL GPFKIN GPFPG PRINTS SDERIV SUBILR THERM EF2D ENCALC
OPTION	INPUTB PROBLM SUMPRT
OUPT	BLKDTA SHCK THERMP DETON FROZEN OUT1 RKTOUT VARFMT EFMT
PATHL	READAT SAVDAT CNTRL SINT SUBIL SDERIV SUBILR
PCHILF	CHAR
PCTBL	READAT SAVDAT SUMPRT OUT1 TRAN

LABELED COMMON	REFERRED BY SUBROUTINE
PCTBL	PTAB
PERF	MAIN ODES ROCKET SHCK DETON EQLBRM FROZEN OUT1 RKTOUT TPCALC
PERFX	ODES ROCKET SHCK DETON EQLBRM FROZEN OUT1 RKTOUT
PEXIT	SUMPRT SUMPRT1 CNTR91 CNTRL
PLUMEC	SUMPRT TWOD CHAR CNTRL PRINT CNTR21 CNTR31 CNTR41 PRINTS
POINTS	MAIN ODES ROCKET SHCK THERMP DETON EQLBRM FROZEN HCALC MATRIX OUT1 RKTOUT TPCALC

LABELED COMMON	REFERRED BY SUBROUTINE
POINTS	CHAR
POINTX	ODES
	ROCKET
	SHCK
	THERMP
	DETON
	EQLBRM
	FROZEN
	HCALC
	MATRIX
	RKTOUT
PPPXX	CHAR
	CNTRL
	SUBILR
PRES	BLMAIN
	INPUTB
	BLEDGE
	COEF
	COEF1
	EDDY
PRFGAS	MAIN
	PROBLM
	SUMPRT
	TWOD
	TDK
	CHAR
	DSPT
	GPF
	INPT
	PRINT
	SINT
	WLPT
	AXISPT
	INPTR
	INPTR1
	INPTRS
	INPTS
	PRINTS
	SHCKA
	SHCKA1
	SHCKL
	SHCKR
	SHCKW1
	ATSHCK
	ENCALC
PRNTRX	BLPLTS
PTABLE	MAIN1D
	ODKINP
	PRES
	FLU
	IAUX
PTSAVE	MAIN
	ODES
PUNCHC	PROBLM
	PRINT
	PTAB
	PRINTS
RATES	ODKINP
	REAXIN
	PRATES
RDCARD	MAIN
RDIREX	MAIN
	ODES
	PACK
	SEARCH
	STOICC
	CONVRT
	REAXIN
	SELECT
	PRATES
RELPOT	BLW
	PROBLM
	SUMPRT
	SUMPRT1
REPEAT	MAIN
	ODES
	PROBLM
	READAT
	ODKINP
	TDK
	CHAR
	CNTR91
	GETIL
	GETILV
	PRINT
	PTAB

LABELED COMMON	REFERRED BY SUBROUTINE
REPEAT	PRINTS
RLMNR	BLMAIN COEF1
RVACOM	MAIN1D ODKINP OUTPUT INT
SAVODE	MAIN ODES
SAVPRI	SUMPRT PRINTS
SCLFTR	INPUTB READBL BLEDGE
SCRJT1	ODES
SHCK1	PROBLM SUMPRT CHAR CNTR91 WLPT CNTR41 CNTRL1 PRINTS
SHCK2	SUMPRT CHAR WLPT CNTR16 CNTR21 CNTR31 CNTR41 PRINTS
SHGAMA	MAIN ODK PROBLM SUMPRT ODKINP TDK CHAR DERIV SINT SDERIV
SHOCKC	PROBLM SUMPRT TDK TRAN CHAR
SKIP	CNTRL1 INPTR
SPECES	ODES ROCKET SAVE SEARCH SHCK THERMP CPHS DETON EQLBRM FROZEN HCALC MATRIX OUT1 RKTOUT
SPECEX	ODES ROCKET SAVE SHCK THERMP CPHS DETON EQLBRM FROZEN HCALC MATRIX RKTOUT
SPINFO	MAIN BLMAIN ODES PACK ROCKET SEARCH SHCK SUMPRT CPHS EQLBRM ODKINP OUT1

LABELED COMMON	REFERRED BY SUBROUTINE
SPINFO	RKTOUT
	SELECT
	SUMPRT1
	PTAB
SSUMS	ROCKET
	OUT1
STREAM	ODES
	SUMPRT
	TWOD
	MAIN1D
	TRAN
	CHAR
	GETIL
	GETILV
	GPFKIN
TABL	BLOCKD
	INPUTB
	OUTPBL
	READBL
	BLEDGE
	COEF1
	WRPROF
TABS	BLMAIN
	OUTPBL
	BLSEG
TBLDT1	MAIN
	ODES
	PROBLM
	READAT
	SAVDAT
	MAIN1D
	ODKBLM
	ODKINP
	TRAN
	GETIL
	GETILV
	IAUX
	PRINT
	PTAB
	PRINTS
TBLDT2	MAIN
	ODES
	READAT
	SAVDAT
TBLDT2	MAIN1D
	OUT1
	IAUX
	PRINT
	PTAB
	PRINTS
TBRSAV	ODKINP
	REAXIN
	SELECT
TDKMAX	TDK
	CHAR
	CNTRL
	DSPT
	INPT
	INSRT
	PRINT
	SUBIL
	WLPT
	AXISPT
	CNTR12
	CNTR13
	CNTR14
	CNTR16
	CNTR21
	CNTR31
	CNTR41
	CNTRL1
	CNTRL2
	FTHRST
	GETPT
	GPFKIN
	GPFPG
	INPTR
	INPTR1
	INPTRS
	INPTS
	INTEXT
	PRINTS
	SAVPT
	SHCKA
	SHCKA1
	SHCKL
	SHCKR
	SHCKW
	SHCKW1
	SUBILR
	WLCALC
	ATSHCK

LABELED COMMON	REFERRED BY SUBROUTINE
TEMP	BLSEG EDDY
TEQEC	ODES
THISPT	ROCKET
THMO	BLOCKD BLMAIN INPUTB IVPL OUTPBL READBL BLEDGE BLSEG COEF1 EDDY
THRST	FTHRST
TOTSC	MAIN READAT SAVDAT MAIN1D TRAN FCALC GETIL GETILV IAUX
TSTABL	MAIN READAT SAVDAT TWOD MAIN1D GETIL GETILV IAUX
TTDK	ODK OUTPUT
TW1	INPUTB
TWOPHZ	PACK CONVRT MAIN1D ODKINP OUTPUT
WALL	BLOCKD BLMAIN INPUTB OUTPBL SOLV5 BLEDGE BLSEG COEF COEF1 EDDY
WALLTM	BLOCKD INPUTB BLEDGE
WTYPE	BLW PROBLM SUMPRT SUMPRT1
XTNDED	BLOCKD BLMAIN INPUTB READBL BLEDGE
YSAVE	BLSEG WRPROF
ZDEBUG	READAT SAVDAT STF DERIV THERM
ZLAST	SUMPRT TDK CNTRL PRINT CNTRL1 CNTRL2 PRINTS
ZTRAN	MAIN READAT SAVDAT TWOD MAIN1D TRAN GETIL GETILV IAUX INT

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5. PROGRAM SUBROUTINES

This section contains descriptions of the TDK subroutines. TDK is organized into 6 modules, as follows: MCM, ODE, ODK, TRANS, MOC, and BLM. The subroutines descriptions are presented by modules, i.e., the MCM subroutines are given in Section 5-1, the ODE subroutines are given in Section 5-2, etc. At the present time, complete descriptions are not available for all of the MOC subroutines.

5.1 MCM SUBROUTINES

The Master Control Module is used to control the execution of TDK by selecting the computation modules to be exercised. The MCM is also used to process output files for the purpose of creating printed and plotted output. The MCM consists of the following subroutines:

MAIN
BLKDTA
FIND
GAUELM
ITER
LTCPHS
MATCH
MUK
0MEGA
PR0BLM
READAT
SAVDAT
SKPB1
SKPB2
SLP
SPLN
SUMPRT
TTAPE
UNIT

MAIN provides the entry point to TDK and is the master subroutine for the entire program.

5.1.1 PROGRAM MAIN

This is the main program for TDK and as such provides communication between modules, defines the upper level labeled common blocks, and initializes certain logical control variables. MAIN calls the thermodynamic tape generation subroutine, TTAPE, as required. Subroutine PR0BLM is called to read the $DATA namlist and determine the sequence of modules to be executed. Subroutines 0DE and 0DK are called to perform equilibrium/frozen and one dimensional kinetic calculations. Subroutine TW0D is called to perform transonic and two dimensional method of characteristics calculations. Subroutine BLMAIN is called to perform the boundary layer calculations. Subroutine BLW is called to calculate the displaced nozzle wall. Subroutine BLH is called to calculate the increase in propellant enthalpy contributed by the regenerative cooling circuits. The 0DE, 0DK, TRANS, and MOC calculations are then repeated if the repeat option has been specified.

5.1.2 SUBROUTINE BLKDTA

BLKDTA contains atomic data stored in AT0M(i,j) and many of the variables used with the variable format, FMT. The AT0M variables are defined in appendix B, Reference 3. The format variables are stored in the common labeled 0UPT and are described here.

A variable format was used so that one format, FMT, could be used in the final output with changes in the number of decimal places according to the sizes of the numbers. The format is used to print a label and from 1 to 13 associated numbers. The labels contain 14 alphanumeric characters stored in four words and printed with 3A4,A2. The numbers are all printed in a field of 9. FMT is initially set in BLKDTA as follows:

FMT	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	(1H	,3A4	,A2,	F9.	0,	F9.	0,	F9.	0,	F9.	0,
FMT	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	
	F9.	0,	F9.	0,	F9.	0,	F9.	0,	F9.	0,	
FMT	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)		
	F9.	0,	F9.	0,	F9.	0,	F9.	0	)		

where the spaces are stored as blanks.

Some variables set in BLKDTA to modify FMT are as follows:

Variable:	F0	F1	F2	F3	F4	F5	FB	FMT13	FMT9X	FMT19
Storage:	0,	1,	2,	3,	4,	5,		13,	9X,	I9,

The following is a list of variables used as labels and printed with 3A4, A2 in FMT:

Variable	Stored label
FP	P, ATM
FT	T, DEG K
FH	H, CAL G
FS	S, CAL/(G) (K)
FM	M, MOL WT
FV	(DLV/DLP) T
FD	(DLV/DLT) P
FC	CP, CAL/(G) (K)
FG	GAMMA (S)
FL	SON VEL, M/SEC
FR1	PC/P
FC1	CF
FN	MACH NUMBER
FR	CSTAR, FT/SEC
F1	ISP, LB-SEC/LB
FA	IVAC, LB-SEC/LB
FA1, FA2	AE/AT

5.1.3 SUBROUTINE FIND

This subroutine locates the index, I, in a table such that $X(I) \leq X \leq X(I+1)$.

5.1.4 Subroutine GAUELM(A,B,X,N,M,NDIM,MDIM,LDIM,EPS,KERR)

This subroutine solve a linear system of equations using Gaussian elimination with row interchange.The equation is put in matrix form as:

$$A X = B$$

where A,B and X are matrices of proper dimensions.

Calling Sequence

A,B,X	Matrices coefficients
N,M	Dimensions used: A(N,N), X(N,M), B(N,M)
NDIM	Maximum row dimension of A
MDIM	Maximum row dimension of B
LDIM	Maximum row dimension of X
EPS	Lower bound for the absolute value of the pivot
KERR	Error indicator,nonzero means error

5.1.5 SUBROUTINE ITER (F1, X1, XNEW, N00)

The purpose of this subroutine is to find the root or zero of the algebraic equation

$$f(X) = 0$$

using the method of secant or false position. In particular this subroutine is designed to take advantage of the fact that the secant method will always find the root of the above equation if the root has been spanned.

Calling Sequence:

F1	is the value of the dependent variable, f, corresponding to the value of X1.
X1	is the value of the independent variable, X, which corresponds to F1.
XNEW	is the predicted or new value of the independent variable
N00	is a flag such that

N00 = -1 the first time ITER is called.

N00 = +1 upon subsequence calls.

Restrictions:

The user is expected to check for convergence as there are no internal checks made in ITER.

Method:

Subroutine ITER utilizes the secant method predictor formula

$$X_{i+1}=X_i-f_i \cdot (X_i-X_{i-1})/(f_i - f_{i-1})$$

where the subscript i refers to the current value of X and f except for the first iteration in which the value of X is perturbed only slightly. When the root has been spanned the subroutine saves 2 back value of f and X in order that the root may always be straddled and thus found. The linkage to the subroutine is set up so that if bounds on the root are known, then the value of XNEW may be disregarded and bounded values may be used for the first two guesses. This type of linkage necessitates that the value of X1 must be set equal to XNEW or the bounded value of X. In order to speed up convergence, if the error within the bounded domain of the dependent variable exceeds a ratio of 10, then the new value of X is set equal to one half of the range.

5.1.6 SUBROUTINE LTCPHS

This subroutine processes the low temperature C_p, H, S Thermodynamic Data extension input as described in detail in Section 6.1.

5.1.7 SUBROUTINE MATCH

This subroutine is called by RØCKET to supply subroutine MUK with a vector of internal sequence numbers which point to the appropriate Lennard-Jones parameters used by MUK to calculate transport properties. The input to MATCH is the species name (from the SUB array) and the output corresponds to the index numbers in the table in the MUK write up.

5.1.8 Subroutine MUK (CP, XW, T, C, IT, N, XM, XMT, TK, PR)

This routine calculates the viscosity, thermal conductivity and Prandtl number for a gas composed of a mixture of species.

CALLING SEQUENCE:

CP	is an array of N specific heats of the species ($ft^2/sec^2\ ^\circ R$)	(INPUT)
XW	is an array of N molecular weights of the species (slug/slug mole)	(INPUT)
T	is the temperature of the gas ($^\circ R$)	(INPUT)
C	is an array of N mass fractions of the species	(INPUT)
IT	is an array of N indices of the species into a table of collision diameter (σ) and energy of attraction (ϵ/k)	(INPUT)
N	is the number of species in the gas	(INPUT)
XM	is an array of N viscosities of the species, ($lbf \cdot sec/ft^2$)	(ØUTPUT)
XMT	is the total viscosity of the gas, ($lbf \cdot sec/ft^2$)	(ØUTPUT)
TK	is the thermal conductivity of the gas, ($ft \cdot lbf/ft^2\ sec\ (^\circ R/ft)$)	(ØUTPUT)
PR	is the Prandtl number of the gas,	(ØUTPUT)

Method:

$$C_p = \sum_{i=1}^{N} C_i C_{p_i}$$ Specific Heat

$$M_w = \frac{1}{\sum_{i=1}^{N} \frac{C_i}{M_{w_i}}}$$ Molecular Weight

$$X_i = C_i \cdot \frac{M_w}{M_{w_i}}$$

$$T_i^* = \frac{T/1.8}{(\epsilon/k)_i}$$

$$\Omega_i = \text{table } (T_i^*)$$

table of Ω vs T^*

$$\sigma_i = \text{table } (i)$$

table of σ and ϵ/k vs. individual species

$$\mu_i = \frac{4.15822 \text{x} 10^{-8} \sqrt{M_{w_i} \, T}}{\sigma_i^2 \, \Omega_i}$$

$$\Phi_{i_j} = \frac{1}{2^{3/2}} \left(1 + \frac{M_{w_i}}{M_{w_j}} \right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j} \right)^{1/2} \left(\frac{M_{w_j}}{M_{w_i}} \right)^{1/4} \right]^2$$

$$\mu = \sum_{i=1}^{N} \left[\mu_i \left(1 + \sum_{\substack{j=1 \\ j \neq i}}^{N} \Phi_{i_j} \frac{X_j}{X_i} \right)^{-1} \right]$$

viscosity of the gas

$$K_i = \frac{\mu_i \, R}{M_{w_i}} \left(.45 + 1.32 \frac{C_{p_i}}{(R/M_{w_i})} \right)$$

$$K = \left[\sum_{i=1}^{N} K_i \left(1 + 1.065 \sum_{\substack{j=1 \\ j \neq i}}^{N} \Phi_{i_j} \frac{X_j}{X_i} \right)^{-1} \right]$$

thermal conductivity

$$P_r = \frac{C_p \mu}{K}$$

Prandtl number

Equations for K_i and μ_i are from Reference 14. The values of the collision integral are from Table 2 of Appendix B in Reference 15. The relations used to calculate μ and K of the mixture are from References 15 and 16, respectively.

Also from Reference 14 are the values of the collision diameters, σ, and energy of attraction, ε/k.

Table 5-1 correlates the chemical name of the species to the internal number assigned to it by the subroutine. Also included is the key-punch name assigned to the species, since lower-case letters and subscripts are non-standard features in most computer configurations.

Ref.14. Svehla, R. H. , "Estimated Viscosities and Thermal Conductivities of Gases at High Temperagures", NASA TR R-132, 1962.

Ref.15. Bird, R. B., Stewart, W.E., Lightfoot, E.N., Transport Phenomena , John Wiley & Sons. Inc. New York, 1960.

Ref.16. Mason, E. A., and Saxena, S. C., Physics of Fluids, Volume 1, No. 5, pp. 361-369, 1958.

Table 5-1: SPECIES NAMES AND IDENTIFIERS

Species Number	Chemical Name	Key Punch Name
1	Al	AL
2	AlCl	ALCL
3	$AlCl_3$	ALCL3
4	AlF	ALF
5	AlF_3	ALF3
6	AlN	ALN
7	AlO	ALO
8	AlS	ALS
9	Al_2	AL2
10	Air	AIR
11	Ar	AR
12	AsH_3	ASH3
13	B	B
14	BBr_3	BBR3
15	BCl	BCL
16	BCl_2	BCL2
17	BCl_3	BCL3
18	BF	BF
19	BF_2	BF2
20	BF_3	BF3
21	BI_3	BI3
22	BO	BO
23	$B(OCH_3)_3$	B(OCH3)3
24	B_2	B2
25	B_2H_6	B2H6
26	B_2O_3	B2O3
27	Be	BE
28	$BeBr_2$	BEBR2
29	BeCl	BECL
30	$BeCl_2$	BECL2
31	BeF	BEF
32	BeF_2	BEF2
33	BeI_2	BEI2
34	Be_2	BE2

Species Number	Chemical Name	Key Punch Name
35	Br	BR
36	BrF	BRF
37	BrF_3	BRF3
38	BrO	BRO
39	Br_2	BR2
40	C	C
41	$CBrF_3$	CBRF3
42	CBr_4	CBR4
43	CCl	CCL
44	$CClF_3$	CCLF3
45	CCl_2	CCL2
46	CCl_2F_2	CCL2F2
47	CCl_3	CCL3
48	CCl_3F	CCL3F
49	CCl_4	CCL4
40	CF	CF
51	CF_2	CF2
52	CF_3	CF3
53	CF_4	CF4
54	CH	CH
55	$CHBrClF$	CHBRCLF
56	$CHBrCl_2$	CHBRCL2
57	$CHBr_3$	CHBR3
58	$CHClF_2$	CHCLF2
59	$CHCl_3$	CHCL3
60	CHF_3	CHF3
61	CH_2BrCl	CH2BRCL
62	CH_2ClF	CH2CLF
63	CH_2CL_2	CH2CL2
64	CH_2F_2	CH2F2
65	CH_2I_2	CH2I2
66	CH_3Br	CH3BR
67	CH_3Cl	CH3CL

Species Number	Chemical Name	Key Punch Name
68	CH_3F	CH3F
69	CH_3I	CH3I
70	CH_3OH	CH3OH
71	CH_4	CH4
72	CN	CN
73	CO	CO
74	COS	COS
75	CO_2	CO2
76	CP	CP
77	CS	CS
78	CS_2	CS2
79	C_2	C2
80	C_2H_2	C2H2
81	C_2H_4	C2H4
82	C_2H_6	C2H6
83	C_2H_5Cl	C2H5CL
84	C_2H_5OH	C2H5OH
85	C_2N_2	C2N2
86	CH_3OCH_3	CH3OCH3
87	CH_2CHCH_3	CH2CHCH3
88	CH_3CCH	CH3CCH
89	cyclo-C_3H_6	CYCLO-C3H6
90	C_3H_8	C3H8
91	n-C_3H_7OH	N-C3H7OH
92	CH_3COCH_3	CH3COCH3
93	CH_3COOCH_3	CH3COOCH3
94	n-C_4H_{10}	N-C4H10
95	iso-C_4H_{10}	ISO-C4H10
96	$C_2H_5OC_2H_5$	C2H5OC2H5
97	$CH_3COOC_2H_5$	CH3COOC2H5
98	n-C_5H_{12}	N-C5H12
99	$C(CH_3)_4$	C(CH3)4
100	C_6H_6	C6H6

Species Number	Chemical Name	Key Punch Name
101	C_6H_{12}	C6H12
102	n-C_6H_{14}	N-C6H14
103	Cd	CD
104	Cl	CL
105	ClCN	CLCN
106	ClF	CLF
107	ClF_3	CLF3
108	ClO	CLO
109	Cl_2	CL2
110	F	F
111	FCN	FCN
112	F_2	F2
113	H	H
114	HBr	HBR
115	HCN	HCN
116	HCl	HCL
117	HF	HF
118	HI	HI
119	HS	HS
120	H_2	H2
121	H_2O	H2O
122	H_2O_2	H2O2
123	H_2S	H2S
124	He	HE
125	Hg	HG
126	$HgBr_2$	HGBR2
127	$HgCl_2$	HGCL2
128	HgI_2	HGI2
129	I	I
130	ICl	ICL
131	I_2	I2
132	Kr	KR
133	Li	LI
134	LiBr	LIBR

Species Number	Chemical Name	Key Punch Name
135	LiCN	LICN
136	LiCl	LICL
137	LiF	LIF
138	LiI	LII
139	LiO	LIO
140	Li_2	LI2
141	Li_2O	LI2O
142	Mg	MG
143	MgCl	MGCL
144	$MgCl_2$	MGCL2
145	MgF	MGF
146	MgF_2	MGF2
147	Mg_2	MG2
148	N	N
149	NF_3	NF3
150	NH	NH
151	NH_3	NH3
152	NO	NO
153	NOCl	NOCL
154	N_2	N2
155	N_2O	N2O
156	Na	NA
157	NaBr	NABR
158	NaCN	NACN
159	NaCl	NACL
160	NaF	NAF
161	NaI	NAI
162	NaO	NAO
163	NaOH	NAOH
164	Na_2	NA2
165	Na_2O	NA2O
166	Ne	NE
167	O	O
168	OF	OF

Species Number	Chemical Name	Key Punch Name
169	OF_2	OF2
170	OH	OH
171	O_2	O2
172	P	P
173	PCl	PCL
174	PCl_3	PCL3
175	PF	PF
176	PF_3	PF3
177	PH_3	PH3
178	PN	PN
179	PO	PO
180	PS	PS
181	P_2	P2
182	P_4	P4
183	S	S
184	SF_6	SF6
185	SO	SO
186	SO_2	SO2
187	S_2	S2
188	S_2F_2	S2F2
189	Si	SI
190	$SiCl_3$	SICL
191	$SiCl_4$	SICL4
192	SiF	SIF
193	$SiFCl_3$	SIFCL3
194	SiF_2Cl_2	SIF2CL2
195	SiF_3Cl	SIF3CL
196	SiF_4	SIF4
197	SiH_4.	SIH4
198	SiO	SIO
199	SiO_2	SIO2
200	SiS	SIS
201	Si_2	SI2
202	$SnBr_2$	SNBR2
203	$SnCl_4$	SNCL4
204	UF_6	UF6
205	Xe	XE
206	Zn	ZN

5.1.9 Subroutine OMEGA

This subroutine calculates the exponent, ω, used in the viscosity-temperature relationship

$$\mu = \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{\omega}$$

using the method of least squares. That is, it calculates the value of ω which gives the smallest sum of the errors squared. This form of the viscosity-temperature relationship was selected since the BLM module requires viscosity data in this manner.

In order to supply the maximum amount of accuracy and also to minimize the variation in data due to the selection of an exit area ratio, it was decided to match the throat value of viscosity exactly and select an ω which would provide the best fit for viscosity at the chamber and exit of the motor.

The form of the error, E, was taken to be

$$E = \ln \mu/\mu^* - \omega \ln T/T^*$$

Squaring the errors, differentiating with respect to ω, and setting the results equal to zero, yields the following value for ω

$$\omega = (\ln T_c/T^* \ln \mu_c/\mu^* + \ln T_e/T^* \ln \mu_e/\mu^*)/(\ln T_c/T^*)^2 + (\ln T_e/T^*)^2)$$

where

T = temperature

μ = viscosity

e = refers to the exit plane

c = refers to the chamber

* = refers to the throat plane

5.1.10 SUBROUTINE PR0BLEM

Subroutine PR0BLEM sets those default values that are concerned with the computational options of the program, such as the module execution flags (0DE, 0DK, TDK, BLM, TDE, IRPEAT, and IRSTRT). The $DATA namlist is read (see Section 6.). Flags controlling the sequence of module execution are set as determined by the options requested through the $DATA input. Nozzle geometry parameters are placed into the GEOM array for communication to the various modules.

5.1.11 SUBROUTINE READAT(NTAPE)

Subroutine READAT is called by Program MAIN to read data written by subroutine SAVDAT on unit NTAPE (=15) for the purpose of restarting the ODE and ODK modules.

5.1.12 SUBROUTINE SAVDAT (NTAPE)

Subroutine SAVDAT is called by Program MAIN to write data on unit NTAPE (=15) to be used later for restarting the ODE and ODK modules. This data is read later by subroutine READAT.

5.1.13 Subroutine SKPB1(XA,YA,XE,YE,THA,THR,C1,D1,E1)

This subroutine computes the coefficients for the skewed parabola defined by two points and the tangent at one of these points and the axis angle. The equation of a skewed-parabola is

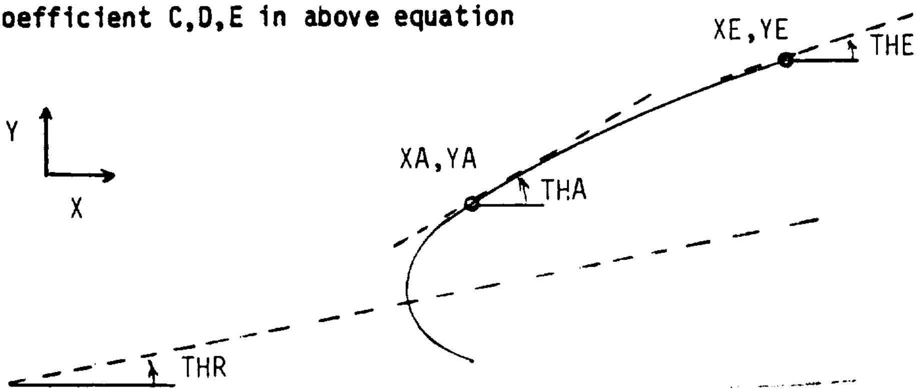
$$(Y-\tan(Tr)\ X)^2 + C\ X + D\ Y + E = 0$$

where Tr is the axis angle.

The subroutine solves for the coefficient C,D and E by using the condition on the two points and their tangents. The resulting equations form a linear system of 3 equations in 3 unknowns which is solved by Gaussian elimination with improvement correction using subroutin GAUELM.

Calling sequence:

XA,YA	coordinates of attachment point
XE,YE	coordinates of nozzle exit lip
THA	attachment angle
THR	axis angle, Tr
C1,D1,E1	coefficient C,D,E in above equation



5.1.14 Subroutine SKPB2(XA,YA,XE,YE,THA,THE,B1,C1,D1,E1)

This subroutine computes the equation for a skewed parabola defined by two points and their tangents. The equation for a skewed parabola is

$$(B\ X+Y)^2 + C\ X + D\ Y + E = 0$$

Subroutine SKPB1 and the secant method are used to solve for the axis angle that gives rise to the given exit lip angle.

Calling sequence:

XA,YA	coordinate of attachment point
XE,YE	coordinate of exit lip point
THA	attachment angle
THE	exit lip angle
B1,C1, D1,E1	coefficients B, C, D and E in above equation

5.1.15 SUBROUTINE SLP (X, Y, N, MFLAG, YP, W1, W2, W3, IFLAG)

The purpose of this subroutine is to supply derivatives for a tabulated function. The end point derivatives may be specified or are calculated internally by parabolic interpolation. Interior point derivatives may be found by a cubic spline fit procedure.

Calling Sequence:

X	is a table of independent variables, x_i	
Y	is a table of the dependent variables, y_i	
N	is the number of entries in each of the tables X, Y, and YP. $i = 1, \ldots N$	
MFLAG	this entry is a flag, m, such that	
	$m > 0$	implies x is equally spaced
	$m < 0$	implies x is not equally spaced
	$\lvert m \rvert = 1$	y' will be continuous
	$\lvert m \rvert = 2$	y' and y'' will be continuous
YP	is a table of the derivative, y'_i	
W1	working storage of length N	
W2	working storage of length N	
W3	working storage of length N	
IFLAG	this entry is a flag, i, such that	
	$i = o$	implies value for YP(1) and YP(N) will be calculated internally by parabolic differencing
	$i = 1$	implies values for YP(1) and YP(N) will be input

Method

The cubic spline fit procedure utilizes the interpolation formula given below:

$$\begin{aligned} y &= A(x - x_o)^3 + B(x - x_o)^2 + C(x - x_o) + D \\ y' &= 3A(x - x_o)^2 + 2B(x - x_o) + C \\ y'' &= 6A(x - x_o) + 2B \end{aligned}$$

The piecewise cubic fit to a tabular function by the above relations will yield a discontinuity in the second derivative y'', between adjacent fits of:

$$y''_{1_{01}} - y''_{1_{12}} = \frac{1}{h_{01}}\left(2y'_0 + 4y'_1 - 6\,\frac{k_{01}}{h_{01}}\right) - \frac{1}{h_{12}}\left(6\,\frac{k_{12}}{h_{12}} - 4y'_1 - 2y'_2\right)$$

where

$$h_{01} = x_1 - x_0$$

$$h_{12} = x_2 - x_1$$

$$k_{01} = y_1 - y_0$$

$$k_{12} = y_2 - y_1$$

The method consists of setting the left-hand side of the above relation equal to zero so that the second derivative is continuous across juncture points. As applied to a tabular function, the above procedure results in a set of linear simultaneous equations (tri-diagonal) to be solved for the y'_i, provided that values for y' at the end points are known.

5.1.16 SUBROUTINE SPLN

Performs either cubic or linear interpolation between two given points.

Cubic interpolation for a function and its first two derivatives is performed as described below:

Given function values y_n and y_{n+1} and first derivative values y'_n and y'_{n+1} at x_n and x_{n+1}, this subroutine evaluates $y(x)$, $y'(x)$, and $y''(x)$ for $x_n \leq x < x_{n+1}$ using:

$$y = A(x - x_n)^3 + B(x - x_n)^2 + C(x - x_n) + D$$

$$y' = y'_n + \frac{x - x_n}{x_{n+1} - x_n} \cdot [y'_{n+1} - y'_n]$$

$$y'' = (y'_{n+1} - y'_n)/h$$

where:

$$A = \frac{1}{h^3} \cdot [(y'_{n+1} + y'_n)h - 2k]$$

$$B = -\frac{1}{h^2} \cdot [(y'_{n+1} + 2y'_n)h - 3k]$$

$$C = y'_n$$

$$D = y_n$$

$$h = x_{n+1} - x_n$$

$$k = y_{n+1} - y_n$$

Linear interpolation for a function and its first two derivatives is performed as described below:

$$y = y_n + \frac{x - x_n}{x_{n+1} - x_n} \cdot [y_{n+1} - y_n]$$

$$y' = \frac{y_{n+1} - y_n}{x_{n+1} - x_n}$$

$$y'' = 0.0$$

5.1.17 SUBROUTINE SUMPRT

This subroutine is called by Program MAIN to write the "TDK PERFORMANCE SUMMARY" output that is printed after the execution of the MOC and/or BLM modules. An example of this output together with a detailed description is given in Section 7 of this report, Input and Output for Example Cases.

5.1.18 SUBROUTINE TTAPE

When a THERM0 directive card is read by the main program this subroutine is called to generate a master Thermodynamic Data tape (Logical Unit 25). The input Thermodynamic Data is in curve fit form and is identical to that required for the 0DE computer program described in NASA SP-273, Reference 3. The format for this curve fit data is described in the User's Manual, Section 6.1.

5.1.19 SUBROUTINE UNIT

This subroutine is called by Program MAIN and is used to establish a consistent set of physical constants and conversion factors for the engineering units that are used throughout the program. The values are stored in C0MM0N/C0NSTS/C000(25). The values used have been taken from the back cover of Zucrow and Hoffman, Reference 10.

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5.2 ØDE MODULE SUBROUTINES

The one-Dimensional Equilibrium module is used to calculate ideal engine performance. Engine performance can also be calculated assumming that the chemical composition is frozen at the chamber (stagnation) conditions. Gas mixture properties, including transport properties, are also calculated by the ØDE module to be used by the TDE, BLM and other options of the program. The ØDE module is a modified version of the chemical Equilibrium Compositions (CEC) program that is described in Reference 3. Reference 3 should be referred to for a more complete description of this program. The ØDE module consists of the following subroutines:

ØDES
CPHS
DETON
EFMT
EQLBRM
FRØZEN
GAUSS
HCALC
MATRIX
ØUT1
REACT
RKTØUT
RØCKET
SAVE
SEARCH
SHCK
THERMP
TPCALC
TSCALC
VARFMT

5.2.1 SUBROUTINE ØDES

This is the main program for ØDE and corresponds to the Main Program described in Reference 3. Generally, the routine performs the following functions:

1. Reads code cards THERMØ, REACTANTS, ØMIT, INSERT, and NAMELISTS and directs flow of program accordingly.
2. Stores THERMØ data on tape.
3. Calls subroutine REACT to read and process REACTANTS cards.
4. Reads ØMIT and INSERT cards and stores species names.
5. Initializes variables in namelist $ØDE.
6. Reads and writes namelist $ØDE.
7. Converts assigned densities, if any, (RHO(i) in $ØDE) to specific volumes: VLM(i) = 1/RHO(i).
8. Stores the number of pressures or volumes in NP.
9. Stores values of o/f in ØXF array. If o/f values have not been input directly, they are calculated as follows:

Values	Code	o/f calculation in main program
Oxidant to fuel weight ratio, o/f	ØF = .TRUE.	ØXF(i) = o/f
Fuel to air weight ratio, f/a	FA = .TRUE.	ØXF(i) = 1/(f/a)
Percent fuel, %F	FPCT = .TRUE.	ØXF(i) = (100-%F)/(%F)
Equivalence ratio, r	ERATIØ = .TRUE.	$ØXF(i) = \frac{-rV^{-(2)} - V^{+(2)}}{rV^{-(1)} + V^{+(1)}}$
If above values not specified	default to	$ØXF(i) = \frac{WP(1)}{WP(2)} = 1.0$

10. Makes necessary adjustments to consider charge balance if IØNS = .TRUE.. This is done by adding 1 to NLM and E to LLMT array.
11. Calls SEARCH to pull required THERMØ data from tape and to store the data in core.
12. Sets initial estimates for compositions. These estimates are set with each $ØDE read. They are used only for the first point in the lists of variables in namelist (e.g., the first o/f and the first T and P in a TP problem). All succeeding points use results from a previous point for estimates.

For the first point the program assigns an estimate of 0.1 for n, the total number of kilogram-moles per kilogram. The initial estimate of number of moles of each gaseous species per kilogram of mixture n_j is set equal to 0.1/m where m is the total number of gaseous species. Condensed species are assigned zero moles.

13. Sets IUSE(j) positive for condensed species listed on INSERT cards (see IUSE array).
14. Calls THERMP if TP, HP, SP, TV, UV, or SV is true.
15. Calls DET0N if DETN is true.
16. Calls SHCK if SH0CK is true.
17. Calls R0CKET is RKT is true.

5.2.2 SUBROUTINE CPHS

This subroutine evaluates the thermodynamic functions $\frac{Cp^\circ}{R}$, $\frac{H^\circ_T}{RT}$, $\frac{S^\circ_T}{R}$ from the curve fit coefficients. Two sets of coefficients are used for two adjacent temperature intervals. The functions evaluated are presented below:

$$\frac{Cp^\circ_T}{R} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4$$

$$\frac{H^\circ_T}{RT} = a_1 + \frac{a_2T}{2} + \frac{a_3T^2}{3} + \frac{a_4T^3}{4} + \frac{a_5T^4}{5} + \frac{a_6}{T}$$

$$\frac{S^\circ_T}{R} = a_1 \ln T + a_2T + \frac{a_3T^2}{2} + \frac{a_4T^3}{3} + \frac{a_5T^4}{4} + a_7$$

$$\frac{G^\circ_T}{RT} = \frac{H^\circ_T}{RT} - \frac{S^\circ_T}{R}$$

When the temperature falls below the lower limit of the curve fit coefficients, the above thermodynamic functions are obtained via linear interpolation from the input for subroutine LTCPHS.

5.2.3 SUBROUTINE DETON

This subroutine does the calculations required to obtain Chapman-Jouget detonation properties as described in the section CHAPMAN-JOUGET DETONATIONS of Reference 3. The calculation involves a Newton-Raphson iteration to determine detonation conditions in addition to the iteration for determining equilibrium compositions.

5.2.4 SUBROUTINE EFMT

Subroutine EFMT (E-format) writes statements in a special exponent form. This form is similar to the standard FORTRAN E-format, but the letter E and some of the spaces have been removed for compactness. It is used to write density and mole fractions with the TRACE option.

5.2.5 SUBROUTINE EQLBRM

EQLBRM is the control routine for the equilibrium module which calculates equilibrium compositions and thermodynamic properties for a particular point. A free-energy minimization technique is used. The program permits calculations such as (1) chemical equilibrium for assigned thermodynamic states (T,P), (H,P), (S,P), (T,V), (U,V), or (S,V), (2) theoretical rocket performance for both equilibirum and frozen compositions during expansion, (3) incident and reflected shock properties, and (4) Chapman-Jouguet detonation properties. The program considers condensed species as well as gaseous species. A detailed description of the equations and computer program for computations involving chemical equilibria in complex systems is given in Reference 3. Figures 4(a) through 4(c) of Reference 3 gives a complete flow diagram for this subroutine.

The equilibrium compositions are obtained by a Newton-Raphson iteration. The iteration equations are those of the modified Huff method.[18] These equations are presented as Table 5-2. The corrections to the estimates that are obtained from this set of iteration equations are unaffected by the choice of components and are only affected by the current estimates. These equations make no distinction between components and constituents, and thus any species can be dropped from the calculation. The iteration equations give corrections to the moles of each condensed species and the variables A and T directly. The corrections to the moles of gaseous species are obtained from the following equation:

$$\Delta \ln n_i = - \mathcal{F}_i + \sum_{k=1}^{\ell} a_{ki} \, \Delta \ln u_k + \mathcal{H}_i \, \Delta \ln T \qquad (i = 1, 2, \ldots, m)$$

It is sometimes disadvantageous to apply the entire correction called for by the iteration equations. Consequently an empirical convergence parameter λ ($0 < \lambda \leq 1$) is used to control the size of the corrections. A numerical value for λ is determined at each iteration. Methods for evaluating λ are discussed later under Evaluation of Convergence Parameter λ. New estimates are obtained from the following equations:

$$\ln n_i^{(j+1)} = \ln n_i^{(j)} + \lambda \, \Delta \ln n_i \qquad (i = 1, 2, \ldots, m)$$

$$n_i^{(j+1)} = n_i^{(j)} + \lambda \, \Delta n_i \qquad (i = m + 1, m + 2, \ldots, n)$$

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TABLE 5-2. - ITERATION EQUATIONS TO DETERMINE EQUILIBRIUM COMPOSITIONS FOR EITHER ASSIGNED PRESSURE AND TEMPERATURE, ASSIGNED PRESSURE AND ENTHALPY, OR ASSIGNED PRESSURE AND ENTROPY

$\Delta \ln u_1$	$\Delta \ln u_2$	$\Delta \ln u_3$	. . . .	Δn_{n-1}	Δn_n	$-\Delta \ln A$	$\Delta \ln T$ (*)	Constant
r_{11}	r_{12}	r_{13}	. . . .	$a_{1,n-1}$	$a_{1,n}$	$\sum_{k=1}^{n} a_{1,k}n_k$	$\sum_{k=1}^{m} a_{1,k}\mathcal{H}_k n_k$	$A\,\Delta b_1 + \sum_{k=1}^{m} a_{1,k}n_k \mathcal{F}_k$
r_{21}	r_{22}	r_{23}	. . . .	$a_{2,n-1}$	$a_{2,n}$	$\sum_{k=1}^{n} a_{2,k}n_k$	$\sum_{k=1}^{m} a_{2,k}\mathcal{H}_k n_k$	$A\,\Delta b_2 + \sum_{k=1}^{m} a_{2,k}n_k \mathcal{F}_k$
r_{31}	r_{32}	r_{33}	. . . .	$a_{3,n-1}$	$a_{3,n}$	$\sum_{k=1}^{n} a_{3,k}n_k$	$\sum_{k=1}^{m} a_{3,k}\mathcal{H}_k n_k$	$A\,\Delta b_3 + \sum_{k=1}^{m} a_{3,k}n_k \mathcal{F}_k$
. . .	. . .	. . .	. . . .	. . .	. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . . .	. . .	. . .	. . .	. . .	. . .
$a_{1,n-1}$	$a_{2,n-1}$	$a_{3,n-1}$	. . . .	0	0	0	$\mathcal{H}_{n-1}$	$\mathcal{F}_{n-1}$
$a_{1,n}$	$a_{2,n}$	$a_{3,n}$	. . . .	0	0	0	$\mathcal{H}_n$	$\mathcal{F}_n$
$\sum_{k=1}^{m} a_{1,k}n_k$	$\sum_{k=1}^{m} a_{2,k}n_k$	$\sum_{k=1}^{m} a_{3,k}n_k$	. . . .	0	0	0	$\sum_{k=1}^{m} \mathcal{H}_k n_k$	$\sum_{k=1}^{m} \mathcal{F}_k n_k + \Delta P$
$\sum_{k=1}^{m} a_{1,k}\mathcal{H}_k n_k$	$\sum_{k=1}^{m} a_{2,k}\mathcal{H}_k n_k$	$\sum_{k=1}^{m} a_{3,k}\mathcal{H}_k n_k$	. . . .	$\mathcal{H}_{n-1}$	$\mathcal{H}_n$	$\sum_{k=1}^{n} \mathcal{H}_k n_k$	$\sum_{k=1}^{n} \mathcal{C}_k n_k + \sum_{k=1}^{m} \mathcal{H}_k \mathcal{H}_k n_k$	$A\,\Delta h + \sum_{k=1}^{m} \mathcal{H}_k n_k \mathcal{F}_k$
$\sum_{k=1}^{m} a_{1,k}\mathcal{S}_k n_k$	$\sum_{k=1}^{m} a_{2,k}\mathcal{S}_k n_k$	$\sum_{k=1}^{m} a_{3,k}\mathcal{S}_k n_k$	. . . .	$\mathcal{S}_{n-1}$	$\mathcal{S}_n$	$\sum_{k=1}^{n} \mathcal{S}_k n_k$	$\sum_{k=1}^{n} \mathcal{C}_k n_k + \sum_{k=1}^{m} \mathcal{S}_k \mathcal{H}_k n_k$	$A\,\Delta s + \Delta P + \sum_{k=1}^{m} \mathcal{S}_k n_k \mathcal{F}_k$

Iteration for assigned pressure and temperature

Iteration for assigned pressure and enthalpy

Iteration for assigned pressure and entropy

* This column not used for assigned pressure and temperature.

$$\ln A^{(j+1)} = \ln A^{(j)} + \lambda\, \Delta \ln A$$

$$\ln T^{(j+1)} = \ln T^{(j)} + \lambda\, \Delta \ln T$$

The indices j and j+1 signify the estimates for the j^{th} and $(j+1)^{st}$ iterations. When the iteration has converged, the moles of gaseous species n_i will be numerically equal to the partial pressures p_i $(i = 1, 2, \ldots, m)$.

After the equilibrium compositions have been determined, the three independent first derivatives c_p, $(\partial \ln Mw/\partial \ln T)_p$, and $(\partial \ln Mw/\partial \ln P)_T$ can be evaluated by a procedure analogous to that described in reference 19. The calculation of c_p and $(\partial \ln Mw/\partial \ln T)_p$ requires the derivatives $(\partial \ln n_i/\partial \ln T)_p$ $(i = 1, 2, \ldots, m)$, $(\partial n_i/\partial \ln T)_p$ $(i = m+1, m+2, \ldots, n)$, and $(\partial \ln A/\partial \ln T)_p$. Following the procedure of reference 19 for the elimination of linear combination terms, the set of equations in Table 5-2 is obtained for the derivatives $(\partial \ln u_i/\partial \ln T)_p$ $(i = 1, 2, \ldots, \ell)$, $(\partial n_i/\partial \ln T)_p$ $(i = m+1, m+2, \ldots, n)$, and $(\partial \ln A/\partial \ln T)_p$. The $(\partial \ln n_i/\partial \ln T)_p$ are related to these by

$$\left(\frac{\partial \ln n_i}{\partial \ln T}\right)_p = \sum_{k=1}^{\ell} a_{ki} \left(\frac{\partial \ln u_k}{\partial \ln T}\right)_p + \varkappa_i \qquad (i = 1, 2, \ldots, m)$$

Writing the equation for evaluating the specific heat and substituting the above equation gives

$$c_p = \frac{R}{A}\left[\sum_{k=1}^{\ell}\sum_{i=1}^{m} a_{ki}\varkappa_i n_i \left(\frac{\partial \ln u_k}{\partial \ln T}\right)_p + \sum_{i=m+1}^{n} \varkappa_i \left(\frac{\partial n_i}{\partial \ln T}\right)_p + \sum_{i=1}^{m} \varkappa_i n_i \left(\frac{-\partial \ln A}{\partial \ln T}\right)_p + \sum_{i=1}^{m} \mathcal{E}_i n_i + \sum_{i=1}^{m} \varkappa_i \varkappa_i n_i\right]$$

TABLE 5-3 - EQUATIONS FOR EVALUATING DERIVATIVES WITH RESPECT TO TO LOGARITHM OF TEMPERATURE AT CONSTANT PRESSURE

$\left(\frac{\partial \ln u_1}{\partial \ln T}\right)_P$	$\left(\frac{\partial \ln u_2}{\partial \ln T}\right)_P$	$\left(\frac{\partial \ln u_3}{\partial \ln T}\right)_P$	. . .	. . .	$\left(\frac{\partial n_{n-1}}{\partial \ln T}\right)_P$	$\left(\frac{\partial n_n}{\partial \ln T}\right)_P$	$-\left(\frac{\partial \ln A}{\partial \ln T}\right)_P$	Constant
r_{11}	r_{12}	r_{13}	. . .	. . .	$a_{1,n-1}$	$a_{1,n}$	$\sum_{k=1}^{n} a_{1,k} n_k$	$-\sum_{k=1}^{m} a_{1,k} \mathcal{H}_k n_k$
r_{21}	r_{22}	r_{23}	. . .	. . .	$a_{2,n-1}$	$a_{2,n}$	$\sum_{k=1}^{n} a_{2,k} n_k$	$-\sum_{k=1}^{m} a_{2,k} \mathcal{H}_k n_k$
r_{31}	r_{32}	r_{33}	. . .	. . .	$a_{3,n-1}$	$a_{3,n}$	$\sum_{k=1}^{n} a_{3,k} n_k$	$-\sum_{k=1}^{m} a_{3,k} \mathcal{H}_k n_k$
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
$a_{1,n-1}$	$a_{2,n-1}$	$a_{3,n-1}$	. . .	. . .	0	0	0	$-\mathcal{H}_{n-1}$
$a_{1,n}$	$a_{2,n}$	$a_{3,n}$	. . .	. . .	0	0	0	$-\mathcal{H}_n$
$\sum_{k=1}^{m} a_{1,k} n_k$	$\sum_{k=1}^{m} a_{2,k} n_k$	$\sum_{k=1}^{m} a_{3,k} n_k$	. . .	. . .	0	0	0	$-\sum_{k=1}^{m} \mathcal{H}_k n_k$

The solution of the equations in Table 5-3 also gives one of the molecular weight derivatives by means of the relation

$$\left(\frac{\partial \ln Mw}{\partial \ln T}\right)_P = \left(\frac{\partial \ln A}{\partial \ln T}\right)_P$$

The derivative $(\partial \ln M/\partial \ln P)_T$ can be calculated from

$$\left(\frac{\partial \ln Mw}{\partial \ln P}\right)_T = \frac{P}{\sum\limits_{k=1}^{l}\sum\limits_{i=1}^{m}\left(a_{ki} n_i \frac{\partial \ln u_k}{\partial \ln A}\right)_T} - 1$$

where the required partial derivatives are obtained by a solution of the equations of Table 5-4 of this report. It should be noted that the matrix elements of Tables 5-3 and 5-4 are identical with the corresponding elements of Table 5-2 except for the sign of the last column in Table 5-3. The isentropic exponent, γ, used in the calculations of the velocity of sound is

$$\gamma \equiv \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s = \frac{1}{\left[1 + \left(\frac{\partial \ln Mw}{\partial \ln P}\right)_T\right] - \frac{R}{c_p Mw}\left[1 - \left(\frac{\partial \ln Mw}{\partial \ln T}\right)_P\right]^2}$$

Convergence in an iterative calculation involves two numerical problems: (1) how to assure numerical convergence, and (2) to determine at what stage the iteration should be terminated. Both of these are discussed in the following sections.

Evaluation of Convergence Parameter λ

When poor estimates are used in a Newton-Raphson iteration, the iteration equations will invariably give corrections that are too large. If these corrections were to be used directly, they could produce a nonconvergent iteration. This type of situation normally occurs in the early stages of a calculation.

TABLE 5-4. - EQUATIONS FOR EVALUATING DERIVATIVES WITH RESPECT TO LOGARITHM OF A AT CONSTANT TEMPERATURE

$\left(\frac{\partial \ln u_1}{\partial \ln A}\right)_T$	$\left(\frac{\partial \ln u_2}{\partial \ln A}\right)_T$	$\left(\frac{\partial \ln u_3}{\partial \ln A}\right)_T$	. . .	. . .	$\left(\frac{\partial n_{n-1}}{\partial \ln A}\right)_T$	$\left(\frac{\partial n_n}{\partial \ln A}\right)_T$	Constant
r_{11}	r_{12}	r_{13}	. . .	. . .	$a_{1,n-1}$	$a_{1,n}$	$\sum_{k=1}^{n} a_{1,k} n_k$
r_{21}	r_{22}	r_{23}	. . .	. . .	$a_{2,n-1}$	$a_{2,n}$	$\sum_{k=1}^{n} a_{2,k} n_k$
r_{31}	r_{32}	r_{33}	. . .	. . .	$a_{3,n-1}$	$a_{3,n}$	$\sum_{k=1}^{n} a_{3,k} n_k$
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
$a_{1,n-1}$	$a_{2,n-1}$	$a_{3,n-1}$	. . .	. . .	0	0	0
$a_{1,n}$	$a_{2,n}$	$a_{3,n}$	. . .	. . .	0	0	0

At later stages of the iteration when the problem seems to be converging satisfactorily, the iteration sometimes attempts to make large increases in the partial pressures of species that are present in trace amounts. In both of these cases it is essential to place some restriction on the size of the correction. This is accomplished by introducing a convergence parameter λ.

The numerical value of the convergence parameter λ is determined on the basis of two empirical rules, which experience has shown to be satisfactory. For the variables T, A, and n_j for those gaseous species for which $\ln(n_j/P_0) > -18.5$ and for which $\Delta \ln n_j > 0$, a number λ is defined as

$$\lambda_1 \equiv \frac{2}{\max(|\Delta \ln T|, |\Delta \ln A|, \Delta \ln n_j)} \quad (j = 1, 2, \ldots, m)$$

This limits the change in T and A and the increase in n_j, for those gaseous species whose gas phase mole fraction exceeds 10^{-8}, to a factor $e^2 = 7.3891$. For those gaseous species for which $\ln(n_j/P_0) \leq -18.5$ and $\Delta \ln n_j > 0$, a number λ_2 is defined as

$$\lambda_2 \equiv \min\left(\frac{\ln P_0 - 9.212 - \ln n_j}{\Delta \ln n_j}\right) \quad (j = 1, 2, \ldots, m)$$

This prevents a gaseous species with a mole fraction less than 10^{-8} from increasing its partial pressure so that its gas phase mole fraction would exceed 10^{-4}. The parameter λ to be used is defined in terms of λ_1 and λ_2 as

$$\lambda \equiv \min(1, \lambda_1, \lambda_2)$$

Criteria for Convergence

Equilibrium compositions. - It is assumed that the iteration has converged to the correct composition when

$$\frac{n_j}{\sum_{k=1}^{n} n_k} |\Delta \ln n_j| < 0.5\text{x}10^{-5} \quad (j = 1, 2, \ldots, m)$$

and

$$\frac{|\Delta \; n_j|}{\sum_{k=1}^{n} n_k} < 0.5\text{x}10^{-5} \quad (j = m + 1, m + 2, \ldots, n)$$

This has the effect of insuring accuracy to five places in composition when it is expressed as mole fractions.

5.2.6 SUBROUTINE FR0ZEN

Subroutine FR0ZEN is called from subroutine R0CKET to calculate the temperature and thermodynamic properties for the following assigned conditions:

1. Composition frozen at combustion conditions.
2. An assigned exit pressure.
3. An assigned entropy equal to the entropy at combustion conditions.

The iteration procedure used for obtaining the exit temperature is discussed in the section Procedure for Obtaining Frozen Rocket Performance (p.40, Reference 3.)

For a mixture of fixed composition, entropy, and pressure, the temperature is calculated by a Newton-Raphson iteration. The correction to **the current estimate for temperature is obtained from**

$$\Delta \ \ln T = \frac{\mathcal{S}_f - \mathcal{S}_f^\circ}{\sum\limits_{i=1}^{n} \mathcal{E}_i x_i}$$

The improved estimate for temperature is then obtained by means of

$$\ln T^{(j+1)} = \ln T^{(j)} - \Delta \ \ln T$$

For frozen composition, the three independent first partial derivatives are:

$$c_p = R \frac{\sum\limits_{i=1}^{n} \mathcal{E}_i x_i}{Mw_c \sum\limits_{i=1}^{m} x_i}$$

and

$$\left(\frac{\partial \ \ln Mw}{\partial \ \ln T} \right)_P = 0$$

and

$$\left(\frac{\partial \ln Mw}{\partial \ln P} \right)_T = 0$$

The isentropic exponent γ is

$$\gamma = \frac{c_p Mw_c}{c_p Mw_c - R}$$

The throat conditions are evaluated with the aid of a secondary Newton-Raphson iteration using the equation

$$\left(\frac{P_c}{P}\right)_{k+1} = \frac{\left(\frac{P_c}{P}\right)_k}{1 + \frac{2Mw(h_c - h_k^*)}{(\gamma + 1)\ RT}}$$

where $(P_c/P)_k$ is the k^{th} estimate for pressure ratio at the throat and h_k^* is the value of h^* for the pressure corresponding to this pressure ratio and an entropy equal to the combustion entropy. The initial estimate for P_c/P and T at the throat is described below.

An excellent estimate of the throat pressure ratio for both equilibrium and frozen compositions is

$$P_c/P = \left(\frac{\gamma_c + 1}{2}\right)^{\frac{\gamma_c}{\gamma_c - 1}}$$

This relation usually gives a throat pressure ratio, which is correct to three places. The throat temperature is estimated from the equation

$$T = \frac{2}{1 + \gamma_c}\ T_c$$

The throat conditions for a rocket nozzle are assumed to be satisfied if

$$\left|\frac{h_c - h^*}{h_c - h}\right| \le 0.4\text{x}10^{-4}$$

This condition in effect makes certain that the Mach number will satisfy the condition that

$$M = 1\ \underline{+}0.2\text{x}10^{-4}$$

5.2.7 SUBROUTINE GAUSS

Subroutine GAUSS is used to solve the set of simultaneous linear iteration equations constructed by subroutine MATRIX. The solution is effected by performing a Gauss reduction using a modified pivot technique. In this modified pivot technique only rows are interchanged. The row to be used for the elimination of a variable is selected on the basis that the largest of its elements, after division by the leading element, must be smaller than the largest element of the other rows after division by their leading elements.

The solution vector is stored in X(k). In the event of a singularity, IMAT (which is equal to the number of rows) is set equal to IMAT - 1. IMAT is tested later in subroutine EQLBRM.

5.2.8 SUBROUTINE HCALC

The purpose of HCALC is to calculate thermodynamic properties for reactants under certain circumstances. HCALC is called from entry NEW0F of SAVE and DET0N.

HCALC is called from NEW0F when CALCH is set true. CALCH is set true in the main program when zeros have been punched in card columns 37 and 38 on one or more REACTANTS cards. The zeros are a code indicating that the enthalpy (or internal energy for UV problems) for the reactant should be calculated from the THERM0 data at the temperature punched on the card. This temperature has been stored in the RTEMP array. CPHS is called to calculate the enthalpy. The value is sorted in the ENTH array and printed in the final tables.

The properties calculated in subroutine HCALC, their FORTRAN symbols, and the conditions for which they are used are as follows:

Property	FORTRAN symbol	Equation	
$\mathcal{H}$ (k)T	HPP(k)	(192)	SHØCK problem. DETN problem with T schedul HP, RKT, or DETN problem if 00 in cc 37 and 3
h_o/R	HSUB0	(193)	SHØCK problem. DETN problem with T schedule HP, RKT, or DETN problem if 00 in cc 37 and 3
$\mathcal{U}$ (k)T	HPP(k)	(194)	UV problem if 00 in cc 37 and 38
u'_o/R	HSUB0	(195)	UV problem if 00 in cc 37 and 38
M_o	AM1	(197)	SHØCK or DETN problem
m_i	EN(j)	(205)	SHØCK problem
$\mathcal{C}_o$	CPR1	(206)	SHØCK problem
$\mathcal{S}_o$	S0	(207)	SHØCK problem

The quantity m_i was deliberately subscripted differently from EN(j) to allow for the fact that the same compound may have a different index as a reactant than as a reaction species. Thus, for example, O_2 (g) might be the third reactant read in from REACTANTS cards and also the tenth species read in by SEARCH. In this case m_3 would be stored in EN(10).

5.2.9 SUBROUTINE MATRIX

This subroutine sets up the matrices corresponding to tables I through IV of Reference 3. The assigned thermodynamic state being set up (tables I and II) is specified by the following codes:

Assigned thermodynamic state	Codes
TP	TP = .TRUE. VOL = .FALSE. CONVG = .FALSE.
HP	HP = .TRUE. VOL = .FALSE. CONVG = .FALSE.
SP	SP = .TRUE. VOL = .FALSE. CONVG = .FALSE.
TV	TP = .TRUE. VOL = .TRUE. CONVG = .FALSE.
UV	HP = .TRUE. VOL = .TRUE. CONVG = .FALSE.
SV	SP = .TRUE. VOL = .TRUE. CONVG = .FALSE.

After convergence of any of the previous six probelms, setup of the derivative matrices (tables III and IV) is specified by the following codes:

Derivative	Codes
DLVTP	CONVG = .TRUE. LOGV = .FALSE.
DLVPT	CONVG = .TRUE. LOGV = .FALSE.

5.2.10 SUBROUTINE 0UT1

This subroutine, together with entries 0UT2 and 0UT3, writes statements common to all problems. 0UT1 writes statements giving the data on REACTANTS and on o/f, percent fuel, equivalence ratio, and density.

Entry 0UT2. - This entry writes the statements for printing values of pressure, temperature, dentity, enthalpy, entropy, molecular weight, $(\partial \ln V/\partial \ln P)_T$ (if equilibrium), $(\partial \ln V/\partial \ln T)_P$ (if equilibrium), heat capacity, γ_S, and sonic velocity. These variables and corresponding labels are printed with a variable format described in BLKDTA.

Entry 0UT3. - Entry 0UT3 writes statements giving the equilibrium mole fractions of reaction species.

5.2.11 SUBROUTINE REACT

The purpose of subroutine REACT is to read and process the data on the REACTANTS cards. The subroutine is called from the main program after a REACTANTS code card has been read. The data on these cards are described in the REACTANTS Cards section (p. 62) of Reference 3. References to page numbers and equations given below also pertain to Reference 3.

The reactants may be divided into two groups according to card column 72 on the REACTANTS cards. The two groups are oxidants (O in cc 72) and fuels (cc 72 ≠ O). We generally keypunch F in card column 72 for fuels even though this is not necessary. The contents of card column 72 are read into F0X. Depending on the contents of F0X, program variables relating to oxidants or fuels are subscripted 1 for oxidants and 2 for fuels.

The FORTRAN symbols for the properties read from the REACTANTS cards and their associated properties (discussed in INPUT CALCULATIONS, p. 55 of Reference 3 are as follows:

Property	FORTRAN symbol
$a_{ij}^{(k)}$	ANLM(j,m)[a]
$W_j^{(k)}$	PECWT(j) (if no M in cc 53)
$N_j^{(k)}$	PECWT(j) (if M in cc 53)
$(H_T^o)_j^{(k)}$	ENTH(j) (if not UV problem and 00 not in cc 37 and 38)
$(U_T^o)_j^{(k)}$	ENTH(j) (if UV problem and 00 not in cc 37 and 38)
$\rho_j^{(k)}$	DENS(j)

[a] Each of the j REACTANTS cards contains from 1 to 5 stoichiometric coefficients read (indicated by subscript m) into ANUM(j,m) and their corresponding chemical symbols read into NAME(j,m). In relating an ANUM(j,m) with $a_{ij}^{(k)}$, the index i associated with a particular chemical element is determined from the chemical symbol in NAME(j,m).

If there are several oxidants their properties are combined by subroutine REACT into properties of a total oxidant using the relative proportion of each oxidant given on the REACTANTS cards. Similarly, if there are several fuels, their properties are combined into properties of a total fuel. The total oxidant and total fuel properties discussed in INPUT CALCULATIONS[3] and their associated FORTRAN symbols are as follows:

Property	FORTRAN symbol	Equation
$b_i^{(k)}$	BOP(i,k)	(187)
$M_j^{(k)}$	RMW(j)	(190)
$\mathcal{H}^{(k)}_T$	HPP(k) (if not UV problem and 00 not in cc 37 and 38)	(192)
$\mathcal{U}^{(k)}_T$	HPP(k) (if UV problem and 00 not in cc 37 and 38)	(194)
$M^{(k)}$	AM(k)	(196)
$\rho^{(k)}$	RH(k)	(198)
$V^{+(k)}$	VPLS(k)	(200)
$V^{-(k)}$	VMIN(k)	(201)
$W_j^{(k)} \Big/ \sum_{j=1}^{NREAC} W_j^{(k)}$	PECWT(j)	

If any of the $\rho_j^{(k)}$ are zero then RH(1) = RH(2) = 0.

These total oxidant and total fuel properties are subsequently combined into total reactant properties by using the values of oxidant-fuel mixture ratios obtained from the main program. This is done in NEWØF, an entry in SAVE.

Other common variables set by REACT are LLMT, NAME, ANUM, ENTH, FAZ, RTEMP, FOX, DENS, RMW, MØLES, NLM, NEWR, and NREAC.

A provision is made for eliminating a second tape search when two consecutive sets of REACTANTS cards contain the same elements. This is done by saving the element symobls (LLMT(ℓ)) in LLMTS(ℓ), the kilogram-atoms per kilogram (BOP(ℓ,k)) in SBOP(ℓ,k), and the number of elements (NLM) in NLS.

Atomic weights M_i used in equation (190)[3] are stored in ATØM(2,i). The corresponding chemical symbols are stored in ATØM(1,i). The oxidation states of the chemical elements V_i^+ or V_i^- used in equations (200) and (201)[3] are stored in ATØM(3,i). The ATØM array is stored by BLKDTA.

5.2.12 SUBROUTINE RKTØUT

This subroutine calculates various rocket performance parameters from previously calculated thermodynamic properties.

It is also the control program for writing rocket performance output. It contains the WRITE statements that apply specifically to rocket parameters and it calls subroutine ØUT1 and entries ØUT2 and ØUT3 for the WRITE statements common to all problems. The rocket parameters are printed with the variable format, FMT, described in BLKDTA.

The following formulas used in computing the various performance parameters were derived from the one-dimensional forms of continuity, energy, and momentum equations and the following assumptions: zero velocity in the combustion chamber, perfect gas law, complete combustion, homogeneous mixing, adiabatic combustion, and isentropic expansion. (The units used were h = cal/gm, T = °K, P = lb force/sq in., A = sq in., w = lb mass/sec, and $g_c = 32.174$ (lb mass/lb force) (ft/sec^2).)

Specific impulse with ambient and exit pressures equal, (lb force) (sec)/lb mass:

$$I = 294.98 \sqrt{\frac{h_c - h}{1000}}$$

Specific impulse in vacuum (ambient pressure zero), (lb force) (sec)/lb mass:

$$I_{vac} = I + P \frac{A}{w}$$

Characteristic velocity, ft/sec:

$$c^* = g_c P_c \left(\frac{A}{w}\right)_t = 32.174 \, P_c \left(\frac{A}{w}\right)_t$$

Coefficient of thrust:

$$C_F = \frac{g_c I}{c^*} = 32.174 \, \frac{I}{c^*}$$

Mach number:

$$M = \frac{U}{U_s} = \frac{I}{\sqrt{\frac{86.4579 \, \gamma T}{Mw}}}$$

5.2.13 SUBRØUTINE RØCKET

This subroutine is the control program for the RKT problem (rocket performance calculations discussed in section RØCKET PERFORMANCE).[3] A flow diagram for this subroutine is given in Figure 5 of Reference [3] Subroutine RØCKET obtains the required thermodynamic properties for equilibrium performance by calling subroutine EQLBRM. For frozen performance, subroutine RØCKET calls subroutine FRØZEN to obtain the required thermodynamic properties. Rocket performance parameters are then obtained by calling subroutine RKTØUT. In addition to calling RKTØUT and FRØZEN, and in addition to using controls common to all problems (discussed in section MODULAR FORM OF THE PROGRAM, p. 75, Reference 3) subroutine RØCKET also does the following:

1. It reads and processes the input data in RKTINP namelist.
2. It calculates estimates for throat pressure ratios.
3. It calculates estimates for pressure ratios corresponding to assigned area ratios (if any).

5.2.14 SUBROUTINE SAVE

This subroutine has several functions, all of which are concerned with saving some information from a completed calculation for subsequent use in later calculations. The primary purpose is to save computer time by having good initial estimates for compositions.

These estimates for the next point, NPT, come from either the point just completed, ISV, or some other previous point. The flow of the routine is directed by ISV as follows:

1. ISV positive. Transfer compositions for point just completed for use as initial estimates for next point (transfer EN(j,ISV) to EN(j,NPT)).
2. ISV negative. Save values of ENLN(j) for gases and EN(j) for condensed in SLN(j), ENN in ENSAVE, ENNL in ENLSAV, IQ1 in IQSAVE, JSØL in JSØLS, JLIQ in JLIQS, and NLM in LL1. (These values are saved because they are to be used as initial estimates for some future point and they may be overwritten in the meantime.) Make ISV positive and transfer EN(j,ISV) to EN(j,NPT).
3. ISV zero. Use the data previously saved (as discussed in 2.) as initial estimates for current point. Restore IUSE codes and inclusion or exclusion of "E" as an element for IØNS option.

Entry NEWØF. - NEWØF combines the properties of total oxidant and total fuel calculated in subroutine REACT with an o/f value to give properties for the total reactant. NEWOF is called for each mixture assigned in the MIX array in the $ØDE namelist. It is called from either THERMP, RØCKET, SHCK, or DETON. The calculated properties and corresponding FORTRAN symbols are as follows:

Property	FORTRAN symbol	Equation
b_i^o	B0(i)	(191)
h_o/R	HSUB0 (if not UV problem)	(193)
u'_o/R	HSUB0 (if UV problem)	(195)
ρ_o	RHØP	(199)
r	EQRAT	(204)

Subroutine HCALC is called by Entry NEWØF to calculate the enthalpies for each reactant that has zeros keypunched in card columns 37 and 38 in its REACTANTS card.

Values of HPP(2), HPP(1), HSUB0, B0P(i,2), B0P(i,1), and B0(i) are printed out.

5.2.15 SUBROUTINE SEARCH

This subroutine selects the Thermodynamic Data to be used in the problem. A scan is made of the master Thermodynamic Data tape and those species that are consistent with the chemical system under consideration are selected. As the thermodynamic data are being selected, the subroutine also complies a set of formula numbers, a_{ij}, from the formulas of the reaction products. A short Thermodynamic Data file is also generated for use in subsequent calculations (multizone).

A check is made near the beginning of the routine to prevent THERMØ data from exceeding their storage allotments. These variables are all in labeled common SPECIES and are currently dimensioned for 150 species. However, this dimension may be reduced to save storage.

SEARCH is called from the main program when the logical variable NEWR is true. NEWR is set true in REACT to indicate a new chemical system. REACT also stores chemical element symbols for the current chemical system in the LLMT array. SEARCH stores THERMØ data in core for each species whose elements are included in the LLMT array (unless the species name was listed on an ØMIT card).

The THERMØ data are stored in common variables TLØW, TMID, THIGH, SUB, A, CØEF, and TEMP. SEARCH writes out the names and dates of species whose data are stored in core.

SEARCH initializes the IUSE array. IUSE(j) for gaseous species are set equal to zero. IUSE(j) for condensed species are set equal to negative integers. For the chemical system under consideration, the first possible condensed species is set equal to -1, the second to -2, and so on, with one exception. In the event there are two or more condensed phases of the same species, each phase is given the same negative integer. Thus, if IUSE(j) for $B_2O_3(\ell)$ is set equal to -4, for example, IUSE(j) for $B_2O_3(s)$ will also be set equal to -4. A description of the IUSE array is given below.

The various condensed phases of a species are expected to be adjacent in the THERMØ data as they are read from tape. These phases must be either in increasing or decreasing order according to their temperature intervals.

NS contains the total number of species stored in core. NC contains the total number of condensed species (counting each condensed phase of a species as a separate species).

EQLBRM. For condensed species, the sign is adjusted as species are included or excluded in the current iteration.

For the IØNS option, IUSE(j) values for ionic species are set to -10000 when the mole fractions of all ionic species are less than 10^{-8}.

IUSE array. - Each value in the IUSE array is associated with a species. These values of IUSE serve two purposes:

1. They indicate which species are to be included in the current iteration (IUSE(j) < 0 for excluded species and IUSE(j) ≥ 0 for included species).
2. They indicate multiple phases of the same species if absolute values of IUSE(j) are equal.

The IUSE(j) are initialized in subroutine SEARCH and the main program as follows:

1. IUSE(j) = 0 for all gaseous species.
2. IUSE(j) = n for all condensed species whose names have been listed on INSERT cards. The number n indicates the species was the n^{th} condensed species whose THERMØ data were read from tape.
3. IUSE(j) = -n for all condensed species not listed on INSERT cards where n is defined in 2.

These initial values of IUSE(j) may be adjusted later in subroutine

5.2.16 SUBROUTINE SHCK

Subroutine SHCK is the application module for the SH0CK problems. It calculates the shock parameters discussed in the section "INCIDENT AND REFLECTED SHOCKS". It reads and processes the input data in SHKINP namelist. Depending on which options are specified, it calculates incident shock conditions based on compositions frozen at initial conditions and/or based on equilibrium compositions after shock. It also calculates, based on specified options, frozen and/or equilibrium reflected shock conditions relative to equilibrium and/or frozen incident shock conditions.

5.2.17 SUBROUTINE THERMP

This subroutine is the application module for TP, HP, SP , TV, UV and SV problems. Common variables which must be set according to the assigned thermodynamic states are given in the section Application Modules (p. 76) of Reference 3. For these problems, the variables TP, HP, SP, S0, and V0L are set or read in subroutine 0DES. HSUB0 is set either in SAVE (entry NEW0F) or HCALC. The general flow of the routine is given in figure 3 of Reference 3.

Indices run from 1 to NP both for assigned pressures P and assigned volumes (V in 0DE and VL in THERMP). Indices run from 1to NT for assigned temperature T. NP and NT are set in the subroutine 0DES.

5.2.18 SUBROUTINE TPCALC

This subroutine is used to obtain equilibrium values of C_p, γ, R, and h from given values of T and P. Subroutine EQLBRM is called to obtain the solutions.

5.2.19 SUBROUTINE TSCALC

This subroutine finds equilibrium solutions from given values of T and S. The method used is to call subroutine TPCALC to find equilibrium solutions from given values of T and P, then the P value is adjusted until the input value of S is matched. Iteration on P is done using subroutine ITER (secant method). Subroutine TSCALC is used to construct the gas properties tables used by the BLM which are discussed in Section 2.6.3.

5.2.20 SUBROUTINE VARFMT

Subroutine VARFMT (variable format) adjusts the number of decimal places printed in F-format in the variable format. FMT, according to the size of the number. It is used for P_c/P_e, P, and A_e/A_t. Variable format is described in BLKDTA.

5.3 ODK MODULE SUBROUTINES

The One-Dimensional Kinetics (ODK) module is used to calculate the loss in nozzle performance caused by finite-rate chemistry of the expansion products. The method of analysis used is described in Section 2.1 and 2.2. Since the ordinary differential equations that are solved can be extremely stiff, a stable integration method is required. The integration method is described in Section 3.1.

The ODK module consists of the following subroutines:

- ODK
- CHTYPE
- CONVRT
- DERIV
- ECNV1
- EF
- FLU
- FNDLM
- GTF
- IAUX
- INT
- LESK
- MAIN1D
- MGET
- NUMBR
- ODKBLM
- ODKINP
- ODWALL
- OUTPUT
- PACK
- PACKCD
- PRATES
- PREAX
- PRES
- PRNTCK
- REAXIN
- SELECT
- STF
- ST0ICC
- STORNU
- SUBNE
- TABGEN

5.3.1 SUBROUTINE ODK

This subroutine acts as the driver for the one dimensional kinetic expansion calculation (ØDK). It calls subroutine ODKINP to read the $ODK input. Subroutine PACK is then called to prepare master tables for the chemical species and reactions to be used. Then subroutine MAIN1D is called which is the main program for the ODK module.

5.3.2 SUBROUTINE CHTYPE (KRD, ITY, NC)

Given the array KRD containing in each entry one character, left justified, this subroutine stores an interger code into the corresponding entry of array ITY. NC is the number of characters (consecutive entries) in KRD which are to be processed. The character-code table is as follows.

Character	Code
=	-4
*	-3
+	-2
0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
all others	-1

5.3.3 SUBROUTINE CØNVRT

This subroutine converts input data from the externally input units to internally used computation units. In order to conserve computation time during the kinetic expansion, parameters such as molecular weights, are included in these conversions. **Barred values are input quantities.**

a) Reaction rate ratio input for reactions requiring third body terms
units: unitless
internal units: (lbs-mass/lb-mole)$^{-1}$
formula: $XMM_{j,i} = \overline{XMM}_{j,i}/Mw_i$

b) Pre-exponential reaction rate parameter
input units: cm, °K, g-mole, sec
internal units: ft^3, °R, lb-mole, sec

$$a_j = \frac{\bar{a}_j \cdot (.0160183)^{\lambda_j}\, 1.8^{\bar{n}_j}}{\prod\limits_{i=1}^{n} Mw_i^{\;\nu'_{ij}}}$$

Where λ depends on the order of the reaction, i.e. where $\lambda = (\Sigma\nu) - 1$ for binary exchange and $\Sigma\nu$ for third body recombination. Also:

$$.0160185 = \frac{3.53147 \cdot 10^{-5}\ \text{ft}^3}{1\ \text{cm}^3} \cdot \frac{1\ \text{g-mass}}{2.20462 \cdot 10^{-3}\ \text{lbs-mass}}$$

c) **Exponential Term:**
input units: kcal/mole
internal units: °R
formula: $b_j = \bar{b}_j \cdot 905.770$

$$\text{where } 905.770 = \frac{1000\ \text{cal}}{1\ \text{kcal}} \cdot \frac{1}{1.98726\ \text{cal/mole-°K}} \cdot \frac{1.8°\text{R}}{1.0°\text{K}}$$

d) Equilibrium Constant Multiplicative Factor:

Input units: not input

internal units: (lbs-mass) - °R/ft^3

formula:

$$\mathrm{DATEF}(J) = \frac{\prod\limits_{i=1}^{\text{products}} Mw_i}{\prod\limits^{\text{reactants}} Mw_i} (0.73034)^{-(\nu'-\nu)}$$

where

$$.73034 = 49{,}721.011 \cdot \frac{\text{ft - poundals}}{(\text{lbs-mole})\ ^\circ R} \cdot \frac{1 \text{ atmos}}{68{,}059.59 \text{ poundals/ft}^2}$$

i.e.

$$.73034 = (RJG)/(144\ g\ 14.69)$$

e) Pressure:

input units: PSIA

internal units: poundals/ft^2

formula: $P = \bar{P} \cdot 4633.056$

where

$$4633.056 = \frac{144 \text{ in}^2}{1 \text{ ft}^2} \cdot 32.174 \frac{\text{ft}}{\text{sec}^2}$$

f) The initial reference enthalpy is computed using

$$H_{\text{Ref}} = \sum_{i=1}^{N} c_i h_i + \frac{V^2}{2}$$

Subroutine CØNVRT has been modified to calculate the total amount of condensed phase present at the kinetic expansion initial conditions.

5.3.4 SUBROUTINE DERIV

This subroutine computes the total derivatives f_i and the partial derivatives β_{ij} described in the analysis presented in Section 3

The implicit integration method used to integrate the differential equations governing the chemical system, i.e.

$$y_i' = f_i(x, y_1, \ldots ; y_{NSP+3}) \qquad i=1, \ldots, NSP+3$$

where the variables

$$y_i \qquad i=1, \ldots, NSP+3$$

are $\quad V, \rho, T, C_i \qquad i=1, \ldots, NSP$

respectively, requires evaluation of the Jacobian of the system, i. e.

$$\beta_{ij} = \frac{\partial f_i}{\partial y_j} \qquad \begin{array}{l} i=1, \ldots, NSP+3 \\ j=1, \ldots, NSP+3 \end{array}$$

Subroutine DERIV computes only certain of the β_{ij} (those taken with respect to C_i) and the others are computed in subroutine FLU.

Also calculated by DERIV are the reaction rates, k_j, and the net production rates, X_j.

The generalized chemical reaction which is handled by this subroutine is defined by:

$$\sum_{i=1}^{NSP} \nu_{ij} \bar{M}_i \rightleftarrows \sum_{i=1}^{NSP} \nu'_{ij} \bar{M}_i$$

where $\bar{M}_i$ represents the i^{th} chemical species.

The reverse reaction rate constant is defined by the equation:

$k_j \quad$ SK(J) $\quad = a_j \cdot T^{-n_j} \cdot \exp(-b_j/T)$

The net production rate for a reaction is given by:

$X_j \quad$ X(J) $\quad = \left[K_j \cdot \prod_{i=1}^{NSP} C_i^{\nu_{ij}} - \rho^{\lambda_j} \cdot \prod_{i=1}^{NSP} C_i^{\nu'_{ij}}\right] \cdot k_j \cdot M_j \, \rho^{(\Sigma \nu_{ij})-1}$

where: λ_j depends on the order of the reaction*

with $M_j = \sum_{i=1}^{NSP} XMM_{j,i} \cdot C_i$ for reactions requiring a third body

and $M_j = 1$ for all other reactions

where $XMM_{ji} \equiv m_{ji}/Mw_i$, $m_{ji} = a_{ij}/a_{kj}$

The net individual species production rate is given by the equation:

$$\frac{dC_i}{dx} \quad FN(I) = \bar{K}_i \cdot \sum_{j=1}^{\ell} \psi_{ij} \cdot X_j$$

where:

$$\bar{K}_i = (Mw_i \cdot \rho \cdot r^*)/V$$

$$\psi_{ij} \equiv \nu'_{ij} - \nu_{ij}$$

The partial derivatives of the net species production rate with respect to: the chemical species; the gas velocity; the gas density; and the gas temperature are:

$$\beta(C_k, C_i) \quad BT(I,K) = \bar{K}_i \cdot \sum_{j=1}^{\ell} \psi_{ij} \frac{\partial X_j}{\partial C_i} \qquad i = 1, \ldots, NSP \quad k = 1, \ldots, NSP$$

$$\beta(C_i, V) \quad PHI(I,1) = -\frac{1}{V} \frac{dC_i}{dx} \qquad i = 1, \ldots, NSP$$

$$\beta(C_i, \rho) \quad PHI(I,2) = \frac{1}{\rho} \cdot \frac{dC_i}{dx} + \bar{K}_i \sum_{j=1}^{m} \psi_{ij} \frac{\partial X_j}{\partial \rho} \qquad i = 1, \ldots, NSP$$

$$\beta(C_i, T) \quad PHI(I,3) = \bar{K}_i \sum_{j=1}^{\ell} \psi_{ij} \frac{\partial X_j}{\partial T} \qquad i = 1, \ldots, NSP$$

---

* $\lambda_j = \sum_{i=1}^{NSP} (\nu'_{ij} - \nu_{ij})$ so that $\lambda_j = 0$ for binary exchange, $\lambda_j = 1$ for most dissociation recombination reactions.

The subscript notation used above is:

i = Species subscript

j = Reaction subscript

ℓ = Total number of chemical reactions

m = Number of reactions requiring third body terms

NSP = Total number of gaseous species

Subroutine DERIV calls subroutine FLU to calculate the derivatives and partial derivatives of V, P, and T. In the event of solidification, this routine also recalculates the condensed phase species derivatives and their partial derivatives and recalls subroutine FLU to recalculate the flow derivatives.

5.3.5 SUBROUTINE ECNV1

This subroutine translates a BCD string of characters into one floating point numeric value. E, I, and F formats are permitted with the result always a floating point number. It is called by subroutine REAXIN to decode numeric fields in the species and reactions cards. The subroutine is coded entirely in FORTRAN. A BCD string of blanks will result in a floating point zero returned value.

5.3.6 SUBROUTINE EF

This subroutine computes equilibrium constants, K_j,

$$K_j \quad EK(J) = \frac{DATEF(J)}{T^{\lambda_j}} \cdot \exp\left[- \sum_{i=1}^{n} Ft_i \cdot \nu_{ij} + \sum_{i=1}^{n} Ft_i \cdot \nu'_{ij} \right]$$

also computed are

$$\frac{dK_j}{dT} \quad DKT(J) = \left[\frac{ - \sum_{i=1}^{n} \frac{Ht_i}{R_i} \cdot \nu_{ij} + \sum_{i=1}^{n} \frac{Ht_i}{R_i} \cdot \nu'_{ij} }{T} - \lambda_j \right] \cdot \frac{K_j}{T}$$

where: Ft_i = species free energy at the current temperature

Ht_i = species enthalpy at the current temperature

DATEF (J) = is defined in subroutine CØNVRT

5.3.7 SUBROUTINE FLU

This subroutine computes the total derivatives f_i and the partial derivatives α_i and β_{ij} for the fluid dynamic equations. While the flow is subsonic, pressure defined fluid dynamic equations are used. When the flow becomes supersonic, area defined fluid dynamic equations are used. The summation terms, energy exchange term B, the diabatic heat addition term A, the Mach number, and all the partial derivatives of these terms are computed. For a subsonic integration the pressure and its derivatives are obtained from the subsonic pressure table. For a supersonic integration the area ratio and its derivatives are computed from the input geometric constraints.

The calculations logically fall into three types: a) Those done for all integrations; b) Those done only for subsonic integration; c) Those done only for supersonic integration. The following will adhere as closely as possible to a sequential description of the computations.

The operators $\Phi(i,l)$, $l = 1,2,3$ are defined as

$$\Phi(i,1) = \beta(C_i, V)$$

$$\Phi(i,2) = \beta(C_i, \rho)$$

$$\Phi(i,3) = \beta(C_i, T)$$

The total derivatives, $f_i = \frac{dC_i}{dx}$, for $i = 1, \ldots, n$ are computed as

$$f_i = \frac{\omega_i r^*}{\rho V}$$

where n is the total number of species, NSP.

For an ODTDK problem, tables of Cp, R, AA, BB, as functions of temperature are written on logical unit JANAF.

Computation of the Summation Terms and their derivatives:

First Summation

S1	S1	$= \frac{1}{R} \cdot \sum_{i=1}^{n} \frac{dC_i}{dx} \cdot R_i$
$\frac{\partial S1}{\partial V}$	DS1V	$= \frac{1}{R} \cdot \sum_{i=1}^{n} \Phi_{(i,1)} \cdot R_i$
$\frac{\partial S1}{\partial \rho}$	DS1RØ	$= \frac{1}{R} \cdot \sum_{i=1}^{n} \Phi_{(i,2)} \cdot R_i$
$\frac{\partial S1}{\partial T}$	DS1T	$= \frac{1}{R} \cdot \sum_{i=1}^{n} \Phi_{(i,3)} \cdot R_i$
$\frac{\partial S1}{\partial C_i}$	DS1C(I)	$= \frac{1}{R} \cdot \left[\sum_{j=1}^{n} \beta_{(C_j, C_i)} \cdot R_j - S1 \cdot R_i \right] \quad i = 1, \ldots, n$

Second Summation

S2	S2	$= \frac{1}{R \cdot T} \cdot \sum_{i=1}^{n} \frac{dC_i}{dx} \cdot h_i$
$\frac{\partial S2}{\partial V}$	DS2V	$= \frac{1}{R \cdot T} \cdot \sum_{i=1}^{n} \Phi_{(i,1)} \cdot h_i$
$\frac{\partial S2}{\partial \rho}$	DS2RØ	$= \frac{1}{R \cdot T} \cdot \sum_{i=1}^{n} \Phi_{(i,2)} \cdot h_i$
$\frac{\partial S2}{\partial T}$	DS2T	$= \frac{1}{R \cdot T} \cdot \sum_{i=1}^{n} \left[\Phi_{(i,3)} \cdot h_i + \frac{dC_i}{dx} \cdot Cp_i \right] - \frac{S2}{T}$
$\frac{\partial S2}{\partial C_i}$	DS2C(I)	$= \frac{1}{R} \cdot \left[\sum_{j=1}^{n} \frac{\beta_{(C_j, C_i)} \cdot h_i}{T} - S2 \cdot R_i \right] \quad i = 1, \ldots, n$

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* R_i is the gas constant/molecular wt. of species i

Computation of the Energy Exchange Term B and its Derivatives:

B BB $= \frac{\gamma-1}{\gamma} \cdot S2$

$\frac{\partial B}{\partial V}$ DBBV $= \frac{\gamma-1}{\gamma} \cdot \frac{\partial S2}{\partial V}$

$\frac{\partial B}{\partial \rho}$ DBBRØ $= \frac{\gamma-1}{\gamma} \cdot \frac{\partial S2}{\partial \rho}$

$\frac{\partial B}{\partial T}$ DBBT $= \frac{\gamma-1}{\gamma} \cdot \frac{\partial S2}{\partial T} + \frac{S2}{\gamma^2} \cdot \frac{\partial \gamma}{\partial T}$

$\frac{\partial B}{\partial C_i}$ DBBC(I) $= \frac{\gamma-1}{\gamma} \cdot \frac{\partial S2}{\partial C_i} + \frac{S2}{\gamma^2} \cdot \frac{\partial \gamma}{\partial C_i}$ $i = 1, \ldots, n$

Computation of the Diabatic Heat Addition Term A and its Derivatives:

A AA $= S1-B$

$\frac{\partial A}{\partial V}$ DAAV $= \frac{\partial S1}{\partial V} - \frac{\partial B}{\partial V}$

$\frac{\partial A}{\partial \rho}$ DAARØ $= \frac{\partial S1}{\partial \rho} - \frac{\partial B}{\partial \rho}$

$\frac{\partial A}{\partial T}$ DAAT $= \frac{\partial S1}{\partial T} - \frac{\partial B}{\partial T}$

$\frac{\partial A}{\partial C_i}$ DAAC(I) $= \frac{\partial S1}{\partial C_i} - \frac{\partial B}{\partial C_i}$ $i = 1, \ldots, n$

Computation of the Mach number and its derivatives:

$$M^2 \qquad \text{XM2} = \frac{V^2}{\gamma\cdot R\cdot T}$$

$$\frac{\partial M^2}{\partial V} \qquad \text{DM2V} = \frac{2\cdot M^2}{V}$$

$$\frac{\partial M^2}{\partial T} \qquad \text{DM2T} = -\frac{M^2}{T} - \frac{M^2}{\gamma}\cdot\frac{\partial\gamma}{\partial T}$$

$$\frac{\partial M^2}{\partial C_i} \qquad \text{DM2C(I)} = -M^2\cdot\left[\frac{\partial\gamma}{\partial C_i}\cdot\frac{1}{\gamma}+\frac{R_i}{R}\right] \qquad i = 1,\ldots,n$$

For the subsonic portion of the nozzle, pressure defined fluid dynamic equations are used. The pressure, and its first and second derivatives are computed via interpolation in the pressure table generated by subroutine PRES. The Subsonic Gas Velocity derivatives are computed:

$$\frac{dV}{dx} \qquad \text{FNX(1)} = -\frac{1}{\rho\cdot V}\cdot\frac{dP}{dx}$$

$$\frac{\partial[\text{FNX(1)}]}{\partial x} \qquad \text{AL(1)} = -\frac{1}{\rho\cdot V}\cdot\frac{d^2P}{dx^2}$$

$$\beta(V,V) \qquad \text{BETA (1,1)} = -\frac{1}{V}\cdot\frac{dV}{dx}$$

$$\beta(V,\rho) \qquad \text{BETA(1,2)} = -\frac{1}{\rho}\cdot\frac{dV}{dx}$$

The Subsonic Gas Density derivatives are computed:

$$\frac{d\rho}{dx} \qquad \text{FNX(2)} = \rho\cdot\left[\frac{dP}{dx}\cdot\frac{1}{\gamma\cdot P} - A\right]$$

$$\frac{\partial[\text{FNX(2)}]}{\partial x} \qquad \text{AL(2)} = \frac{\rho}{\gamma\cdot P}\cdot\left[\frac{d^2P}{dx^2} - \left(\frac{dP}{dx}\right)^2\cdot\frac{1}{P}\right]$$

$$\beta(\rho,V) \qquad \text{BETA}(2,1) = -\rho \cdot \frac{\partial A}{\partial V}$$

$$\beta(\rho,\rho) \qquad \text{BETA}(2,2) = -\frac{1}{\rho} \cdot \frac{d\rho}{dx} - \rho \cdot \frac{\partial A}{\partial \rho}$$

$$\beta(\rho,T) \qquad \text{BETA}(2,3) = -\rho \cdot \frac{\partial A}{\partial T} - \frac{\rho}{P\cdot\gamma^2} \cdot \frac{\partial \gamma}{\partial T} \cdot \frac{dP}{dx}$$

$$\beta(\rho,C_i) \qquad \text{BETA}(2,i+3) = -\frac{\rho}{\gamma^2 P} \cdot \frac{\partial \gamma}{\partial C_i} \cdot \frac{dP}{dx} - \rho \cdot \frac{\partial A}{\partial C_i} \qquad i = 1,\ldots,n$$

The Subsonic Gas Temperature derivatives are computed:

$$\frac{dT}{dx} \qquad \text{FNX}(3) = T \cdot \left[\frac{\gamma-1}{\gamma} \cdot \frac{1}{P} \cdot \frac{dP}{dx} - B\right]$$

$$\frac{\partial[\text{FNX}(3)]}{\partial x} \qquad \text{AL}(3) = \frac{\gamma-1}{\gamma} \cdot \frac{T}{P} \cdot \left[\frac{d^2P}{dx^2} - \left(\frac{dP}{dx}\right)^2 \cdot \frac{1}{P}\right]$$

$$\beta(T,V) \qquad \text{BETA}(3,1) = -T \cdot \frac{\partial B}{\partial V}$$

$$\beta(T,\rho) \qquad \text{BETA}(3,2) = -T \cdot \frac{\partial B}{\partial \rho}$$

$$\beta(T,T) \qquad \text{BETA}(3,3) = \frac{1}{T} \cdot \frac{dT}{dx} + T \frac{1}{\gamma^2 \cdot P} \frac{dP}{dx} \frac{\partial \gamma}{\partial T} - T \frac{\partial B}{\partial T}$$

$$\beta(T,C_i) \qquad \text{BETA}(3,\ i+3) = T \cdot \left[\frac{1}{\gamma^2 \cdot P} \cdot \frac{dP}{dx} \cdot \frac{\partial \gamma}{\partial C_i} - \frac{\partial B}{\partial C_i}\right] \qquad i = 1,\ldots n$$

For the supersonic portion of the nozzle, area defined fluid dynamic equations are used. The area ratio, and its derivatives are computed according to the input geometric constraints.

Area ratio and its derivatives:

1) On the circular arc of radius R_d (input item RWTD) defining the downstream throat region, $X \leq X_{tangent}$

$$a = \left[1 + R_d - \left(R_d^2 - x^2\right)^{1/2}\right]^2$$

$$\frac{da}{dx} = \frac{2x}{\left(R_d^2 - x^2\right)^{1/2}} \cdot \left[1 + R_d - \left(R_d^2 - x^2\right)^{1/2}\right]$$

$$\frac{d^2a}{dx^2} = \left[\frac{2}{\left(R_d^2 - x^2\right)^{1/2}} + \frac{2x^2}{\left(R_d - x^2\right)^{3/2}}\right] \cdot \left[1 + R_d - \left(R_d - x^2\right)^{1/2}\right] + \frac{2x^2}{R_d^2 - x^2}$$

2) For a conical nozzle and $X > X_{tangent}$

$$a = \left[r_t + \left(x - x_t\right) \tan \Theta_t\right]^2$$

$$\frac{da}{dx} = 2\left[r_t + \left(x - x_t\right) \tan \Theta_t\right] \cdot \tan \Theta_t$$

$$\frac{d^2a}{dx^2} = 2 \tan^2 \Theta_t$$

3) For a contoured nozzle and $X > X_{tangent}$

$$a = Y^2$$

$$\frac{da}{dx} = 2 \cdot Y \cdot \frac{dY}{dx}$$

$$\frac{d^2a}{dx^2} = 2 \cdot \left[Y \frac{d^2Y}{dx^2} + \left(\frac{dY}{dx} \right)^2 \right]$$

where Y, dY/dx, d^2Y/dx^2 are computed via interpolation in the table of derivatives of the input wall table generated in Subroutine SLP.

The Supersonic Gas Velocity derivatives are computed:

$$\frac{dV}{dx} \qquad \mathrm{FNX(1)} = \frac{V}{M^2-1} \cdot \left[\frac{1}{a} \frac{da}{dx} - A \right]$$

$$\frac{\partial[\mathrm{FNX(1)}]}{\partial x} \quad \mathrm{AL(1)} = \frac{V}{M^2-1} \cdot \frac{1}{a} \cdot \left[\frac{d^2a}{dx^2} - \frac{1}{a} \cdot \left(\frac{da}{dx} \right)^2 \right]$$

$$\beta(V,V) \qquad \mathrm{BETA(1,1)} = \frac{1}{V} \cdot \frac{dV}{dx} - \frac{1}{M^2-1} \cdot \frac{dV}{dx} \cdot \frac{\partial M^2}{\partial V}$$

$$- \frac{V}{M^2-1} \cdot \frac{\partial A}{\partial V}$$

$$\beta(V,\rho) \qquad \mathrm{BETA(1,2)} = - \frac{V}{M^2-1} \cdot \frac{\partial A}{\partial \rho}$$

$$\beta(V,T) \qquad \mathrm{BETA(1,3)} = - \frac{1}{M^2-1} \cdot \frac{dV}{dx} \cdot \frac{\partial M^2}{\partial T} - \frac{V}{M^2-1} \cdot \frac{\partial A}{\partial T}$$

$$\beta(V,C_i) \qquad \mathrm{BETA(1,i+3)} = - \frac{1}{M^2-1} \cdot \frac{dV}{dx} \cdot \frac{\partial M^2}{\partial C_i} - \frac{V}{M^2-1} \cdot \frac{\partial A}{\partial C_i} \qquad i=1,\ldots,n$$

The Supersonic Gas Density derivatives are computed:

$$\frac{d\rho}{dx} \qquad \text{FNX(2)} \qquad = -\rho\cdot\left[\frac{M^2}{M^2-1}\cdot\left(\frac{1}{a}\cdot\frac{da}{dx}-A\right)+A\right]$$

$$\frac{\partial[\text{FNX(2)}]}{\partial x} \qquad \text{AL(2)} \qquad = -\rho\cdot\frac{M^2}{M^2-1}\cdot\frac{1}{a}\cdot\left[\frac{d^2a}{dx^2}-\frac{1}{a}\left(\frac{da}{dx}\right)^2\right]$$

$$\beta(\rho,V) \qquad \text{BETA(2,1)} \qquad = \rho\cdot\left[\frac{1}{(M^2-1)^2}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\cdot\frac{\partial M^2}{\partial V}+\frac{1}{M^2-1}\cdot\frac{\partial A}{\partial V}\right]$$

$$\beta(\rho,\rho) \qquad \text{BETA(2,2)} \qquad = \frac{1}{\rho}\cdot\frac{d\rho}{dx}+\frac{\rho}{M^2-1}\cdot\frac{\partial A}{\partial\rho}$$

$$\beta(\rho,T) \qquad \text{BETA(2,3)} \qquad = \rho\cdot\left[\frac{1}{(M^2-1)^2}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\cdot\frac{\partial M^2}{\partial T}+\frac{1}{M^2-1}\cdot\frac{\partial A}{\partial T}\right]$$

$$\beta(\rho,C_i) \qquad \text{BETA(2,i+3)} = \rho\cdot\left[\frac{1}{(M^2-1)^2}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\frac{\partial M^2}{\partial C_i}+\frac{1}{M^2-1}\frac{\partial A}{\partial C_i}\right]$$

$$i = 1,\ldots,n$$

The Supersonic Gas Temperature derivatives are computed:

$$\frac{dT}{dx} \qquad \text{FNX(3)} \qquad = -T\cdot\left[(\gamma-1)\cdot\frac{M^2}{M^2-1}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)+B\right]$$

$$\frac{\partial[\text{FNX(3)}]}{\partial x} \qquad \text{AL(3)} \qquad = -T\cdot\frac{M^2}{M^2-1}\cdot\frac{\gamma-1}{a}\cdot\left[\frac{d^2a}{dx^2}-\frac{1}{a}\cdot\left(\frac{da}{dx}\right)^2\right]$$

$$\beta(T,V) \qquad \text{BETA(3,1)} \qquad = T\cdot\left[\frac{\gamma-1}{(M^2-1)^2}\left(\frac{1}{a}\frac{da}{dx}-A\right)\cdot\frac{\partial M^2}{\partial V}+\gamma-1\cdot\frac{M^2}{M^2-1}\cdot\frac{\partial A}{\partial V}-\frac{\partial B}{\partial V}\right]$$

$$\beta(T,\rho) \qquad \text{BETA(3,2)} \qquad = T\cdot\left[\gamma-1\cdot\frac{M^2}{M^2-1}\cdot\frac{\partial A}{\partial\rho}-\frac{\partial B}{\partial\rho}\right]$$

$$\beta(T,T) \qquad \text{BETA}(3,3) \quad = \quad \frac{1}{T}\cdot\frac{dT}{dx} + T\cdot\left[\frac{\gamma-1}{(M^2-1)^2}\left(\frac{1}{a}\frac{da}{dx}-A\right)\frac{\partial M^2}{\partial T} \right.$$

$$+\gamma-1\cdot\frac{M^2}{M^2-1}\cdot\frac{\partial A}{\partial T} - \frac{\partial B}{\partial T}$$

$$\left. -\frac{M^2}{(M^2-1)}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\frac{\partial\gamma}{\partial T}\right]$$

$$\beta(T,C_l) \qquad \text{BETA}(3,l+3) = \quad T\cdot\left[\frac{\gamma-1}{(M^2-1)^2}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\cdot\frac{\partial M^2}{\partial C_l} + \gamma-1\cdot\frac{M^2}{M^2-1}\cdot\frac{\partial A}{\partial C_l}\right.$$

$$\left. -\frac{\partial B}{\partial C_l} - \frac{M^2}{M^2-1}\cdot\left(\frac{1}{a}\frac{da}{dx}-A\right)\frac{\partial\gamma}{\partial C_l}\right]$$

$l = 1, \ldots, n$

5.3.8 SUBROUTINE FNDLM (IC, NS, IP, IDLM)

Given a card image stored 80A1 in the IC array, this subroutine searches left to right, starting with character number NS, until a match is found to the input character IDLM. The character number is returned in IP. If no match is found, a -1 is returned in IP. This subroutine is used by subroutines MGET, PRATES, and REAXIN to locate field delimiters.

5.3.9 SUBROUTINE GTF

This subroutine computes the effective gas constant, gaseous heat capacity, γ, $\partial\gamma/\partial T$, $\partial\gamma/\partial C_i$ from the following formulae:

$$R = \sum_{i=1}^{NSP} C_i \cdot R_i$$

$$Cp = \sum_{i=1}^{NSP} C_i \cdot Cp_i$$

$$\gamma = \frac{Cp}{Cp-R}$$

$$\frac{\partial\gamma}{\partial T} = -\frac{\gamma\cdot(\gamma-1)}{Cp} \cdot \sum_{i=1}^{NSP} C_i \cdot \frac{\partial Cp_i}{\partial T}$$

$$\frac{\partial\gamma}{\partial C_i} = \gamma\cdot(\gamma-1)\cdot\left[\frac{R_i}{R} - \frac{Cp_i}{Cp}\right] \qquad i = 1, \ldots, n$$

For condensed phases, $R_i=0$, to account for the assumption that the particles exert no pressure on the gas.

5.3.10 SUBROUTINE IAUX (HL, H, QK, RK, JX)

This subroutine performs implicit integration according to the method discussed in Section 3. The increments for the chemical species concentrations and the fluid dynamic variables at the forward point are calculated by solving the appropriate implicit finite difference formulas. Subroutine IAUX also performs explicit integration, using a modified Euler method, when the gas temperature falls below an input value.

The calling sequence parameters are:

HL - last integration step size

H - current integration step size

QK - last increments for variables

RK - computed increments for variables

JK - 1 initial 3 steps
- 2 general step
- 3 special step
- 4 restart step

The total derivatives, $f_{i,n}$, and partial derivatives, $\beta_{i,j,n}$ at the back point are calculated in subroutines DERIV and FLU.

The special step calculation is used at print stations, in halving the step size if required, or for integrating to specific calculation stations. If the special step calculation is used to determine the properties at a print station, the calculation is resumed using the general step calculation and the previous step size.

After each integration step, subroutine IAUX obtains the derivatives at the then current axial position.

For implicit integration the equations used are:

Initial Step and Restart

$$k_{i,1} = \left[f_{i,o} + \alpha_{i,o} h + \sum_{j=1}^{N} \beta_{i,j,o} k_{j,1}\right] \cdot h$$

General Step

$$k_{i,n+1} = \frac{1}{3}\left[k_{i,n} + 2 \cdot \left(f_{i,n} + \alpha_{i,n} h + \sum_{j=1}^{N} \beta_{i,j,n} k_{j,n+1}\right) \cdot h\right]$$

Special Step

$$k_{i,n+1} = \frac{h_{n+1}^{2}}{(2h_{n+1}+h_{n}) \cdot h_{n}}\left[k_{i,n} + \left[f_{i,n} + \alpha_{i,n} h_{n+1} + \sum_{j=1}^{N} \beta_{i,j,n} k_{j,n+1}\right] \cdot \frac{h_{n}}{h_{n+1}} (h_{n+1}+h_{n})\right]$$

For explicit integration the above equations are used deleting the partial derivative terms α and β.

If the TDK problem directive was selected, gas tables for the Transonic Analysis Subprogram are written on logical unit ITSTAB.

If the option to generate input tables for the Turbulent Boundary Layer Nozzle Analysis Computer Program was selected, tables of M, P/P_c, T/T_c, C_p, V, ρ are tabulated using subroutine TABGEN.

5.3.11 SUBROUTINE INT

Provides control for the implicit integration procedure, determines the proper set of nonhomogeneous equations to solve, and, after each integration step, computes the next integration step size according to the following relations:

$$h_{n+2} = 2h_{n+1}, \qquad \left|\frac{k_{i,n+1} - 2k_{i,n} + k_{i,n-1}}{3y_{max}}\right|_{MAX} < \frac{\delta}{20}$$

$$h_{n+2} = \frac{1}{2}h_{n+1}, \qquad \left|\frac{k_{i,n+1} - 2k_{i,n} + k_{i,n-1}}{3y_{max}}\right|_{MAX} > \delta$$

$$h_{n+2} = h_{n+1}, \qquad \frac{\delta}{20} \le \left|\frac{k_{i,n+1} - 2k_{i,n} + k_{i,n-1}}{3y_{max}}\right|_{MAX} \le \delta$$

where

$$y_{max} = \max \; [\,|y_{i,n}|, 10^{-5}] \qquad ; i = 1, 2, \ldots \; NSP+3$$

On option, (JF=1) only the fluid dynamic variables are used in determining the next integration step size.

If the step size is halved for the fourth step, the integration is restarted using one-half the original step size.

The correspondence between equation number and physical property is:

Equation Number	Property
1	Velocity of Gas
2	Density of Gas
3	Temperature of Gas
4 NSP+3	Gaseous species mass fraction (1...NSP) correspondence to (4...NSP + 3)

When the flow is supersonic, continuity is used to control the integration step size to insure that:

$$\left|\frac{(\rho VA)_{N+1} - (\rho VA)_{N}}{(\rho VA)_{N+1}}\right| < CONDEL$$

where CONDEL is an input relative criterion with a default value 10^{-5}.

5.3.12 SUBROUTINE LESK (Y)

This subroutine is a single precision linear equation solver which is used to perform the matrix inversions required by subroutine IAUX. Gaussian elimination is used with row interchange taking place to position maximum pivot elements after the rows are initially scaled.

5.3.13 SUBROUTINE MAIN1D

This subroutine provides the overall logic control for the one-dimensional kinetic expansion. The following functions are controlled:

1) Variable initialization
2) Option to start the kinetic expansion from equilibrium throat conditions
3) Controls of the integration to hit specific area ratios, the nozzle throat point, the nozzle tangent point, and the requested end point
4) Controls of the switch from the subsonic pressure defined equations to the supersonic area defined equations when ($M^2 \geq 1.02$)
5) Controls the switch from implicit to explicit integration.

For the normal mode of operation of the program, this subroutine locates the throat in the following manner:

The gaseous mass flow per unit area (ρv) is calculated and stored as a function of nozzle axial location for the present and past integration step. When

$$(\rho v)_{n+1} < (\rho v)_n$$

where n refers to the n^{th} integration step, the throat location is calculated from:

$$X^* = X_n + \frac{(X_n - X_{n-1})^2 \cdot \left[(\rho v)_{n+1} - (\rho v)_n\right] + (X_{n+1} - X_n)^2 \cdot \left[(\rho v)_n - (\rho v)_{n-1}\right]}{2 \cdot \left[(X_{n+1} - X_n) \cdot \left[(\rho v)_n - (\rho v)_{n-1}\right] - (X_n - X_{n-1}) \cdot \left[(\rho v)_{n+1} - (\rho v)_n\right]\right]}$$

and the $n+1^{th}$ integration step is repeated using a step size of $X^* - X_n$ to determine the throat conditions.

To prevent the location of a false throat due to roughness of an input pressure table, ten integration steps are required before the throat will be sought.

Through the downstream throat radius of curvature the step size is controlled so as to be less than or equal to RWTD*SIN(THETA)/25.0, Subroutine MAIN1D also contains the logic to control the integration through solidification of multiple condensed liquid phases if they are present. This logic allows the integration procedure to hit the beginning and ending of solidification exactly and to turn on the solidification equations in subroutine DERIV via the flag IFMELT in COMMON/LKMELT/.

5.3.14 SUBROUTINE MGET

This subroutine is used to decode the M's in the 3rd body reactions. It uses subroutine FNDLM to locate the field delimiter, and subroutine ECNV1 to translate the M value from a character to a floating point number.

5.3.15 SUBROUTINE NUMBR

This FORTRAN subroutine converts a one character BCD number to a integer number.

5.3.16 SUBROUTINE ODKBLM

If BLM is to be run folowing the execution of a Two-Dimensional Frozen (TDF=1.) calculation, then subroutine ODK calls ODKBLM to obtain the required gas properties. These consist of gas viscosity, Prandtl number, and total enthalpy; followed by tables of C_{pg}, Y, h, and R vs temperature. All of the above properties are written on unit LUBLM. The properties correspond to a) the chamber equilibrium species compositions expanded in a frozen state, or b) the input species compositions expanded in a frozen state.

5.3.17 SUBROUTINE ØDKINP

This subroutine provides the input processing for the kinetic expansion calculation. It performs the following functions:

1) Variable initialization to nominal values

2) Calls subroutine REAXIN to input the reactions cards and species cards if necessary

3) For an ØDE-ØDK problem, calls subroutine SELECT to select those species to be considered for the kinetic expansion calculation

4) Reads $ØDK namelist input data

5) Converts nozzle geometric parameters from input units: inches, degrees; to internal computational units: feet, radians

6) Computes nozzle tangent coordinates using:

$$r_t = 1 + R_d (1 - \cos \theta)$$

$$x_t = R_d \sin \theta$$

7) For conical nozzles, computes the axial coordinate for the exit station from the following relation:

$$x_{exit} = \frac{\sqrt{\epsilon} - r_t + x_t \cdot \tan \theta}{\tan \theta} \qquad x_{exit} \geq x_t$$

$$x_{exit} = \left\{ R_d^2 - (1 + R_d - \sqrt{EP})^2 \right\}^{\frac{1}{2}} \qquad x_{exit} < x_t$$

8) For conical nozzles, the internal axial print stations are computed using:

$$X_j = \frac{\sqrt{ARPRNT(J)} - r_t + x_t \cdot \tan \theta}{\tan \theta} \qquad X_j \geq X_t$$

$$X_j = \left\{ R_d^2 - \left[1 + R_d - (ARPRNT(J))^{\frac{1}{2}} \right]^2 \right\}^{\frac{1}{2}} \qquad X_j < X_t$$

9) The sum of input or selected species concentrations is checked for unity ($\pm$ XMFTST, where XMFTST is an input number), and then normalized.

10) If the input parameter RZNØRM is input, the input contoured nozzle table is normalized by RZNØRM.

In addition to the above, the following are done in the ØDKINP routine.

a) If the nozzle geometry has been input via the $DATA namelist, ØDKINP stores the variables from this input into the correct locations and performs the appropriate unit conversions.
b) Accepts the parabolic and circular arc options (IWALL=2 and 3) from the $DATA namelist. This is done by computing the nozzle wall points and derivatives at 20 equally spaced points and substituting them into the tables used in the contoured wall input option.
c) Accepts as input the quantities needed to calculate the zero particle lag flow equations.

5.3.18 SUBROUTINE ODWALL

This subroutine is called by subroutine ODKINP for the purpose of calculating the nozzle wall contour and setting print stations for ODK when the following wall options are used:

IWALL = 2	parabola,
IWALL = 3	circular arc,
IWALL = 6	skewed parabola

5.3.19 SUBROUTINE OUTPUT

This subroutine provides conversion from internal computational units to output engineering units and the calculation of performance parameters. The following output parameters are computed by this subroutine:

The pressure (in PSIA) is computed from:

$$P_{(PSIA)} = P/4633.056$$

The gaseous species mole fractions are computed from:

$$C_{i,m} = \frac{R_i}{R} \cdot C_i$$

The gas molecular weight is computed from:

$$Mw = 49721.011/R$$

The percentage mass fraction change is computed from:

$$\% \Delta \text{(Mass Fraction)} = 100.0 \cdot (1.0 - \sum_{i=1}^{n} C_i)$$

The gas heat capacity is computed from:

$$Cp_g(\text{BTU/LB-}^{\circ}\text{R}) = 3.9969 \cdot 10^{-5} \cdot Cp_g$$

The gas enthalpy is computed from:

$$H_g(\text{BTU/LB}) = 3.9969 \cdot 10^{-5} \cdot \sum_{i=1}^{n} C_i \cdot h_i$$

At the throat, the characteristic exhaust velocity (ft/sec) is computed from:

$$C^* = \frac{P_c}{\rho^* \cdot V^*}$$

The vacuum specific impulse is computed from:

$$ISP_{VAC} = \frac{V + P/P_c \, \epsilon \, C^*}{g}, \; g = 32.174$$

The vacuum thrust coefficient is computed from:

$$C_{F_{VAC}} = \frac{I_{sp_{vac}} \, g}{C^*}$$

The percentage enthalpy change is computed from:

$$\% \Delta H_T = \frac{100 \cdot (HREF_c - HREF)}{V^2/2}$$

where

$$HREF = \sum_{i=1}^{NSP} C_i \cdot h_i + V^2/2$$

$HREF_c$ is HREF evaluated at the initial condition for the ØDK integration (i.e. at the initial contraction ratio, ECRAT).

In addition the actual molecular weight of the mixture of gases and condensed phases is also printed out.

5.3.20 SUBROUTINE PACK

On the basis of those species currently being considered, this subroutine packs species and reaction information from the master tables into those control sections utilized by the one-dimensional kinetic expansion subprogram.

The following is a sequential description of the packing procedures:

1) Thermodynamic data for the species being considered is read into core storage.
2) The chemical species'molecular weights are computed
3) The symbolic reactions are checked for mass balance.
4) For a contoured nozzle the slope at each input wall point is computed using subroutine SLP. The wall coordinates, and each computed slope are printed for each input wall point and the print stations are set to the input axial coordinates.

In addition to the above, the PACK routine processes condensed phases by setting $R_i=0$ for those species and storing pointers for up to 10 condensed phase species (5 pairs). This routine also calculates the print positions for specified area ratios when the contoured (spline) wall option is selected.

5.3.21 SUBROUTINE PACKCD (KRD, IPK, KNT)

This subroutine packs down a card image stored 80A1 in the KRD array by removing blanks. The packed card image is returned in the IPK array. The number of non blank characters found is returned in KNT.

5.3.22 SUBROUTINE PRATES

This subroutine processes the input reaction rate constant data to determine the form of the reaction rate. Three types of reactions are allowed, as shown in Table 5-5.

Table 5-5: EXPRESSIONS FOR THE REACTION RATE CONSTANTS, k

Reaction Expression	Input*	Comments
$k = P_1 T^{-P_2} e^{-P_3 * 1000/RT}$	A = P_1, N = P_2, B = P_3	Arrhenius form
as above	KF or KR = P_1, P_2, P_3	
$k = e^{(P_1 + P_2/T^{1/3} + P_3/T^{2/3})}$	KF or KR = *P_1, P_2, P_3	Landau-Teller form
$\log_{10} k = P_1 + P_2 T$	KF or KR = % P_1, P_2	Log 10 form

* P_1, P_2, and P_3 are numbers written with E or F format

5.3.23 SUBROUTINE PREAX

This subroutine processes the chemical reaction as determined by subroutine PRATES. It returns the stoichiometric coefficients and the corresponding species names.

5.3.24 SUBROUTINE PRES

This subroutine is used (when JPFLAG = 1) to compute the derivatives of an input pressure table.

This subroutine is also used (when JPFLAG = 0) to generate a pressure table through use of an average expansion coefficient, Ne. The generated table extends from the initial contraction ratio through the nozzle attachment point plus one normalized throat radius.

Input Pressure Table Derivative Computation (JPFLAG = 1)

If a pressure table of NTB entries is input, the table of first derivatives is computed using:

$$\left.\frac{dP}{dx}\right|_{x_1} = 0$$

$$\left.\frac{dP}{dx}\right|_{x_n} = \frac{P(x_{n+1}) - P(x_{n-1})}{x_{(n+1)} - x_{(n-1)}} \quad , \quad 1 < n < NTB$$

$$\left.\frac{dP}{dx}\right|_{x_{NTB}} = \frac{P(x_n) - P(x_{n-1})}{x_{(n)} - x_{(n-1)}} \quad , \quad n = NTB$$

The pressure at the initial axial position is obtained by interpolation using subroutine SPLN.

Internally Computed Pressure Table Computation (IPFLAG = 0)

An average equilibrium pressure expansion coefficient from the chamber to the throat, N_e, is computed by iteration using subroutine SUBNE. The initial value for $N_e^{(1)}$ is 1.2.

The approximate equilibrium contraction ratio at the initial axial position is computed from:

$$a_c = \left[\frac{N_e - 1}{2} \cdot \frac{\left[\frac{2}{N_e+1}\right]^{\frac{N_e+1}{N_e-1}}}{\left(\frac{P_i}{P_c}\right)^{\frac{2}{N_e}} \cdot \left[1 - \left(\frac{P_i}{P_c}\right)^{\frac{N_e-1}{N_e}}\right]} \right]^{\frac{1}{2}}$$

where P_i = pressure at the initial axial position

P_c = equilibrium chamber pressure

A check is then made to determine the compatibility between the nozzle geometry and the requested contraction ratio.

If

$$\sqrt{a_c} < 1 + \left[R_u + R_i\right] \cdot \left[1 - \cos \theta_i\right],$$

the circular arcs R_u and R_i overlap and the following error message is printed:

INLET GEOMETRY INCOMPATIBLE WITH INITIAL CONDITIONS

The program will proceed to the next case.

Tables for pressure and its derivatives are constructed as functions of area ratio, a, and expansion coefficient, Ne. Formula used for the j + 1 iteration for pressure is:

$$\frac{P^{(j+1)}}{P_c} = \frac{P^{(j)}}{P_c} + 2\left\{\frac{N_e-1}{N_e}\cdot\left[1-\left(\frac{P^{(j)}}{P_c}\right)^{\frac{N_e-1}{N_e}}\right]^{-1}\cdot\left(\frac{P^{(j)}}{P_c}\right)^{-\frac{1}{N_e}} - \frac{2}{N_e}\cdot\left(\frac{P^{(j)}}{P_c}\right)^{-1}\right\}^{-1}\cdot\left\{\left[\frac{N_e-1}{2}\cdot\frac{[2/(N_e+1)]^{(N_e+1)/(N_e-1)}}{\left(\frac{P^{(j)}}{P_c}\right)^{2/N_e}\cdot\left[1-\left(\frac{P^{(j)}}{P_c}\right)^{(N_e-1)/N_e}\right]}\right]^{-1/2}\cdot a - 1\right\}$$

for j = 1

$$\left.\frac{P^{(1)}}{P_c}\right|_{x_{n+1}} = \left.\frac{P}{P_c}\right|_{x_n} + \left.\frac{d(P/P_c)}{dx}\right|_{x_n}(x_{n+1} - x_n)$$

where n refers to the nth table entry.

The pressure derivative formula used is:

$$\frac{d(P/P_c)}{dx} = \left[\frac{N_e-1}{N_e}\left(\frac{P}{P_c}\right)^{-\frac{1}{N_e}}\left[1-\left(\frac{P}{P_c}\right)^{\frac{N_e-1}{N_e}}\right]^{-1} - \frac{2}{N_e}\left(\frac{P}{P_c}\right)^{-1}\right]^{-1}\cdot\frac{2}{a}\;\frac{da}{dx}$$

Next, tables for pressure and its derivatives are constructed by the program. Table entries are at increments of

$-x_i/75$	for	$x_i < x < 0$
$(R_d \sin \theta)/25$	for	$0 < x < R_d \sin \theta$

and

$1/25$	for	$R_d \sin \theta < x < R_d \sin \theta + 1$

where the initial nozzle axial position, x_i, is computed from:

$$x_i = -\left[(R_u + R_i) \cdot \sin \theta_i + \frac{\sqrt{a_c} - 1 - (R_u + R_i) \cdot (1 - \cos \theta_i)}{\tan \theta_i} \right]$$

See Figure 5-1 below:

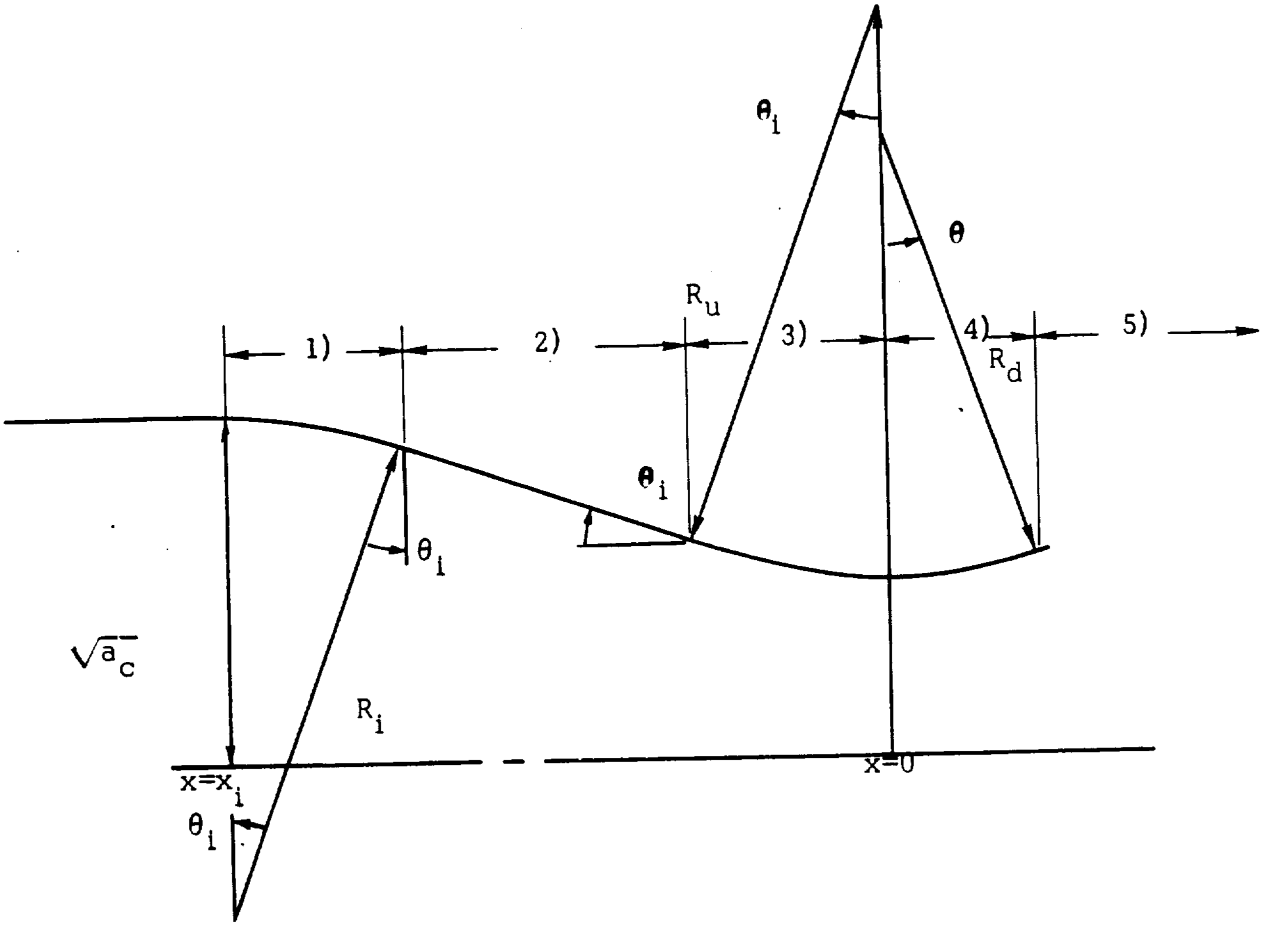


Figure 5-1 NOZZLE GEOMETRY

Area ratio and its derivative and (a and $\frac{da}{dx}$) are found by the five formulae below:

1) $x < x_i + R_i \sin \theta_i$

$$a = \left[\sqrt{a_c} - R_i\left(1 - \sqrt{1 - \frac{(x-x_i)^2}{R_i^2}}\right)\right]^2$$

$$\frac{da}{dx} = \frac{-2(x-x_i)}{\left[R_i^2 - (x-x_i)^2\right]^{1/2}} \cdot \sqrt{a}$$

2) $x_i + R_i \sin \theta_i < x < -R_u \sin \theta_i$

$$a = \left[\sqrt{a_c} - R_i(1 - \cos \theta_i) - (x-x_i - R_i \sin \theta_i) \tan \theta_i\right]^2$$

$$\frac{da}{dx} = -2 \cdot \sqrt{a} \cdot \tan \theta_i$$

3) $-R_u \cdot \sin \theta_i < x < 0$

$$a = \left[1 + R_u\left(1 - \sqrt{1 - \frac{x^2}{R_u^2}}\right)\right]^2$$

$$\frac{da}{dx} = \frac{2x}{\left[R_u^2 - x^2\right]^{1/2}} \cdot \sqrt{a}$$

4) $0 < x < R_d \cdot \sin \theta$

$$a = \left[1 + R_d\left(1 - \sqrt{1 - \frac{x^2}{R_d^2}}\right)\right]^2$$

$$\frac{da}{dx} = \frac{2x}{\left[R_d^2 - x^2\right]^{1/2}} \cdot \sqrt{a}$$

5) $R_d \cdot \sin\theta < x \le R_d \cdot \sin\theta + 1$

for cone

$$a = \left[r_t + (x - x_t) \cdot \tan\theta \right]^2$$

$$\frac{da}{dx} = 2 \cdot a \cdot \tan\theta$$

for contour

$$a = Y^2$$

$$\frac{da}{dx} = 2 \cdot Y \cdot \frac{dY}{dx}$$

Three special points are included in the pressure table. These are a point at $x = x_i$ such that

$$\frac{P}{P_c} = \frac{P_i}{P_c}$$

$$\frac{d(P/P_c)}{dx} = 0$$

and two points at $x = 0$ such that

$$\frac{P}{P_c} = \left(\frac{P^*}{P_c} \right)_{\text{equilibrium}}$$

$$\frac{d(P/P_c)}{dx} = - \frac{N_e}{\sqrt{R^*}} \cdot \left[\frac{2}{N_e + 1} \right]^{\frac{3N_e - 1}{2(N_e - 1)}}$$

with $R^* = R_u$ and $R^* = R_d$, respectively.

The following items are input directly to the computer program as described in Section 6 and shown in Figure 6-1, left to right.

R_i	RI
R_u	RWTU
θ_i	THETAI
θ	THETA
R_d	RWTD

5.3.25 SUBROUTINE PRNTCK

For the ODK option to print starting at step ND1, printing every ND3rd step up to step ND2, this suboutine checks whether or not the current step should be printed. If it is to be printed this subroutine calls subroutine 0UTPUT.

5.3.26 SUBROUTINE REAXIN

This subroutine processes SPECIES, REACTI0NS, and THIRD B0DY REAX RATE RATI0S input cards. Reference may be made to Section 6.5 for a complete description of input requirements. A table of all species appearing in the input reaction set is generated for further processing by subroutine SELECT if required.

5.3.27 SUBROUTINE SELECT

This subroutine provides the interface logic required to select the minimum species list required for the kinetic expansion calculations. The subroutine is only used for the 0DE-0DK interface. The list of all species appearing in the input reaction set is matched against the list of species considered for the equilibrium calculation. All species which appear in both a reaction and the equilibrium calculation list are selected for the kinetic expansion calculation. If a species appears in the reaction set but has not been considered for the equilibrium calculation, the program prints an error message and terminates the current case.

If the INERTS directive was specified those species specified under that directive will be added to the list for the kinetic expansion calculation along with the other species selected.

If the INERTS directive was not specified, all those species, considered for the equilibrium calculation, whose mole fractions are greater than or equal to an input selection criterion will also be selected for the kinetic expansion calculation. Species selected in this way will be listed as inert species on the program ouput since they do not enter into chemical reaction.

This subroutine also selects pairs of condensed phases if either of the phases passes one of the above selection criteria.

5.3.28 SUBROUTINE STF

This subroutine evaluates the thermodynamic functions Cp_T^o/R, H_T^o/RT, S_T^o/R, from curve fit coefficients. The subroutine uses the same procedure as subroutine CPHS. The additional functions $d(Cp_T^o)/dt$ and free energy, G_T^o/RT, are also computed. The calculated functions are then converted to the internal computational units for use by the kinetic expansion calculations. Also, low temperature thermodynamic data from tables are used when required if the LTCPHS directive was specified in the program input.

5.3.29 SUBROUTINE STOICC

For each reaction this subroutine constructs two vectors of stoichiometric coefficients, one for reactants and one for products. Up to 10 reactants and 10 products may be considered for each reaction. The total number of entries in the resultant linear reaction table is 600, i.e., the sum of all stoichiometric coefficients can not exceed 600.

5.3.30 SUBROUTINE STORNU

The purpose of this subroutine is to store the stoichiometric coefficients into the ITABLE arrays in COMMON/CSP RXC/. The coefficients will be positive for reactant species and negative for product species.

5.3.31 SUBROUTINE SUBNE

Calculates the average equilibrium pressure expansion coefficient from the chamber to the throat by iteration from the following formula (Newton's method):

$$N_e^{(n+1)} = N_e^{(n)} + \frac{\left(\frac{2}{N_e^{(n)}+1}\right)^{\frac{N_e^{(n)}}{N_e^{(n)}-1}} - \frac{P_e^*}{P_c}}{\left(\frac{2}{N_e^{(n)}+1}\right)^{\frac{N_e^{(n)}}{N_e^{(n)}-1}} \left(\frac{1}{N_e^{(n)}-1}\right)\left[\frac{1}{N_e^{(n)}-1} \ln \left(\frac{2}{N_e^{(n)}+1}\right) + \frac{N_e^{(n)}}{N_e^{(n)}+1}\right]}$$

where $N_e^{(1)} = 1.2$.

P_e^* is the equilibrium throat pressure

P_c is the equilibrium chamber pressure

This subroutine is used by subroutine PRES.

5.3.32 SUBROUTINE TABGEN (IFLAG, LTABLE,XTAB,YTAB,LUSED, X, Y, IERRØR, NY)

This subroutine records a tabular function (X,Y(NY)) in tables of fixed length. The first and last event will always be tabulated and the table will either contain all of the values specified or will be at least half full. Once the number of events exceed the table length, the table will be repacked by the deletion of every other table entry and tabulation will proceed choosing every $2^{\underline{N}\text{th}}$ event(N=0, 1, 2. . . etc., where N is the number of times the table must be repacked). The table spacing will be a power of two except for the last event which will always be tabulated.

The calling sequence parameters are:

IFLAG - denotes type of entry to subroutine
  = - 1 first entry
  = 0 normal entry
  = + 1 last entry
LTABLE - length of tables available for tabulation
XTAB - table for tabulation of the variable X
YTAB - table for tabulation of the variable
LUSED - number of table entries currently used (output)
X - the variable X
Y - the variable Y
IERRØR - error flag
NY - number of Y variables to be tabulated

Note: One Dimensional Mach Number Tabulation Procedure

At the initial axial position, X and Mach number are recorded. TABGEN is then used with LTABLE=50 (assuring 25 saved values). The last recorded values are the end values for the transonic tables.

5.4 TRANS MODULE SUBROUTINES

The transonic flow module (TRANS) calculates the two-dimensional flow conditions in the throat region of the nozzle. It is used to obtain an initial data line for the MOC module. The analysis is based on a modification to the method of Sauer[8]. A detailed derivation and description of the method used is given in Reference 9. An abreviated description of the method is presented in Section 2.4. Setion 2.4 described how the method has been adapted to treat flows with variable mixture ratio.

The TRANS module consists of the following subroutines:

TRAN
BANDI
FCALC
FINDT
GETIL
GETILV
NEWT
PTAB
SAUER
TRIM

5.4.1 SUBROUTINE TRAN

This subroutine is the controlling program for the transonic calculations, and is used to construct an initial data line for the method of characteristics calculations. Subroutine TRAN reads the Namelist $TRANS input as described in section 6. The calculations given below are performed by this subroutine. The method of analysis used is described in detail in reference

Transonic Calculations

From data supplied by the ODK subprogram expansion coefficients, γ_n, are computed for each of N zones as

$$\bar{\gamma}_n = \frac{\ln(P_\ell/P_1)_n}{\ln(\rho_\ell/\rho_1)_n} \qquad n = 1, \ldots, N$$

The nomenclature for numbering zones and the slipline locations dividing the zones is given in Figure 5.2.

Slipline locations, Y_n, are calculated (using subroutine TRIM) as

$$\begin{bmatrix} (1+A_1K_1), & -1 & & & \\ -A_2K_2, & (1+A_2K_2), & -1 & & \\ & \cdot & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & \cdot & \\ & & & -A_{N-1}K_{N-1}, & (1+A_{N-1}K_{N-1}) \end{bmatrix} \begin{bmatrix} Y_1^2 \\ Y_2^2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ Y_{N-1}^2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ 1 \end{bmatrix}$$

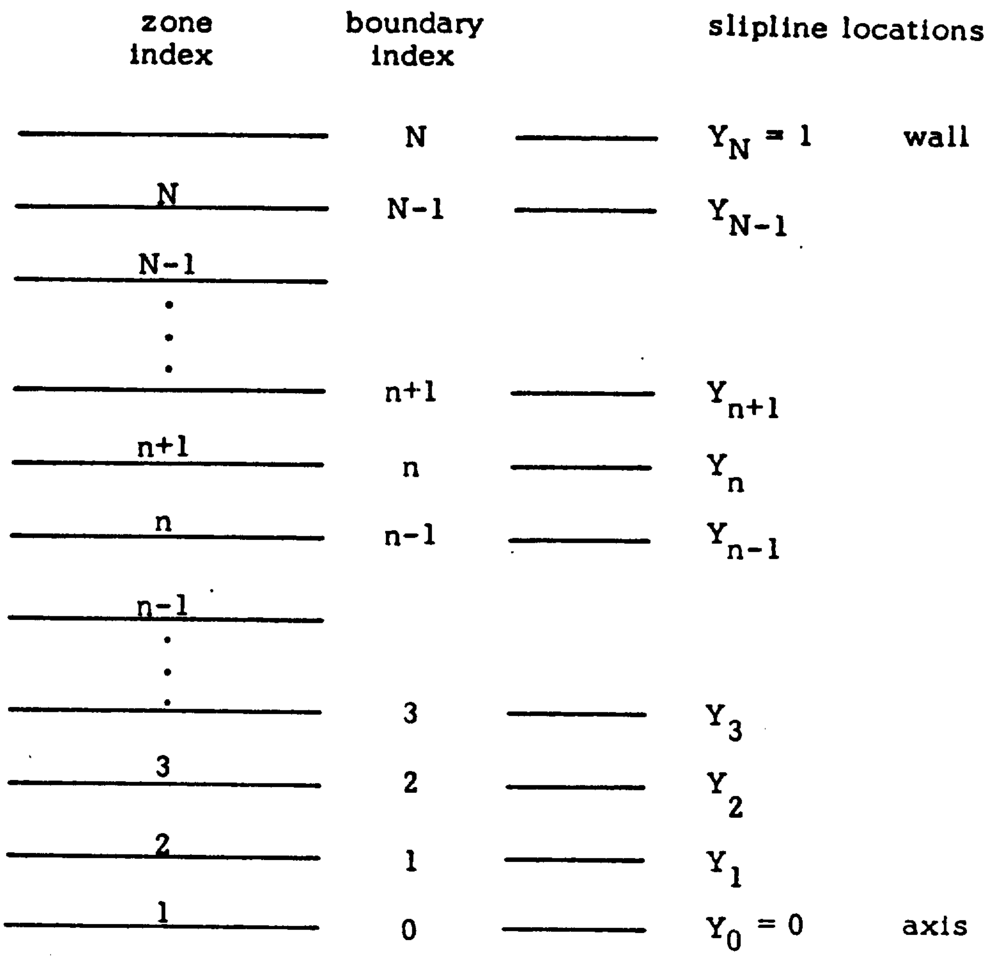


Figure 5-2: Nomenclature for the Numbering of Zones

where

$$A_n = \frac{\rho^*_n \; a^*_n}{\rho^*_{n+1} \; a^*_{n+1}}$$

$$K_n = \frac{\dot{m}_{n+1}}{\dot{m}_n} \qquad n = 1,2, \ldots N-1$$

The sonic conditions ρ^*_n and a^*_n are provided by the ODK subprogram and the partial mass flow rates, $\dot{m}_n$, are input.

Newton's method (subroutines NEWT and BANDI) is used to calculate the transonic coefficients B_{0_n}, B_{1_n}, C_{1_n}, and C_{2_n}. Subroutine FCALC evaluates the boundary conditions which must be satisfied.

Distribution of Initial Line Points

Subroutine TRAN next calculates the location of points on the initial data line used to start the method of characteristics calculations. First the radial position coordinates, r_i, are computed. A sinusoidal distribution of the following form is used:

$$r_i = \{r_w \sin\left(\frac{i}{N}\frac{\pi}{2}\right)\}^{\epsilon_1} \qquad i = 0,1,2....N$$

where

N is the number of points on the initial line before editing.

ϵ_1 is an exponent used for modifying the distribution function. Ordinarily a value of 1.2 is used.

r_w is the radial coordinate at which the initial data line intersects the wall.

The values computed for r_i are then edited to prevent locating points too close to sliplines, or too close to the wall. Some of the editing procedures can be controlled by input, as described in Section 6.6.

The axial coordinate positions, z_i , are then computed. First, a value of z_{axis} is found such that the Mach number at $r = 0, z = z_{axis}$ is the same as at the point r_w, z_w. The values of z_i are located on a parabola as follows:

$$z_i = z_w + \left((r_w - r_i)/r_w \right)^2 * (z_{axis} - z_w)$$

where z_{axis} is located on the axis half way between the sonic point and the point with a pressure equal to the pressure at the wall at r=0.

With r_i and z_i determined the transonic analysis is used to obtain corresponding values of pressure and flow angle. Using pressure as an independent variable, the flow tables computed by ODK (ODE if the TDE option used) are searched and values of ρ, V, T, and chemical species concentrations are obtained by interpolation. Subroutine GETIL is called for this purpose when one or more zones of constant mixture ratio are used, and subroutine GETILV is called when a variable mixture ratio is used.

Once constructed, the initial data line is integrated to obtain the nozzle flow coefficient C_D , where

$$C_D = \dot{m}_{2D} / \dot{m}_{1D}$$

and the result is printed.

Subroutine PTAB is called to write a table of boundary layer edge conditions for the results obtained up to the initial data line. This file is written on unit LUBLM and is continued later by subroutine PRINT as further values are computed using the MOC. If edge conditions for BLIMP-J are to be prepared, they are written on unit 50.

5.4.2 SUBROUTINE BANDI (A, NBW, NEQ, NMAX, B, X, INEW, KERR)

Purpose

BANDI solves a set of linear equations $Ax = b$ where A is a nonsymmetric band matrix.

Restrictions

The matrix A is destroyed.

Usage

Calling sequence:

```
CALL BANDI (A, NBW, NEQ, NMAX, B, X, INEW, KERR)
```

where

A	is a matrix of at least NEQ rows and NBW columns (see below) which initially contains the elements of the band matrix, stored as follows: To solve a system of the form

$$
\begin{aligned}
a_{11}x_1 + a_{12}x_2 &= b_1 \\
a_{21}x_1 + a_{22}x_2 + a_{23}x_3 &= b_2 \\
a_{32}x_2 + a_{33}x_3 + a_{34}x_4 &= b_3 \\
a_{43}x_3 + a_{44}x_4 + a_{45}x_5 &= b_4 \\
a_{54}x_4 + a_{55}x_5 &= b_5
\end{aligned}
$$

To transform an original (N by M) MATRIX A(I, J) into a packed (N by NBW) BANDED MATRIX AB (I, J), the following transformation applies.

$$AB(I, JB) = A(I, J)$$

where $JB = \left(\frac{NBW}{2} + 1\right) - (I - J)$

and NBW = BAND WIDTH

$$\begin{array}{cccc}
 & A_{i,1} & A_{i,2} & A_{i,3} \\
A_{1,j} & 0.0 & a_{11} & a_{12} \\
A_{2,j} & a_{21} & a_{22} & a_{23} \\
A_{3,j} & a_{32} & a_{33} & a_{34} \\
A_{4,j} & a_{43} & a_{44} & a_{45} \\
A_{5,j} & a_{54} & a_{55} & 0.0
\end{array}$$

NBW	is the width of the band (odd).
NEQ	is the number of equations in the system.
NMAX	is the maximum number of rows for which A has been dimensioned.
B	is the right-hand vector for the system.
X	is the solution vector returned by BANDI.
INEW	is a flag, set = 0 unless the coefficient matrix A is unchanged from a previous call to BANDI, in which case set INEW = 1.
KERR	is an error flag returned by BANDI: = 0 if no error; = 1 if any diagonal element becomes zero during triangularization of A.

Method

BANDI finds the solution vector X by single-pass Gaussian elimination. If INEW = 0, the coefficient matrix A is upper-triangularized by forward substitution. Backward substitution then yields the solution X. If INEW = 1, BANDI assumes that the coefficient matrix A has already been reduced on a previous entry and that only the right-hand vector B has changed. Therefore, the forward substitution is bypassed.

Programming Information

Note that the matrix A is upper-triangularized by BANDI, destroying the original band matrix coefficients. For very large or ill-conditioned systems, one may increase the accuracy of the solution as follows:

1) Save the original band matrix coefficients from A in a similar matrix AP.

2) Call BANDI with INEW = 0 to obtain a solution x_0 of $Ax = b$.

3) Calculate $b_n = Ax_n$ using the coefficients saved in AP. (A subroutine BMMULT exists to do this.)

4) Calculate a new right-hand vector $e_n = b-b_n$.

5) Call BANDI with INEW = 1 to solve the system $A\delta x_n = e_n$.

6) Set $x_{n+1} = x_n + \delta_n$.

7) Repeat steps 3-6 until the desired convergence is attained.

Error Return

If, during triangularization of the matrix, any diagonal element becomes zero, an appropriate message is printed and KERR is set to unity before returning to the calling program.

5.4.3 SUBROUTINE FCALC

The purpose of this subroutine is the evaluation of boundary condition functions required to be zero by the transonic analysis. Subroutine FCALC is called by subroutine NEWT in which Newton's Method is used to find the zeros.

Input:

Y_n	slipline heights $n = 1, \ldots N - 1$
γ_n	specific heat ratio for each zone $n = 1, \ldots N$
$B_{0_n}, B_{1_n}, C_{1_n}, C_{2_n}$	estimates for the constant coefficients sought by NEWT to satisfy the boundary conditions $n = 1, \ldots N$
N	total number of zones

Output:

The values of the following functions are computed and output. If the boundary conditions are correctly satisfied, each of these ($F_{1_n}, F_{2_n}, F_{3_n}, F_{4_n}$) are zero.

At the sliplines, $n = 1, \ldots N - 1$

linear term $v_n = v_{n+1}$ (i.e. match on streamline angle, 1st order);

$$F_{1_n} = \left[\frac{1}{2}(\gamma_n + 1) B_{1_n}^2 Y_n + C_{1_n} Y_n^{-1}\right] - \left[\frac{1}{2}(\gamma_{n+1} + 1) B_{1_{n+1}}^2 Y_n + C_{1_{n+1}} Y_n^{-1}\right]$$

constant term $v_n = v_{n+1}$;

$$\begin{aligned} F_{2_n} = & \left[\frac{1}{16}(\gamma_n + 1)^2 B_{1_n}^3 Y_n^3 + \frac{1}{2}(\gamma_n + 1) B_{1_n} C_{1_n} Y_n (\ln Y_n - \frac{1}{2}) \right. \\ & \left. + \frac{1}{2}(\gamma_n + 1) B_{1_n} B_{0_n} Y_n + C_{2_n} Y_n^{-1}\right] \\ & - \left[\frac{1}{16}(\gamma_{n+} + 1)^2 B_{1_{n+1}}^3 Y_n^3 + \frac{1}{2}(\gamma_{n+1} + 1) B_{1_{n+1}} C_{1_{n+1}} Y_n (\ln Y_n - \frac{1}{2}) \right. \\ & \left. + \frac{1}{2}(\gamma_{n+1} + 1) B_{1_{n+1}} B_{0_{n+1}} Y_n + C_{2_{n+1}} Y_n^{-1}\right] \end{aligned}$$

linear term $P_n = P_{n+1}$;

$$F_{3_n} = \gamma_n B_1 P^*_n - \gamma_{n+1} B_{1_{n+1}} P^*_{n+1}$$

constant term $P_n = P_{n+1}$;

$$F_{4_n} = \left\{ \gamma_n \left[\frac{1}{4} (\gamma_n + 1) B^2_{1_n} Y^2_n + C_{1_n} \ln Y_n + B_{0_n} \right] - 1 \right\} P^*_n$$
$$- \left\{ \gamma_{n+1} \left[\frac{1}{4} (\gamma_{n+1} + 1) B^2_{1_{n+1}} Y^2_n + C_{1_{n+1}} \ln Y_n + B_{0_{n+1}} \right] - 1 \right\} P^*_{n+1}$$

At the wall , n = N

linear term $v_N (1, z) = z$;

$$F_{1_N} = \frac{1}{R'} - \left[\frac{1}{2} (\gamma_N + 1) B^2_{1_N} + C_{1_N} \right]$$

constant term $v_N (1, z) = z$;

$$F_{2_N} = \left[\frac{1}{16} (\gamma_N + 1)^2 B^3_{1_N} - \frac{1}{4} (\gamma_N + 1) B_{1_N} C_{1_N} \right.$$
$$\left. + \frac{1}{2} (\gamma_N + 1) B_{1_N} B_{0_N} + C_{2_N} \right]$$

Since at the axis $v_1 (0, z) = 0$ it is required that $C_{1_1} = C_{2_1} = 0$.

5.4.4 SUBROUTINE FINDT

This subroutine is called by subroutine GETILV to read unit 16, which is a direct access file containing flow properties computed by ODK. Values are found from the file as a function of the input pressure, and values at the pressure are obtained from these by linear interpolation.

5.4.5 SUBROUTINE GETIL (IZ, IP, PPSI)

If one or more zones of constant mixture ratio are to be used, then this subroutine generates the initial data entries for the MOC module. The values are obtained using subroutine SPLIN for interpolation in the gas tables generated by the One Dimensional Kinetic module. The values obtained are ρ, V, T, and the chemical species concentrations. The values used for interpolation are read from unit KSTF1.

5.4.6 SUBROUTINE GETILV

If variable mixture ratio is to be used, then this subroutine generates initial data line entries for the MOC module. Values are obtained as a function of pressure using subroutine FINDT. The method described in Section 2.4.4 is used to obtain values at each initial data line point.

5.4.7 SUBROUTINE NEWT(M,F,MF,N,VAR,NVAR,FCALC,WF,PERTV,EPS1,MAXIT,NUMIT,BIN,AB,NBW,KERR)

Given a set of n functions in n unknown variables where each function is coupled as below:

$$f_i(X_j) \qquad i = 1, \ldots, n$$

$$j = i-k, \ldots, i+k$$

$$\text{and } 1 \leq j \leq n$$

this routine will attempt by Newton's method to find values

$$X_1, X_2, \ldots X_n$$

such that

$$\sum_{i=1}^{n} f_i^2 (X_j) = 0.$$

Method

Newton's method is used to iterate for a solution vector. The matrix of partial derivatives, J, required by the method is generated automatically by the subroutine. This matrix will be banded of width 2k+1. The matrix inversion is performed by subroutine BANDI. In the event Newton's method yields a vector which is farther from a solution in a least squares sense than the previous estimate, the increment vector is halved. Newton's algorithm for the $(k+1)^{th}$ iterant is:

$$X^{(k+1)} = X^{(k)} - J^{(k)^{-1}} f^{(k)}.$$

Restrictions

The user must supply initial values for the solution vector and also a subroutine to evaluate the functions. The subroutine must communicate with NEWT through COMMON statements. Subroutine BANDI is required.

Usage

Call NEWT(M, F, MF, N, VAR, NVAR, FCALC, WF, PERTV, EPS1, MAXIT, NUMIT,
NUMIT, BIN, AB, NBW, KERR)

Index to Calling Sequence:

Input:	M, MF, N, VAR, NVAR, WF, PERTV, EPS1, MAXIT, NBW
Output:	VAR, F, NUMIT, KERR
Working:	BIN, AB

Explanation of Calling Sequence:

1) M is the length of the array containing the n functions.

2) F is the array containing the n function values evaluated by FCALC.

3) MF is an array of M control words:

   if MF(I)=0, include F(I)
   if MF(I)=1, exclude F(I)

4) N is the length of the array containing the n variables.

5) VAR is the array containing the n variables, $x_i \quad i = 1, \ldots n$

6) NVAR is an array of N control words:

   if NVAR(J)=0, include VAR(J)
   if NVAR(J)=1, exclude VAR(J)

7) FCALC is a name for the subroutine which calculates the functions, F(I). A program which calls NEWT must have an EXTERNAL statement containing this name.

8) WF is an array of n weighting factors. These are used in conjunction with EPS1 to determine whether a solution has been reached.

   ω_i = WF(I)

9) PERTV is a perturbation factor used in calculating the partial derivatives required by Newton's method. If PERTV = ϵ, then:

$$\frac{\partial F}{\partial x} = \frac{F(x+\delta) - F(x)}{\delta}, \text{ where } \delta = \max\left(|\epsilon x|, \epsilon * 10^{-3}\right)$$

10) EPS1 is an error bound used to determine whether a solution has been reached. If ϵ_1 = EPS1, then a solution is claimed when

$$\sum_{i=1}^{n} (\omega_i F_i)^2 \leq \epsilon_1$$

11) MAXIT is the maximum number of iterations allowed.

12) NUMIT is the number of iterations required for solution.

13) BIN is an array required by LESK and must be at least of dimension N + 1.

14) AB is a two-dimensional array containing the augmented matrix of subroutine LESK and must be at least of dimension AB(M, N+1).

15) NBW band width = 2k+1, see subroutine BANDI.

16) KERR error indicator, see subroutine BANDI.

5.4.8 SUBROUTINE PTAB (PØNED)

This subroutine is used to write a table of boundary layer edge conditions for the results obtained up to the initial data line for the MOC. Unit LUBLM is used for passing this data to BLM. If edge conditions for BLIMP-J are to be prepared, they are written on unit 50 (i.e., IPTAB = 1 in $ODE, see Section 6.4.3.2.).

The following procedure is followed to make the one-dimensional throat coincident with the axisymmetric throat.

1) The pressure, P_{1D}, at the axisymmetric throat (r=1, x=0) must be given (PØNED in the calling sequence above).

2) The axial position, x*, in the one-dimensional gas tables corresponding to the above pressure is obtained by interpolation. The points downstream of this axial position are deleted.

3) The table of axial positions (saved in the one-dimensional calculations - TABGEN) is recoordinated to fit smoothly with the axisymmetric geometry using:

$$x' = x_i + (x - x_i) \left(\frac{-x_i}{x^* - x_i} \right)$$

where

x' = recoordinated axial position

x = tabulated axial position

x_1 = initial axial position

x^* = axial position from 2) above

4) The radial coordinate, corresponding to each recoordinated axial coordinate, is computed using the input geometric constraints. Reference may be made to Figure 6-1 for a description of the inlet and throat geometry.

5) The axial and radial coordinates and the fluid properties are punched. The punched cards may be input directly to the boundary layer computer program.

5.4.9 SUBROUTINE SAUER (R, X, Y, G, N, I, PPS, THETA)

The purpose of this subroutine is to compute fluid dynamic properties in the transonic region of a rocket nozzle. The method used is based on the analysis of Sauer and is applicable to the situation where the flow is assumed divided into N zones (i.e. striated), each of which is characterized by a constant expansion coefficient, γ_n. The analysis has been further modified so as to extend its range of applicability to nozzles with small ($R/r^* \geq .5$) radius of curvature in the throat section.

Given position coordinates (r, x), this subroutine returns the fluid dynamic properties (P/P^*, θ).

Calling Sequence

Input;

R	radial position coordinate, r
X	axial position coordinate, x
Y	vector Y_n; n = 1 . . N containing the zone boundary coordinates
G	vector γ_n; n = 1, . . . N containing the zone expansion coefficients
N	total number of zones

Output

I	zone number, n, corresponding to r
PPS	P/P^* at (r, x)
THETA	θ at (r, x), the gas streamline angle in radian

Method

$$R' = R + \frac{\gamma}{4}$$

$$X = \left(\frac{R}{R'}\right)^{1/2} x$$

If only one zone is specified (N = 1), then

$$u' = \frac{1}{4} (\gamma + 1) B_1^2 r^2 + B_0 + B_1 X$$

$$v' = \frac{1}{16} (\gamma + 1)^2 B_1^3 r^3 + \frac{1}{2} (\gamma + 1) B_1 B_0 r + \frac{1}{2} (\gamma + 1) B_1^2 r x$$

where

$$B_1^2 = \frac{2}{(\gamma + 1)} \quad \frac{1}{R'}$$

$$B_0 = -\frac{1}{4} \quad \frac{1}{R'}$$

If more than one zone is specified ($N \geq 2$), then

$$u' = \frac{1}{4}(\gamma + 1)\, B_1^2\, r^2 + C_1 \ln r + B_0 + B_1 X$$

$$v' = \frac{1}{16}(\gamma + 1)^2 B_1^3 r^3 + \frac{1}{2}(\gamma + 1)\, B_1 C_1\, r\, (\ln r - \frac{1}{2}) + \frac{1}{2}(\gamma + 1)\, B_1 B_0\, r + C_2\, r + \left[\frac{1}{2}(\gamma + 1)\, B_1^2\, r + C_1/r\right] x$$

where the coefficients B_0, B_1, C_1, C_2 are input through COMMON/NAMBC/ and the n^{th} value is selected, corresponding to the n^{th} zone. The zone, n, is determined such that

$$Y_{n+1} \geq r \geq Y_n$$

For all N

$$u = 1 + u'$$

$$v = v'$$

$$P/P^* = 1 - \gamma_n u'$$

$$\theta = \arctan (v/u)$$

5.4.10 SUBROUTINE TRIM (A, X, B, N, NN)

This subroutine solves the system

$$\bar{\bar{A}}\bar{X} = \bar{b}$$

for $\bar{X}$ where $\bar{\bar{A}}$ is tridiagonal, i. e.;

$$\text{all } a_{ij} = 0 \quad \text{if} \quad i > j+1 \quad \text{or} \quad i < j-1.$$

The method used is Gaussian elimination.

Calling Sequence

A Is the input coefficient matrix and must be dimensioned at least A(N, 3). The elements a_{ij} must be input as

$$\begin{bmatrix} - & A(1,2) & A(1,3) \\ A(2,1) & A(2,2) & A(2,3) \\ A(3,1) & A(3,2) & A(3,3) \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ A(N,1) & A(N,2) & - \end{bmatrix} = \begin{bmatrix} - & a_{11} & a_{12} \\ a_{21} & a_{22} & a_{23} \\ a_{32} & a_{33} & a_{34} \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ a_{n,n-1} & a_{nn} & - \end{bmatrix}$$

The contents of A will be destroyed by TRIM.

X Is the output solution vector $\bar{X}$ and must be dimensioned at least X(N).

B Is the input vector $\bar{b}$ and must be dimensioned at least B(N). The contents of B will be destroyed by TRIM.

N Is the order of the system. $N \geq 2$ is required.

NN Is the dimension of A (NN,3), X(NN), and B(NN) in the calling program.

5.5 MOC MODULE SUBROUTINES

The Method of Characteristics (MOC) module is used to calculate the loss in nozzle performance caused by flow divergence, including the effects of chemistry and mixture ratio variation. The effect of shock waves can also be calculated. Obtaining an accurate nozzle performance prediction usually requires a closely spaced characteristics mesh. In order to allow both shock waves and a fine mesh, random access files are used for storing and retrieving mesh point information.

The TDK module consists of the following subroutines:

TDK
ATSHCK
AXISPT
CHAR
CHECK
CKEXIT
CKSHCK
CNTRL
CNTRL1
CNTRL2
CNTR12
CNTR13
CNTR14
CNTR16
CNTR21
CNTR31
CNTR91
CRIT
CUBIC
DSPT
EF2D
ENCALC
ERR0RZ
FTHRST
GETPT
GPF
GPFKIN
GPFPG
INPT
INPTR
INPTRS
INPTR1
INPTS
INSRT
INTEXT
ITER1
ITER2
ITER3
MLCK
MRCK
MRCK1
NESK
PRINT
PRINTS
SAVPT
SCK
SDERIV
SETID
SHCKA
SHCKA1
SHCKL
SHCKR
SHCKW
SHCKW1
SH0CK
SINT
SUBIL
SUBILR
TCALC
THERM
TSTDK
TW0D
WALL
WLCALC
WLPT

5.5.1 SUBROUTINE TDK

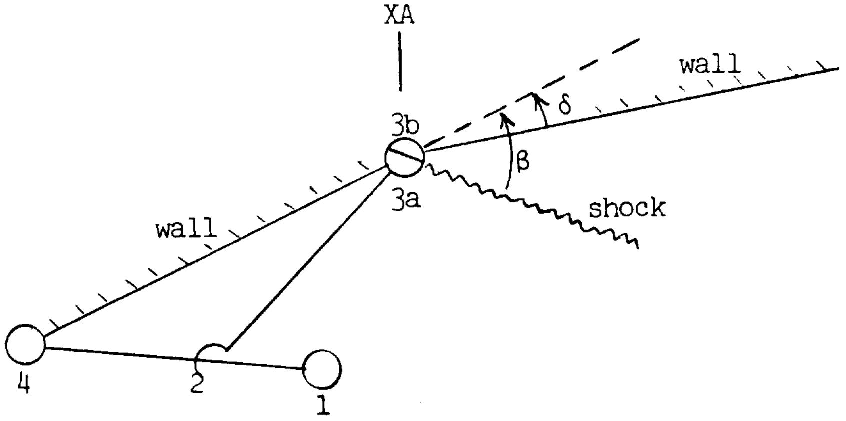
This subroutine is called by subroutine MAIN and is the driver for the MOC module. It performs the functions described below.

First, the MOC mesh point arrays P, PP, Q, Q3A, and Q4A, are initialized to zero. If the TDE option is to be executed, then the equilibrium gas properties tables described in Section 2.5.2 are converted to the system of units used internally by the MOC module and are stored for its use. Subroutine CHAR is then called to read the $MOC Namelist input, and perform all calculations that are preliminary to the MOC construction.

If the MOC construction is to ignore shocks (SH0CK=0 IN $M0C), then subroutine CNTRL is called, otherwise subroutine CNTRL91 is called.

5.5.2 SUBROUTINE ATSHCK

This subroutine calculates an attached shock point at axial position XA on the nozzle wall. Properties on the upstream side of the shock are calculated at point 3a. Values used in the calculation of point 3a are from the known points 4 and 1. Properties on the downstream side of the shock are then calculated at point 3b. Point 3b is found by solving the shock relations given the upstream conditions at point 3a and a streamline deflection angle equal to the change in wall angle at position XA.



The procedure consists of 4 steps, as follows:

1) Locate point 2 on the RRC 4-1 such that the LRC from point 2 reaches the wall at XA.

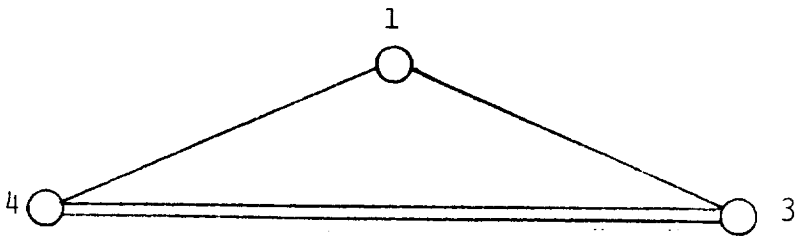
2) Using point 2 and point 4, calculate values at point 3a.

3) Iterate step 1 and 2 until the point 3a properties converge.

4) Find the shock angle, β_3 , corresponding to the upstream conditions at point 3a and a streamline deflection angle equal to the change in wall angle at position XA.

5.5.3 SUBROUTINE AXISPT

This subroutine calculates an axis point (or point on a center body of radius, r_c) using the known points 4 and 1.



center body of radius, r_c,
or axis streamline (r_c=0)

Points 1 and 4 are known points and point 3 is the unknown point to be computed. At point 3:

$$r_3 = r_c$$

and

$$\theta_3 = 0.$$

Initial estimates for values at point 3 are:

$$A_3=A_4,\ \beta_3=\beta_4,\ \alpha_3=\alpha_4,\ \gamma_3=\gamma_4$$

and

$$G_3 = G_1$$

$$A_3G_3H_3 = A_1G_1H_1$$

$$G_3H_3 = G_1H_1$$

The axial location of point 3 is calculated from

$$x_3 = x_1 + \frac{r_c - r_1}{\tan 1/2(\theta_1 - \alpha_1 - \alpha_3)}$$

The flow properties at point 3 are calculated from

$$P_3 = P_1 + \frac{P_3 + P_1}{2} \{ \frac{1}{2} [-A_1 G_1 H_1 - A_3 G_3 H_3 + (G_1 H_1 + G_3 H_3) \frac{\sin\theta}{r_1}] (x_3 - x_1)$$

$$- \frac{1}{2} (G_1 + G_3)\ \theta_1 \}$$

$$\rho_3 = \rho_4 [\frac{P_3}{P_4}]^{\frac{1}{2} [\frac{1}{\gamma_4} + \frac{1}{\gamma_3}]} \exp \{ - \frac{1}{2} [A_4 + A_3][x_3 - x_4] \}$$

$$T_3 = T_4 [\frac{P_3}{P_4}]^{\frac{1}{2} [\frac{1}{\gamma_4} + \frac{1}{\gamma_3}]} \exp \{ - \frac{1}{2} (B_4 + B_3)(x_3 - x_4) \}$$

For the 1st iteration (all iterations if constant γ option):

$$V_3 = \{ V_4^2 - 4 (P_3 - P_4)/(\rho_3 + \rho_4) \}^{\frac{1}{2}}$$, Bernoulli Equation

For subsequent iterations (calculated in GPFKIN or GPFPG):

$$V_3 = \{ 2(H_t - \sum c_i h_i) \}^{\frac{1}{2}}$$, Energy Equation

The above equations are iterated (i=1,...) until x_3, P_3, ρ_3, T_3, and V_3 converge to the required accuracy.

Throughout the method of characteristics computations the variables used are equivalenced to entries in dimensioned arrays. This equivalency of variables is always in the same order as prescribed in Table 5-6. This equivalencing occurs for the I subscript in the following arrays: P(I,J), PP(I,J), PS(I), PSS(I), Q(I,J), Q3A(I), and Q4A(I).

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TABLE 5-6 EQUIVALENCE TABLE FOR MOC VARIABLES

I		Variable	Units
P(1,J)	=	P, pressure	lb f/ft^2
2		ρ, density	lb m/ft^3
3		θ, streamline angle	radians
4		V, velocity	ft/sec
5		r, radial coordinate	
6		x, axial	
7		T, temperature	°R
8		A, term computed in subroutine GPF	
9		B, " " " " "	
10		C, " " " " "	
11		D, " " " " "	
12		Stream function (0 at axis, 1 at wall)	
13		F, term computed in subroutine GPF	
14		G, " " " " "	
15		H, " " " " "	
16		α, " " " " "	
17		γ, " " " " "	
18		dividing streamline flag	
19		zone number	
20		point ID no. in direct access file	
21		β, shock angle	
22		point type (axis, interior, etc.)	
23		Mach no.	
24		ID no. of previous streamline pt.	
25		ID no. of previous pt. on the char.	
26		ID no. of next pt. on the char.	
27		ID no. of pt. on the other side of shock	
28-30		not used currently	
31		c_1, mass fraction of species 1	
.			
.			
.			
60		c_{60}, mass fraction of species 60	

5.5.5 SUBROUTINE CHECK (N0)

This subroutine compares current and previous values of the flow variables P_3, ρ_3, θ_3, V_3, r_3, x_3, and T_3 for relative convergence by calling subroutine CRIT. As soon as a variable is encountered failing the test, the variables are updated one iteration and the program returns with the convergence flag set as failed (N0 = 1). If convergence is achieved the variables are updated one iteration and the subroutine returns with the convergence flag set as passed (N0 = 0).

5.5.6 Subroutine CKEXIT (P, EFLAG)

This subroutine checks if a point, P, is outside the nozzle by comparing the axial location, Z, against the nozzle length, ZEXIT.

If Z ≥ ZEXIT * 1.03, then set EFLAG = 2.

If ZEXIT * 1.03 > Z ≤ ZEXIT, then set EFLAG = 1.

5.6.7 Subroutine CKSHCK (SFLAG)

This subroutine checks for a crossing of right-running characteristics, which determines the start point of a right-running shock wave. The shock flag, SFLAG, is set to 1 when a crossing has occured, or will occur at the next point.

5.5.8 SUBROUTINE CNTRL

The purpose of this subroutine is to control the construction of the finite difference mesh for the method of characteristics solution of the supersonic nozzle flow when the LRC method is used (SH0CK=0 in $M0C). Left running characteristics and fluid streamlines are constructed starting at the nozzle throat point ($r = 1$, $x = 0$). These left running characteristics extend from the initial data line or nozzle axis to the wall. The mesh points are calculated by subroutines INPT, AXISPT, WLPT and DSPT under control of this subroutine.

Additional points are inserted in the mesh by subroutine CNTRL by property averaging using subroutine INSRT. The circumstances which cause point insertion are listed below. In each case a point is inserted along the initial line or the previous streamline and the calculation of point 3 is repeated:

1) If subroutine INPT or DSPT find point 1 to fall beyond the nozzle wall.
2) If subroutine INPT finds point 1 to fall above a dividing streamline point.
3) If subroutine INPT or DSPT find

$$|\theta - \theta_4| > \Delta\theta_{t\omega} \text{ , input item DTWI}$$

4) If a wall point on the circular arc immediately downstream of the throat is calculated such that

$$|\theta_3 - \theta_4| > \Delta\theta_{\omega c} \text{ , input item DWWCI}$$

or if a wall point between the circular arc and the nozzle exit point is calculated such that

$$|\theta_3 - \theta_4| > \Delta\theta_{\omega} \text{ , input item DWWI}$$

5) When iterating to locate the end of the nozzle wall. (Input tolerance of EPW).

6) If subroutine AXISPT, INPST, DSPT, or WLPT locate point 3 such that its distance from point 4 is greater than input item DS times the square root of the Mach number.

At the end of each completed characteristic surface the mesh points are examined and points discarded as described below. Only interior points (ID=2) are to be discarded.

For $n = 2$ to $n = \text{IPPW}-1$, (i.e., from the initial line or axis to the wall) discard point n if

$$|\theta_{n-1} - \theta_n| + |\theta_{n+1} - \theta_n| < \varepsilon_\theta^2$$

and

$$(r_{n-1} - r_n)^2 + (z_{n-1} - z_n)^2 < \varepsilon_s^2$$

where ε_θ and ε_s are the input quantities ETHI and ES.

Whenever a mesh point calculation or insertion is completed successfully, the output subroutine, PRINT, is called so that the point may be printed.

Subroutine CNTRL also integrates the wall pressure by trapezoidal rule to determine the axial component of force existing between adjacent wall points,

$$\Delta F = 2\pi r^{*2} \int_{r_4}^{r_3} P\ r\ dr = \frac{\pi}{2} (P_3 - P_4)(r_3^2 - r_4^2)\ r^{*2}$$

Total thrust is item found by

$$F_t = F + 2\pi r^{*2} \int_{1}^{r_2} P\ r\ dr$$

where F is the thrust across the initial line as calculated by subroutine CHAR.

DETAILED DISCUSSION OF CNTRL

Detailed documentation for subroutine CNTRL of the TDK computer program is presented on the following pages. It is intended that this documentation be read in conjunction with the FORTRAN listing of subroutine CNTRL.

The CNTRL subroutine calculates flow field points using point calculation subroutines and constructs the method of characteristics point mesh. The points are calculated in the Q array. The left running characteristic (LRC) under construction is stored in the P array, and the previous characteristic is stored in the PP array. In these two dimensional arrays (i.e., Q, P, and PP) the column number is the point number and the row number is the flow field property number. The flow field properties storage is defined in Table 5-6, subroutine CHAR, and is the same for all three arrays. For dividing streamline points, two arrays are required for Points 3 and 4. Storage for these extra points are provided in Q.

Besides the point calculation subroutines (AXISPT, DSPT, INPT, and WLPT), subroutines ERRORZ, INSRT, PRINT, SPLN, SUBIL, and TIMERX, are the only other subroutines called directly from CNTRL.

The CNTRL subroutine is divided into areas 1 through 9. A description of the programming of each of these areas is presented below. Presented in Table 5-7 are definitions for the variables used by subroutine CNTRL. FORTRAN variables which are input to the program have not been included in Table 5-7. These variables are described in Section 6.7.1.

Area 1:

In this area of CNTRL constants are initialized and the Point 3 arrays are zeroed. Other variables needed by CNTRL are initialized in subroutine CHAR. Subroutine SUBIL is called and the first initial line point is brought in and stored in PP(i, 1). The point is also placed in the Point 1 working storage and printed. The same procedure is followed for the second initial line point; this time storing the point in P(i, 1). A check is made to see if an error was detected by subroutine PRINT. The point counters IP for the P array and IPP for the PP array are set to one.

Area 2:

This area defines the general procedure for initial line point set up. The initial line point counter, MS, is incremented and IP and IPP are initialized to one. Initial line point number MS is brought in and stored in P(i, 1). It is also placed in Point 1 and printed. If a dividing streamline point calculation is indicated (i.e., PS [JFLAG] not zero), the point is also stored into the next point in PP.

Area 3:

The counters IPP and IP are incremented and the print subroutine is called with ID as set by the point subroutine just completed (see subroutine PRINT for the definitions of ID). If too many points have been calculated along the LRC (i.e., IP < IPMX) the error flag is set to 7 and CNTRL is exited. Otherwise, the values just calculated in Q(i, 3) are stored in the LRC array and Q(i, 3) is cleared. If the Point 3 is a single point (interior point), this part of the logic is complete. Otherwise, Q3A(1) is placed in Point 3 and Area 3 is repeated.

Area 3.5

If the exit plane option has been requested (EXITPL = true), no check is made on the end of wall flag (E0W2) that otherwise is used to stop the calculation. The E0W2 flag is set when the end of the wall has been reached within a tolerance of EPW (nominally .01).

If the exit plane calculation has been requested, as soon as the nozzle calculation is complete (i.e., E0W2 set to one) the wall is artifically extended a distance DELWX in the axial direction. The slope used for this extension is that of the last two points in the wall table. The flag EXITCK is used to assure that this is only done once. The point just calculated is written on unit ITSTAB to be used later as the first exit plane point. The statement "BEGIN EXIT PLANE CALCULATION" is printed.

If the exit plane option has been requested and the programming described in the above paragraph has been executed, the last entry in the insert table, IT(LAST), is checked. If the insertion process is complete and the last two points calculated fall on either side of the exit plane, values at the exit plane are found by interpolation and written on unit ITSTAB for later use. If the point just written out is an axis point, or if the first point on the LRC is beyond the exit plane, the program goes to statement 1700 to write out the exit plane summary and to terminate the calculation. Otherwise the program proceeds to Area 4.

If the exit plane calculation is in progress and the LRC has already crossed the exit plane successfully, checks are made to see if NCHEPE, NPTEPE, and P(6, IP) are within their minimum values. If so, Area 4 is entered at the beginning, otherwise it is entered at 1610 and a special check is made.

Area 4:

If Area 4 is entered at the beginning, a check is made to see if the point just used on the previous LRC was the last point (IPPW) on the LRC. If not, the program goes to Area 7. Otherwise, starting at 1610 NCHEPE is checked as follows; if EXITCK is true, and the point just calculated is not beyond the exit plane, and NCHEPE exceeds its maximum value, transfer is made to Area 9 and the error message "EXIT PLANE OPTION REQUIRES LARGER NCHMXE, NPTMXE" is printed. If no error was found, the program sets IPPW = IP and checks to see if the insertion table is empty. If so, the program transfers to Area 7.

If the insert table is not empty, it is necessary to restart the LRC calculation at the last point entered in the table. The reason for this is as follows. Whenever it is necessary to insert a point along a streamline, the inserted point will start a new LRC. It is then necessary to complete this new LRC and then come back to the point of insertion and complete the LRC that was being computed when the insertion occured. This procedure is carried out in Area 4 by mapping point numbers IT(LAST) through IP of the P array into the PP array. IP is then set to IT(LAST)-1 and IPP is set to IT(LAST)+1 so that the LRC calculation can start from the point of last insertion. This point is then removed from the IT table by setting LAST = LAST-1. The program then goes to Area 7.

Area 5:

Area 5 is entered when a LRC has been completed. This means that the insertion table has been emptied. Next, the PP array is updated by transferring into it the values in the P array. If the LRC just completed is in the nozzle, the LRC surface is integrated from the axis (or initial line) to the wall using the trapezoidal rule method to obtain the mass flow rate. The integral to each point is stored in the array XMASSF. Tests are made on the input variable MASSFL and print out of the mass flow is done accordingly. Next, an adjustment is made to the pressure so that mass flow is conserved. The density is recalculated from the perfect gas law. At the end of Area 5 the edit logic using ε_o and ε_s is carried out as discussed earlier. The characteristic number, LRC, is then updated and the program transfers to Area 2 if the next LRC starts from the initial line, and to Area 6 if the next LRC starts from the axis.

Area 6:

Area 6 is entered when it has been determined that an axis point is to be calculated. The point counters (IP and IPP) and the insert counters (CS) are initialized and Points 1 and 4 are set up. The axis point subroutine is called and return is made with either the axis point calculated or the INSERT flag set. If an insert is requested or if Point 3 is found to be farther than a distance DS downstream from Point 4, a new Point 1 is inserted half way between the old Point 1 and Point 4. Inserts are counted and an error is detected if more than the maximum are required.

If the axis point has been successfully calculated and an insert was required, then subroutine PRINT is called to print the inserted point. Transfer is then made to Area 3.

Area 7:

Area 7 is entered for the purpose of performing a wall point calculation. If the point to be calculated is not a wall point the program goes to Area 8. If a wall point is to be calculated checks are made concerning the exit plane option. If the exit plane option is in effect, the point to be calculated is either on an LRC which: (1) ends upstream of the nozzle exit plane (EXITCK false), or (2) is one of the NCHMXE LRC's ending on the nozzle wall extension, or (3) is a LRC farther downstream which is ended as soon as a point is calculated with an axial coordinate greater than XEXTEN. In the first two cases the wall point calculation proceeds normally as described in the next paragraph. In the third case the program goes to Area 9 and constructs an end point for the LRC so that it can be finished without a wall point, and then goes to Area 4. However, if the point just calculated is beyond XEXTEN then it is not necessary to go to Area 9 and the program goes directly to Area 4.

The wall point calculation logic is as described in Area 6 for an axis point with the exceptions noted below. The Point 2 is set up rather than Point 1. After a wall point is calculated, the streamline angle is checked to be sure it has not turned more than $\Delta\theta_w$. The axial pressure component is integrated to determine the thrust increment for the wall differential just completed (see the equations discussed earlier). If a point was inserted on the previous streamline, it is entered into the insert table. When the wall point procedure is completed the program goes to Area 3.

Area 8:

Area 8 is entered for the purpose of performing an interior point or a dividing streamline double point calculation. The point calculation logic is as follows. A check is made to determine if the point to be calculated is a interior point or a dividing streamline point. Points 2 and 4 are set up accordingly and the appropriate point calculation subroutine is called (INPT or DSPT). If it is necessary to insert a point, the insert procedure is the same in both cases and is also the same as used for a wall point calculation as previously described. These three point calculations are set up differently, but use the same code for the insert procedures.

Area 9:

This area of the subroutine contains the error termination procedure, the nozzle exit plane summary print procedure, two error messages, and the end point procedure for the exit plane option.

The error termination procedure begins by calling the error subroutine, ERR0RZ, giving it the number of the error statement to be printed. Subroutine PRINT is then called so as to print the last point calculated. If exit plane points have been saved, these also are printed. Subroutine CNTRL is then exited.

The nozzle exit plane summary print procedure is as follows. A title is printed, then each exit plane point is read from unit ITSTAB and printed uing subroutine PRINT. Subroutine CNTRL is then exited.

The two error messages printed in Area 9 relate to the exit plane option. When this option was added to the program, these messages were placed here rather than in subroutine ERR0RZ.

The end point procedure for the exit plane option found at the end of Area 9 is that described in Area 7.

TABLE 5-7

DEFINITIONS FOR FORTRAN VARIABLES USED BY SUBROUTINE CNTRL†

Variables beginning with I through N are typed as integer. All others are typed as real unless noted as logical. No other types are used. Assumed values are listed in parentheses.

Variable	Definition
ARATI0	Area ratio of wall point
CS	Insertion counter
CSMAX	Maximum allowed number of insertions (20.)
DELWX	Length of nozzle extension for exit plane option (10.)
DS2	DS * DS; where DS is input
E0W1	Flag set in WLPT when the end of nozzle wall is detected
E0W2	Flag set in WLPT when iterations to reach end of wall point are complete
ES2	ES * ES; where ES is input
EXITCK	Logical variable set true for the exit plane option as soon as the end of the nozzle is reached
EXITPL	Logical input variable. Input true if the exit plane option is desired (.FALSE.)
ID	Point type input to subroutine PRINT
IERR	Error flag, set to error number

---

† The following input variables are used by subroutine CNTRL: DS, DTWI, DWWI, EPW, ES, ETHI, IMAX, and IMAXF. These variables are discussed in Section 6.7.1

TABLE 5-7

DEFINITIONS FOR FORTRAN VARIABLES USED BY SUBROUTINE CNTRL

(Continued)

Variable	Definition
IMX	Number of variables for a point
INSERT	Insert flag. A non-zero value asks CNTRL to insert a point
IP	Point counter for the LRC under construction
IPMX	Maximum number of points allowed on a LRC (151)
IPP	Point counter for the last LRC finished
IPPS	Value of IPP for Point 4
IPPW	The largest IPP value, that of the wall point
IT (20)	Insertion table where the point numbers are stored for insertions requiring LRC completion
ITSTAB	Unit on which exit plane points are stored until printed (29)
JFLAG	Index for flag in the point arrays identifying dividing streamline double points
LAST	Number of last entry into IT array
LASTMX	Maximum number of LRC generating insertions for the original LRC (20)
LRC	Number of LRC
MASSFL	Input variable controlling the mass flow print out (1)
MS	Initial line point counter
MW	Wall point counter
N	Statement number for ASSIGNED G0 T0 controlling the point calculations
NCHEPE	For exit plane option, LRC counter in the wall extension region

TABLE 5-7

DEFINITIONS FOR FORTRAN VARIABLES USED BY SUBROUTINE CNTRL

(Continued)

Variable	Definition
NCHMXE	For exit plane option, number of LRC's to be calculated on the wall extension (6)
NEXITP	Exit plane point counter
NPTEPE	For exit plane option, LRC counter in the region beyond the wall extension
NPTMXE	For exit plane option, maximum number of LRC's allowed in the region beyond the wall extension (10)
P(70,275)	Array in which LRC is constructed
PP(70,275)	Array containing LRC just completed
PS(70)	Working storage for initial line point
PW(1208)	Array containing wall point coordinates
Q(70,5)	Working storage for point calculations, column number is the point number
Q3A(70)	Working storage for Point 3A of dividing streamline double point
Q4A(70)	Working storage for Point 4A of dividing streamline double point
REXIT	Radial coordinate at end of nozzle wall
XEXIT	Axial coordinate at end of nozzle wall
XEXTEN	For exit plane option, length of nozzle extension reached after LRC number NCHMXE
XMASSF(275)	Array containing integrated mass flow rate of each LRC point

5.5.9 Subroutine CNTRL1

Given a right-running characteristic (RRC) stored in the PP(-,-) array, and the starting point of the next RRC stored in P(-,IP), this subroutine computes a RRC emanating from P(-,IP). The RRC is traced until it reaches the axis, or goes outside the nozzle.

5.5.10 Subroutine CNTRL2

This subroutine performs the same function as subroutine CNTRL1, but applies to a left-running characteristic (LRC). Here, the calculation is carried out until the LRC reaches the wall.

5.5.11 Subroutine CNTR12

This is a control subroutine for the shock calculation. It is called after an induced right-running shock has been detected. Its function is to compute a right-running shock point, followed by the construction of a LRC to the wall. The procedure is repeated until the end of nozzle is reached, or the shock wave reflects off the center line. At this point control is returned to CNTR91 and CNTR13 is called.

5.5.12 Subroutine CNTR13

This is a control subroutine for the shock calculation. Its function is to compute a left-running shock point, followed by the construction of a RRC from the shock point to the axis. The procedure is repeated until the end of the nozzle is reached, or the shock wave reflects off the wall. At this point control is returned to CNTR91 and CNTR14 is called.

5.5.13 Subroutine CNTR14

This is a control subroutine for the shcok calculation. Its function is to compute a right-running shock point, followed by the construction of a LRC from the shock point to the wall. The procedure is repeated until the end of the nozzle is reached, or the shock wave reflects off the axis. CNTR14 is similar in function to CNTR12, but it is designed for multiple reflections, while CNTR12 is designed to start the induced shock calculation.

5.5.14 Subroutine CNTR16

This is a control subroutine for the shock calculation. Its function is to compute a second attached shock wave. The construction is as follows. First, the flow field is computed assuming the second shock wave is negligible. When the end of the nozzle is reached, then subroutine CNTR16 is called. By using existing information an attached shock is calculated at the wall location having axial coordinate XB. Next, a right-running shock wave is constructed from XB. A LRC is traced from each shock point to the nozzle wall using subroutine CNTR12. The calculations stop when the wall end point is reached.

5.5.15 Subroutine CNTR21

This is a control subroutine for the shock calculation. Its function is to compute right-running characteristics beginning at the bottom of the initial data line. Successive RRC's are constructed starting at the initial data line and ending at the axis or exit plane. Once the wall is reached, successive RRC's are constructed starting at the wall and ending at the axis or exit plane. The procedure is repeated until the nozzle end point is reached. However, if an induced right-running shock is detected, then control is returned to CNTR91 and subroutine CNTR12 is called.

5.5.16 Subroutine CNTR31

This is the control subroutine for the attached shock wave calculation. First, it computes right-running characteristics beginning at the bottom of the initial data line. Successive RRC's are constructed starting at the initial data line and ending at the axis or exit plane. Once the wall is reached, successive RRC's are constructed starting at the wall and ending at the axis or exit plane. The procedure is repeated until position XA is reached on the wall. Control is then returned to CNTR91 and subroutine CNTR14 is called.

5.5.17 Subroutine CNTR91

This is the master control subroutine for the shock calculations. It calls subroutine CNTR12, CNTR13, CNTR14, CNTR16, CNTR21, and CNTR31 as required to compute the flow field from the initial line to the end of the nozzle.

5.5.18 SUBROUTINE CRIT (XN, XM, NO)

The purpose of this subroutine is to compare two valves for absolute or relative convergence and return an indicator stating if convergence has been achieved.

Calling Sequence:

XN	x_n , input
XM	x_m , input
NO	indicator, output NO = 0 implies convergence NO = 1 implies no convergence

where:

if $|x_m - x_n| < \epsilon_1$ then NO = 0 , return

if $|x_n| = 0$ then NO = 1 , return

if $|x_m - x_n| / |x_n| < \epsilon_2$ then NO = 0 , return

otherwise NO = 1 , return

$$\epsilon_1 = \epsilon_2 = 5 \cdot 10^{-5}$$

5.5.19 SUBROUTINE CUBIC (X,Y,YP,N,ARG,YARG)

The purpose of this subroutine is to perform cubic interpolation for a tabulated function whose derivatives are known.

Calling Sequence:

X	is a table of the independent variable, x_i, such that $x_{i+1} \geq x_i$
Y	is a table of the dependent variable, $y_i = y(x_i)$
YP	is a table of the derivatives of the dependent variable $y_i' = y'(x_i)$
N	is the number of entries in each of the above tables; $i = 1, \ldots N$
ARG	is the argument, x, for which interpolation is requested
YARG	is the result, $y = y(x)$

Restrictions:

The calling program must define arrays for the dummy variables X, Y, and YP. These arrays must be at least of lengths N + 1, N, and N respectively. The subroutine will save its last used table position number in X(N + 1).

If $x < x_1$ the program returns $y = y_1$

If $x > x_N$ the program returns $y = y_N$

Method:

Given : $x_0 \leq x < x_1$

so that y_0, y_0' y_1, and y_1' are known. The cubic interpolation formula given below is used to determine y

$$y = A(x - x_0)^3 + B(x - x_0)^2 + C(x - x_0) + D$$

where

$$A = \frac{1}{h^3}\left[\left(y_1' + y_0'\right) h - 2k\right]$$

$$B = \frac{-1}{h^2}\left[\left(y_1' + 2y_0'\right) h - 3k\right]$$

$$C = y_0'$$

$$D = y_0$$

and

$$h = x_1 - x_0$$

$$k = y_1 - y_0$$

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5.6 BLM SUBROUTINES

The Boundary Layer Module (BLM) is used to calculate the loss in nozzle performance due to a viscous boundary layer and its interaction with the nozzle wall. The effects of both drag and heat transfer are included. The method used is described in Section 2.6.

The BLM consists of the following subroutines:

- BLMAIN
- BLEDGE
- BLH
- BLØCKD
- BLPLTS
- BLSEG
- BLTABL
- BLW
- CØEF
- CØEF1
- CUBICB
- DIFF
- EDDY
- INPUTB
- IVPL
- LINI
- ØUTPBL
- RBL
- READBL
- SØLV5
- WRPROF

The BLM is entered through subroutine BLMAIN. The boundary layer is divided into segments consisting of equally spaced grid lines. The control subroutine for analyzing a segment is subroutine BLSEG. There can be as many as 101 grid lines per segment, and as many as 10 segments. Many of the variables used in the BLM analysis are stored in arrays. The most important array variables are listed in Table 5-8.

TABLE 5-8: ARRAYS USED BY THE BLM

Variable (with dimension)		Common /Name/	Contents
A	(101)	/GRD/	$(\eta_j - \eta_{j-1})/2$, grid spacing
ALFA	(101)	/AL/	α_e, angle of b.l. to nozzle center line
ALMDA	(101)	/EDGE/	λ_e, mean free path at edge
B	(101,2)	/BLC1/	b, see equation 2.6-12
BC	(101)	/BLC1/	$(\rho\mu/\rho_e\mu_e)$, see equation 2.6-12
C	(101,2)	/BLC1/	(ρ_e/ρ), see equation 2.6-12
CII	(101)	/MISCT/	I_1, integral, see equation 2.6-21
CK	(101)	/BLC2/	γ versus T, gas property table
CKE	(101)	/EDGE/	γ_e versus T_e
CNUE	(101)	/EDGE/	(μ_e/ρ_e)
CP	(101)	/BLC2/	C_p versus T, gas property Table
CPE	(101)	/EDGE/	C_{p_e} versus T_e
CQ	(101)	/WALL/	$(\rho v)_w$ versus T_w
D	(101,2)	/BLC1/	d, see equation 2.6-12
E	(101,2)	/BLC1/	e, see equation 2.6-12
HHE	(101)	/EDGE/	H_e, total enthalpy at edge
HSE	(101)	/EDGE/	h_e^*, static enthalpy at edge
HSW	(101)	/WALL/	h_w^*, static enthalpy at wall
PE	(101)	/EDGE/	P_e, pressure at edge
P1	(101)	/PRES/	m_1, see equation 2.6-13
P2	(101)	/PRES/	m_2, see equation 2.6-13
P3	(101)	/PRES/	m_3, see equation 2.6-14
RIN0	(201)	/BC0N/	r_o, radial coordinate of b.l., input
RKK	(101)	/BLC2/	k versus T, gas property table

RHØE	(101)	/EDGE/	ρ_e, density at edge
RMU	(101)	/BLC1/	μ versus T, gas property table
RMUE	(101)	/EDGE/	μ_e, viscosity at edge
RR	(101)	/BLC2/	R_g versus T, gas property table
RX	(101)	/EDGE/	R_ξ, local Reynold No., $U_e\xi/\nu_e$
RO	(101)	/GRD/	$(r_o/L)^k$, local radius of body revolution (L=1)
S	(201)	/GBLK/	x, surface distance, equally spaced
SØ	(201)	/GBLK/	x, surface distance, input
T	(101)	/BLC2/	T, temperature for gas property tables
TE	(101)	/EDGE/	T_e, temperature at edge
TVCT	(101)	/MISCT/	$(1-t)^{2k}$ where $t = y \cos\phi/r_o$, transverse curvature
TW	(101)	/WALL/	T_w, temperature at wall
U	(101,2)	/BLC1/	$f' = U/Ue$
UE	(101)	/EDGE/	U, velocity at edge
V	(101,2)	/BLC1/	f'', shear parameter
WW	(101)	/WALL/	g_w', dimensionless total enthalpy gradient at wall
X	(101)	/GRD/	ξ, see XØ
XINØ	(201)	/BCØN/	X, axial coordinate, input
XØ	(101)	/GBLK/	ξ, transformed surface distance, see equation 2.6-6a
Y	(101)	/MISCT/	$\eta = y/y$

5.6.1 SUBROUTINE BLMAIN

This is the main program for the BLM. The functions performed by this routine are described below.

Input data is read by calling subroutine INPUTB. INPUTB also prepares tables and initializes variables and indexes required for subsequent calculations. Next, subroutine IVPL is called, and initial velocity and temperature profiles are computed on a finite difference grid.

The boundary layer is divided into segments with as many as 101 grid lines per segment. For each segment, 1 through NSEG, the following events occur. First, subroutine BLEDGE is called to prepare tables of variables that describe conditions at the wall and at the inviscid edge of the boundary layer. Next, subroutine BLSEG controls the computation of the boundary layer. It computes the growth of the boundary layer from the beginning to the end of each segment, i.e., up to 101 grid lines.

Subroutine BLMAIN prints out text heading the numerical output of the program.

At the end of the print out for each segment, BLMAIN prints the following quantities which are evaluated at the last point on the segment:

Mean Free Path

$$\lambda = 1.26 \ \nu /(gRT)^{1/2} \qquad \text{(ft)}$$

Total Integrated Wall Heat Flux

$$Q_w = \int \dot{q}_w \, d\,A \qquad \text{(BTU/sec)}$$

At the end of the print out for the last segment, the following additional quantities (evaluated at the last point) are printed:

Knudsen No. based on δ^*

$$Kn_{\delta^*} = \lambda / \delta^*$$

Nozzle Mass Flow

$\dot{m}_{2D}$ (lbm/sec)

Boundary Layer Specific Impulse Loss

$\Delta I_{sp,BL} = \Delta F_{BL} / \dot{m}_{2D}$ (sec)

5.6.2 SUBROUTINE BLEDGE (ISEG)

This subroutine constructs the boundary conditions for segment number ISEG of the boundary layer. Tables containing the boundary layer coordinates XIN0, RIN0, S0, AND X0 (see Table 5-8) are input. The begining and ending axial coordinates for the segment, XSEG(ISEG) and XSEG(ISEG+1), and the number of subdivisions to be used, NISPS(ISEG), are also input (see Section 6.8-3). Using this information, tables that are equally spaced in boundary layer length are prepared. These tables are (see Table 5-8):

X,S,RO,XI,TE,UE,PE,TW,CQ,CPE,CKE,HSE,HSW,ALFA.

The above tables are then printed under the heading "BOUNDARY CONDITIONS (IHFLAG = I1)".

5.6.3 SUBROUTINE BLH

This subroutine is used to calculate the propellant enthalpy picked up by the regenative cooling circuits. The method used is described in Section 6.8.4, Regenerative Cooling Heat Transfer. It consists of integrating the wall heat flux over the surface area covered by the regen cooling circuits and dividing the results by the engine mass flow rate. The wall heat flux is calculated by subroutine OUTPBL. The integrated heat flux is read from the BLM linkage file (unit 12) using subroutine RBL. As many as three circuits are allowed. The subroutine prints out the results of the calculations under the label "PROPELLANT ENTHALPY FROM THE COOLING CIRCUITS".

5.6.4 Block Data BLØCKD

This subprogram initializes the variables listed below:

NXT - total number of x-stations, set for 101

NTR - location of transition, set for 3

ETAE - transformed boundary-layer thickness for first station, set for 8. The boundary-layer thickness for other stations is computed internally.

VGP - variable grid parameter set for 1.14.

RUMI - reference viscosity set for 0.250 x10^{-4} lb_m/ft-sec*

TI - reference temperature for viscosity, set for 1500°R.

ØMEGA - exponent in the density-viscosity relationship set for 0.76

PR - molecular Prandtl number, Pr, set for 0.72

ITYPE - through this flag the flow type is specified as follows:
a nozzle (ITYPE=1), and external axisymmetric body (ITYPE=2), or a two-dimensional external flow in which flow starts as a stagnation point flow (ITYPE=3). Set for 1.

CQ - mass transfer parameter, set for 0. It is equal to $(\rho v)_w$ and has units of lb_m/ft^2-sec

IHFLAG - this flag indicates whether the wall temperature is input (IHFLAG=0) or wall heat flux (IHFLAG=1). Set for 1.

NTAB - in the computer program C_p, γ, k, R are specified as functions of T(=TO) and form a "fluid-property table". NTAB refers to the number of TO values in this table. It is set here as 3, maximum being 101.

---

* The assumed values of RMUI, TI, ØMEGA, PR, CPO and CKO are for air.

TO - values of temperature for the table.

CPO - specific heat at constant pressure, Set ft^2/sec^oR. for 101 * 6006.

CKO - ratio of specific heat at constant pressure to specific heat at constant volume, dimensionless. Set for 101 * 1.4.

IPRNT - the flag that controls the print output. Set for 0.

IPRNT=0 corresponds to short print and

IPRNT=1 corresponds to long print

Short print consists of the boundary-layer parameters such as δ^*, θ, H, c_f, $R_{\delta *}$, R_θ, R_s, c_H, ΔF, and ΔI_{sp}.

Long print includes short print plus the velocity and temperature profiles. These are defined in Subroutine ØUTPBL.

QF - This is the factor that converts input values of heat flux (TQW(1) entries when IHFLAG=1) from the input units of BTU/in^2sec. to the internal program units of lbm/sec^3.
QF= $3.605259*10^6$,
i.e.;
$\dot{q}_w$ (lbm/sec^3) = 144 Jg $(BTU/in^2\text{-}sec)$.

5.6.5 SUBROUTINE BLPLTS

This subroutine performs all the plotting for the BLM module. Data written by the BLM on data files is read and plots are made for requested items. Plot capabilities include displacement thickness, momentum thickness and wall temperature versus axial station. Also available are temperature and velocity profiles through the boundary layer at selected area ratios. Inputs for using the BLM plotting are described in Section 6.8.5.

5.6.6 SUBROUTINE BLSEG

The over-all logic of the boundary layer computations is controlled by this subroutine. A flow chart of the logic is presented in Figure 5-3. The nozzle is divided into segments, and subroutine BLSEG computes the growth of the boundary layer from the beginning to the end of the segment when called by subroutine BLMAIN. There are 100 grid lines in a segment, and these are counted using the FORTRAN variable NX. Each grid line is iterated until the solution converges. Iterations are counted using FORTRAN variable IT.

Subroutine BLSEG checks the convergence of the iterations by using the wall shear parameter f''_w as a convergence criterion. For laminar flows, calculations are considered converged when

$$f''_w < 10^{-4}$$

If f''_w becomes negative during the iterations, calculations are stopped. For turbulent flows a relative convergence criterion is used, as follows:

$$\frac{f''_w}{f''_w + .5\, f''_w} < .02$$

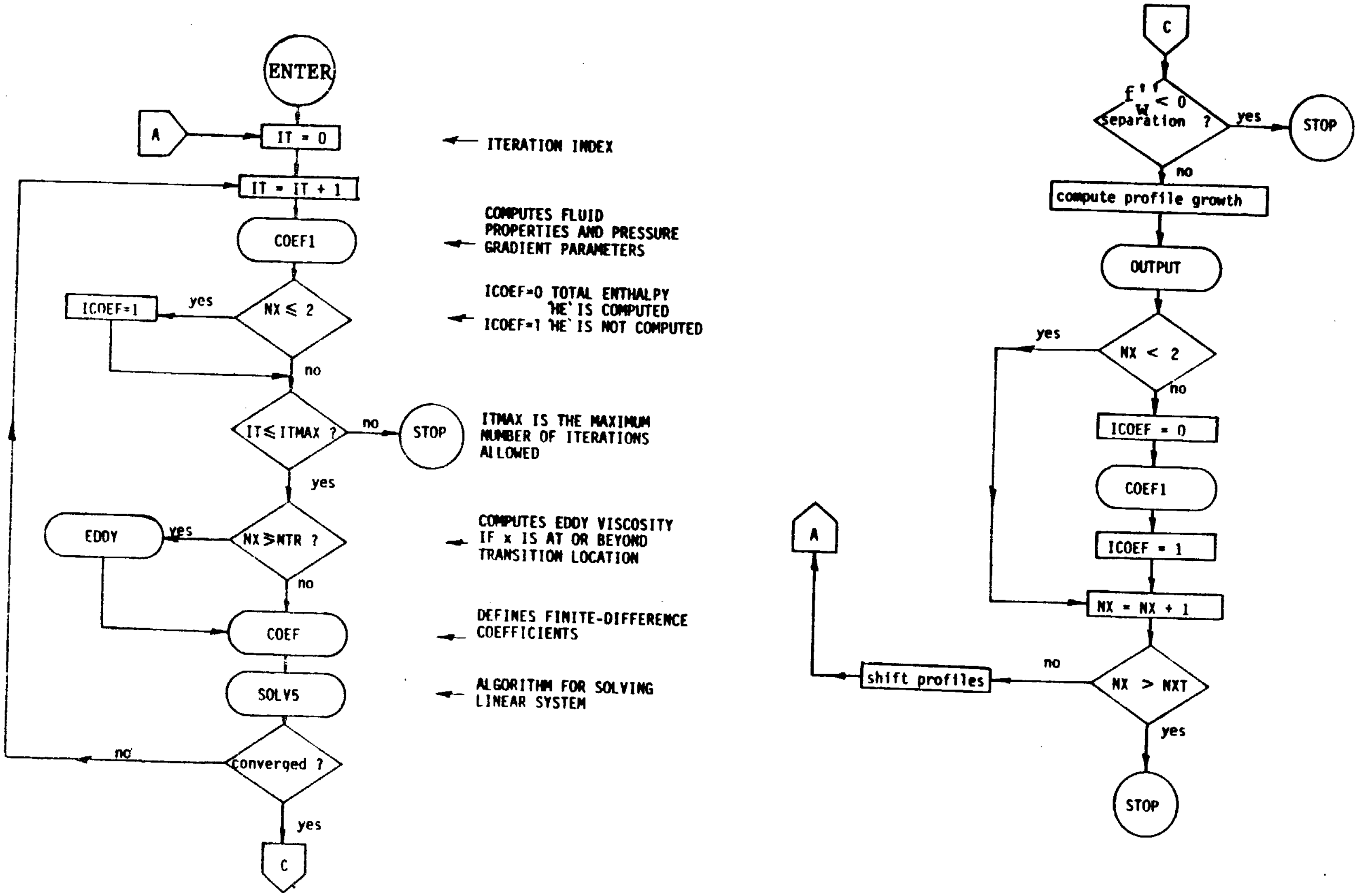

Figure 5-3: Flow Diagram for Subroutine BLSEG of BLM

5.6.7 SUBROUTINE BLTABL (INTERP, NTAB, XTAB, YTAB, XOUT, YOUT)

The purpose of this subroutine is to generate a table

y_i vs. x_i

from a given table of

$\bar{y}_j$ vs. $\bar{x}_j$

Method:

Given $\bar{y}_j$, $\bar{x}_j$ $j=1,2...NJ$

and x_i $i=1,2,..NI$

This subroutine interpolates to find

y_i $i=1,2,...NI$

One of these following interpolation methods can be selected: linear, linear log, or cubic.

Calling Sequence:

INTERP	Interpolation method; input = 1 for linear, using subroutine LINI = 2 for linear log, using subroutine LINI = 3 for cubic, using subroutine CUBICB
NTAB	NJ, number of entries input for XTAB and YTAB
XTAB	$\bar{x}_j$ input
YTAB	$\bar{y}_j$, input versus $\bar{x}_j$
NOUT	NI, number of entries input for XOUT
XOUT	x_i, input
YOUT	y_i, outupt versus x_i

5.6.8 SUBROUTINE BLW

This subroutine uses results obtained from the BLM analysis for the boundary layer displacement thickness, δ^*, to obtain a displaced wall contour. The wall is either displaced inwards (when given the real wall), or outwards (when designing the real wall), a distance δ^* normal to the original contour. The nozzle throat radius is also corrected by $-\delta^*$ or $+\delta^*$, respectively. The results of these calculations are printed.

The values of δ^* vs X that are required for the above calculations are obtained from unit 12 using subroutine RBL.

5.6.9 SUBROUTINE CØEF

This subroutine contains the coefficients of the linearized momentum and energy equations written in a form described in Chapter 8 of Reference 13.

Ref. 13. Bradshaw, P., Cebeci, T., and Whitelaw, J.H., Engineering Calculation Methods for Turbulent Flows. Academic Press, London, 1981.

5.6.10 SUBROUTINE C0EF1

This subroutine calculates the fluid properties and the pressure-gradient parameters used in the momentum and energy equations.

For most applications boundary-layer calculations are carried out based on the assumption that the external flow is isentropic and that the total enthalpy H_e is constant. This assumption is not used here. H_e is allowed to vary along the nozzle length. The following procedure is used for this purpose:

The static enthalpy, h^*, is computed from

$$h^* = \int_{T_o}^{T_e} C_p(T)dT + h^*(T_o)$$

and stored together with C_p(CPO), γ(CKO), k(RKKO), R(RRO) all expressed as functions of T(TO) thus forming a "fluid property table." This table is used to interpolate fluid properties across the layer.

The boundary-layer equations require that at two adjacent x-stations the total edge enthalpy H_e must be constant. To provide for variation in H , local similarity ideas are used.

For two adjacent x-stations, 1 and 2, an average H_e is defined as:

$$H_e = 1/2[H_e^*(1) + H_e^*(2)] \tag{1}$$

Then with an initial dimensionless total enthalpy ratio g known from the boundary-layer solutions, static enthalpy, h_j, is computed from.

$$h_j = g_j H_e - \frac{u_e^2(f_j')^2}{2} \tag{2}$$

Once h_j is known, then using the "fluid property table", values for C_{pj}, T_j, γ_j, R_j and k_j are found by interpolation, and μ_j is found from

$$\mu_j = \mu_r\left(\frac{T_j}{T_r}\right)^{\omega}$$

The edge values of density ρ_e, μ_e, $\nu_e(=\mu_e/\rho_e)$ and $R_x(u_e x/\nu_e)$ are then computed. Edge values corresponding to j = J and ρ_e are computed from

$$\rho_e = \frac{p_e}{T_J R_J}$$

Next, the coefficients c, b, e, d and the pressure gradient parameters m_1, m_2, m_3 appearing in the momentum and energy equations are computed.

Finally, wall conditions are computed depending on whether the wall temperature or heat flux are specified. When the wall temperature is given the dimensionless total enthalpy ratio at the wall, which serves as a boundary condition, is computed as:

$$g_w = \frac{h_w^*}{H_e}$$

In the case of specified heat flux q_w, the dimensionless total enthalpy gradient, g_w', is computed as

$$q_w' = - \frac{\xi}{\sqrt{R_\xi}} \left(\frac{L}{r_o}\right)^k \frac{\rho_e}{\rho_w} \frac{C_{p_w}}{k_w H_e} \dot{q}_w (\xi)$$

Here the units of each term are as follows:

$$\rho = \frac{lb_m}{ft^3} \qquad H_e = \left(\frac{ft}{sec}\right)^2$$

$$C_p = \frac{ft^2}{sec^2 R} \qquad \xi = ft$$

At the convergence of the solutions for a given x-station, this subroutine is also used to account for the nonconstant nature of the total edge enthalpy. To explain this point, let us assume that we have done all that is described in COEF1, and that we can solve the equations at the specified x-station. Since the equations are nonlinear, solutions are iterated until a convergence criterion is met and then subroutine OUTPBL is called to print the desired quantites from that station. Before we increment the value of x and shift the profiles to perform calculations at the next x-station, we call COEF1 to compute a new value of H_e from Equation (1) and recompute static enthalpy variation from Equation (2) and redefine all the fluid properties and pressure gradient parameters at that x-station for the calculations to be done at the next x-station.

5.6.11 SUBROUTINE CUBICB

Subroutine CUBICB is used for interpolation in a table with unequally spaced points. It uses a third-order polynomial to interpolate the data between four points.

5.6.12 SUBROUTINE DIFF

Subroutine DIFF is used to determine the derivative at each point in an input table.

5.6.13 SUBROUTINE EDDY

This subroutine contains the formulas used in the Cebeci-Smith eddy-viscosity model. The eddy-viscosity model is described in Section 2.6.2.

5.6.14 SUBROUTINE INPUTB

This subroutine reads input data defining the problem to be solved by the Boundary Layer Module. Data calculated by the MOC module is read by calling subroutine READBL.

Next, user input data is read from unit 5 for the $BLM Namelist data set. These input-items are described in Section 6.8 of this report.

This subroutine also calculates the surface distance from the input (r_o/c) and (x/c) values for NXIN-stations. The printed surface distance is dimensional and is expressed in feet.

The input NXIN-stations are then redistributed in order to have 101 x-stations uniformly distributed, except for the first five stations which are generated non-uniformly. The input values of $u_e(x)$, $p_e(x)$, $T_e(x)$, $(\rho v)_w$, (x/c), (y/c) are then interpolated for the new x-stations to be used in the boundary-layer calculations. In this subroutine, a total enthalpy, $H_e^*(x)$, is computed for each x-station by using the interpolated values of T , and u and the equation

$$H_e^*(x) = h_e + \frac{u_e^2}{2}$$

This subroutine prints out part of the input geometry which consists of

$$x, r_o, s, u_e, P_e$$

5.6.15 SUBROUTINE IVPL

Since the boundary-layer equations are nonlinear, before they are solved at the stagnation point, they need initial velocity and temperature profiles. This subroutine provides the necessary data to start the calculations.

5.6.16 Subroutine LINI (X, Y, N, ARG, YARG, NSAVE)

The purpose of this subroutine is to linearly interpolate from tables of values and to save its place in the table.

Calling Sequence:

X	is a table of the independent variables, x_i
Y	is a table of the dependent variables, y_i
N	is the number of entries in each table
ARG	is the argument for the X table
YARG	is the result of the interpolation
NSAVE	is a cell in which the table index is saved.

Restrictions:

If the argument exceeds the table of independent variables, the result is set equal to the appropriate table limit of the dependent variable.

5.6.17 SUBROUTINE ØUTPBL

Through the flag IPRNT discussed in Subroutine BLOCKD, this subroutine prints out the velocity and temperature profiles and the boundary-layer parameters δ^*, θ, H, c_f, $R_{\delta*}$, R_s, C_H as well as the thrust decrement ΔF due to the boundary layer.

They are defined by the following formulas:

Displacement thickness, δ^*(DELS), in ft.

$$\delta^* = \int_0^\infty \left(1 - \frac{\rho u}{\rho_e u_e}\right) dy$$

Momentum thickness θ (THETA), in ft.

$$\theta = \int_0^\infty \frac{\rho u}{\rho_e u_e} \left(1 - \frac{u}{u_e}\right) dy$$

Shape Factor, h, dimensionless

$$h = \delta^*/\theta$$

Local skin-friction coefficient, c_f(CF), dimensionless

$$c_f = \frac{\tau_w}{1/2 \rho_e u_e^2}$$

Reynolds number based on displacement thickness, $R_\delta*$

$$R_\delta* = \frac{u_e \delta^*}{\nu_e} \quad , \nu_e = \mu_e / \rho_e$$

Reynolds number based on surface distance, R_s

$$R_s = \frac{u_e s}{\nu_e}$$

Stanton number, C_H(CH), dimensionless

$$C_H = \frac{\dot{q}_w}{\rho_e u_e (H_w - H_e)}$$

Thrust decrement ΔF, in lb_f

$$\Delta F = 2\pi r_o \theta \rho_e u_e^2 \cos\phi - 2\pi r_o \delta^* \cos\phi (P_e - P_a)$$

Here X and r_o correspond to the nozzle coordinates, s to the surface distance; all expressed in feet. The units of velocity u and pressure p_e are ft/sec and lb_f/ft^2, respectively.

In addition, this subroutine prints out the interpolated values of input geometry referred to as "edge conditions". It consists of X, r_o, s, u_e and p_e.

5.6.18 SUBROUTINE RBL (X, FX, IDX)

This subroutine reads the BLM linkage file (unit 12) and locates X_i and X_{i+1} such that

$$X_i \geq X \geq X_{i+1}$$

The value FX is then found by linear interpolation

$$FX = FX_i + (X - X_i)(FX_{i+1} - FX_i)/(X_{i+1} - X_i)$$

where FX is the variable number IDX stored on the file.

5.6.19 SUBROUTINE READBL

The purpose of this subroutine is to transfer data from the ODE and MOC modules to the BLM module.

If ODE has been run, values defining viscosity, Prandtl number, and edge total enthalpy are mapped for use by the BLM. The ODE linkage data is then read from unit LUBLM for use by BLM. The data file is checked for possible errors, and if detected, one of the following warning or error messages will be printed:

"NO LINKAGE FOUND, EXPECT MANUAL INPUT"

OR

"DATA FROM xxxxx MODULE OUT OF ORDER IN MODULE BLM. CARD xxxxx HAS SEQUENCE NO. xxxxx"
****

OR

"INCORRECT CARD TYPE IN DATA FROM TDK FOUND BY READBL. EDG OR GPT EXPECTED xxxx FOUND AT SEQUENCE NO. xxxxx"
****

OR

"INCORRECT CARD TYPE IN DATA FROM TDK FOUND BY READBL. END EXPECTED, xxxx, FOUND AT SEQ. NO. xxxxx"
****

The last three errors above terminate program execution immediately after printing.

If no errors are encountered, the items read by subroutine READBL will include the nozzle mass flow rate, nozzle wall coordinates and associated edge temperature, pressure, and velocity data, and also the gas property tables.

If ODE was not run, the following message is printed:

"BLM MODULE COULD NOT FIND DATA FROM TD2P MODULE -- WILL ASSUME DATA TO BE READ IN $BLM"

****

5.6.20 SUBROUTINE S0LV5

This subroutine solves the matrix equation for which coeficients were computed by subroutine C0EF. One call to S0LV5 yields one pass through the elimination procedure. This procedure consists of a forward sweep, followed by a backward sweep of the system. The elimination scheme is specialized to treat this particular matrix equation.

5.6.21 SUBROUTINE WRPR0F

This subroutine interpolates between two wall stations and writes temperature and velocity profile data at selected area ratios onto a data file for post plotting. Area ratios are selected by input into the APROF array in the $BLM namelist, see Section 6.8.5.

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6.0 PROGRAM USER'S MANUAL.

Description of the Computer Program Input.

The TDK computer program consists of five modules, ODE, ODK, TRANS, MOC, and BLM. All of these modules are required to perform a complete two dimensional non-equilibrium nozzle performance calculation with a boundary layer. Various options exist in the program, however, which exercise the above modules alone, in part, or in combination.

Data is read by the program sequentially in the order required for the execution of the modules. This order is as follows:

Thermodynamic data,
Data common to the modules,
ODE module inputs,
ODK module inputs,
TRANS module inputs,
MOC module inputs, and
BLM module inputs.

A more detailed description of these input data sets is presented in Table 6-1. The documentation in which each of the data sets is completely described is also indicated in Table 6-1.

Of the data sets listed in Table 6-1, only the $DATA data set is required for every computer run. Input of the other data sets is required only if the options they contain are to be used. For example, input of the thermodynamic data is not required if an existing thermodynamic data file is to be used.

Table 6-1. Input Data Set Description

Card Input	Section No.,	Description
THERMO	6.1,	thermodynamic data cards, see Tables 6-2 and 6-3
.		
.		
END		
LOW T CPHS	6.1.1,	extension of thermodynamic data to temperatures below 300^{o}K, see Table 6-5
.		
.		
END LOW T CPHS		
TITLE	6.2,	one or more title cards
DATA	6.3,	data directive card
$DATA	6.3,	data namelist for module selection, and geometry
$END		
REACTANTS	6.4,	reactants directive card
.	6.4.1,	reactants cards, see Tables 2-6 and 2-7
.	6.4.1,	blank card required to end reactants cards
OMIT	6.4.2,	cards to omit species
INSERT	6.4.2,	cards to insert species
NAMELISTS	6.4.3,	ODE directive card
$ODE	6.4.3,	ODE namelist
SPECIES	6.5.1,	species cards for ODK
.		
.		
REACTIONS	6.5.2,	reaction cards for ODK
.		
.		
LAST REAX		
INERTS	6.5.2.6,	inerts cards for ODK. (to inert those species that are not named in reactions)
.		
.		

Card Input	Section No.,	Description
THIRD BODY	6.5.2.7,	reaction rate ratios for third bodies
.		
.		
LAST CARD		
$ODK	6.5.3	ODK module namelist
$END		
$TRANS	6.6	TRANS module namelist
$END		
$MOC	6.7	MOC module namelist
$END		
$BLM	6.8	BLM module namelist
$END		

Table 6-1 can be used as a guide when preparing input for given problem. It lists the data sets in the order in which they must appear in the data deck, and also shows the special cards which must appear in each set (first card, last card, etc.) if the program is to function properly. The table is basically self-explanatory when used together with the detailed input descriptions which follow.

Certain special options to the computer program are described separately in Section 6.9.

An input data card listing for a sample case is presented in Section 7, followed by the corresponding computer output. In preparing input to the computer program it is useful to review this input card listing.

Successive cases can be run using the computer program but complete data should be input for each case.

6.1 Thermodynamic Data.

Ordinarily, a thermodynamic data file is available for use with the program, and is assigned to logicial unit 25. The input described here can be used to generate a thermodynamic data file if one is not available.

This data set is identical to the THERMO DATA described in Appendix D of NASA SP-273 (i.e. Reference 3).

Using this data set, thermodynamic data curve fit coefficients may be read from cards. The curve fit coefficients are generated by the PAC computer program described in NASA TN D-4097 (i.e. Reference 20).

The thermodynamic data (i.e. $C^o_{p_T}$, etc.) are expressed as functions of temperature using 5 least squares curve fit coefficient (a_{1-5}) and two integration constants (a_{6-7}) as follows:

$$\frac{C^o_{p_T}}{R} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4$$

$$\frac{H^o_T}{RT} = a_1 + \frac{a_2T}{2} + \frac{a_3T^2}{3} + \frac{a_4T^3}{4} + \frac{a_5T^4}{5} + \frac{a_6}{T}$$

$$\frac{S^o_T}{R} = a_1 \ln T + a_2T + \frac{a_3T^2}{2} + \frac{a_4T^3}{3} + \frac{a_5T^4}{4} + a_7$$

For each species, two sets of coefficients $(a_{1-7}$ and $a'_{1-7})$ are specified for two adjacent temperature intervals, lower and upper respectively. For the data available in Reference 3 the lower temperature interval is 300° to 1000°K and the upper temperature interval is 1000°K to 5000°K.

Ref. 20. McBride, B.J., and Gordon, S., "Fortran IV Program for Calculation of Thermodynamic Data", NASA TN-D-4097, Aug. 1967.

The input format required for this thermodynamic data is defined in Table 6-2. Data cards for the species AR, H, H_2, H_2O, N_2, O, OH, and O_2 are listed in Table 6-3 as examples. Thermodynamic data coefficients for many chemical species are supplied with the computer program. A list of these species is presented in Table 6-4. (For temperature range below 300° K see Section 6.1.1)

Data Tape Generation and Usage:

A computer run using thermodynamic data card input will generate a data tape on logical unit JANAF. This tape may then be saved and used at a later time. The program writes the THERMO data card images on unit JANAF as read but with two minor exceptions. The THERMO code card and the card numbers in card column 80 are omitted.

If thermodynamic data cards are not input, the program assumes the thermodynamic data is on logical unit JANAF. Logical unit JANAF is currently assigned a value of 25.

TABLE 6-2 FORMAT FOR THERMODYNAMIC DATA CARDS

Card order	Contents	Format	Card column
1	THERMO	3A4	1 to 6
2	Temperature ranges for 2 sets of coefficients: lowest T, common T, and highest T	3F10.3	1 to 30
3	Species name	3A4	1 to 12
	Date	2A3	19 to 24
	Atomic symbols and formula	4(A2,F3.0)	25 to 44
	Phase of species (S,L, or G for solid, liquid, or gas, respectively	A1	45
	Temperature range	2F10.3	46 to 65
	Integer 1	I15	80
4	Coefficients a_i' (i = 1 to 5) in equations (6-1) to (6-3) (for upper temperature interval)	5(E15.8)	1 to 75
	Integer 2	I5	80
5	Coefficients in equations (6-1) to 6-3) (a_6', a_7' for upper temperature interval and a_1, a_2, and a_3 for lower)	5(E15.8)	1 to 75
	Integer 3	I5	80
6	Coefficients in equations (6-1) to (6-3) (a_4,a_5,a_6,a_7 for lower temperature interval)	4(E15.8)	1 to 60
	Integer 4	I20	80
(a)	Repeat cards numbered 1 to 4 in cc 80 for each species		
(Final card)	END (Indicates end of thermodynamic data)	3A4	1 to 3

[a] Gaseous species and condensed species with only one condensed phase can be in any order. However, the sets for two or more condensed phases of the same species must be adjacent. If there are more than two condensed phases of a species their sets must be either in increasing or decreasing order according to their temperature intervals.

TABLE 6-3. THERMO DATA CARDS FOR AN O_2/H_2 PROPELLANT (SPECIES AR, H, H_2, H_2O, N_2, O, OH, AND O_2)

```
THERMO
   300.000  1000.000  5000.000
AR                  L 5/66AR 1.00 0.00 0.00 0.G   300.000  5000.000
  .25000000E 01 0.              0.              0.              0.
 -.74537502E 03  .43660006E 01  .25000000E 01 0.              0.
 0.             0.              -.74537498E 03  .43660006E 01
H                   J 6/74H  1.   0.   0.   0.G   300.000  5000.000
  .24999996E+01  .70881143E-09 -.38728927E-12  .85096613E-16 -.65768080E-20
  .25474390E+05 -.45989618E+00  .25000002E+01 -.19925608E-08  .54929899E-11
 -.64292197E-14  .26794037E-17  .25474390E+05 -.45989941E+00
H2                  J 3/61H  2.0  0.0  0.0  0.G   300.000  5000.000
  .31001901E+01  .51119464E-03  .52644210E-07 -.34909973E-10  .36945345E-14
 -.87738042E+03 -.19629421E+01  .30574451E+01  .26765200E-02 -.58099162E-05
  .55210391E-08 -.18122739E-11 -.98890474E+03 -.22997056E+01
H2O                 J 3/61H  2.0  1.00 0.00 0.G   300.000  5000.000
  .27167633E+01  .29451374E-02 -.80224374E-06  .10226682E-09 -.48472145E-14
 -.29905826E+05  .66305671E+01  .40701275E+01 -.11084499E-02  .41521180E-05
 -.29637404E-08  .80702103E-12 -.30279722E+05 -.32270046E+00
N2                  J 9/65N  2.0  0.0  0.0  0.G   300.000  5000.000
  .28963194E+01  .15154866E-02 -.57235277E-06  .99807393E-10 -.65223555E-14
 -.90586184E+03  .61615148E+01  .36748261E+01 -.12081500E-02  .23240102E-05
 -.63217559E-09 -.22577253E-12 -.10611588E+04  .23580424E+01
O                   J 6/74O  1.   0.   0.   0.G   300.000  5000.000
  .25352638E+01 -.14371898E-04 -.11360139E-07  .66005131E-11 -.61181626E-15
  .29230265E+05  .49575621E+01  .29558662E+01 -.17061536E-02  .25925154E-05
 -.17837980E-08  .45709012E-12  .29143654E+05  .29243614E+01
OH                  J12/70O  1.H  1.0  0.0  0.G   300.000  5000.000
  .29131230E+01  .95418248E-03 -.19084325E-06  .12730795E-10  .24803941E-15
  .39647060E+04  .54288735E+01  .38365518E+01 -.10702014E-02  .94849757E-06
  .20843575E-09 -.23384265E-12  .36715807E+04  .49805456E+00
O2                  J 9/65O  2.0  0.0  0.0  0.G   300.000  5000.000
  .36219535E+01  .73618264E-03 -.19652228E-06  .36201558E-10 -.28945627E-14
 -.12019825E+04  .36150960E+01  .36255985E+01 -.18782184E-02  .70554544E-05
 -.67635137E-08  .21555993E-11 -.10475226E+04  .43052778E+01
END
```

Table 6-4. SPECIES WITH THERMODYNAMIC DATA PROVIDED.

E
AL
AL+
AL-
ALBO2
ALBR
ALBR3
ALC
ALCL
ALCL+
ALCLF
ALCLF+
ALCLF2
ALCL2
ALCL2+
ALCL2-
ALCL2F
ALCL3
ALF
ALF+
ALF2
ALF2+
ALF2-
ALF2O
ALF2O-
ALF3
ALF4-
ALH
ALI
ALI3
ALN
ALO
ALO+
ALO-
ALOCL
ALOF
ALOH
ALOH+
ALOH-
ALO2
ALO2-
ALO2H
ALS
AL2
AL2BR6
AL2CL6
AL2F6
AL2I6
AL2O
AL2O+
AL2O2
AL2O2+
AR
AR+
B
B+
B-
BCL
BCL+
BCLF
BCL2
BCL2+
BCL2-
BCL3
BF
BF2
BF2+
BF2-
BF3
BH
BHF2
BH2
BH3
BN
BO
BOCL
BOF
BOF2
BO2
BO2-
BS
B2
B2O
B2O2
B2O3
B3O3CL3
B3O3F3
B3O3H3
BA
BABR
BABR2
BACL
BACL2
BAF
BAF+
BAF2
BAOH
BAOH+
BAO2H2
BAS
BE
BE+
BEBO2
BEBR
BEBR2
BECL
BECL+
BECLF
BECL2
BEF
BEF2
BEH
BEH+
BEI
BEI2
BEN
BEO
BEOH
BEOH+
BEO2H2
BES
BE2O
BE2OF2
BE2O2
BE3O3
BE4O4
BI
BIS
BR
BR2
C
C+
C-
CCL
CCL2
CCL2F2
CCL3
CCL3F
CCL4
CF
CF+
CF2
CF2+
CF3
CF3+
CF4
CH
CH+
CH2
CH2O
CH2O2
CH3
CH3CL
CH2OH
CH3O
CH4
CH3OH
CN
CN+
CN-
CN2
CNN
CO
COCL
COCLF
COCL2
COF
COF2
COS
CO2
CO2-
CP
CS
CS2
C2
C2-
C2CL2
C2F2
C2F4
C2H
C2HF
C2H2
C2H4
C2H4O2
C2H4O4
C2H5
C2H6
CH3N2CH3
C2H5OH
CH3OCH3
C2N
C2N2
C2O
C3
C3H6O
N-C3H7
I-C3H7
C3H8
1-C3H7OH
C3O2
C4
C4H8O4
N-C4H10
I-C4H10
C4N2
C5
C6H5
C6H6
CA
CA+
CABR
CABR2
CACL
CACL2
CAF
CAF2
CAI
CAI2
CAO
CAOH
CAOH+
CAO2H2
CAS
CA2
CL
CL+
CL-
CLCN
CLF
CLF3
CLO
CLO2
CL2
CL2O
CR
CRN
CRO
CRO2
CRO3
CS
CS+
CSCL
CSF
CSO
CSOH
CSOH+
CS2
CS2CL2
CS2F2
CS2O

Table 6-4. (cont.)

CS2O2H2
CS2SO4
CU
CU+
CUCL
CUF
CUF2
CUO
CU2
CU3CL3
D
D+
D-
DCL
DF
DOCL
D2
D2+
D2-
D2O
D2S
F
F-
FCN
FO
FO2
F2
F2O
FS2F
FE
FE+
FE-
FEC5O5
FECL
FECL2
FECL3
FEO
FEO2H2
FES
FE2CL4
FE2CL6
H
H+
H-
HALO
HBO
HBO+
HBO-
HBO2
HBS

HBS+
HBR
HCN
HCO
HCO+
HCP
HCL
HD
HD+
HD-
HDO
HF
HI
HNCO
HNO
HNO2
HNO3
HOCL
HOF
HO2
HSO3F
H2
H2+
H2-
H2F2
H2N2
H2O
H2O2
H2S
H2SO4
H3B3O6
H3F3
H4F4
H5F5
H6F6
H7F7
HE
HE+
HG
HGBR2
I
I2
K
K+
KBO2
KCN
KCL
KF
KF2-
KH

KO
KO-
KOH
KOH+
K2
K2C2N2
K2CL2
K2F2
K2O2H2
K2SO4
KR
LI
LI+
LIALF4
LIBO2
LICL
LIF
LIFO
LIF2-
LIH
LIN
LIO
LIO-
LIOH
LIOH+
LION
LI2
LI2CL2
LI2F2
LI2O
LI2O2
LI2O2H2
LI2SO4
LI3CL3
LI3F3
MG
MG+
MGBR
MGBR2
MGCL
MGCL+
MGCLF
MGCL2
MGF
MGF+
MGF2
MGF2+
MGH
MGI
MGI2

MGN
MGO
MGOH
MGOH+
MGO2H2
MGS
MG2
MG2F4
N
N+
N-
NCO
ND
ND2
ND3
NF
NF2
NF3
NH
NH2
NH3
NO
NO+
NOCL
NOF
NOF3
NO2
NO2-
NO2CL
NO2F
NO3
N2
N2+
N2-
N2D2
N2H4
N2O
N2O+
N2O4
N2O5
N3
NA
NA+
NAALF4
NABO2
NABR
NACN
NACL
NAF
NAF2-

NAH
NAI
NAO
NAO-
NAOH
NAOH+
NA2
NA2C2N2
NA2CL2
NA2F2
NA2O
NA2O2H2
NA2SO4
NB
NBO
NBO2
NE
NE+
NI
NICL
NICL2
NIO
NIS
O
O+
O-
OD
OH
OH+
OH-
O2
O2+
O2-
O3
P
P+
PCL3
PF
PF+
PF-
PF2
PF2+
PF2-
PF3
PF5
PH
PH3
PN
PO
PO2

Table 6-4. (cont.)

PS
P2
P4
P406
P4010
PB
PBBR
PBBR2
PBBR4
PBCL
PBCL+
PBCL2
PBCL2+
PBCL4
PBF
PBF2
PBF4
PBI
PBI2
PBI4
PBO
PBS
PB2
S
S+
S-
SCL
SCL2
SCL2+
SD
SF
SF+
SF-
SF2
SF2+
SF2-
SF3
SF3+
SF3-
SF4
SF4+
SF4-
SF5
SF5+
SF5-
SF6
SF6-
SH
SN
SO

SOF2
SO2
SO2CLF
SO2CL2
SO2F2
SO3
S2
S2CL
S2CL2
S2F2
S2O
S8
SI
SI+
SIBR
SIBR2
SIBR3
SIBR4
SIC
SIC2
SIC4H12
SICL
SICL2
SICL3
SICL4
SIF
SIF2
SIF3
SIF4
SIH
SIH+
SIHBR3
SIHCL3
SIHF3
SIHI3
SIH2BR2
SIH2CL2
SIH2F2
SIH2I2
SIH3BR
SIH3CL
SIH3F
SIH3I
SIH4
SII
SII2
SIN
SIO
SIO2
SIS

SI2
SI2C
SI2N
SI3
SR
SRBR
SRCL
SRCL2
SRF
SRF+
SRF2
SRI2
SRO
SROH
SROH+
SRO2H2
SRS
TA
TAO
TAO2
TI
TI+
TI-
TICL
TICL2
TICL3
TICL4
TIO
TIOCL
TIOCL2
TIO2
V
VCL4
VN
VO
VO2
XE
XE+
ZN
ZN+
ZN-
ZR
ZRN
ZRO
ZRO2
AL(S)
AL(L)
ALBR3(S)
ALBR3(L)
ALCL3(S)

ALCL3(L)
ALF3(A)
ALF3(B)
ALF3(L)
ALI3(S)
ALI3(L)
ALN(S)
AL2O3(A)
AL2O3(L)
AL2SIO5(AN)
AL6SI2O13(S)
B(S)
B(L)
BN(S)
B2O3(L)
B3O3H3(C)
BA(A)
BA(B)
BA(C)
BA(L)
BABR2(S)
BABR2(L)
BACL2(A)
BACL2(B)
BACL2(L)
BAF2(AB)
BAF2(C)
BAF2(L)
BAO(S)
BAO(L)
BAO2H2(S)
BAO2H2(L)
BAS(S)
BE(S)
BE(L)
BEAL2O4(S)
BEAL2O4(L)
BEBR2(S)
BECL2(S)
BECL2(L)
BEF2(LQZ)
BEF2(HQZ)
BEF2(L)
BEI2(S)
BEI2(L)
BEO(A)
BEO(L)
BEO2H2(B)
BES(S)
BI(S)

BI(L)
BI2S3(S)
BR2(L)
C(GR)
CA(A)
CA(B)
CA(L)
CABR2(S)
CABR2(L)
CACO3(CAL)
CACL2(S)
CACL2(L)
CAF2(A)
CAF2(B)
CAF2(L)
CAO(S)
CAO(L)
CAO2H2(S)
CAS(S)
CASO4(S)
CR(S)
CR(L)
CRN(S)
CR2N(S)
CR2O3(S)
CR2O3(L)
CS(S)
CS(L)
CSCL(A)
CSCL(B)
CSCL(L)
CSF(S)
CSF(L)
CSOH(A)
CSOH(C)
CSOH(L)
CS2SO4(II)
CS2SO4(I)
CS2SO4(L)
CU(S)
CU(L)
CUF(S)
CUF2(S)
CUF2(L)
CUO(S)
CUO2H2(S)
CUSO4(S)
CU2O(S)
CU2O(L)
CU2O5S(S)

Table 6-4. (cont.)

FE(A)
FE(C)
FE(D)
FE(L)
FEC5O5(L)
FECL2(S)
FECL2(L)
FECL3(S)
FECL3(L)
FEO(S)
FEO(L)
FEO2H2(S)
FEO3H3(S)
FES(A)
FES(B)
FES(C)
FES(L)
FESO4(S)
FES2(S)
FE2O3(S)
FE2S3O12(S
FE3O4(S)
H2O(S)
H2O(L)
H2SO4(L)
HG(L)
HGBR2(S)
HGBR2(L)
HGO(S)
I2(S)
I2(L)
K(S)
K(L)
KCN(S)
KCN(L)
KCL(S)
KCL(L)
KF(S)
KF(L)
KHF2(A)
KHF2(B)
KHF2(L)
KOH(A)
KOH(B)
KOH(L)
KO2(S)
K2CO3(S)
K2CO3(L)
K2O(S)
K2O2(S)

K2S(1)
K2S(2)
K2S(3)
K2S(L)
K2SO4(A)
K2SO4(B)
K2SO4(L)
LI(S)
LI(L)
LIALO2(S)
LIALO2(L)
LICL(S)
LICL(L)
LIF(S)
LIF(L)
LIH(S)
LIH(L)
LIOH(S)
LIOH(L)
LI2O(S)
LI2O(L)
LI2SO4(A)
LI2SO4(B)
LI2SO4(L)
LI3N(S)
MG(S)
MG(L)
MGAL2O4(S)
MGAL2O4(L)
MGBR2(S)
MGBR2(L)
MGCO3(S)
MGCL2(S)
MGCL2(L)
MGF2(S)
MGF2(L)
MGI2(S)
MGI2(L)
MGO(S)
MGO(L)
MGO2H2(S)
MGS(S)
MGSO4(S)
MGSO4(L)
MGSIO3(CL)
MGSIO3(RE)
MGSIO3(PR)
MGSIO3(L)
MGTIO3(S)
MGTIO3(L)

MGTI2O5(S)
MGTI2O5(L)
MG2SIO4(S)
MG2SIO4(L)
MG2TIO4(S)
MG2TIO4(L)
VN(S)
NA(S)
NA(L)
NAALO2(A)
NAALO2(B)
NABR(S)
NABR(L)
NACN(S)
NACN(L)
NACL(S)
NACL(L)
NAF(S)
NAF(L)
NAI(S)
NAI(L)
NAOH(A)
NAOH(L)
NAO2(S)
NA2CO3(1)
NA2CO3(2)
NA2CO3(L)
NA2O(C)
NA2O(A)
NA2O(L)
NA2O2(A)
NA2O2(B)
NA2S(1)
NA2S(2)
NA2S(L)
NA2SO4(IV)
NA2SO4(I)
NA2SO4(L)
NA3ALF6(A)
NA3ALF6(B)
NA3ALF6(L)
NA5AL3F14(S)
NA5AL3F14(L)
NB(S)
NB(L)
NBO(S)
NBO(L)
NBO2(S)
NBO2(L)
NB2O5(S)

NB2O5(L)
NI(A)
NI(B)
NI(L)
NIS(B)
NIS(A)
NIS(L)
NIS2(S)
NIS2(L)
NI3S2(1)
NI3S2(2)
NI3S2(L)
NI3S4(S)
P(V)
P4O10(S)
PB(S)
PB(L)
PBBR2(S)
PBBR2(L)
PBCL2(S)
PBCL2(L)
PBF2(A)
PBF2(B)
PBF2(L)
PBI2(S)
PBI2(L)
PBO(RD)
PBO(YW)
PBO(L)
PBO2(S)
PBS(S)
PBS(L)
PB3O4(S)
S(S)
S(L)
SCL2(L)
S2CL2(L)
SI(S)
SI(L)
SIC(B)
SIO2(LQZ)
SIO2(HQZ)
SIO2(HCR)
SIO2(L)
SI2N2O(S)
SI3N4(A)
SR(S)
SR(L)
SRCL2(1)
SRCL2(2)

SRCL2(L)
SRF2(S)
SRF2(L)
SRO(S)
SRO(L)
SRO2H2(S)
SRO2H2(L)
SRS(S)
TA(S)
TA(L)
TAC(S)
TAC(L)
TA2O5(S)
TA2O5(L)
TI(A)
TI(B)
TI(L)
TIC(S)
TIC(L)
TICL2(S)
TICL3(S)
TICL4(L)
TIN(S)
TIN(L)
TIO(A)
TIO(B)
TIO(L)
TIO2(RU)
TIO2(L)
TI2O3(1)
TI2O3(2)
TI2O3(L)
TI3O5(A)
TI3O5(B)
TI3O5(L)
TI4O7(S)
TI4O7(L)
V(S)
V(L)
VCL2(S)
VCL3(S)
VCL4(L)
VO(S)
VO(L)
V2O3(S)
V2O3(L)
V2O4(1)
V2O4(2)
V2O4(L)
V2O5(S)

Table 6-4. (cont.)

V2O5(L)
ZN(S)
ZN(L)
ZNSO4(A)
ZNSO4(AP)
ZNSO4(B)
ZR(A)
ZR(B)
ZR(L)
ZRN(S)
ZRN(L)
ZRO2(A)
ZRO2(B)
ZRO2(L)

6.1.1 THERMODYNAMIC DATA BELOW 300°K.

If the temperature at any point computed by ODE, ODK, or TDK is found to be below the Thermodynamic Data lower temperature limit, T_ℓ, the polynomial curve fit data (see Section 6.1) will be extrapolated to obtain values for the thermodynamic data. The extrapolated data can be inaccurate. The LØW T CPHS data set can be used to input low temperature data for those species for which extrapolation of the JANNAF data is not accurate. Only Cp vs. T is input. Enthalpy and entropy are obtained by integrating Cp vs. T within the computer program.

The lower temperature limit, T_ℓ, in the Thermodynamic Data supplied with the program is 300°K. Thermodynamic Data below the temperature, T_ℓ, may be input by data cards as described under "Input Specifications for Low Temperature Thermodynamic Data".

An example of this input is given in Table 6-5 which shows a card listing extending the Thermodynamic Data for the 18 chemical species given in Appendix A. Data in Table 6-5 is taken directly from the JANAF tables. The source references for these data are as follows:

Ref. 21: CO, CO_2, CL_2, F, HCL, H_2O, and NO.

Ref. 22: CL.

Ref. 23: CLF, F_2, F, HF, H_2, N, N_2, O, OH, and O_2.

Ref. 21: Stull, D.R., Prophet, H., et al., JANAF Thermochemical Tables, Second Edition, NSRDS-NBS 37, National Standard Reference Data Series, National Bureau of Standards, June 1971.

Ref. 22: JANAF Thermochemical Tables, 1974 Supplement, J. Phys. Chem. Ref. Data 3,311 (1974).

Ref. 23: JANAF Thermochemical Tables, 1982 Supplement, J. Phys. Chem. Ref. Data 11,695 (1982).

The Input Specifications for Low Temperature Thermodynamic Data.

The first card is a directive card that identifies the start of the low temperature thermodynamic data input. It reads as follows, columns 1 through 10:

```
LOW T CPHS
```

The next card contains a species name consisting of 12 characters, or less, left justified to column 1. An integer is placed in column 21 indicating the number of T, Cp values that follow. A value of 1,2, or 3 can be used. For example:

```
H20                 2
```

Next, the thermodynamic data for the species named above is input. There must be one pair of T, Cp values per card. These cards are numbered consequently in column 45. They are read as 2F10.0,20X,I5. For example, for H_2O:

```
100.                 7.961                           1
200.                 7.969                           2
```

Species name cards and thermodynamic data cards for other species, if any, follow.

A final directive card is used to identify the end of the low temperature thermodynamic data. It reads as follows, columns 1 through 14:

```
END LOW T CPHS
```

Table 6-5. Low Temperature Thermodynamic Data Input

```
col. 1         11        21                      45

     LOW T CPHS
     CO                  2
     100.      6.956                             1
     200.      6.957                             2
     CO2                 2
     100.      6.981                             1
     200.      7.734                             2
     CL                  2
     100.      4.968                             1
     200.      5.038                             2
     CLF                 2
     100.      6.961                             1
     200.      7.200                             2
     CL2                 2
     100.      7.001                             1
     200.      7.576                             2
     F                   2
     100.      5.068                             1
     200.      5.403                             2
     F2                  2
     100.      6.958                             1
     200.      7.095                             2
     H                   2
     100.      4.968                             1
     200.      4.968                             2
     HCL                 2
     100.      6.959                             1
     200.      6.961                             2
     HF                  2
     100.      6.962                             1
     200.      6.962                             2
     H2                  2
     100.      6.729                             1
     200.      6.560                             2
     H2O                 2
     100.      7.961                             1
     200.      7.969                             2
     N                   2
     100.      4.968                             1
     200.      4.968                             2
     NO                  2
     100.      7.721                             1
     200.      7.721                             2
     N2                  2
     100.      6.956                             1
     200.      6.957                             2
     O                   2
     100.      5.665                             1
     200.      5.433                             2
     OH                  2
     100.      7.798                             1
     200.      7.356                             2
     O2                  2
     100.      6.956                             1
     200.      6.961                             2
     END LOW T CPHS
```

6.2 Title Cards

This input permits labeling of runs with alphanumeric information. As many title cards as desired may be input in sequence. Card format is as follows:

col 1-5	col 6-77
TITLE	any alphanumeric information

The last card that is input will be used as a printed title for the output summary table, and a title for the linkage file to BLIMP (see Section 6.4.3.2, IPTAB).

It is not necessary to input title cards.

6.3 DATA Directive and $DATA Namelist Input.

The DATA directive and the $DATA Namelist input set described below must always be input. It is required for all problems since it contains the input that controls which calculation modules are to be executed.

The first input item must be a single card, called the DATA directive card. The format of this card is as follows: the letters DATA must be punched in columns 1 through 4. The DATA card is used to inform the program that the $DATA namelist input is to follow.

The card following the DATA card must contain the name $DATA, and all cards in the namelist input set must start in column 2 or greater. Since Namelist input is card interpretive, items can be input in any order. The last card in the set must contain $END.

Users unfamiliar with Namelist input are referred to their FORTRAN reference manual.

Item	Description	Units	Assumed Value(s)
DATA	DATA directive card		-
$DATA	Namelist name, read in Subroutine PRØBLM		-

6.3.1 Specification of Modules to be Executed.

If a module is to be executed, it is necessary to indicate the fact by input of a module flag as described below. For example, if a problem requires that the ØDE module be run, it is necessary to input ØDE = 1. Only certain combinations of modules are allowed. These are described in Table 6-6. The module flags are:

Item		Description	Units	Assumed Value(s)
ØDE	=	Set ØDE = 1 if the ODE module is to be executed.	none	0.
ØDK	=	Set ØDK = 1 if the ODK module is to be executed.	none	0.
TDE	=	Set TDE = 1 if the TDE option of the MØC module is to be executed	none	0.
TDK	=	Set TDK = 1 if the TDK option of the MØC module is to be executed	none	0.
TDF	=	Set TDF = 1 if the TDF option of the MØC is to be executed	none	0.
TTDK	=	Set TTDK=1 to run the TDK option with tables supplied by ODK replacing the TDK kinetic calculations. See Section 2.5.3.	none	0.
BLM	=	Set BLM = 1 if the BLM option of the MØC module is to be executed	none	0.
PFGØPT	=	Set PFGØPT = 1 if the constant properties option of the MOC module is to be executed. See Section 6.9.1 for input instructions.	none	0.

Table 6-6: Usage of the Module Flags

Input	Mode of Execution
ODE=1,	ODE is run alone. Options other than the rocket (RKT=T) option are allowed. See Section 6.4.3 and Reference 3.
ODE=1, ODK=1,	ODE is run. ODK is run with ODE providing start conditions. See Section 6.5.1.
ODK=1,	ODK is run alone with initial conditions supplied by the user. See Sections 6.5.1 and 6.5.1.1, and 6.5.3.6.
ODE=1, ODK=1, TDK=1,	ODE is run. ODK is run with ODE providing start conditions. TDK is run with ODK and TRANS providing MOC initial data line conditions. The number of ODE and ODK runs will be equal to NZONES.
ODE=1, ODK=1, TDK=1, BLM=1,	As above with a BLM run added.
ODE=1, ODK=1, TDK=1, BLM=1, IRPEAT=1,	As above with ODE, ODK, and TDK repeated using the BLM results. See Section 6.8.4. This option is for including the BLM results with regen cooling.
ODE=1, ODK=1, TDK=1, BLM=1, IRPEAT=2,	As above except that the ODE and ODK runs are not repeated because there is no heat input correction due to regen cooling.
ODE=1, ODK=1, TTDK=1, BLM=1 IRPEAT=1 or 2	As above except that TDK will use tables computed by ODK and not compute its own reacting chemistry.
TDE=1,	ODE will be run for NZONES. TDE is run with ODE chemical equilibrium gas properties, and with TRANS providing MOC initial data line conditions.
TDE=1, BLM=1,	As above with BLM.
TDE=1, BLM=1, IRPEAT=1 or 2,	As above with TDE repeated.

Table 6-6: Usage of the Module Flags (continued)

Input	Mode of Execution
ØDE=1, ØDK=1, TDF=1,	ØDE is run. ØDK is run with ØDE providing start conditions. However, the ØDK run will have a frozen chemical composition. TDK will also be run with a frozen composition.
ØDE=1, ØDK=1, TDF=1, BLM=1,	As above with BLM.
ØDE=1, ØDK=1, TDF=1, BLM=1, IRPEAT=1 or 2,	As above with TDF repeated.
BLM=1,	BLM is run alone. This option requires a large amount of input that is provided automatically when BLM is run after TDE, TDK or TDF.
PFGØPT=1,	The TRANS and MØC modules are run with constant gas properties. See Section 6.9.1.

6.3.2 Inputs for Control for the Program.

Item		Description	Units	Assumed Value(s)
IRPEAT	=	Set IRPEAT = 1 or 2 to request that a TDK (or TDE) calculation be automatically repeated after the BLM module has been used to calculate a displaced nozzle wall. If IRPEAT = 1, the ODE and ODK module executions will be repeated with adjusted enthalpies for regen cooling, see Section 6.8.4. If IRPEAT = 2, the ØDE and ØDK module executions will not be repeated. The system enthalpy will be unchanged.	none	0
IRSTRT	=	The program allows for a limited restart capability. If the MOC module has been run successfully and units 11,15,(23 if TDE), and 29 have been saved, then the run can be continued by inputing IRSTRT = 2, This will restart the program after the MOC calculation and before the BLM calculation. The restart handles all options involving BLM.	none	

Item		Description	Units	Assumed Value(s)
NZ0NES	=	Number of zones N, to be used in the analysis. The 0DE and 0DK modules will be executed N times. Zone 1 represents the flow adjacent to the nozzle axis, and Zone N represents flow adjacent to the nozzle wall.	none	1
SI	=	If SI=0, English units are to be used for input and output. If SI=1, SI units are to be used for input and output. The SI units required for input are shown in parenthesis.	none	0
I0FF	=	When BLM is run with the MOC module, values defining the boundary layer edge conditions; x_e, y_e, U_e, T_e, and P_e are automatically calculated and stored in the XIN0, RIN0, UE0, TE0, and PE0 arrays. If I0FF is not input, then these values are stored starting with the first entry in each array. If I0FF is input then these values are stored starting in the I0FF + 1 entry of each array. Values must then be input into entries 1 through I0FF. The boundary layer calculations will start at position XIN0(1) of these arrays using the $BLM input. This input allows the user to account for the development of the boundary layer in the nozzle chamber, upstream of ECRAT. I0FF < 100. If I0FF is input, do not input NXIN0 $BLM.		0
BLMF	=	This flag controls the choice of gas properties and edge properties to be used by the BLM. (See Section 2.6.3, etc.) If TDK has been run, then for BLMF=F, equilibrium (0DE) properties will be used. If TDK has been run, then for BLMF=T, frozen (0DF) properties will be used. For TDE, equilibrium properties will always be used. For TDF, frozen properties will always be used.	none	F

6.3.3 Specification of nozzle geometry.

To eliminate redundancy, all geometry inputs that are common throughout the modules are input here. Note that the center of the nozzle geometry coordinate system is at the centerline at the throat plane, and that all coordinates are normalized by the nozzle throat radius, r_t. Hence, axial positions upstream of the throat are always negative numbers. In the figures describing the geometry, positive angles are shown as counter-clockwise, and negative angles are shown as clockwise.

Geometric area ratios at which ODE and ODK print out is to be made are specified using the input arrays ASUB(1) and ASUP(1).

The nozzle geometry is defined in Figure 6-1. The ODK calculations start at the downstream end of the combustion chamber with a subsonic area ratio of ECRAT, as shown. The circular arcs RI and RWTU cannot overlap. Thus, it is necessary that ECRAT, RI, RWTU, and THETAI be input such that

$$\sqrt{\mathrm{ECRAT}} > 1 + (\mathrm{RI} + \mathrm{RWTU})\,(1 - \cos \mathrm{THETAI}).$$

If this condition is not met, subroutine PRES of ODK will print the terminal error message:

INLET GEOMETRY INCOMPATIBLE WITH INITIAL CONDITIONS.

In addition, the transonic analysis requires that a value of RWTU $\geq$ .5 be input.

The wall geometry downstream of the nozzle throat can be specified using any one of several options. All of these geometries begin with a circular arc of radius RWTD which extends from the throat point through an angle of THETA. Geometries that can be input to both the ODK and MOC modules are described in Section 6.3.3.1.

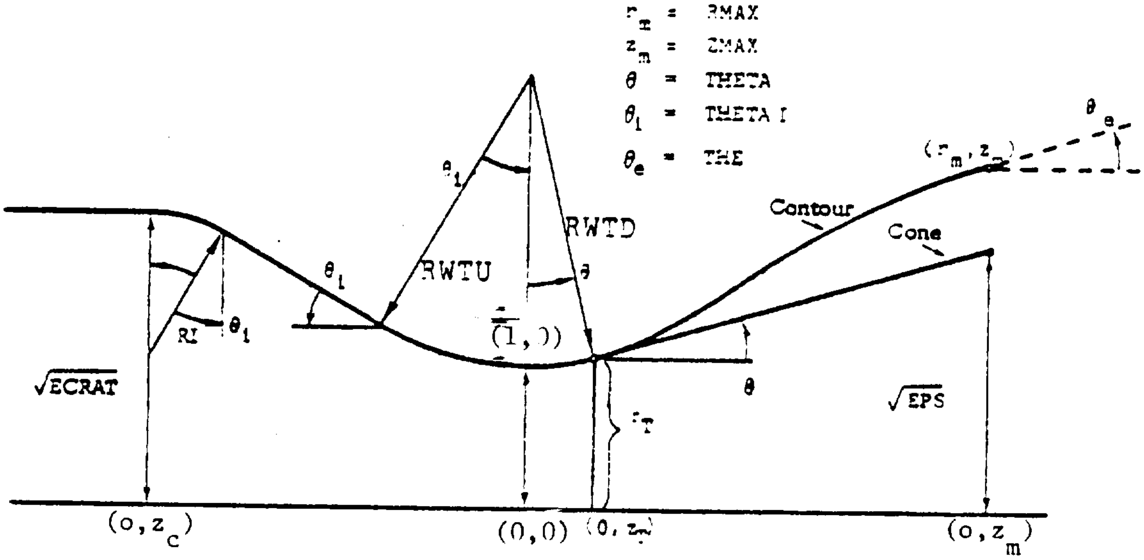


Figure 6-1: Nozzle Geometry, all coordinate values are normalized by RSI = r_t.

Item		Description	Units	Assumed Value(s)
RSI	=	Nozzle throat radius, r_t	in, (meters)	0.
ASUB(1)	=	Subsonic area ratios at which information will be printed.	none	0.
NASUB	=	Number of entries in the ASUB array ≤ 50. Entries must be monotonic decreasing in value.	none	0.
ASUP(1)	=	Supersonic area ratios at which information will be printed. Entries must be monotonic increasing in value.	none	0.
NASUP	=	Number of entries in the ASUP array ≤ 50.	none	0.
ECRAT	=	Nozzle inlet contraction ratio for use in ODE and ODK calculations.	none	0.
RI	=	Normalized inlet wall radius.	none*	0.
THETAI	=	Nozzle inlet angle.	degrees	0.
RWTU	=	Upstream normalized wall throat radius RWTU $\geq$ .5 is required.	none*	0.
ITYPE	=	Type of nozzle wall to be input. ITYPE = 0, if the real wall contour is input. ITYPE = 1, if the potential flow wall contour is input. If IRPEAT = 1 or 2, then the nozzle wall will be displaced by $\pm\delta^*$ as calculated by BLM when the TDK (or TDE) calculations are repeated. This displacement is $-\delta^*$ for the real wall (ITYPE = 0), or $+\delta^*$ for the potential flow wall (ITYPE = 1).	none	0.

---

* Normalized by the throat radius, r_t

6.3.3.1 Exhaust Nozzle Geometry Specification, for ØDK and the MØC Modules.

Item			Description	Units	Assumed Value(s)
IWALL	=		option flag for specifying the downstream wall.	none	0
	=	1	cone option (input RWTD, THETA, and EPS)		
	=	2	parabolic nozzle contour option (input RWTD, THETA, RMAX, ZMAX)		
	=	3	circular arc nozzle contour option (input as for IWALL=2)		
	=	4	nozzle contour (spline) option (input RWTD, THETA, THE, RS, ZS, NWS)		
	=	5	cone with specified end point. (input RWTD, RMAX, and ZMAX)		
	=	6	skewed parabola option. (input RWTD, THETA, RMAX, ZMAX, THE)		

The items required for the various IWALL options are:

RWTD	=	downstream wall throat radius of curvature ratio**	none*	0.
THETA	=	nozzle attachment angle		
THE	=	nozzle exit angle (input if IWALL=4, or 6)	deg.	0.
EPS	=	nozzle expansion ratio (input if IWALL=1 only)	deg.	0.
RMAX	=	normalized radius at the nozzle exit plane (input if IWALL=2 or 3)	none*	0.
ZMAX	=	normalized axial position at the nozzle exit plane (input if IWALL = 2 or 3)	none*	0.

---

* Normalized by the throat radius r_t

** If a corner expansion (i.e. Prandtl-Meyer fan) is desired, a value of RWTD = .05 is recommended. Experience has shown that values smaller than this give the same result but are computationally less efficient.

Item		Description	Units	Assumed Value(s)
RS(2)	=	table of normalized wall radii downstream of the nozzle tangency point (input if IWALL=4). The input tables RS and ZS start with the second entry because the first entry is calculated automatically by the program, i.e., RS(1)=r_T and ZS(1)=z_T in Figure 6-1. The wall angle at this position is also calculated so that the spline contour will be properly joined to the nozzle throat contour.	none[+]	0.
ZS(2)	=	table of normalized axial position downstream of the nozzle tangency point (input if IWALL=4).	none[+]	0.
NSW	=	total number of entries in the RS, ZS tables. Includes the first entry. NWS-≤ 50 (input if IWALL=4).	none	0
RZNORM	=	optional normalizing factor for the RS, ZS, RIN, ZIN tables. For example, if RS, ZS, and RIN, ZIN were input as dimensional numbers, RZNORM would be the throat radius in those units.	none	1.

[+] See the input variable RZNORM.

6.4 ØDE INPUT DATA (ALL PROBLEMS SPECIFYING ØDE)

The ØDE input data described here is exactly as defined in NASA SP-273, Reference 3, except namelists input $INPT2 and $RKINP have been combined into a single list named $ØDE. Any type of equilibrium calculation available with the computer program described in Reference 3 can thus be computed using the $ØDE input data*. In this document, however, only the RKT option of namelist is described. The RKT option differs from that of Reference 3 for problem types other then single zone ØDE.

The ØDE input data consists of the following input groups:

1.	REACTANTS	directive card, followed by up to 15 data cards, followed by a blank card, specifying reactants.
2.	ØMIT and INSERT	directives to omit or insert species for equilibrium/frozen calculations.
3.	NAMELISTS	directive card followed by input namelist $ØDE specifying input case data.

6.4.1 REACTANTS CARDS

This set of cards is required for all ØDE problems. The first card in the set contains the word REACTANTS punched in card columns 1 to 9. The last card in the set is blank. In between the first and last cards may be any number of cards up to a maximum of 15, one for each reactant species being considered. The cards for each reactant must give the chemical formula and the relative amount of the reactant. For some problems, enthalpy values are required. The format and contents of the cards are summarized in Table 6-7. A list of some REACTANTS cards is given in Table 6-8

Relative amounts of reactants. - The relative amounts of reactants may be specified in several ways. They may be specified in terms of moles, mole fraction, or mole percent (by keypunching M in card column 53) or in terms of weight, weight fraction, or weight percent (blank in column 53).

Relative amounts of total fuel to total oxidants can also be input. For this situation, each reactant must be specified as a fuel or an oxidizer by keypunching an F or O, respectively, in column 72 of the REACTANTS card. The amounts

---

*These options include TP, HP, SP, TV, UV, or SV problems, Chapman-Jouguet detonation problems, and incident or reflected shock problems.

TABLE 6-7 REACTANTS CARDS

Order	Contents	Format	Card columns
First	REACTANTS	3A4	1 to 9
Any	One card for each reactant species (maximum 15). Each card contains:		
	(1) Atomic symbols and formula numbers (maximum 5 sets)[a]	5(A2, F7.5)	1 to 45
	(2) Relative weight[b] or number of moles	F7.5	46 to 52
	(3) Blank if (2) is relative weight or M if (2) is number of moles	A1	53
	(4) Enthalpy or internal energy[a], cal mole	F9.5	54 to 62
	(5) State: S, L, or G for solid, liquid or gas, respectively	A1	63
	(6) Temperature associated with enthalpy in (4), °K	F8.5	64 to 71
	(7) F if fuel or O if oxidant	A1	72
	(8) Density in g cm^3 (optional)	F8.5	73 to 80
Last	Blank		

[a] Program will calculate the enthalpy or internal energy (4) for species in the THERMO data at the temperature (6) if zeros are punched in card columns 37 and 38. (See section Reactant enthalpy for additional information.)

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

TABLE 6-8 LISTING OF SAMPLE REACTANTS CARDS

```
REACTANTS
H 2.
N .7808810 .209795AR.004662                                    100.     0.          G298.15  F
                                                               100.     -7.202164G298.15  O


REACTANTS
N 1.       H 4.       CL1.      O 4.
C 1.       H 1.869550 .031256S .008415                        72.06    -70730.  S298.15  F
AL1.                                                          18.58    -2999.082L298.15  F
MG1.       O 1.                                                9.00    *C.0     S298.15  F
H 2.       O 1.                                                 .20    -143700. S298.15  F
                                                                .16    -68317.4 L298.15  F


REACTANTS
H 2.
O 2.                                             .00       100.     0.        G298.15  F
                                                  00       100.0    0.0       G298.15  O


REACTANTS
N 2.       H 8.       C 2.
N 2.       H 4.                                            50.0     12734.8  L298.15  F  .786
F 2.                                                       50.0     12050.   L298.15  F 1.003
                                                           100.     -3030.892L 85.24  O 1.54


REACTANTS
LI1.
F 2.                                                       100.     0.         S298.15  F
                                                           100.     -3030.892L 85.24  O 1.54


REACTANTS
N 2.       H 4.
BE1.                                                        80.     12100.    L298.15  F 1.003
H 2.       O 2.                                             20.     0.0       S298.15  F 1.85
                                                           100.     -44880.   L298.15  O 1.407
```

---

*Listed above are six examples. Each example must end with a blank card.

given on the REACTANTS cards are relative to total fuel or total oxidant rather than total reactant.

There are four options in the $0DE namelist for indicating relative amounts of total fuel to total oxidant as follows:

1. Oxidant to fuel weight ratio (0F is true)
2. Equivalence ratio (ERATI0 is true)
3. Fuel percent by weight (FPCT is true)
4. Fuel to air or fuel to oxidant weight ratio (FA is true)

For each option, except 0DE with NZ0NES=1, the values are given in the 0FSKED array of $0DE (described in Section 6.4.3). For 0DE with NZ0NES=1, the MIX array is used as described in Reference 3.

Reactant enthalpy. Assigned values for the total reactant are calculated automatically by the program from the enthalpies of the individual reactants. Values for the individual reactants are either keypunched on the REACTANTS cards or calculated from the THERM0 data as follows:

Enthalpies are taken from the REACTANTS cards unless zeros are punched in card columns 37 and 38. For each REACTANTS card with the "00" code, an enthalpy will be calculated for the species from the THERM0 data for the temperature given in card columns 64 to 71.

When the program is calculating the individual reactant enthalpy for values from the THERM0 data, the following two conditions are required:

1. The reactant must also be one of the species in the set of THERM0 data. For example, $NH_3(g)$ is in the set of THERM0 data but $NH_3(\ell)$ is not. Therefore, if $NH_3(g)$ is used as a reactant its enthalpy could be calculated automatically, but that of $NH_3(\ell)$ could not be.
2. The temperature T must be in the range $T_{low}/1.2 \le T \le T_{high} \times 1.2$ where T_{low} to T_{high} is the temperature range of the THERM0 data.

For cases with NZ0NES > 1 (see Problem card, Section 6.3) it may be desirable to modify the enthalpy of each zone. This can be done by using the DELH input array. For the i^{th} zone the i^{th} DELH entry will be added to the system enthalpy as computed by ØDE from the reactants cards (see above). For example, overall system enthalpy of the propellants in the tank can be input through the reactants cards and the work added or extracted per zone can be input by the DELH entries. An alternate method would be to input zero enthalpy on the Reactants cards and input enthalpy per zone by the DELH entries.

6.4.2 ØMIT and INSERT Cards

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

6.4.2.1 ØMIT Cards

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

6.4.2.2 INSERT Cards

These cards contain the names of condensed species only. They have been included as options for two reasons.

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

The second and less important reason is that if one knows that one or several particular condensed species will be present among the final equilibrium compositions for the first assigned point, then a small amount of computer time can be saved by using an INSERT card. Those condensed species whose chemical formulas are included on an INSERT card will be considered by the program during the initial iterations for the first assigned point. If the INSERT card were not used, only gaseous species would be considered during the initial iterations. However, after convergence, the program would automatically insert the appropriate condensed species and reconverge. Therefore, it usually is immaterial whether or not INSERT cards are used. For all other assigned points the inclusion of condensed species is handled automatically by the program.

6.4.3 $ØDE NAMELIST INPUT

The ØDE subprogram contains namelist input sections $ØDE and $SHKINP. The Namelist $ØDE must be preceded by a card with NAMELISTS punched in card columns 1-9.

The $ØDE Namelist is required if ØDE =1. or TDK =1, in $DATA as described in section 6.3.

For the ØDE problem type any of nine (9) different equilibrium problems can be solved. These are TP, HP, SP, TV, UV, SV, RKT, DETN, and SHØCK. For the ØDE-ØDK, ØDE-ØDK-TDK, or TDE problem type, only the RKT problem can be solved. In this section only the RKT input option is discussed. Reference 9 is to be used to prepare input for the other equilibrium problems.

The variables input by the $ØDE namelist are listed in Table 6-9. Additional information about some of these variables follows:

Pressure units. - The program assumes the pressure in the P schedule to be in units of atmospheres unless either PSIA = true, or SI = true.

Relative amounts of fuel(s) and oxidizer(s). - These quantities may be specified by assigning 1 to 15 values for either o/f, %F, f/a, or r. If no value is assigned for any of these, the program assumes the relative amounts of fuel(s) and oxidizer(s) to be those specified on the REACTANTS cards. (See discussion in REACTANTS Cards, Section 6.4.1 and Section 5.2.1)

RKT problem. - Only one value for chamber pressure, P, is to be input for cases with NZØNES > 1 (see $DATA input, Section 6.3). The stagnation pressure used for the i^{th} zone will be the value input for P multiplied by the i^{th} value input in the schedule XP. If not input, all XP entries are assumed equal to one. For TDK type problems, zone one is taken about the nozzle axis of symmetry and the last zone is bounded by the nozzle wall. Similarly, the i^{th} zone will have a mixture ratio equal to the i^{th} entry in the ØFSKED schedule.

Print out will be given for the chamber pressure condition (i.e. stagnation) and the throat condition. Print out may be requested at other conditions by use of the PCP schedule and the SUBAR and SUPAR schedules.

The program will calculate both equilibrium and frozen performance unless FRØZ = F or EQL = F are input. If FRØZ = F, only equilibrium performance will be calculated. If EQL = F, only frozen performance will be calculated.

Ordinarily, rocket problems are run by specifying chamber values for P and H. It is possible, however, to run 1 zone cases (N ZONES = 1 in $DATA) by specifying P and T. For example:

```
$ODE
RKT = 1
P   = chamber pressure,
T   = chamber temperature,
```

can be used to set the chamber temperature and run the rocket problem. The resulting chamber enthalpy will be calculated and included in the output.

TABLE 6-9 VARIABLES IN \$ØDE NAMELIST

Variable	No. of entries	Type	Value before read	Definition and comments
RKT	1	L	False	Rocket problem^a
P	26	R	0	Assigned pressures: stagnation pressure for rocket problems: values in atm unless PSIA, or SI = .T., (see below)
SI	1	L	False	^{a}Values in P array are in N/m^2
PSIA	1	L	False	^{a}Values in P array are in psia units
XP	50	R	1.	Multipliers for the ith zone stagnation pressure (zone 1 = inner zone)
ØF	1	L	False	Oxidant to fuel weight ratios are to be input^a
ERATIØ	1	L	False	Equivalence ratios are to be input^a
FPCT	1	L	False	Percent fuel by weight are to be input^a
FA	1	L	False	Fuel to air weight ratios are to be input^a
ØFSKED	50	R	0	For a Rocket problem, and NZØNES ≥ 1, ØFSKED will be used rather than MIX (see Reference 3). Relative amounts of total oxidant to total fuel are input as defined by ØF, ERATIØ, FPCT, or FA. For ØDE-ØDK-TDK and TDE problem types these values define the oxidant to fuel ratios for each zone (zone 1 = inner zone)
DELH	50	R	0	Corresponding to each zone this value will be added to the system enthalpy input thru the reactants cards. Units are BTU/# if PSIA=.T., joule/kilogram if SI=.T., otherwise cal/gram.
DELH1	50	R	0	Corresponding to each zone this value will be added to the system enthalpy. These values can be used as a 1st estimate for the heat returned to the main combustion chamber by regen cooling circuits (ØFC input in \$BLM). The BLM will recalculate these values and, if IRPEAT =1 in \$DATA, rerun the ØDE, ØDK, TDK (or TDE) analysis. Same units as DELH.

^{a}If variable is set to be true.

Note: For rocket problems, only one value stagnation pressure can be input. This value multiplied by the i th entry of XP will be used for the stagnation pressure of the i th zone.

Table 6-9 (cont'd)

Variable	No. of entries	Type	Value before read	Definition and comments
I0NS	1	L	False	Consider ionic species[a]
WFL0W	1	R	0	Input nozzle mass flow option for 0DE-0DK-TDK or TDE problems. If a value for WFL0W is input an expansion with this mass flow will be computed. The values input for P and XP are used as estimates for computing stagnation pressure for each zone. The program will adjust these stagnation pressures to obtain the desired nozzle mass flow within a tolerance of RELERR. Units are lbs/sec if PSI=.T. otherwise kilograms/sec.
RELERR	1	R	.0005	Relative difference between requested and computed mass flow rate. The program stops if this error is exceeded.
PCP	50	R	0	Compute and print solutions at these values of chamber pressure to pressure ratio (entries must be >1.)
SUBAR	50	R	0	Compute and print solutions at these values of subsonic area ratios (entries must ≠ 1.)
SUPAR	50	R	0	Compute and print solutions at these values of supersonic area ratio (entries must ≠ 1)
ECRAT	1	R	0	Subsonic area ratio to start 0DK calculations with computed equilibrium conditions. The SUBAR input table must include an entry equal to ECRAT.
EQTHST	1	L	False	To start 0DK calculations with computed equilibrium conditions at the nozzle throat.[a]
EQL	1	L	True	Calculate rocket performance assuming equilibrium composition during expansion[b].
FR0Z	1	L	True	Calculate rocket performance assuming frozen composition during expansion[b].
LISTSP	1	L	False	List names and dates of all species residing on thermodynamic data used[a].
KASE	1	I	0	Optional assigned number associated with case.

[a] If variable is set to be true.

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

6.4.3.1 Variable Mixture Ratio Option

The MOC can be run with a variable mixture ratio option by setting VARMIX=.TRUE., and inputting values into the STREAM(1) table as described below.

When the variable mixture ratio option is used, there are no sliplines in the flow. Instead, the flow mixture ratio will vary from the axis ($\psi=0$) to the wall ($\psi=1$) as specified in the tables of ØFSKED vs. STREAM. Sliplines can not be used when the shock option is invoked (SHØCK=1 in $MØC), because shock-slipline interaction is not provided in the program. Thus, if the shock option is requested and there is variation in mixture ratio from streamline to streamline, then the variable mixture ratio option must be used.

The program will not function properly if the spacing in the mixture ratio table, ØFSKED(1), is too large. The required spacing depends on the chemical system. As a rule each entry in ØFSKED(1) must differ no more than 4 or 5% from its adjacent values depending on the stoichiometry of the system. There are no spacing requirements for the STREAM (1) table. However, the first entry must be 0 and successive entries must increase monotonically with the last entry equal to 1.

The tables XP(1), DELH(1), and DELH1(1) of $ØDE can be used, in which case each entry corresponds to entries in ØFSKED(1) and STREAM(1).

If VARMIX=.TRUE., the XM(1) table of $ØDK and $TRANS will be computed by the program and need not be input.

Item	Description	Assumed Value(s)
VARMIX=	If VARMIX=.FALSE., do not use variable mixture ratio option. If VARMIX=.TRUE., the variable mixture ratio option is to be used. The following must be input: NZ0NES in $DATA, 0FSKED(1) in $0DE and STREAM(1) in $0DE, below.	F
STREAM(1)=	If VARMIX=.TRUE., values must be input here corresponding to the O/F values input in 0FSKED(1). The values input represent $(O/F)_i$ vs ψ_i $i=1,\ldots,$NZ0NES where ψ_i represents the mass flow between streamline i and the axis, divided by the total mass flow. Thus $\psi = 0$ at the axis, and $\psi = 1$ at the wall. The ith entry of 0FSKED is $(O/F)_i$. The ith entry of STREAM is ψ_i $0 \leq \psi_i \leq 1$ $i =,\ldots,$NZ0NES ≤ 50 and $\psi_i < \psi_{i+1}$	-

6.4.3.2 OPTION TO PUNCH TABLES FOR BOUNDARY LAYER PROGRAM INPUT

(DOES NOT APPLY TO BLM)

Conditions computed along the nozzle wall can be output as punched cards for input to the BLIMP ,TBL or MABL boundary layer analysis computer programs. These conditions are taken by the boundary layer computer program as being the inviscid flow condition at the edge of the boundary layer. Tables to be punched are: x, y, and P/P_c (i.e. the nozzle wall coordinates and the ratio of pressure to chamber pressure along the wall). The tables are punched in NAMELIST format readable by BLIMP.

A maximum of 50 entries upstream of the throat are saved and punched. The wall point at the end of every characteristic is punched up to a maximum of 500 total table entries. The user may specify a number by which the punched table will be offset. Thus, the first point may be output with identification 5 by input of IØFF=4. The use of IØFF enables the user to extend the table by adding points upstream.

If punched cards for input to a boundary layer program are required, the following items must be input as part of the $ØDE Namelist input:

Item Name		Description
IPTAB	=	If IPTAB=1, one title card will be punched (this will be the last title card input as described in 6.2) followed by tables of X, Y, and P/P_c along the nozzle wall. These cards are for input to the BLIMP or MABL computer programs. The first point punched will correspond to beginning of the converging section of the nozzle (i.e. at ECRAT; see Figure 6-1, also table 6-9).
IØFF	=	The first point to be punched will be numbered as IØFF+1.
IPTBL	=	If IPTBL and IPTAB=1, tables of M, T/T_c, C_p, V, and ρ, will also be punched. These additional cards are required for input to the TBL computer program (i.e. the December 21, 1973 version).

If a TDE problem is specified, the following items <u>must</u> also be input when IPTAB=1: RSI, RWTU, THETAI, and RI in $DATA.

These items define the nozzle geometry from the combustion chamber through the throat as shown in Figure 6-1. For a TDE option it is necessary that IPTBL=0.

6.5 ODK INPUT DATA

ØDK input data is required if ØDK =1 or TDK =1 in $DATA as described in Section 6.3. The ODK input data consists of three data groups as follows:

SPECIES	data group
REACTIONS	data group
$ ØDK	data group

These data groups are described below in sections 6.5.1, 6.5.2, and 6.5.3, respectivly.

6.5.1 SPECIES

Species used by the computer program are determined in several possible ways, depending upon the problem type. Methods used to determine chemical species for each probelm type are discussed below.

ØDK

If ØDE=0 and ØDK=1 in $DATA, then species names and concentrations must be input, see Section 6.5.1.1.

ØDE-ØDK

If ØDE=1 and ØDK=1 in $DATA, then the initial start conditions for the kinetic expansion are obtained from an ØDE equilibrium calculation. The [illegible] generated by the equilibrium calculation generally contains many more species than the 40 species for which the ØDK subprogram is dimensioned. Therefore a selection processes is required to interface the ØDE calculated equilibrium start conditions with the ØDK kinetic expansion calculations. This selection is performed using the following rules:

Rule 1 If a species appears in a reaction, it is selected for the kinetic calculation.

Rule 2 If a species is specified using INERTS directive it is selected for the kinetic calculations.

Rule 3 If any species has a mole fraction greater than an input criterion, it is selected for the kinetic calculation.

Species which are selected but which do not appear in a reaction are treated as Inert and listed as such on the output list of selected species.

ØDE-ØDK-TDK

For problems with ØDE=0 and ØDK=1, species are selected by the above rules. However, for multizone TDK cases it is necessary that each zone have the same species list. Thus the INERTS input (see Section 6.5.2.) must be used to assure the same species are selected for each zone.

6.5.1.1 SPECIES CARD OPTION FOR INPUT OF INITIAL SPECIES CONCENTRATIONS

(APPLIES ONLY IF ØDE=0 AND ØDK=1 IN $DATA)

This input begins with a single card with SPECIES in columns 1 through 7 and with either MASS FRACTIØNS or MØLE FRACTIØNS in columns 9 through 22. If the identifier for mass or mole fractions is omitted, mass fractions are assumed. Up to 40 species cards may be input. Only those species specified by input species cards will be considered for an ØDK problem. The order of the input species cards is independent of the order in which the species appear on the master Thermodynamic Data file.

A chemical species is identified symbolically by 12 alphanumeric characters and must correspond identically with the species name as it appears on the Thermodynamic Data file. A complete list of the current species names are listed in Table 6-4 (condensed species, however, may not be specified in the species list.) The species symbol may not contain the characters * or =.

Col	Function
1-10	Not used
11-22	Species symbol (left justified)
23-30	Not used
31-60	Value of initial species concentration (if zero must be input as 0.0) free field F or E format
61-80	User Identification if desired

This type of input also requires input of other items that otherwise would be provided by ODE. These other items (P_c, T_c, V_c, etc.) are input with the $ODK data set and are described in Section 6.5.3.6. Example input is given in Table 6-12.

6.5.2 THE INPUT OF CHEMICAL REACTIONS

Chemical reactions must be input if 0DK=1 in $DATA.

Up to 50 reactions with an implied third body and a total 150 reactions may be input to the program. Only one card per reaction, and only one reaction per card is permitted. Cards specifying third body reactions must precede cards specifying all other reactions. Species names appearing in the symbolic reaction set must correspond identically with the species names as they appear in the master Thermodynamic Data (see Table 6-4).

The symbolic reaction set contains directive cards and reaction/data cards in groups as outlined below:

REACTI0NS	Directive for start of symbolic reaction input
. .	Reactions with implied third body species
END TBR REAX	Directive for end of third body reactions
. . .	All other reactions
LAST REAX	Directive for end of reactions
INERTS	Specified Inert Species
THIRD B0DY REAX RATE RATI0S	Directive for start of third body reaction rate ratios
. . .	
LAST CARD	Directive for end of REACTI0NS input

The content and format of each type of card are defined below:

6.5.2.1 REACTIONS Through LAST REAX

The symbolic reaction input begins with a card containing the word REACTIONS in columns 1 through 9.

Columns 11 to 23 can be used to specify the nominal direction of the reaction rate data. For example the card

```
REACTIONS     FORWARD RATES
```

will cause all reaction rate data to be in the forward (left to right) direction unless otherwise specified. The word REVERSE instead of FORWARD means the rate data is input in the reverse direction. If left out, the nominal rate direction will be the forward direction.

Up to 50 dissociation reactions and a total of 150 reactions may be input following the REACTIONS card. Only one card per reaction and only one reaction per card is permitted. Cards specifying reactions with third bodies must precede cards specifying reactions without third bodies. The content and format of the reaction cards is defined below.

The general form of a reaction is:

$$\Sigma \nu_i * \alpha_i = \Sigma \nu_i' * \alpha_i$$

where the α_i's are species names and the ν_i's are the stoichiometric coefficients. The left hand side of the above equation represents the reactants and the right hand side the products.

Each species name must correspond identically with the species name as it appears in the Thermodynamic Data File, e.g., see Table 6-4.

The stoichiometric coefficients must be intergers and an * must separate the stoichiometric coefficient from the species name. If no stoichiometric coefficient is given, the value 1 is assumed. It is also required that

$$\Sigma \nu_i \leq 10$$

$$\Sigma \nu'_i \leq 10$$

examples:

Reaction			Interpretation		
H+H	=	H2	$H+H$	=	H_2
NA+CL-	=	NACL	$Na^+ + C\ell^-$	=	$NaC\ell$
B+2+M-2	=	BM	$B^{++} + M^{--}$	=	BM
BE+2+2*OH-	=	BEOHOH	$Be^{++} + 2OH^-$	=	$Be(OH)_2$

The reaction rates are defined by three numerical values P1, P2, P3 input as E or F format. Three types of reactions can be input, as discussed below.

Arrhenius form

$\Sigma \nu_i \alpha_i = \Sigma \nu'_i \alpha_i$, Mn , A = P1, N = P2, B = P3

or

$\Sigma \nu_i \alpha_i = \Sigma \nu'_i \alpha_i$, Mn , KF = P1, P2, P3

Input of the above type defines a reaction rate of the form

$$k = P1*T^{-P2} * e^{-P3*1000/RT} \quad , \; R = 1.987$$

Landau-Teller form

$\Sigma \nu_i \alpha_i = \Sigma \nu_i' \alpha_i$, Mn , *KF = P1, P2, P3

Input of the above type defines a reaction of the form

$k = \exp(P1 + P2^{-1/3} + P3^{-2/3})$.

Log 10 form

$\Sigma \nu_i \alpha_i = \Sigma \nu_i' \alpha_i$, Mn , %KF = P1, P2

Input of the above type defines a reaction of the form

$\log_{10} k = P1 + P2*T$.

In the above reactions if KF is replaced by KR, then the rate will be for the reverse (right to left) direction.

The Mn's in the above reactions are the third body descriptors for the reaction. These descriptors are optional for dissociation-recombination reactions, but must be left out for exchange reactions. They are used to multiply the reaction rate by a factor that is defined by the descriptor.

The dissociation-recombination reactions with third body terms must precede other types of rections, and must be followed by the directive starting in column 1:

```
Col 1     ↓
          END TBR REAX
```

All reactions prior to the above directive will have a third body term added to each side of the reaction; e.g.,

H_2 = H + H, M4,...

END TBR REAX

is the same as

H_2 + M4 = H + H + M4,...

where M4 is a generalized third body as specified in Section 6.5.2.3. If no Mn is specified, the generalized third body is assumed to be defined by Mo.

The reaction set is terminated by a card containing LAST REAX in columns 1 to 9.

6.5.2.2 Inert Species Option

Inert species (i.e. species not appearing in reactions) can be included in the input by input of a card with INERTS in columns 1 through 6 followed by a list of inert species names. The species names must each be followed by a comma and each name must be written exactly as in the master Thermodynamic Data. The last comma must be followed by the word END. The species list can continue onto the next card, but a species name cannot overlap onto the next card.

6.5.2.3 Third Body Reaction Rate Ratios

If reaction rate ratios, m_{ij}, are to be input for the dissociation-recombination reactions, a card with THIRD BODY REAX RATE RATIOS in columns 1 through 27 must be input next. If this card is deleted from the input, the program assumes all $m_{ij} = 1$. If this card is included in the input, it must be followed either by a card with ALL EQUAL 1.0 in columns 1 through 13 (which sets all m_{ij}=1) or by cards defining the Mn's as described below.

The Mn's on the reaction cards are used to identify a group of third body efficiencies which pertain to all of the reactions which declare that grouping. The format of the Mn statement is

$$Mn = m_j * \alpha_j, m_k * \alpha_k, \ldots, etc$$

where

n = integer between 0 and 100 inclusive
m_j = multiplier for the species named α_j
α_j = species name
.
.
.
etc.

If no multiplier is given for an α, a value of 1.0 is assumed. The user may declare that all of the third body reaction rate ratios for a particular grouping are 1.0 by using the statement

```
Mn = *
```

If no Mn is declared on the reaction card, then M0 is assumed.

Example: (fictitious rates)

```
REACTIONS FORWARD RATES

H + OH = H2O, A = 7.5E23, N = 2.6, B = 0.0,
O + H = OH, M2, KF = 4.0 + 18, 1, 0,
O + O = O2, M2, KF = 1.2E17, 1, 0,
H2 = H + H, M3, KR = 6.4E17, 1, 0,
END TBR REAX
      .
      .
      .
LAST REAX
THIRD BODY REAX RATE RATIOS
M0 = .5*H2, 20.*H2O,
M2 = .5*H2, 5*H2O ,
M3 = *
LAST CARD
```

In the above example the first reaction does not declare an Mn, so M0 is used. The second and third reactions share the same third body reaction rate ratios by declaring the same group identifier, M2. The fourth reaction uses the identifier M3 which has all of its third body efficiencies set equal to 1.0.

6.5.2.4 LAST CARD

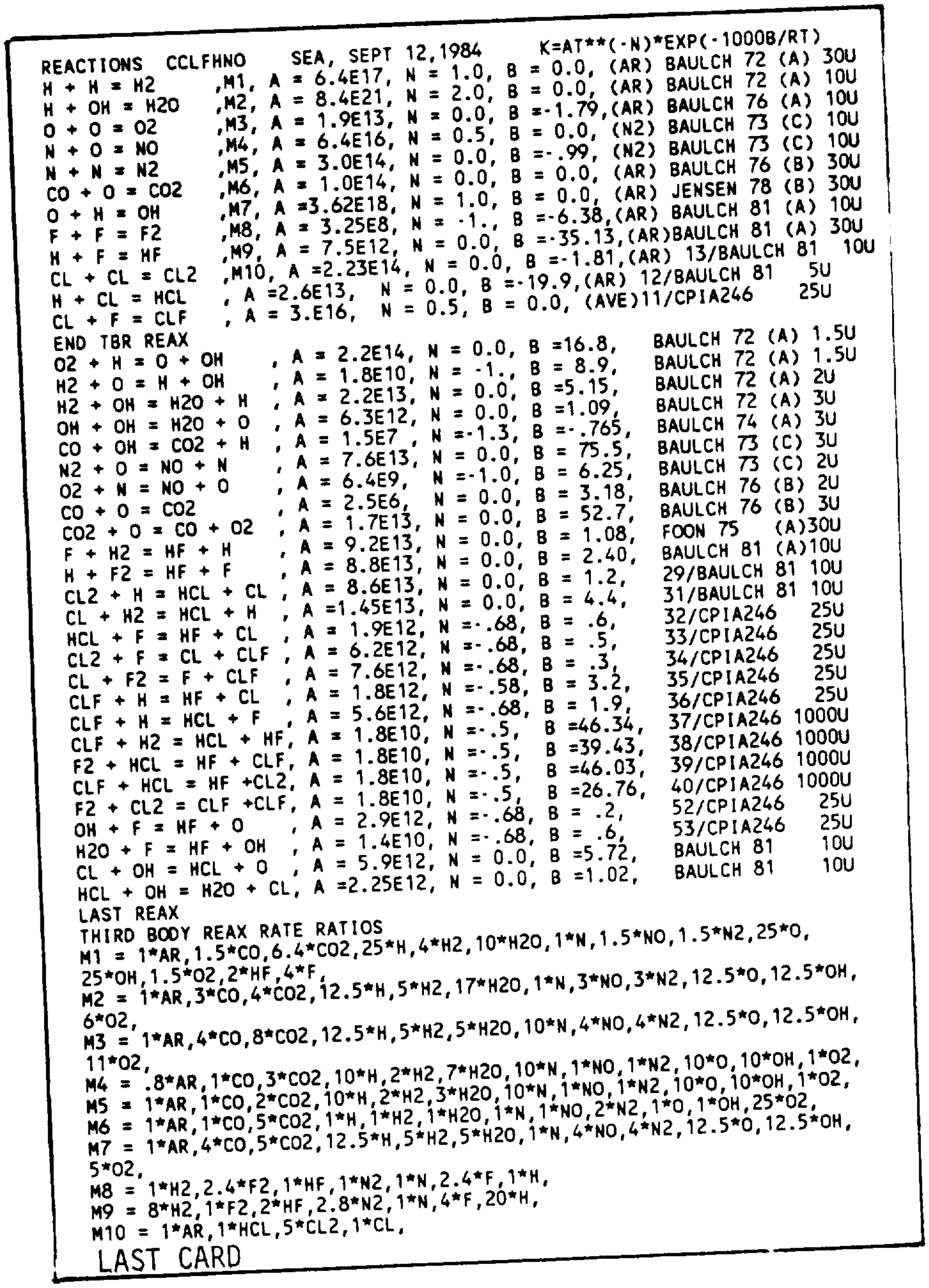
The reaction input data is terminated by a card containing LAST CARD in columns 1 through 9.

6.5.2.5 Master Reaction Set

A master reaction set is presented in Table 6-10. It contains chemical species and reactions found necessary for C, Cℓ, F, H, N, and O systems according to the study presented in Appendix A in which the rate data was updated with a literature survey through June 1984. Third body efficiencies are included. For any given chemical system that is to be analyzed, great care must be taken in selecting the appropriate reaction set. Table 6-10 may or may not be sufficient.

Table 6-11 presents a minimal reaction set for Oxygen/Hydrogen systems. The third body efficiencies are included in Table 6-11 and illustrate their usage.

TABLE 6-10 REACTIONS AND RATE DATA FOR C,CL,F,H,N, AND O SYSTEMS
(SEE APPENDIX A)



```
REACTIONS  CCLFHNO    SEA, SEPT 12,1984    K=AT**(-N)*EXP(-1000B/RT)
H + H = H2        ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U
H + OH = H2O      ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U
O + O = O2        ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U
N + O = NO        ,M4, A = 6.4E16, N = 0.5, B = 0.0, (N2) BAULCH 73 (C) 10U
N + N = N2        ,M5, A = 3.0E14, N = 0.0, B =-.99, (N2) BAULCH 73 (C) 10U
CO + O = CO2      ,M6, A = 1.0E14, N = 0.0, B = 0.0, (AR) BAULCH 76 (B) 30U
O + H = OH        ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U
F + F = F2        ,M8, A = 3.25E8, N = -1., B =-6.38,(AR) BAULCH 81 (A) 10U
H + F = HF        ,M9, A = 7.5E12, N = 0.0, B =-35.13,(AR)BAULCH 81 (A) 30U
CL + CL = CL2     ,M10, A =2.23E14, N = 0.0, B =-1.81,(AR) 13/BAULCH 81  10U
H + CL = HCL      , A =2.6E13,  N = 0.0, B =-19.9,(AR) 12/BAULCH 81   5U
CL + F = CLF      , A = 3.E16,  N = 0.5, B = 0.0, (AVE)11/CPIA246    25U
END TBR REAX
O2 + H = O + OH      , A = 2.2E14, N = 0.0, B =16.8,   BAULCH 72 (A) 1.5U
H2 + O = H + OH      , A = 1.8E10, N = -1., B = 8.9,   BAULCH 72 (A) 1.5U
H2 + OH = H2O + H    , A = 2.2E13, N = 0.0, B =5.15,   BAULCH 72 (A) 2U
OH + OH = H2O + O    , A = 6.3E12, N = 0.0, B =1.09,   BAULCH 72 (A) 3U
CO + OH = CO2 + H    , A = 1.5E7 , N =-1.3, B =-.765,  BAULCH 74 (A) 3U
N2 + O = NO + N      , A = 7.6E13, N = 0.0, B = 75.5,  BAULCH 73 (C) 3U
O2 + N = NO + O      , A = 6.4E9,  N =-1.0, B = 6.25,  BAULCH 73 (C) 2U
CO + O = CO2         , A = 2.5E6,  N = 0.0, B = 3.18,  BAULCH 76 (B) 2U
CO2 + O = CO + O2    , A = 1.7E13, N = 0.0, B = 52.7,  BAULCH 76 (B) 3U
F + H2 = HF + H      , A = 9.2E13, N = 0.0, B = 1.08,  FOON 75    (A)30U
H + F2 = HF + F      , A = 8.8E13, N = 0.0, B = 2.40,  BAULCH 81 (A)10U
CL2 + H = HCL + CL   , A = 8.6E13, N = 0.0, B = 1.2,   29/BAULCH 81 10U
CL + H2 = HCL + H    , A =1.45E13, N = 0.0, B = 4.4,   31/BAULCH 81 10U
HCL + F = HF + CL    , A = 1.9E12, N =-.68, B = .6,    32/CPIA246   25U
CL2 + F = CL + CLF   , A = 6.2E12, N =-.68, B = .5,    33/CPIA246   25U
CL + F2 = F + CLF    , A = 7.6E12, N =-.68, B = .3,    34/CPIA246   25U
CLF + H = HF + CL    , A = 1.8E12, N =-.58, B = 3.2,   35/CPIA246   25U
CLF + H = HCL + F    , A = 5.6E12, N =-.68, B = 1.9,   36/CPIA246   25U
CLF + H2 = HCL + HF, A = 1.8E10, N =-.5,   B =46.34,  37/CPIA246 1000U
F2 + HCL = HF + CLF, A = 1.8E10, N =-.5,   B =39.43,  38/CPIA246 1000U
CLF + HCL = HF +CL2, A = 1.8E10, N =-.5,   B =46.03,  39/CPIA246 1000U
F2 + CL2 = CLF +CLF, A = 1.8E10, N =-.5,   B =26.76,  40/CPIA246 1000U
OH + F = HF + O      , A = 2.9E12, N =-.68, B = .2,    52/CPIA246   25U
H2O + F = HF + OH    , A = 1.4E10, N =-.68, B = .6,    53/CPIA246   25U
CL + OH = HCL + O    , A = 5.9E12, N = 0.0, B =5.72,   BAULCH 81    10U
HCL + OH = H2O + CL, A =2.25E12, N = 0.0, B =1.02,     BAULCH 81    10U
LAST REAX
THIRD BODY REAX RATE RATIOS
M1 = 1*AR,1.5*CO,6.4*CO2,25*H,4*H2,10*H2O,1*N,1.5*NO,1.5*N2,25*O,
25*OH,1.5*O2,2*HF,4*F,
M2 = 1*AR,3*CO,4*CO2,12.5*H,5*H2,17*H2O,1*N,3*NO,3*N2,12.5*O,12.5*OH,
6*O2,
M3 = 1*AR,4*CO,8*CO2,12.5*H,5*H2,5*H2O,10*N,4*NO,4*N2,12.5*O,12.5*OH,
11*O2,
M4 = .8*AR,1*CO,3*CO2,10*H,2*H2,7*H2O,10*N,1*NO,1*N2,10*O,10*OH,1*O2,
M5 = 1*AR,1*CO,2*CO2,10*H,2*H2,3*H2O,10*N,1*NO,1*N2,10*O,10*OH,1*O2,
M6 = 1*AR,1*CO,5*CO2,1*H,1*H2,1*H2O,1*N,1*NO,2*N2,1*O,1*OH,25*O2,
M7 = 1*AR,4*CO,5*CO2,12.5*H,5*H2,5*H2O,1*N,4*NO,4*N2,12.5*O,12.5*OH,
5*O2,
M8 = 1*H2,2.4*F2,1*HF,1*N2,1*N,2.4*F,1*H,
M9 = 8*H2,1*F2,2*HF,2.8*N2,1*N,4*F,20*H,
M10 = 1*AR,1*HCL,5*CL2,1*CL,
LAST CARD
```

TABLE 6-11. REACTIONS AND RATE DATA FOR H,O SYSTEMS.

```
REACTIONS  HO    SEA, SEPT 12,1984     K=AT**(-N)*EXP(-1000B/RT)
H + H = H2       ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U
H + OH = H2O     ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U
O + O = O2       ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U
O + H = OH       ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U
END TBR REAX
O2 + H = O + OH      , A = 2.2E14, N = 0.0, B =16.8,   BAULCH 72 (A) 1.5U
H2 + O = H + OH      , A = 1.8E10, N = -1., B = 8.9,   BAULCH 72 (A) 1.5U
H2 + OH = H2O + H    , A = 2.2E13, N = 0.0, B =5.15,   BAULCH 72 (A) 2U
OH + OH = H2O + O    , A = 6.3E12, N = 0.0, B =1.09,   BAULCH 72 (A) 3U
LAST REAX
THIRD BODY REAX RATE RATIOS
M1=25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
M2=12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
M3=12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
M7=12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
LAST CARD
```

6.5.3 $0DK NAMELIST INPUT.

$0DK Namelist input specifies the conditions for the kinetic expansion calculation. The input is read in subroutine 0DKINP and consists of the following groups of data as outlined below:

6.5.3.1	Specification of Nozzle Geometry
6.5.3.2	Integration Control
6.5.3.3	Print Control
6.5.3.4	Species Selection and Mass/Mole Fraction Check
6.5.3.5	0DK Problem Input

6.5.3.1 Specification of Nozzle Geometry.

All of the nozzle geometry is to be input using the $DATA Namelist input, see Section 6.3.3 and Figure 6-1.

An 0DK calculation will be carried out for each mixture ratio input in 0FSKED of $0DE whenever 0DK = 1 in $DATA.

For a TDK problem, it is necessary that the 0DK calculations be run past the nozzle throat. Usually it is not desirable to run the 0DK calculations all the way to the nozzle exit because of the extra computer time and print out that results. However, if this is desired on a TDK problem, it can be requested by input of item EP as described below.

Item		Description	Units	Assumed Value(s)
$0DK	=	Namelist, read in subroutine 0DKINP.		
EP	=	If TDK = 1 and a value is input here for EP, then each ODK will be run to expansion ratio EP.	none	0

6.5.3.2 INTEGRATION CONTROL

The integration routine controls the step size such that the relative error in the dependent variable increments are less than a prescribed fraction, DEL. Only doubling or halving of the step size is permitted, and on option, either all the variables may be considered (JF=0), or only the fluid dynamic variables (JF=1) may be considered.

When the flow becomes supersonic and the area defined fluid dynamic equations are used, an additional check on continuity is applied in the form

$$\left| \frac{(\rho VA)_{N+1} - (\rho VA)_{N}}{(\rho VA)_{N+1}} \right| < \mathrm{C\emptyset NDEL}$$

where CØNDEL is an input relative criterion.

The step size is held between the two input bounds HMIN and HMAX. Fixed step cases may be run by setting input values for HI, HMAX, HMIN all equal.

Item		Description	Units	Assumed Value(s)
HI	=	initial step size	none	.01
HMAX	=	upper bound on step size	none	0.10001
HMIN	=	lower bound on step size	none	.005
DEL	=	fractional incremental error	none	.001

Item		Description	Units	Assumed Value(s)
TEXPLI	=	temperature below which explicit integration will start. Not recommended.	^{o}R	0
CØNDEL	=	relative error criterion for continuity check for supersonic flow	none	1×10^{-6}
JF	= 0	all variables considered for step size control	none	0
	= 1	only fluid dynamic variables considered for step size control, i.e., ρ,u, and T	none	

6.5.3.3 PRINT CONTROL

Output from the Kinetic Expansion Calculation consists of complete output for each print station selected. The end point of the nozzle is always printed. Print stations are selected from one of the following options:

Item		Description	Assumed Value(s)
JPRNT	= -2	print throat and input area ratios (see ARPRNT)	-2
	= -1	print at internally set area ratios for conical nozzle.* Print at selected wall contour points for contoured nozzles. For the spline fit option (IWALL=4), print out will occur at each entry in ZS of $DATA. For other contours (IWALL=2 or 3), print out will occur at 20 equally spaced axial locations along the nozzle.	
	= 0	print at every integration step	
	= +1	print every ND3rd step up to the throat and then nominal area ratios	
	= +2	print every ND3rd step over entire nozzle	

---

*For JPRNT = -1 and a conical nozzle (i.e. IWALL = 1), the internally set area ratios are:
ARPRNT(1) = 2,3,4,...,39,40,42,...,58,60,64,...116,120,128,...,200,210,220,...,400

If JPRNT is +1 or +2, the following must be input:

Item		Description	
ND1	=	first integration step to be selected for print	-
ND2	=	last integration step to be selected for print	-
ND3	=	print every ND3rd step between ND1 and ND2.	-

If JPRNT is -2, the following must be input:

Item		Description	
ARPRNT(1)	=	requested area ratios for print, must be monotonic increasing and greater than 1.0 If no values are input, will use values from ASUP of $DATA.	-
NJPRNT	=	number of area ratios requested for print ≤ 100.	-

An extended print option may be selected as follows:

Item	Value	Description	
IDYSCI	= 0	no extended print requested	0
	= 1	extended print option selected (<u>not suggested</u>)	

6.5.3.4 SPECIES SELECTION AND MOLE/MASS FRACTION CHECK

In order to interface ODE equilibrium calculated start conditions with the kinetic expansion calculations, special consideration must be made for inert species (those not appearing in the reaction set). Inerts may be selected explicitly by use of the INERTS directive or by use of a relative selection criterion.

If A MULTIZONE TDK PROBLEM IS SPECIFIED INERTS MUST BE SPECIFIED VIA THE INERTS DIRECTIVE. This is required so that the chemistry selected for multizone cases will be compatible.

The INERTS directive is described in Section (6.5.2.2).

The relative selection criterion (ODK or 1 Zone TDK problems,) is described below:

Item Name		Function
EPSEL	=	all species which do not appear explicitly in the reaction set but whose mole fractions are greater then the input value for EPSEL, will be retained for the kinetic expansion. Species selected under this criterion are treated as inert. The program assumes EPSEL = 1.0E-5, unless input.

In some instances it may be desirable to use input species concentrations which do not sum to unity. Species concentrations, either input or from equilibrium start conditions, are summed and the sum checked as described below.

Item Name		Function
XMFTST	=	Input species concentrations are summed and checked versus unity using this input criterion. If $\left| 1 - \sum \text{species concentrations} \right| < \text{XMFTST}$ then the test is passed. The species concentrations will then be normalized such that $\sum \text{species concentrations} = 1$.

The program assumes XMFTST = 1.0E-3, unless input.

If the test is not passed, an error message will be given and the run terminated.

6.5.3.5 Frozen Expansions with the ODK Module

The ODK module can be run using a frozen expansion by input of

SHGAMF = 1,

An example of this option is presented in Table 6-12. Note that the REACTIONS, END TBR REAX, and LAST CARD directives are included in the input, but no chemical reactions are given. This option can be run with ODE, or as in Table 6-12, without ODE. Whenever TDF=1 is input, SHGAMF = 1 is set automatically.

6.5.3.6 ODK PROBLEM INPUT

This input is required when ØDE=0, ØDK=1 are input in $DATA.

A kinetic expansion from input arbitrary start conditions is to be computed. In addition to the input items described in section 6.5.3, an ØDK problem requires input of those items described in Sections 6.5.1.1 and 6.5.2. Input for a hydrazine monopropellant engine is given in Table 6-12 as an example of the ODK problem input.

Item Name		Input Quantity	Units	SI Units
PC	=	chamber pressure	PSIA	N/M²
T	=	initial temperature	°R	°K
V	=	initial gas velocity	ft/sec	m/sec
JPFLAG	= 0	pressure table calculated internally	none	none
	= 1	pressure table input		
ECRAT	=	initial contraction ratio	none	none

For JPFLAG = 0 option the following must be input:

Item Name		Input Quantity	Units	SI Units
PI	=	initial pressure	PSIA	N/M²
PESTAR	=	throat pressure	PSIA	N/M²

For JPFLAG = 1 option the following must be input:

Item Name		Input Quantity	Units
PTB(1)	=	normalized pressure table entries*	none
ZTB(1)	=	normalized pressure table coordinates**	none
NTB	=	number of pressure table entries, ≤ 127	none
Z	=	initial axial position	none

---

* normalized to input chamber pressure, PC

** normalized to input throat radius, RSTAR. ZTB represents the streamline path length.

Table 6-12: Input Data for a Hydrazine Monopropellant Engine

```
THERMO
   300.000  1000.000  5000.000
H2
                         J 3/61H  2.0  0.0  0.0  0.G   300.000  5000.000     1
   .31001901E+01  .51119464E-03  .52644210E-07 -.34909973E-10  .36945345E-14  2
  -.87738042E+03 -.19629421E+01  .30574451E+01  .26765200E-02 -.58099162E-05  3
   .55210391E-08 -.18122739E-11 -.98890474E+03 -.22997056E+01                 4
N2
                         J 9/65N  2.0  0.0  0.0  0.G   300.000  5000.000     1
   .28963194E+01  .15154866E-02 -.57235277E-06  .99807393E-10 -.65223555E-14  2
  -.90586184E+03  .61615148E+01  .36748261E+01 -.12081500E-02  .23240102E-05  3
  -.63217559E-09 -.22577253E-12 -.10611588E+04  .23580424E+01                 4
NH3
                         J 9/65N   1H   300  000  0G   300.000  5000.000     1
 0.24165177E 01 0.61871211E-02-0.21785136E-05 0.37599090E-09-0.24448856E-13  2
-0.64747177E 04 0.77043482E 01 0.35912768E 01 0.49388668E-03 0.83449322E-05  3
-0.83833385E-08 0.27299092E-11-0.66717143E 04 0.22520966E 01                 4
END
TITLE 5 LB THRUSTER, N2H4 MONOPROPELLANT
DATA
 $DATA
 ODK    = 1,
 RSI    = .0937,
 ECRAT  = 29.2,
 RI     = .01,
 THETAI = 70,
 RWTU   = 1.846,
 RWTD   = 1.846,
 IWALL  = 5,
 RMAX = 9.872, ZMAX = 33.404,
 $END
SPECIES MOLE FRACTIONS
          NH3                   .17310
          N2                    .30448
          H2                    .52242
REACTIONS
END TBR REAX
LAST CARD
 $ODK
 JPRNT  = -2,
 EP     = 97.456,
 ARPRNT = 2,5,10,15,20,25,30,40,50,60,70,80,90,97.456,
 NJPRNT = 14,
 SHGAMF = 1,
 PSIA   = T,
 PC     = 106,
 T      = 2030,
 V      = 64.76,
 PI     = 105.97,
 PESTAR = 57.812,
$END
```

6.5.3.7 MASS AVERAGED ØDK ISP

A mass averaged ØDK ISP summary page may be obtained at the end of the ØDK calculations as described below:

Item Name		Description
MAVISP	=1	Specifies mass averaged ISP option
XM(1)	=	Ratio of mass flow rate of each zone (zone 1 = inner zone) to the total mass flow rate.

6.6 $TRANS NAMELIST INPUT.

When a MØC problem has been specified, the input data set $TRANS is required for the transonic calculation.

Item		Description	Assumed Value(s)
$TRANS	=	Namelist, read in subroutine TRAN	
XM(1)	=	Ratio of mass flow rate of each zone (zone 1 = inner zone) to the total mass flow rate. (need not be input if MAVISP = 1 option specified and XM input in $ØDK).	50*0
ALI	=	Number of degrees initial line will be displaced downstream. The program assumes ALI is zero. If ALI is not zero, a symmetric throat is required (RWTD = RWTU).	0
IBUG	=	If input is nonzero, intermediate transonic output will be printed.	0

The following input may be used to control the construction of the initial line:

Item	Description	Assumed Value(s)
MP	Number of points to be placed on the initial line. $MP \leq 275$. A sinusiodal distribution of the following form is used: $r_i = [r_w \sin(\frac{i}{N}\frac{\pi}{2})]^{\varepsilon_1} \quad i = 0,1,2....N$ where N = MP and ε_1 is EXP1 described below. Editing is done to control the spacing, see DRMIN and DRMIN1.	50

Item		Description	Assumed Value(s)
EXP1	=	ε_1 for sinusoidal distribution.	1.2
DRMIN	=	Editing criteria for sinusoidal distribution. The first initial line point below the wall, r_1, will be spaced such that $r_w - r_1 >$ min [DRMIN * RWTD, .025] If a value of SHØCK=1 is to be input in $MOC, then set DRMIN=.001	.01
DRMIN1	=	Editing criteria for sinusoidal distribution. Points on the initial line will be spaced such that $r_n - r_{n-1} >$ DRMIN1	$5*10^{-4}$

$END

6.7 $MOC NAMELIST INPUT.

This data set contains the input items for the supersonic Method of Characteristics (MOC) module. The items are divided into four types, which are described in the following subsections.

6.7.1 Characteristics Mesh Control
6.7.2 MOC Shock Option
6.7.3 Print Control
6.7.4 Inputs from DER
6.7.5 Exit Plane Option

Often no $MOC input is necessary since the default values are usually sufficient.

6.7.1 Characteristics Mesh Control

Item Name		Input Quantity	Units	Assumed Values
$MOC	=	Namelist name, read by subroutine CHAR.		
DS	=	insertions will be made such that successive points along streamlines will not be separated by more than DS $*M^{1/2}$ as described in Subroutine CNTRL.	none	.15
DTWI	=	$\Delta\theta_{t\omega}$ criterion for insertion in subroutines INPT and DSPT as described in Subroutine CNTRL.	degrees	2.
DWWCI	=	throat wall point insertion control parameter $\Delta\theta_{wc}$ described in Subroutine CNTRL.	degrees	.5
DWWI	=	wall point insertion control parameter $\Delta\theta_{\omega}$ described in Subroutine CNTRL.	degrees	3.
EPW	=	the program will insert such that the wall end point is located within a tolerance EPW.	none	.01
ES	=	ε_s for point editing as described in Subroutine CNTRL.	none	.0001

Item Name		Input Quantity	Units	Assumed Values
ETHI	=	ε_θ for point editing as described in Subroutine CNTRL.	degrees	.25
IMAX	=	the maximum number of iterations to be allowed while attempting to achieve a relative convergence for the flow variables of $5*10^{-5}$.	none	10
IMAXF = 1		the program will terminate the case if a printed point requires maximum iterations for convergence.	none	0
or				
IMAXF = 0		the program will continue the case after IMAX iterations per point have occurred.		
STOPIL	=	if a value other than zero is input, then the program will construct the initial data line for the MOC and call EXIT at the end of subroutine CHAR. No MOC calculations will be done.	none	0.
TEXPLI	=	input temperature below which explicit integration for the species concentrations will be used (not recommended).	$^\circ$R, $^\circ$K if SI Units	0.

6.7.2 MOC Shock Option

The shock option can be run for the following problem types:

TDK,
TDF,
PFG0PT.

The shock option cannot be run for the following problem types:

TDE,
TTDK.

There are three methods by which the shocks can be located, as discussed below.

a) Induced Shock Option

If the MOC induced shock option is requested (SH0CK=1, ISHCK=2), then the mesh construction begins at the intersection of the initial data line and the flow axis. RRC's are constructed. After the nozzle wall is reached, succesive RRC's may cross. If so, a shock is inserted into the flow field at the cross-over point. Next, LRC's are constructed starting at the wall, and the region up to the cross-over point is filled in. The LRC construction then continues with the 1st point on each LRC being a right running shock point. When the axis is reached, the shock is reflected as a left running shock. The program then reverts to a RRC construction scheme and the shock is traced until it reaches the wall. It is then reflected from the wall, and is calculated as a right running shock propagating towards the flow axis. Only one shock will be traced, but multiple reflections are allowed.

b) Attached Shock Option

In the case of an attached shock (ISHCK=3), the mesh construction is the same as for the induced shock up to the requested x-location (XA) of the attached shock. Then, instead of looking for a crossing of RRC's, a shock point is attached to the wall at the XA location. The shock strength is determined by the deflection angle of the wall at the XA location. The shock is then traced just like in the case of an induced shock.

c) Multiple Shock Option

Two shocks can be traced with the multiple shock options (ISHCK=6 or 7). The first shock can be either an induced shock (ISHCK=6) or an attached shock (ISHCK=7), but the second shock must be an attached shock. The x-location of the second attached shock is specified by the variable XB.

The mesh construction for this option is now described. The first shock is calculated as above until the end of the nozzle is reached. Next, the calculation of the second shock and part of the flow field affected by it is repeated. In this construction, the first shock may not go to the center line and the two shocks must not cross over inside the nozzle.

ITEM NAME	INPUT QUANTITY	ASSUMED VALUE
SHØCK=	If SHØCK=0, shocks will be ignored and the MOC flow field will use LRC construction. If SHØCK=1, a shock will be inserted traced as described above.	0

ITEM NAME	INPUT QUANTITY	ASSUMED VALUE
ISHCK=	If ISHCK=2, crossing of RRC's will be ignored for all RRC's that originate at the wall upstream of axial coordinate position XA. If the shock is too strong, it cannot be ignored. If ISHCK=3, an attached shock is started at the XA position. If ISHCK=6, two shocks are traced. The first one is an induced shock as in ISHCK=2 and the second is an attached shock at the axial coordinate position XB. If ISHCK=7, two shocks are traced. The first one is an attached shock as in ISHCK=3 and the second is an attached shock at the axial coordinate position XB.	2
XA=	Axial coordinate position on wall discussed under ISHCK, above.	tangent point at end of throat circular arc.
XB=	Axial coordinate position on wall as discussed under ISHCK=6 or 7 above.	0.

6.7.3 Print Control

Item Name		Input Quantity	Units	Assumed Values
N1	=	flow parameters will be printed for every N1th interior point along characteristics selected for print	none	1000
N2	=	every N2th characteristic will be selected for print	none	1000
NC	=	for NC ≠ 0 species concentrations (partial densities) will be printed with the flow parameters. If NC=1 the quantities A, B, γ, heat capacity (BTU/Lb-°R), and enthalpy (ft^2/sec^2) will be appended to the species concentration print.	none	0
MASSFL	=	at the completion of each left running characteristic (LRC) the massflow is integrated. If MASSFL = 0 then no mass flow printed MASSFL = 1 then total mass flow and the number of points on the LRC are printed for each LRC MASSFL = 2 then mass flow for each point along LRC is printed MASSFL = 3 Same as MASSFL = 2 with the addition of execution time at the end of each LRC see Subroutine CHAR	none	1
NDS	=	for NDS = 1 Dividing Streamline Points will be printed. (Nominal) for NDS = 0 Dividing Streamline Points will be suppressed.	none	1

6.7.4 Inputs from DER, Reference 24.

Item Name		Input Quantity	Units
ØFBAR	=	Overall mixture ratio including condensed phases. For print out only.	none
ETABAR	=	Overall evaporation efficiency, i.e. the ratio of gas flow to total propellant flow at the throat. I_{sp}, total = $I_{sp,gas}$ *ETABAR	none
DRPISP	=	Ratio of total condensed phase momentum to the mass flow at the throat. Not used, reserved for future use.	lbf sec/lbm (if SI Units then N sec/kg)

6.7.5 Exit Plane Option

On option, the TDK method of characteristics calculation will continue the mesh construction through the exit plane of the nozzle and print a summary of the exit plane properties.(not operational for the shock option.)

<u>Item</u>		<u>Description</u>	<u>Assumed Value(s)</u>
EXITPL	=	Exit plane calculation requested if set .TRUE.(not operational for shock option.) For the case when two TDK runs are to be made, i.e., when IRPEAT = 1, or 2 in $DATA then the exit plane will be computed for the second TDK run, but not for the first TDK run.	.FALSE.

$END

6.8 Boundary Layer Module (BLM) Input Data, $BLM

This input data set is required if the BLM is to be executed, i.e., if BLM = 1.0 was input in the $DATA namelist. Most of the data required by the BLM is communicated automatically by the 0DE and/or M0C modules, or is preset as assumed values. Hence, these data items do not necessarily need to be input to the BLM module. However, any value that is read in will override the assumed or communicated value.

The input data items to the BLM module are as follows.

Item		Description	Units	Assumed Value(s)
$BLM	=	Namelist name, read in Subroutine INPUTB		
WD0T2D	=	$\dot{w}_{2D}$, nozzle mass flow. If the MOC module was not executed, a value can be input here so that a boundary layer ISP decrement can be computed.	lb/sec	1.
IPRNT	=	If IPRNT = 1, then print the boundary layer profiles at every 5th station.	-	0

6.8.1 BLM Gas Properties

Gas properties that are required by the BLM are γ, C_p, R, and μ versus T, and a value for the Prandtl number, P_r, and the total enthalpy, h_T. Ordinarily these values are supplied automatically by the ODE module. The tables are prepared by ODE using a series of (T,S) equilibrium (or frozen) calculations, where T varies from 600°R to 7000°R at 200°R increments. The chamber entropy value is used for S. Values at 100°R are then extrapolated and added to the table. The tables are printed with the BLM output. Constants defining the gas viscosity, μ, and the Prandtl number, P_r, are also prepared by the ODE module.

Values for any or all of the above items can be input and used in place of the values prepared by ODE. If the ODE module has not been run, then all of the items listed below must be input. The assumed values are for air with constant C_p.

ITEM	DESCRIPTION	UNITS	ASSUMED VALUE(S)
CKO(1) =	Table of ratio of specific heats, γ, versus T.	none	2*1.4
CPO(1) =	Table of specific heat at constant pressure, C_p, versus T	ft/sec-R	2*6006
HS(1) =	Table of static enthalpy, h, versus T	ft^2/sec^2	-6.01E5,3.88E6

ITEM		DESCRIPTION	UNITS	VALUE(S)
HTOTAL	=	Total enthalpy, h_T, such that $h_T = h(T_{chamber})$.	ft^2/sec^2	3.85E6
RRO(1)	=	Table of gas constant, R=1546.33/Mw vs T.	lb-ft/lbm°R	2*53.3
TO(1)	=	Temperatures corresponding to the entries in CKO, CPO, RRO, and HS arrays, above.	°R	440,7000
NTAB	=	number of values entered in the CKO, CPO, and TO arrays. $2 \leq NTAB \leq 101$.	-	3
RMUI	=	Reference viscosity, μ_o, where viscosity is expressed as $\mu = \mu_o(T/T_o)^\omega$	lbm/ft-sec.	$.605934*10^{-4}$
TI	=	reference temperature, T_o, for viscosity. See RMUI, above.	°R	6032
OMEGA	=	Viscosity exponant, ω. See RMUI, above.	-	.76
PR	=	Molecular Prandtl number, Pr.	-	.72

Note: The above default values for μ_o, ω, and Pr are for air.

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ITEM		DESCRIPTION	UNITS	VALUE(S)
HTOTAL	=	Total enthalpy, h_T, such that $h_T = h(T_{chamber})$.	ft^2/sec^2	3.85E6
RRO(1)	=	Table of gas constant, R=1546.33/Mw vs T.	$lb\text{-}ft/lbm\,^oR$	2*53.3
TO(1)	=	Temperatures corresponding to the entries in CKO, CPO, RRO, and HS arrays, above.	^oR	440,7000
NTAB	=	number of values entered in the CKO, CPO, and TO arrays. $3 \leq NTAB \leq 101$.	-	3
RMUI	=	Reference viscosity, μ_o, where viscosity is expressed as $\mu = \mu_o(T/T_o)^\omega$	lbm/ft-sec.	$.605934*10^{-4}$
TI	=	reference temperature, T_o, for viscosity. See RMUI, above.	^oR	6032
OMEGA	=	Viscosity exponant, ω. See RMUI, above.	-	.76
PR	=	Molecular Prandtl number, Pr.	-	.72

Note: The above default values for μ_o, ω, and Pr are for air.

6.8.2 Boundary Layer Edge Conditions

The coordinates for the boundary layer are specified in the RIN0 versus XIN0 table. Conditions at the inviscid edge are specifed in the UE0, TE0, and PE0 versus XIN0 tables. Conditions at the wall are specified in the TQW and CQW versus XTQW tables. The program will redistribute the input stations (up to 501 total) in order to have 101 x-stations uniformly distributed per segment, except for the first five stations which are generated non-uniformly. The input values of y, U_e, T_e, P_e, T_w (or q_w), and $(\rho V)_w$ are interpolated at the new x-stations and used in the boundary-layer calculations.

Values of RINO versus XINO and the conditions at the inviscid edge of the boundary layer will be automatically transmitted from the MOC module if it has been run. Otherwise, they must be input here. See the description of I0FF in $DATA. Conditions at the wall must always be input here.

Item		Description	Units	Assumed Value(s)
XIN0(1)	=	x_e axial coordinate	none	-
RIN0(1)	=	y_e, radial coordinate	none	-
UE0(1)	=	U_e, gas velocity at the inviscid edge	ft/sec	-
TE0(1)	=	T_e, gas static temperature at the inviscid edge	^{o}R	-
PE0(1)	=	P_e, gas pressure at the inviscid edge	psi	-
NXIN0	=	number of items in the XIN0, RIN0, UE0, TE0, and PE0 tables. $2 \le$ NXINO ≤ 501 Do not input if I0FF was input in $DATA.	none	-

Item		Description	Units	Assumed Value(s)
XTQW(1)	=	X_w, axial coordinate for the TQW and CQW tables.	none	-1000.,0.,1000.
IHFLAG	=	Flag specifying wall boundary condition input through TQW array. IHFLAG = 0, for temperature IHFLAG = 1, for heat flux*	-	1
TQW(1)	=	T_w, wall temperature or $\dot{q}_w$, wall heat flux, depending in IHFLAG. For an adiabatic wall, set IHFLAG = 1 and all TQW(1) = 0. For a non-adiabatic wall with prescribed heat flux, set IHFLAG= 1, and note that for heat flux from the boundary layer to the wall, the TQW(1) entries will be negative.	$^{\circ}R$ or $\frac{BTU}{in^2\text{-}sec.}$	501*0.
CQW(1)	=	$(\rho V)_w$, mass transfer parameter at the wall (only useful for suction)	lbm/ft^2-sec	501*0
NTQW	=	Number of axial stations, X_w. Each of the above tables must have this number of entries. $2 \leq$ NTQW ≤ 501.	-	3

---

* Default values are set for an adiabatic wall, i.e., IHFLAG = 1, and TQW(1) = 501*0.

6.8.3 Integration Step Size Control.

Item		Description	Units	Assumed Value(s)
NSEGS	=	Number of Segments, $1 \leq \text{NSEGS} \leq 10$ The boundary layer will be divided into segments of equal length unless values are input into XSEG, below.	none	1
NISPS(1)	=	Number of Integration Steps per Segment, ≤ 101 per segment.	none	10*101
XSEG(1)	=	Vector containing the axial (x) locations which define the wall segments. The vector is always NSEGS + 1 values long. Default values are: $\text{XSEG}(i) = z_c + (z_m - z_c)\,(i-1)/\text{NSEGS} \quad i=1,2,\ldots\text{NSEGS}+1$ where z_c and z_m are the end of the cylindrical combustion chamber, and the end of the nozzle, respectively, as shown in Figure 6-1 . If the boundary layer is to be extended upstream of z_c, the usual procedure is to input XSEG(1) = XIN0(1) and XIN0(1) through XIN0(IOFF), etc., of \$BLM are input by the user as described in \$DATA under input item I0FF.	none	see description
NTR	=	Station at which transition to turbulent flow is allowed. The program starts with an assummed boundary layer profile, and then turns on the eddy viscosity terms for turbulent flow at station NTR. For a laminar boundary layer, set NTR large, i.e. NTR > $\sum$ NISPS(I).	none	3

Note: The default value of NSEGS=1 is often too small for reliable results. The user must specify enough segments and integration steps (NISPS) so that reliable results are computed. In general, nozzles with high area ratio and/or low Renolds number flow will require more integration steps. See example cases in Section 7.

6.8.4 Regenerative Cooling Heat Transfer.

When an engine is cooled using a regenerative device, propellant (usually fuel) is routed around the nozzle so that heat is transmitted from the boundary layer to the coolant. This heat is then returned to the combustion chamber in the form of increased propellant enthalpy. When the nozzle wall temperatures are assumed known (IHFLAG = 0 option), the BLM will calculate the heat flux from the boundary layer to the wall, $\dot{h}_w$(BTU/ft -sec). These values can also be input directly (IHFLAG = 1 option). If the coolant circuit extends from position x_e to position x_o and operates at an efficiency, η , then the propellant enthalpy entering the chamber will be increased by

$$\Delta H = \frac{1}{\dot{m}_T} \eta \int_{x_o}^{x_e} \dot{h}_w dA \qquad \text{(BTU/lbm)}$$

where

$\dot{m}_T$ is the total engine mass flow rate

dA is the nozzle surface area differential, $2\pi r ds$

Using the method outlined above, the BLM will compute increments of propellant enthalpy for up to 3 fuel or oxidizer circuits and print out the resultant enthalpy increments. These can be added to a later computer run by using the DELH1(1) input array. If BLM is to be automatically rerun, then the enthalpy increments will automatically be stored into DELH1(1) for the second pass through ODE, ODK, and TDK. These enthalpy increments can be calculated in two ways. If the enthalpy increase is distributed equally throughout the chamber, then

$$\Delta H_i = \Delta H$$

i.e.

DELH1(1) = ΔH, ΔH, ... etc.

The second method is to assume that a fuel circuit adds enthalpy only to fuel, and an ox circuit adds enthalpy only to ox. It follows that

for a fuel circuit

$$\Delta H_i = \left(\frac{r+1}{r_i+1}\right) \Delta H$$

and for an ox circuit

$$\Delta H_i = \left(\frac{r+1}{r_i+1}\right) \frac{r_i}{r} \Delta H.$$

where r_i is the mixture ratio of zone i and r is the overall chamber mixture ratio.

For either method, the steady state engine cycle balance can be approximated as follows. First, calculate "adjusted tank enthalpies" for the fuel and for the oxidizer and input these on the reactant cards. These values must approximate the energy content of the propellant entering the main combustion chamber accounting for all energy gains and losses, except heat returned to the main combustion chamber by the regen cooling circuit(s). Estimates for these amounts are to be entered using the DELH1(1) input array. An estimate of zero is usually satisfactory. Corrected estimates will be calculated by BLM and stored in DELH1(1) for a second pass through TDK (or TDE). A second pass using these values will be executed automatically if IRPEAT = 1 was input in the $DATA namelist.

Item		Description	Assumed Value(s)
XCO(1)	=	the Ith entry is the starting position for the Ith cooling circuit*.	3*0
XCE(1)	=	the Ith entry is the ending position for the Ith cooling circuit*.	3*0
ETAC(1)	=	the Ith entry is the efficiency for the Ith cooling circuit.	3*1
ØFC(1)	=	Type of coolant for the cooling circuit: ØFC(I) = 0. if there is no ith circuit ØFC(I) = 1. if the Ith circuit is oxidizer ØFC(I) = 2. if the Ith circuit is fuel $I \leq 3$	3*0
DISTRB(1)	=	Flag for method of distributing ΔH increments DISTRB(I) = 0. for equal distribution of heat to chamber DISTRB(I) = 1. for distribution of ox heat to ox in chamber, and fuel heat to fuel in chamber.	3*1.

The Ith entry is for the Ith circuit.

---

* Normalized by the throat radius, r_t.

6.8.5 BLM Plotted Output.

The input described below is used to control plotted output from the BLM. The plot options available from BLM are:

1) Momentum thickness, θ, vs. axial position.
2) Displacement thickness, δ^*, vs. axial position.
3) Wall Temperature, T_w, vs. axial position.
4) Velocity profiles at specified area ratios, or at specified axial locations.
5) Temperature profiles at specified area ratios, or at specified axial locations.

Example plots are presented in Figures 6-2 through 6-5 for types 1 through 5, above.

Item		Description	Assumed Value(s)
IPRØF	=	If IPRØF = 0, then supersonic area ratios are input in APRØF. If IPRØF = 1, then axial locations, x/r_t, are input in APRØF	0
APRØF(1)	=	Area ratios (or axial locations, see IPRØF) at which velocity ratio and temperature ratio profiles will be plotted. Two frames per area ratio will be plotted: U/U_{edge} vs. y/y_{edge} and T/T_{edge} vs. y/y_{edge}.	20*0
NPRØF	=	Number of area ratios (or axial locations) requested in APRØF. NPRØF $\leq$ 20.	0
KDTPLT	=	If KDTPLT = 1, then displacement thickness, δ^*, vs. axial location, x, will be plotted.	0
KMTPLT	=	If KMTPLT = 1, then momentum thickness, θ, vs. axial location, x, will be plotted.	0
KTWPLT	=	If KTWPLT = 1, then wall temperature, T_w, vs. axial location will be plotted.	0

$END

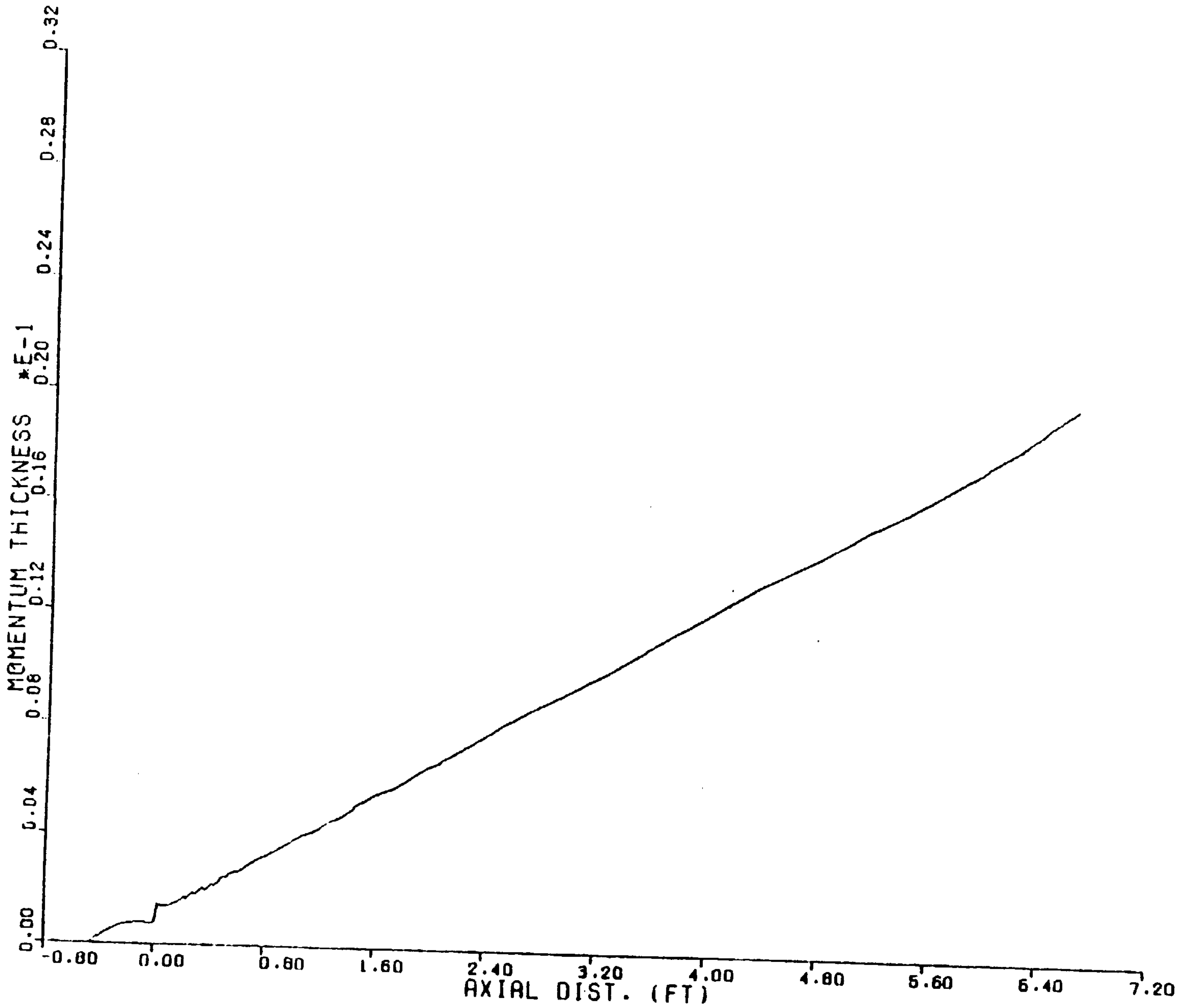

Figure 6-2: Boundary Layer Momentum Thickness vs Axial Position (See Section 7.3)

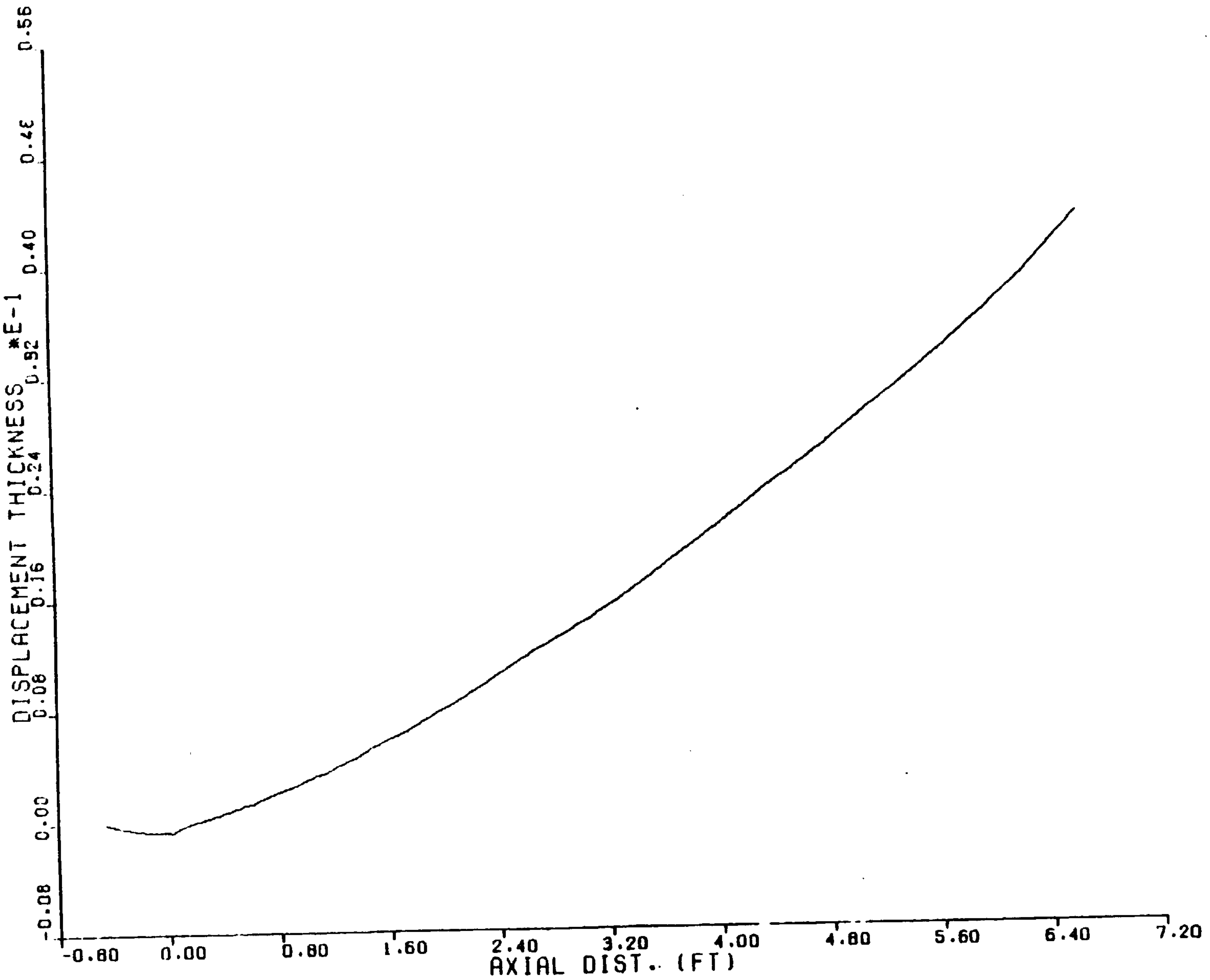

Figure 6-3: Boundary Layer Displacement Thickness vs Axial Position

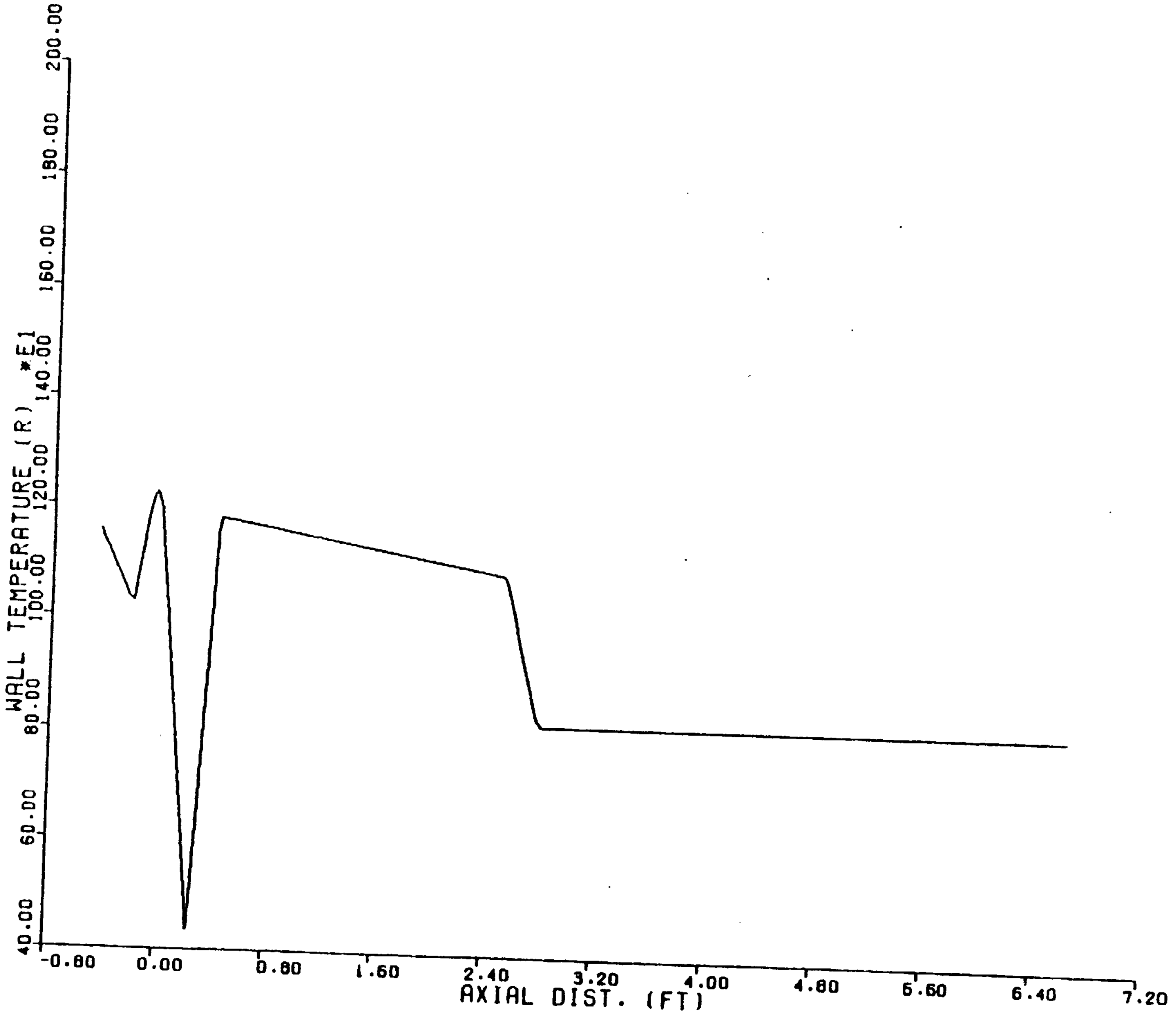

Figure 6-4: Wall Temperature (Input) vs Axial Position

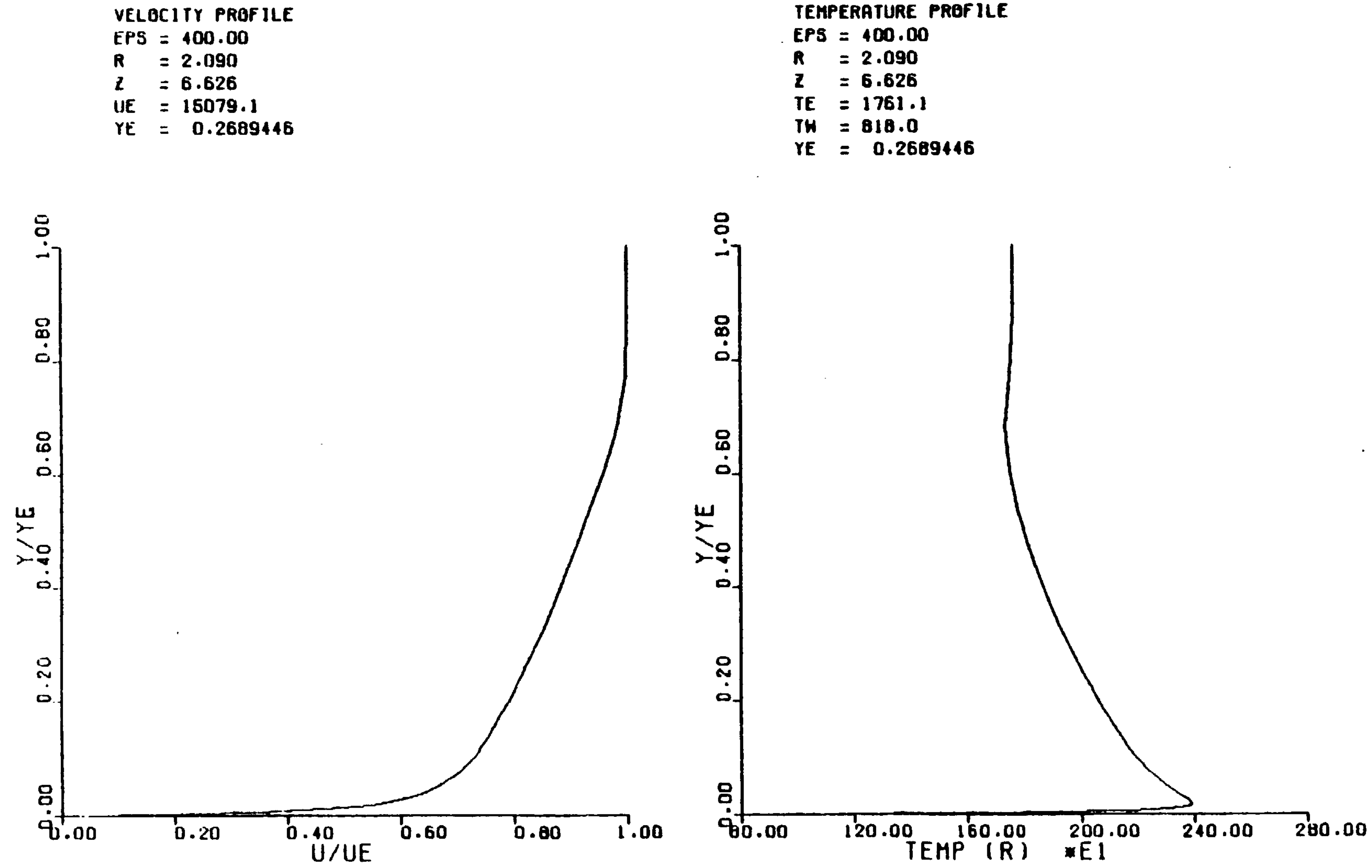

Figure 6-5: Velocity and Temperature Profiles at a Given Area Ratio

6.9 SPECIAL OPTIONS.

6.9.1 Constant Properties Gas Option.

The TDK program contains a useful option by which the real gas chemistry can be replaced by constant properties chemistry. Multiple zones can be calculated. The output includes the nozzle divergence efficiency, η_{DIV}, (see Section 5, subroutine PRINT).

The constant properties gas option is run by input of PFG0PT = 1 in $DATA. Sample input data for the constant properties gas option is listed in Table 6-13.

Only the $DATA, $TRAN and $M0C data sets are to be input. These data sets are input as described in Sections 6.3, 6.6 and 6.7, respectively, with the following required additions to the $TRANS Namelist.

G(1) = Value of specific heat ratio, γ, for each zone, inner to outer, the number of zones is specified in $DATA.

PSA = Chamber pressure in lbs/in^2. (N/m^2 if SI units)

XP(1) = (From Table 6-9) All assumed = 1, if not input.

TC(1) = Chamber temperature, ^oR, for each zone, inner to outer. (^oK if SI units)

RGC(1) = Real gas constant, ft^2/sec^2 ^oR, (i.e., $49721/M_w$ = $g*J*1.986/M_w$) for each zone, inner to outer. (m^2/sec^2 ^oK if SI units). Not needed if XMW is inpu

XMW(1) = Gas Molecular Weight. If input then RGC(1) need not be input.

Table 6-13: Sample Case for the Constant Properties Gas Option.

```
TITLE SAMPLE CASE ONC
DATA
 $DATA
 PFGOPT=1,
 NZONES=1,
 RSI=2,
 RWTU=2, RWTD=.5,
 THETA=35.6738,
 IWALL=4,
 NWS=11,
 RS(2)= 1.16843,1.26475,1.47910,1.73375,2.04940,2.45930,
        3.68226,4.84772,5.79198,6.32481,
 ZS(2)=  .39575, .53008, .82905,1.19473,1.66923,2.32795,
        4.68717,7.68599,10.9601,13.3114,
  THE=11.5813,
  $END
  $TRANS
  G=1.23,
  PSA=100,
  TC=5500,
  XMW=20,
  XM=1,
  ALI=0,
  $END
  $MOC
  $END
```

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6.10 INITIAL VALUES FOR THE $ØDK, $TRANS, AND $TDK INPUTS

The following defines nominal values to which variables will be set if not input. If a variable is ~~not~~ listed, no nominal value is set. Variables are set in the subroutine containing the Namelist read..

$ØDE, set in subroutine ØDES

DELH(I) = 0. , DELH1(I) = 0
ECRAT = 0.
EQL = .TRUE.
EQTHST = .FALSE.
ERATIØ = .FALSE.
FA = .FALSE.
FPCT = .FALSE.
FRØZ = .TRUE.
IØNS = .FALSE.
KASE = 0
LISTSP = .FALSE.
ØF = .FALSE.
ØFSKED(I) = 0.
P(I) = 0.
PCP(I) = 0.
PSIA = .FALSE.
RELERR = .0005
RKT = .FALSE.
SI = .FALSE.
SUBAR(I) = 0.
SUPAR(I) = 0.
WFLØW = 0.
XP(I) = 1.

$ØDK, set in subroutine ØDKINP

CØNDEL = 1.0E-6
DEL = .001
EPS = 0.
EPSEL = 1.0E-5
HI = .01
HMAX = .10001
HMIN = .005
IDYSCI = 0
IWALL = 1
JF = 0
JPFLAG = 0
JPRNT = -1

TEXPLI = 0.
XM(I) = 0.
XMFTST = 1.0E-3

$TRANS, set in subroutine TRAN

ALI = 0.
IBUG = 0
MP = 50
PMCRIT = 1.
PMDEG = 1.
XM(I) = 0.

$TDK, set in subroutine CHAR

DRPISP = 0.
DS = .15
DTWI = 2.
DWWI = 3.
EPW = .01
ES = .0001

$TDK (cont'd)

ETABAR = 1.
ETHI = .25
IMAX = 10
IMAXF = 0
MASSFL = 1
NC = 0
NDS = 1
N1 = 1000
N2 = 1000

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7. INPUT AND OUTPUT FOR SAMPLE CASES

In this section of the report input and output are presented for three engines, as follows:

1) the stratified flow engine.
2) the Pratt and Whitney RL-10 engine (prototype for OTV propulsion).
3) the Rocketdyne Advanced Space Engine, ASE, (prototype for OTV propulsion).

Complete input and output are given for the first case. For the next two cases only the program input and the summary output are given. All of the calculations were performed using a DEC PDP 11/750 VAX computer system.

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7.1 THE STRATIFIED FLOW ENGINE, CASE 1

This test case is the same one that has appeared in all earlier versions of the TDK program manual. It is similar to the Rocketdyne stratified flow engine that is presented in CPIA 246, Ref. 1.

On the following pages input and output for the problem are presented. The engine operates with liquid oxygen/gaseous hydrogen propellants. The injector is assumed to produce a stratified nozzle flow with a mixture ratio of 6.5 near the axis, 8.0 in the central zone, and 5.0 near the wall. Equal mass flow is assumed for each of these zones. Each zone is assumed to have a different stagnation pressure. The pressures are 300, 285, and 270 psia from axis to wall.

The modules used in performing the analysis are ODE, ODK, TDK, and BLM. A brief description of the computer output is presented below, followed by Table 7-1 which is a complete listing of the computer program print out.

The output sequence for case 1 is outlined below:

1. Program name.
2. All input data cards are listed.
3. ODE subprogram output.
    a. Fuel/Oxidizer mixture description and list of species considered.
    b. Equilibrium calculation output; Frozen calculation output.
    c. Summary of · Equilibrium Contraction Ratio conditions.
4. ODK subprogram output.
    a. Listing of Reactions, etc., cards as they are read.
    b. Species list from Reactions.
    c. Reaction table.
    d. Selected species list for kinetic expansion.

e. Dissociation/Recombination reaction rate ratios.

f. Initial and Throat conditions for one dimensional 0DK expansion.

5. 2 and 3 above are repeated for each zone with redundant print omitted.

6. ODK I_{sp} summary.

7. Inputs to the transonic calculations and the calculated results are printed. These include γ, mass flow for each zone and, the slipline locations, Y_n.

8. Number of points on the initial line, characteristics mesh control parameters and table of x vs. r wall coordinates are printed. The wall table is used by TDK to define the nozzle wall downstream of the throat plane (see Subroutine WALL).

9. A table of P, ρ, θ, V, r, x, and mass flow rate is printed corresponding to the initial data line for starting the method of characteristics calculations. The method used to calculate the mass flow rate, $\dot{m}$, and the characteristic velocity, C*, (also printed) is described in Subroutine CHAR.

10. Results of the method of characteristics calculations are then printed. The calculations begin at the initial data line (until the axis is reached) and follow each left running characteristic to the wall.

11. TDK performance summary.

12. BLM title page.

    BLM input geometry, and values of velocity, temperature, and pressure at the edge.

13. Gas properties table supplied by the ODE module.

14. BLM geometry and edge conditions that are equally spaced in X.

15. BLM output data corresponding to 14, above.

16. Nozzle wall geometry displaced inwards a distance δ^* normal to the input wall contour.

17. TDK performance summary, including the effects of the boundary layer.

TABLE 7-1. INPUT AND OUTPUT FOR THE STRATIFIED ENGINE TEST CASE (3 ZONES).

```
$SET NOVERIFY


************************************************************************************************************************
                   TWO  DIMENSIONAL  KINETIC  PROGRAM (TDK), OCTOBER 1985 VERSION

                   SOFTWARE AND ENGINEERING ASSOCIATES, INC.
                   1050 E WILLIAM STREET, SUITE 402, CARSON CITY NEVADA 89701
                   (702) 882 1966
************************************************************************************************************************
```

```
TITLE  3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE
DATA
 $DATA
 NZONES=3, ODE=1, ODK=1, TDK=1, BLM=1,
 ECRAT=3.,ASUB(1)=3.,NASUB=1,
 ASUP(1)=2.,4.,10.,15.,20.,25.,NASUP=1,
 RSI=2.,RWTU=1.,RWTD=1.,THETAI=30,RI=2.,
 IWALL=1, THETA=15.,
 EPS=2.,
 $END
REACTANTS
H 2.                                            100.      -2154.L   20.27F .0709
O 2.                                           99.398     -3102.L   90.180 1.149
N 2.                                             .053     -2939.L   77.350 .808
AR1.                                             .549     -2607.L   90.  0

NAMELISTS
 $ODE
 RKT=.TRUE.,
 P(1)=300.,PSIA=.TRUE.,
 XP(1)=1.,.95,.9,
 OFSKED(1)=6.5,8.,5.,
 $END
REACTIONS
H + H = H2      ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U
H + OH = H2O    ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U
O + O = O2      ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U
O + H = OH      ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U
END TBR REAX
O2 + H = O + OH    , A = 2.2E14, N = 0.0, B =16.8,   BAULCH 72 (A) 1.5U
H2 + O = H + OH    , A = 1.8E10, N = -1., B = 8.9,   BAULCH 72 (A) 1.5U
H2 + OH = H2O + H  , A = 2.2E13, N = 0.0, B =5.15,   BAULCH 72 (A) 2U
OH + OH = H2O + O  , A = 6.3E12, N = 0.0, B =1.09,   BAULCH 72 (A) 3U
LAST REAX
INERTS N2,AR,END
THIRD BODY REAX RATE RATIOS
M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
LAST CARD
 $ODK
 JPRNT=-2,
 EP=2, XM=.3333,.3334,.3333, MAVISP=1,
 $END
 $TRANS
 MP=60,
 XM = .3333,.3333,.3334,
 $END
 $MOC
 NC=0,
 $END
 $BLM
 IHFLAG=1,
 NSEGS=1
 $END

 TITLE  3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE

 DATA
```

```
************************************************************************************************************************

                    CALCULATE ODE AREA RATIO AND PRESSURE SCHEDULES FOR ZONE  1

************************************************************************************************************************
REACTANTS
H   2.0000       0.0000      0.0000      0.0000      0.0000  100.000000      -2154.00  L    20.270  F    0.07090
O   2.0000       0.0000      0.0000      0.0000      0.0000   99.398003      -3102.00  L    90.180  O    1.14900
N   2.0000       0.0000      0.0000      0.0000      0.0000    0.053000      -2939.00  L    77.350  O    0.80800
AR  1.0000       0.0000      0.0000      0.0000      0.0000    0.549000      -2607.00  L    90.000  O    0.00000
NAMELISTS

SPECIES BEING CONSIDERED IN THIS SYSTEM
   L 5/66  AR               J 6/74  H             J 3/61  H2            J 3/61  H2O           J 3/61  N
   J 6/63  NO               J 9/65  N2            J 6/74  O             J12/70  OH            J 9/65  O2
   J 9/65  NH3

OF =    6.500000

                             EFFECTIVE FUEL          EFFECTIVE OXIDANT          MIXTURE
ENTHALPY                         HPP(2)                   HPP(1)                  HSUBO
(KG-MOL)(DEG K)/KG         -0.53769275E+03          -0.48698235E+02          -0.11389750E+03

KG-ATOMS/KG                      BOP(I,2)                 BOP(I,1)                 BO(I)
       H                   0.99209303E+00           0.00000000E+00           0.13227907E+00
       O                   0.00000000E+00           0.62126074E-01           0.53842597E-01
       N                   0.00000000E+00           0.37839032E-04           0.32793829E-04
       AR                  0.00000000E+00           0.13742865E-03           0.11910484E-03

ENTHALPY IN BTU/LBM :
    FROM REACTANTS :          -407.3996
    FROM DELH( )   :             0.0000
    FROM DELH1( )                0.0000
    TOTAL          :          -407.3996
```

```
                                 ZONE =  1
          THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

PC =    300.0 PSIA
                                                                         WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
         CHEMICAL FORMULA                                                (SEE NOTE)    CAL/MOL          DEG K    G/CC
FUEL     H  2.00000                                                        1.00000   -2154.000    L     20.27   0.0709
OXIDANT O  2.00000                                                         0.99398   -3102.000    L     90.18   1.1490
OXIDANT N  2.00000                                                         0.00053   -2939.000    L     77.35   0.8080
OXIDANT AR 1.00000                                                         0.00549   -2607.000    L     90.00   0.0000

O/F=0.6500E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.1228E+01  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                 CHAMBER   THROAT    EXIT     EXIT
PC/P              1.0000   1.7268   1.0236   7.5244
P, PSIA            300.0    173.7    293.1    39.87
T, DEG R            6110     5821     6098     5093
H, BTU/LB         -407.4   -867.9   -427.6  -1976.5
S, BTU/(LB)(R)    4.2737   4.2737   4.2737   4.2737
DEN (LBM/FT3) 0.639E-010.393E-010.625E-010.107E-01

M, MOL WT         13.966   14.156   13.974   14.618
(DLV/DLP)T      -1.04070 -1.03435 -1.04043 -1.01771
(DLV/DLT)P        1.7427   1.6583   1.7393   1.3878
CP,BTU/(LB)(R)    2.7889   2.6242   2.7827   1.9849
CP GAS(SF)        0.8445   0.8383   0.8443   0.8194
GAMMA GAS(SF)     1.2026   1.2011   1.2026   1.1989
GAMMA (S)         1.1290   1.1271   1.1289   1.1289
SON VEL,FT/SEC    4955.8   4800.5   4948.9   4422.3
MACH NUMBER       0.0000   1.0000   0.2034   2.0037

AE/AT                      1.0000   3.0001   2.0000
CSTAR, FT/SEC                7355     7355     7355
CF  VAC                     1.232    3.068    1.471
CF                          0.653    0.137    1.205
IVAC,LBF-SEC/L             281.59   701.30   336.17
I, LBF-SEC/LBM             149.20    31.28   275.41
MOL WT(MIX)       13.966   14.156   13.974   14.618

MOLE FRACTIONS

AR              0.001663 0.001686 0.001664 0.001741
H               0.046578 0.040226 0.046304 0.023887
H2              0.210243 0.204338 0.209987 0.190609
H2O             0.658171 0.685100 0.659338 0.750661
NO              0.000211 0.000176 0.000210 0.000082
N2              0.000123 0.000144 0.000124 0.000199
O               0.008472 0.006379 0.008377 0.002168
OH              0.063976 0.053383 0.063517 0.027171
O2              0.010562 0.008567 0.010478 0.003483
N               3.23E-07 1.96E-07 3.17E-07 3.70E-08
NH3             1.20E-07 7.84E-08 1.18E-07 2.50E-08

NOTE
      WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
      (SF) STANDS FOR (SHIFTING FROZEN)
```

```
                      FROZEN TRANSPORT PROPERTIES CALCULATED FROM EQUILIBRIUM CONCENTRATIONS
STATION                     MU                   K                      PR
                      (LBF-SEC/FT**2)      (LBF/SEC-DEG R)
CHAMBER               0.19873776E-05       0.69233529E-01        0.60607994E+00
THROAT                0.19250290E-05       0.66055410E-01        0.61080652E+00
EXIT                  0.17565214E-05       0.57843409E-01        0.62205720E+00

VISCOSITY EXPONENT (OMEGA) FOR THE FORM MU=MUREF*(T/TREF)**OMEGA IS     0.68215
MUREF FOR INPUT TO BLM=   0.64018110E-04 LBM/(FT-SEC)

     SPECIES CONSIDERED IN TRANSPORT PROPERTIES CALCULATIONS
    AR                   H                    H2                    H2O
    N                    NO                   N2                    O
    OH                   O2                   NH3
```

```
                                         ZONE =  1
                      THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION

PC =    300.0 PSIA                                                              WT FRACTION  ENTHALPY  STATE    TEMP    DENSITY
                                                                                (SEE NOTE)    CAL/MOL           DEG K     G/CC
          CHEMICAL FORMULA                                                        1.00000    -2154.000    L      20.27    0.0709
FUEL      H  2.00000                                                              0.99398    -3102.000    L      90.18    1.1490
OXIDANT O  2.00000                                                                0.00053    -2939.000    L      77.35    0.8080
OXIDANT N  2.00000                                                                0.00549    -2607.000    L      90.00    0.0000
OXIDANT AR 1.00000

O/F=0.6500E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.1228E+01  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                   CHAMBER    THROAT     EXIT      EXIT
PC/P                1.0000    1.7756    1.0248    8.4239
P, PSIA              300.0     169.0     292.8     35.61
T, DEG R              6110      5543      6085      4221
H, BTU/LB           -407.4    -883.1    -428.6   -1959.2
S, BTU/(LB)(R)      4.2737    4.2737    4.2737    4.2737
DEN (LBM/FT3) 0.639E-010.396E-010.626E-010.110E-01

M, MOL WT           13.966    13.966    13.966    13.966
CP,BTU/(LB)(R)      0.8445    0.8324    0.8440    0.7912
GAMMA (S)           1.2026    1.2062    1.2028    1.2193
SON VEL,FT/SEC      5114.8    4878.8    5104.6    4280.2
MACH NUMBER         0.0000    1.0000    0.2019    2.0588

AE/AT                         1.0000    2.9997    2.0000
CSTAR, FT/SEC                   7182      7182      7182
CF  VAC                        1.243     3.071     1.464
CF                             0.679     0.143     1.227
IVAC,LBF-SEC/L                277.36    685.46    326.89
I, LBF-SEC/LBM                151.64     32.03    273.89

MOLE FRACTIONS
AR            0.001663     H             0.046578     H2          0.210243     H2O         0.658171
NO            0.000211     N2            0.000123     O           0.008472     OH          0.063976
O2            0.010562

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS
N             NH3

NOTE
      WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
```

```
        EQUILIBRIUM CONTRACTION CONDITIONS ZONE  1


        TEMPERATURE (DEGR)       0.60978091E+04

        PRESSURE    (PSIA)       0.29308768E+03

        VELOCITY    (FT/S)       0.10067490E+04
SPECIES MOLE FRACTIONS

          1    AR                0.16643750E-02
          2    H                 0.46303634E-01
          3    H2                0.20998725E+00
          4    H2O               0.65933824E+00
          5    N                 0.31651535E-06
          6    NO                0.20977536E-03
          7    N2                0.12402629E-03
          8    O                 0.83772782E-02
          9    OH                0.63517161E-01
         10    O2                0.10477899E-01
         11    NH3               0.11762109E-06




  ZONE =   1

           REACTIONS                                                                         INTERNAL SEQ NUM
           H + H = H2         ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U     **REAX   1  **
           H + OH = H2O       ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U     **REAX   2  **
           O + O = O2         ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U     **REAX   3  **
           O + H = OH         ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U     **REAX   4  **
           O2 + H = O + OH      , A = 2.2E14, N = 0.0, B =16.8,    BAULCH 72 (A) 1.5U     **REAX   5  **
           H2 + O = H + OH      , A = 1.8E10, N = -1., B = 8.9,    BAULCH 72 (A) 1.5U     **REAX   6  **
           H2 + OH = H2O + H    , A = 2.2E13, N = 0.0, B =5.15,    BAULCH 72 (A) 2U       **REAX   7  **
           OH + OH = H2O + O    , A = 6.3E12, N = 0.0, B =1.09,    BAULCH 72 (A) 3U       **REAX   8  **
  THIRD BODY REAX RATE RATIOS
  M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
  M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
  M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
  M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
```

ORIGINAL PAGE IS
OF POOR QUALITY

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                    SELECTED SPECIES FOR KINETIC EXPANSION

                              ZONE =   1

          1      AR                     0.16643750E-02      INERT SPECIES

          2      H                      0.46303634E-01

          3      H2                     0.20998725E+00

          4      H2O                    0.65933824E+00

          7      N2                     0.12402629E-03      INERT SPECIES

          8      O                      0.83772782E-02

          9      OH                     0.63517161E-01

         10      O2                     0.10477899E-01




                    DISSOCIATION RECOMBINATION REACTION RATE RATIOS

                                   ZONE =   1

   1       0.10000E+01   0.25000E+02   0.40000E+01   0.10000E+02   0.10000E+01   0.25000E+02
           0.25000E+02   0.15000E+01

   2       0.10000E+01   0.12500E+02   0.50000E+01   0.17000E+02   0.10000E+01   0.12500E+02
           0.12500E+02   0.60000E+01

   3       0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
           0.12500E+02   0.11000E+02

   4       0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
           0.12500E+02   0.50000E+01
```

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                                       INITIAL CONDITIONS   KINETIC EXPANSION

                                            ZONE =  1     O/F =    6.5000

    FLOW PROPERTIES                                               NOZZLE GEOMETRY

    MACH NUMBER                          0.19707128E+00           THROAT RADIUS (FT)          0.16666667E+00
    VELOCITY (FT/SEC)                    0.10067490E+04           THROAT WALL RADIUS DNSTREAM 0.10000000E+01
    PRESSURE (PSIA)                      0.29308768E+03           CONE ANGLE (DEG)            0.15000000E+02
    DENSITY (LB/FT3)                     0.62570341E-01           EXPANSION RATIO             0.20000000E+01
    TEMPERATURE (DEG-R)                  0.60978091E+04           CONTRACTION RATIO           0.30000982E+01
    ENTHALPY    (BTU/LB)                -0.42886520E+03           INLET ANGLE (DEG)           0.30000000E+02
    GAS MOLECULAR WEIGHT                 0.13979290E+02           INLET WALL RADIUS           0.20000000E+01
    HEAT CAPACITY (BTU/LB-DEG-R)         0.84399462E+00           THROAT WALL RADIUS UPSTREAM 0.10000000E+01
    GAMMA                                0.12025388E+01

                                            CHEMICAL COMPOSITION

  NO.  SPECIES          MASS FRACTION   MOLE FRACTION     NO.  SPECIES          MASS FRACTION   MOLE FRACTION

   1    AR             0.47601466E-02  0.16647248E-02     2    H               0.33414641E-02  0.46313372E-01

   3    H2             0.30307118E-01  0.21003141E+00     4    H2O             0.85040307E+00  0.65947682E+00

   5    N2             0.24874465E-03  0.12405239E-03     6    O               0.95957909E-02  0.83790403E-02

   7    OH             0.77339672E-01  0.63530512E-01     8    O2              0.24003910E-01  0.10480101E-01

  STEP SIZE SET TO HMIN AT THROAT, HMIN WAS TOO LARGE AND HAS BEEN RESET FROM  0.50000E-02 TO  0.25882E-03



                                       THROAT CONDITIONS   KINETIC EXPANSION

                                            ZONE =  1     O/F =    6.5000

    FLOW PROPERTIES                                     PERFORMANCE PARAMETERS

    MACH NUMBER                     0.97005123E+00      VACUUM THRUST COEFFICIENT           0.12318200E+01
    PRESSURE (PSIA)                 0.17345639E+03      VACUUM SPECIFIC IMPULSE (SEC)       0.28156735E+03
    VELOCITY (FT/SEC)               0.48069292E+04      CHARACTERISTIC VELOCITY (FT/SEC)    0.73542783E+04
    DENSITY (LB/FT3)                0.39317060E-01
    TEMPERATURE (DEG-R)             0.58181162E+04      INTEGRATION PARAMETERS
    ENTHALPY    (BTU/LB)           -0.87000177E+03
    GAS MOLECULAR WEIGHT            0.14159413E+02      STEP SIZE                           0.51763811E-03
    HEAT CAPACITY(BTU/LB-DEG)       0.83800578E+00      AXIAL POSITION                      0.00000000E+00
    GAMMA                           0.12011606E+01      PERCENT ENTHALPY CHANGE             0.19432053E-01
                                                        PERCENT MASS FRACTION CHANGE        0.29802322E-04

                                            CHEMICAL COMPOSITION

  NO.  SPECIES          MASS FRACTION   MOLE FRACTION     NO.  SPECIES          MASS FRACTION   MOLE FRACTION

   1    AR             0.47601466E-02  0.16861745E-02     2    H               0.28714454E-02  0.40311620E-01

   3    H2             0.29123077E-01  0.20442639E+00     4    H2O             0.87214732E+00  0.68505377E+00

   5    N2             0.24874465E-03  0.12565080E-03     6    O               0.72312579E-02  0.63956906E-02

   7    OH             0.64192802E-01  0.53410478E-01     8    O2              0.19424904E-01  0.85901842E-02
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                    EXPANSION CONDITIONS  KINETIC EXPANSION   AREA RATIO      2.000

                                   ZONE =  1     O/F =    6.5000

   FLOW PROPERTIES                                    PERFORMANCE PARAMETERS

   MACH NUMBER                 0.19517127E+01         VACUUM THRUST COEFFICIENT         0.14699095E+01
   PRESSURE (PSIA)             0.39578793E+02         VACUUM SPECIFIC IMPULSE (SEC)     0.33598944E+03
   VELOCITY (FT/SEC)           0.88696348E+04
   DENSITY (LB/FT3)            0.10652749E-01
   TEMPERATURE (DEG-R)         0.50478320E+04         INTEGRATION PARAMETERS
   ENTHALPY    (BTU/LB)       -0.19796588E+04
   GAS MOLECULAR WEIGHT        0.14589634E+02         STEP SIZE                         0.33128839E-01
   HEAT CAPACITY(BTU/LB-DEG)   0.81788206E+00         AXIAL POSITION                    0.16775185E+01
   GAMMA                       0..1998068E+01         PERCENT ENTHALPY CHANGE           0.19197460E-01
   CURRENT RO*V*A              0.16490917E+02         PERCENT MASS FRACTION CHANGE      0.65565109E-04

                                         CHEMICAL COMPOSITION

 NO.  SPECIES          MASS FRACTION   MOLE FRACTION    NO.  SPECIES        MASS FRACTION   MOLE FRACTION

  1    AR             0.47601466E-02  0.17374079E-02    2    H             0.17749741E-02  0.25675621E-01

  3    H2             0.26431646E-01  0.19117150E+00    4    H2O           0.92249739E+00  0.74661928E+00

  5    N2             0.24874465E-03  0.12946859E-03    6    O             0.26705684E-02  0.24337531E-02

  7    OH             0.33039320E-01  0.28325036E-01    8    O2            0.85765254E-02  0.39079972E-02


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

                 CALCULATE ODE AREA RATIO AND PRESSURE SCHEDULES FOR ZONE  2

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

SPECIES BEING CONSIDERED IN THIS SYSTEM
    L 5/66  AR               J 6/74  H                J 3/61  H2               J 3/61  H2O              J 3/61  N
    J 6/63  NO               J 9/65  N2               J 6/74  O                J12/70  OH               J 9/65  O2
    J 9/65  NH3

OF =    8.000000
                          EFFECTIVE FUEL          EFFECTIVE OXIDANT          MIXTURE
ENTHALPY                     HPP(2)                   HPP(1)                  HSUBO
(KG-MOL)(DEG K)/KG       -0.53769275E+03          -0.48698235E+02          -0.10303096E+03

KG-ATOMS/KG                  BOP(I,2)                 BOP(I,1)                  BO(I)
       H                 0.99209303E+00           0.00000000E+00           0.11023256E+00
       O                 0.00000000E+00           0.62126074E-01           0.55223178E-01
       N                 0.00000000E+00           0.37839032E-04           0.33634697E-04
       AR                0.00000000E+00           0.13742865E-03           0.12215880E-03

ENTHALPY IN BTU/LBM :
    FROM REACTANTS :        -368.5311
    FROM DELH( ) . :           0.0000
    FROM DELH1( )              0.0000
    TOTAL          :        -368.5311
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                                        ZONE =  2
                  THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

PC =    285.0 PSIA

              CHEMICAL FORMULA                                                   WT FRACTION  ENTHALPY   STATE    TEMP    DENSITY
FUEL       H  2.00000                                                            (SEE NOTE)    CAL/MOL            DEG K    G/CC
OXIDANT O  2.00000                                                                1.00000     -2154.000    L      20.27   0.0709
OXIDANT N  2.00000                                                                0.99398     -3102.000    L      90.18   1.1490
OXIDANT AR 1.00000                                                                0.00053     -2939.000    L      77.35   0.8080
                                                                                  0.00549     -2607.000    L      90.00   0.0000

O/F=0.8000E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.9981E+00  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                   CHAMBER   THROAT    EXIT      EXIT
PC/P                1.0000   1.7234   1.0235    7.4332
P, PSIA              285.0    165.4    278.5     38.34
T, DEG R              6164     5891     6152      5231
H, BTU/LB           -368.5   -777.6   -386.5   -1764.9
S, BTU/(LB)(R)      3.8898   3.8898   3.8898    3.8898
DEN (LBM/FT3) 0.681E-010.420E-010.667E-010.114E-01

M, MOL WT           15.820   16.047   15.830    16.633
(DLV/DLP)T        -1.05080 -1.04558 -1.05058  -1.03203
(DLV/DLT)P          1.9200   1.8641   1.9178    1.6849
CP,BTU/(LB)(R)      2.8639   2.7945   2.8614    2.4984
CP GAS(SF)          0.7526   0.7476   0.7524    0.7332
GAMMA GAS(SF)       1.2003   1.1985   1.2003    1.1947
GAMMA (S)           1.1247   1.1216   1.1246    1.1157
SON VEL,FT/SEC      4667.9   4524.4   4661.6    4176.8
MACH NUMBER         0.0000   1.0000   0.2034    2.0013

AE/AT                        1.0000   3.0001    2.0000
CSTAR, FT/SEC                  6952     6952      6952
CF  VAC                       1.231    3.068     1.471
CF                            0.651    0.136     1.202
IVAC,LBF-SEC/L               266.00   662.83    317.95
I, LBF-SEC/LBM               140.62    29.47    259.81
MOL WT(MIX)         15.820   16.047   15.830    16.633

MOLE FRACTIONS

AR                  0.001933 0.001960 0.001934 0.002032
H                   0.039486 0.034264 0.039258 0.021586
H2                  0.124454 0.115314 0.124069 0.089523
H2O                 0.679569 0.709230 0.680840 0.787126
NO                  0.000356 0.000329 0.000354 0.000243
N2                  0.000088 0.000105 0.000089 0.000158
O                   0.018218 0.015378 0.018092 0.008906
OH                  0.096321 0.085588 0.095856 0.058605
O2                  0.039577 0.037830 0.039508 0.031821
N                   3.26E-07 2.13E-07 3.20E-07 5.77E-08
NH3                 4.32E-08 2.65E-08 4.23E-08 0.00E+00

NOTE
        WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
        (SF) STANDS FOR (SHIFTING FROZEN)
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OF POOR QUALITY

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                    FROZEN TRANSPORT PROPERTIES CALCULATED FROM EQUILIBRIUM CONCENTRATIONS

                                                                 PR
STATION                  MU                  K
                    (LBF-SEC/FT**2)    (LBF/SEC-DEG R)
CHAMBER             0.20423211E-05     0.60462840E-01     0.63557798E+00
THROAT              0.19826757E-05     0.57697557E-01     0.64230150E+00
EXIT                0.18295742E-05     0.50773460E-01     0.66048408E+00

VISCOSITY EXPONENT (OMEGA) FOR THE FORM MU=MUREF*(T/TREF)**OMEGA IS     0.67341
MUREF FOR INPUT TO BLM=   0.65770080E-04 LBM/(FT-SEC)

     SPECIES CONSIDERED IN TRANSPORT PROPERTIES CALCULATIONS
    AR                  H                   H2                  H2O
    N                   NO                  N2                  O
    OH                  O2                  NH3


                                          ZONE =  2
                         THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION


  PC =    285.0 PSIA                                                      WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
                                                                          (SEE NOTE)   CAL/MOL           DEG K    G/CC
          CHEMICAL FORMULA                                                 1.00000    -2154.000    L      20.27   0.0709
  FUEL     H  2.00000                                                      0.99398    -3102.000    L      90.18   1.1490
  OXIDANT O  2.00000                                                       0.00053    -2939.000    L      77.35   0.8080
  OXIDANT N  2.00000                                                       0.00549    -2607.000    L      90.00   0.0000
  OXIDANT AR 1.00000

  O/F=0.8000E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.9981E+00  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                    CHAMBER   THROAT    EXIT     EXIT
  PC/P              1.0000    1.7740   1.0247   8.3924
  P, PSIA            285.0     160.7    278.1    33.96
  T, DEG R            6164      5598     6139     4278
  H, BTU/LB         -368.5    -791.7   -387.4  -1750.9
  S, BTU/(LB)(R)    3.8898    3.8898   3.8898   3.8898
  DEN (LBM/FT3) 0.681E-010.423E-010.667E-010.117E-01

  M, MOL WT         15.820    15.820   15.820   15.820
  CP,BTU/(LB)(R)    0.7526    0.7423   0.7522   0.7071
  GAMMA (S)         1.2003    1.2037   1.2005   1.2160
  SON VEL,FT/SEC    4822.3    4601.9   4812.7   4043.2
  MACH NUMBER       0.0000    1.0000   0.2019   2.0571

  AE/AT                       1.0000   3.0001   2.0000
  CSTAR, FT/SEC                 6783     6783     6783
  CF  VAC                      1.242    3.071    1.464
  CF                           0.678    0.143    1.226
  IVAC,LBF-SEC/L              261.86   647.40   308.75
  I, LBF-SEC/LBM              143.03    30.20   258.51

  MOLE FRACTIONS

  AR          0.001933    H          0.039486    H2         0.124454    H2O        0.679569
  NO          0.000356    N2         0.000088    O          0.018218    OH         0.096321
  O2          0.039577

  ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS
  N           NH3

  NOTE
        WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
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       EQUILIBRIUM CONTRACTION CONDITIONS ZONE  2


       TEMPERATURE (DEGR)       0.61522261E+04

       PRESSURE    (PSIA)       0.27845251E+03

       VELOCITY    (FT/S)       0.94859015E+03
 SPECIES MOLE FRACTIONS

        1    AR                 0.19337191E-02
        2    H                  0.39257679E-01
        3    H2                 0.12406919E+00
        4    H2O                0.68083990E+00
        5    N                  0.31980758E-06
        6    NO                 0.35447202E-03
        7    N2                 0.88794040E-04
        8    O                  0.18091913E-01
        9    OH                 0.95856152E-01
       10    O2                 0.39507885E-01
       11    NH3                0.42287063E-07
```

```
      ZONE =  2

              REACTIONS                                                                                  INTERNAL SEQ NUM
              H + H = H2       ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U               **REAX    1  **
              H + OH = H2O     ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U               **REAX    2  **
              O + O = O2       ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U               **REAX    3  **
              O + H = OH       ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U               **REAX    4  **
              O2 + H = O + OH     , A = 2.2E14, N = 0.0, B =16.8,      BAULCH 72 (A) 1.5U              **REAX    5  **
              H2 + O = H + OH     , A = 1.8E10, N = -1., B = 8.9,      BAULCH 72 (A) 1.5U              **REAX    6  **
              H2 + OH = H2O + H   , A = 2.2E13, N = 0.0, B =5.15,      BAULCH 72 (A) 2U                **REAX    7  **
              OH + OH = H2O + O   , A = 6.3E12, N = 0.0, B =1.09,      BAULCH 72 (A) 3U                **REAX    8  **
      THIRD BODY REAX RATE RATIOS
      M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
      M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
      M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
      M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
```

```
                SELECTED SPECIES FOR KINETIC EXPANSION
                        ZONE =  2

      1      AR                0.19337191E-02      INERT SPECIES
      2      H                 0.39257679E-01
      3      H2                0.12406919E+00
      4      H2O               0.68083990E+00
      7      N2                0.88794040E-04      INERT SPECIES
      8      O                 0.18091913E-01
      9      OH                0.95856152E-01
     10      O2                0.39507885E-01


              DISSOCIATION RECOMBINATION REACTION RATE RATIOS

                             ZONE =  2
  1    0.10000E+01   0.25000E+02   0.40000E+01   0.10000E+02   0.10000E+01   0.25000E+02
       0.25000E+02   0.15000E+01
  2    0.10000E+01   0.12500E+02   0.50000E+01   0.17000E+02   0.10000E+01   0.12500E+02
       0.12500E+02   0.60000E+01
  3    0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
       0.12500E+02   0.11000E+02
  4    0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
       0.12500E+02   0.50000E+01
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                              INITIAL CONDITIONS   KINETIC EXPANSION

                                 ZONE =  2      O/F =    8.0000
   FLOW PROPERTIES
                                                       NOZZLE GEOMETRY
   MACH NUMBER
   VELOCITY (FT/SEC)               0.19693609E+00
   PRESSURE (PSIA)                 0.94859015E+03      THROAT RADIUS (FT)              0.16666667E+00
   DENSITY (LB/FT3)                0.27845251E+03      THROAT WALL RADIUS DNSTREAM 0.10000000E+01
   TEMPERATURE (DEG-R)             0.66738598E-01      CONE ANGLE (DEG)                0.15000000E+02
   ENTHALPY     (BTU/LB)           0.61522261E+04      EXPANSION RATIO                 0.20000000E+01
   GAS MOLECULAR WEIGHT           -0.38846414E+03      CONTRACTION RATIO               0.30000770E+01
   HEAT CAPACITY (BTU/LB-DEG-R)    0.15834289E+02      INLET ANGLE (DEG)               0.30000000E+02
   GAMMA                           0.75226027E+00      INLET WALL RADIUS               0.20000000E+01
                                   0.12002314E+01      THROAT WALL RADIUS UPSTREAM 0.10000000E+01

                                    CHEMICAL COMPOSITION
 NO.  SPECIES                                          NO.  SPECIES
                MASS FRACTION    MOLE FRACTION                       MASS FRACTION    MOLE FRACTION
  1    AR       0.48832833E-02   0.19344053E-02        2    H        0.25014721E-02   0.39271604E-01
  3    H2       0.15811205E-01   0.12411321E+00        4    H2O      0.77537346E+00   0.68108147E+00
  5    N2       0.15724363E-03   0.88825538E-04        6    O        0.18298339E-01   0.18098332E-01
  7    OH       0.10305773E+00   0.95890157E-01        8    O2       0.79917319E-01   0.39521899E-01
 STEP SIZE SET TO HMIN AT THROAT, HMIN WAS TOO LARGE AND HAS BEEN RESET FROM  0.50000E-02 TO  0.25882E-03


                              THROAT CONDITIONS   KINETIC EXPANSION

                                 ZONE =  2      O/F =    8.0000
   FLOW PROPERTIES
                                                       PERFORMANCE PARAMETERS
   MACH NUMBER
   PRESSURE (PSIA)                 0.96897125E+00      VACUUM THRUST COEFFICIENT         0.12309867E+01
   VELOCITY (FT/SEC)               0.16504788E+03      VACUUM SPECIFIC IMPULSE (SEC)     0.26598679E+03
   DENSITY (LB/FT3)                0.45317544E+04      CHARACTERISTIC VELOCITY (FT/SEC)  0.69520313E+04
   TEMPERATURE (DEG-R)             0.41911609E-01
   ENTHALPY     (BTU/LB)           0.58878354E+04      INTEGRATION PARAMETERS
   GAS MOLECULAR WEIGHT           -0.78057233E+03
   HEAT CAPACITY(BTU/LB-DEG)       0.16050882E+02      STEP SIZE
   GAMMA                           0.74743026E+00      AXIAL POSITION                    0.10352762E-02
                                   0.11985229E+01      PERCENT ENTHALPY CHANGE           0.00000000E+00
                                                       PERCENT MASS FRACTION CHANGE      0.15772091E-01
                                                                                         0.59604645E-05
                                    CHEMICAL COMPOSITION
 NO.  SPECIES                                          NO.  SPECIES
                MASS FRACTION    MOLE FRACTION                       MASS FRACTION    MOLE FRACTION
  1    AR       0.48832833E-02   0.19608657E-02        2    H        0.21571529E-02   0.34329250E-01
  3    H2       0.1450505[illegible]E-01   0.11541778E+00        4    H2O      0.79663646E+00   0.70933062E+00
  5    N2       0.15724363E-03   0.90040565E-04        6    O        0.15360956E-01   0.15400880E-01
  7    OH       0.90759225E-01   0.85602134E-01        8    O2       0.75540572E-01   0.37868451E-01
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                    EXPANSION CONDITIONS  KINETIC EXPANSION   AREA RATIO      2.000

                              ZONE =  2     O/F =    8.0000

                                                 PERFORMANCE PARAMETERS
 FLOW PROPERTIES
                                                 VACUUM THRUST COEFFICIENT             0.14708618E+01
 MACH NUMBER                  0.19404051E+01     VACUUM SPECIFIC IMPULSE (SEC)         0.31781805E+03
 PRESSURE (PSIA)              0.38096855E+02
 VELOCITY (FT/SEC)            0.83668779E+04
 DENSITY (LB/FT3)             0.11348549E-01     INTEGRATION PARAMETERS
 TEMPERATURE (DEG-R)          0.51903032E+04
 ENTHALPY    (BTU/LB)        -0.17684902E+04     STEP SIZE                             0.33128839E-01
 GAS MOLECULAR WEIGHT         0.16602911E+02     AXIAL POSITION                        0.16775185E+01
 HEAT CAPACITY(BTU/LB-DEG)    0.73210776E+00     PERCENT ENTHALPY CHANGE               0.14661685E-01
 GAMMA                        0.11954341E+01     PERCENT MASS FRACTION CHANGE          0.29802322E-04
 CURRENT RO*V*A               0.16572239E+02
                                      CHEMICAL COMPOSITION

NO.  SPECIES          MASS FRACTION   MOLE FRACTION   NO.  SPECIES        MASS FRACTION   MOLE FRACTION

 1    AR             0.48832833E-02  0.20283044E-02    2    H            0.13785680E-02  0.22693260E-01

 3    H2             0.11080028E-01  0.91196798E-01    4    H2O          0.85020518E+00  0.78306454E+00

 5    N2             0.15724363E-03  0.93137278E-04    6    O            0.89688255E-02  0.93013961E-02

 7    OH             0.60542941E-01  0.59066691E-01    8    O2           0.62783629E-01  0.32555848E-01


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

               CALCULATE ODE AREA RATIO AND PRESSURE SCHEDULES FOR ZONE  3

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

 SPECIES BEING CONSIDERED IN THIS SYSTEM
     L 5/66  AR            J 6/74  H            J 3/61  H2          J 3/61  H2O         J 3/61  N
     J 6/63  NO            J 9/65  N2           J 6/74  O           J12/70  OH          J 9/65  O2
     J 9/65  NH3

 OF =    5.000000
                            EFFECTIVE FUEL      EFFECTIVE OXIDANT        MIXTURE
 ENTHALPY                      HPP(2)                HPP(1)               HSUBO
 (KG-MOL)(DEG K)/KG        -0.53769275E+03      -0.48698235E+02      -0.13019733E+03

 KG-ATOMS/KG                  BOP(I,2)              BOP(I,1)               BO(I)
        H                  0.99209303E+00       0.00000000E+00       0.16534884E+00
        O                  0.00000000E+00       0.62126074E-01       0.51771730E-01
        N                  0.00000000E+00       0.37839032E-04       0.31532527E-04
        AR                 0.00000000E+00       0.13742865E-03       0.11452387E-03

 ENTHALPY IN BTU/LBM :
     FROM REACTANTS :        -465.7024
     FROM DELH( )   :           0.0000
     FROM DELH1( )             0.0000
     TOTAL          :        -465.7024
```

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                                              ZONE =  3
                THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION

PC =    270.0 PSIA

          CHEMICAL FORMULA                                                            WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
FUEL      H  2.00000                                                                  (SEE NOTE)    CAL/MOL          DEG K    G/CC
OXIDANT O  2.00000                                                                     1.00000    -2154.000    L     20.27   0.0709
OXIDANT N  2.00000                                                                     0.99398    -3102.000    L     90.18   1.1490
OXIDANT AR 1.00000                                                                     0.00053    -2939.000    L     77.35   0.8080
                                                                                       0.00549    -2607.000    L     90.00   0.0000
O/F=0.5000E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.1597E+01  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                CHAMBER   THROAT     EXIT      EXIT
PC/P             1.0000   1.7430    1.0239    7.9454
P, PSIA           270.0    154.9     263.7     33.98
T, DEG R           5728     5381      5714      4414
H, BTU/LB        -465.7   -987.9    -488.7   -2227.9
S, BTU/(LB)(R)   4.8515   4.8515    4.8515    4.8515
DEN (LBM/FT3) 0.513E-010.316E-010.502E-010.861E-02

M, MOL WT        11.684    11.800    11.690    12.011
(DLV/DLP)T     -1.01737  -1.01208  -1.01713  -1.00274
(DLV/DLT)P       1.3315    1.2439    1.3277    1.0655
CP,BTU/(LB)(R)   2.0622    1.8031    2.0513    1.1899
CP GAS(SF)       0.9752    0.9648    0.9748    0.9279
GAMMA GAS(SF)    1.2112    1.2115    1.2112    1.2170
GAMMA (S)        1.1479    1.1526    1.1480    1.1836
SON VEL,FT/SEC   5289.6    5111.9    5281.9    4650.4
MACH NUMBER      0.0000    1.0000    0.2031    2.0193

AE/AT                      1.0000    3.0001    2.0000
CSTAR, FT/SEC                7730      7730      7730
CF  VAC                     1.235     3.069     1.467
CF                          0.661     0.139     1.215
IVAC,LBF-SEC/L             296.73    737.29    352.34
I, LBF-SEC/LBM             158.88     33.35    291.87
MOL WT(MIX)      11.684    11.800    11.690    12.011

MOLE FRACTIONS

AR              0.001338 0.001351 0.001339 0.001376
H               0.037138 0.028055 0.036744 0.008058
H2              0.357397 0.360034 0.357496 0.368565
H2O             0.578544 0.593816 0.579252 0.619108
NO              0.000057 0.000035 0.000056 0.000004
N2              0.000155 0.000168 0.000156 0.000187
O               0.001457 0.000744 0.001420 0.000039
OH              0.022967 0.015300 0.022613 0.002636
O2              0.000946 0.000496 0.000924 0.000027
N               1.22E-07 5.16E-08 1.18E-07 0.00E+00
NH3             3.02E-07 2.06E-07 2.97E-07 7.85E-08

NOTE
       WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
       (SF) STANDS FOR (SHIFTING FROZEN)
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                    FROZEN TRANSPORT PROPERTIES CALCULATED FROM EQUILIBRIUM CONCENTRATIONS

STATION                      MU                 K                  PR
                      (LBF-SEC/FT**2)    (LBF/SEC-DEG R)
CHAMBER              0.18288381E-05     0.77825621E-01     0.57290888E+00
THROAT               0.17521484E-05     0.73574215E-01     0.57443625E+00
EXIT                 0.15203000E-05     0.61276197E-01     0.57555461E+00

VISCOSITY EXPONENT (OMEGA) FOR THE FORM MU=MUREF*(T/TREF)**OMEGA IS     0.71397
MUREF FOR INPUT TO BLM=   0.58952501E-04 LBM/(FT-SEC)

      SPECIES CONSIDERED IN TRANSPORT PROPERTIES CALCULATIONS
     AR                  H                   H2                  H2O
     N                   NO                  N2                  O
     OH                  O2                  NH3
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                                            ZONE =  3
                      THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION

  PC =    270.0 PSIA

              CHEMICAL FORMULA
  FUEL      H  2.00000                                                          WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
  OXIDANT O  2.00000                                                            (SEE NOTE)   CAL/MOL           DEG K    G/CC
  OXIDANT N  2.00000                                                             1.00000    -2154.000    L     20.27   0.0709
  OXIDANT AR 1.00000                                                             0.99398    -3102.000    L     90.18   1.1490
                                                                                 0.00053    -2939.000    L     77.35   0.8080
                                                                                 0.00549    -2607.000    L     90.00   0.0000

  O/F=0.5000E+01  PERCENT FUEL=0.0000E+00  EQUIVALENCE RATIO=0.1597E+01  STOIC MIXTURE RATIO=0.0000E+00  DENSITY=0.0000E+00

                     CHAMBER    THROAT     EXIT      EXIT
  PC/P                1.0000    1.7814    1.0249    8.5450
  P, PSIA              270.0     151.6     263.4     31.60
  T, DEG R              5728      5175      5704      3888
  H, BTU/LB           -465.7   -1000.7    -489.6   -2202.6
  S, BTU/(LB)(R)      4.8515    4.8515    4.8515    4.8515
  DEN (LBM/FT3) 0.513E-010.319E-010.503E-010.884E-02

  M, MOL WT           11.684    11.684    11.684    11.684
  CP,BTU/(LB)(R)      0.9752    0.9588    0.9745    0.9043
  GAMMA (S)           1.2112    1.2156    1.2114    1.2316
  SON VEL,FT/SEC      5433.7    5174.0    5422.4    4514.0
  MACH NUMBER         0.0000    1.0000    0.2017    2.0653

  AE/AT                         1.0000    3.0001    2.0000
  CSTAR, FT/SEC                   7582      7582      7582
  CF  VAC                        1.244     3.072     1.464
  CF                             0.682     0.144     1.230
  IVAC,LBF-SEC/L                293.10    723.82    344.92
  I, LBF-SEC/LBM                160.81     33.99    289.76

  MOLE FRACTIONS

  AR          0.001338
  NO          0.000057              0.037138     H2           0.357397     H2O         0.578544
  O2          0.000946      N2      0.000155     O            0.001457     OH          0.022967

  ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS
  N            NH3

  NOTE
       WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
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    EQUILIBRIUM CONTRACTION CONDITIONS ZONE  3


    TEMPERATURE (DEGR)        0.57135161E+04

    PRESSURE     (PSIA)       0.26368848E+03

    VELOCITY     (FT/S)       0.10733123E+04

SPECIES MOLE FRACTIONS
          1     AR                   0.13387334E-02
          2     H                    0.36743894E-01
          3     H2                   0.35749605E+00
          4     H2O                  0.57925242E+00
          5     N                    0.11801665E-06
          6     NO                   0.56386369E-04
          7     N2                   0.15590010E-03
          8     O                    0.14196864E-02
          9     OH                   0.22612970E-01
         10     O2                   0.92356431E-03
         11     NH3                  0.29670508E-06




  ZONE =  3                                                                       INTERNAL  SEQ  NUM
            REACTIONS                                                             **REAX     1   **
            H + H = H2      ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U   **REAX     2   **
            H + OH = H2O    ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U   **REAX     3   **
            O + O = O2      ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U   **REAX     4   **
            O + H = OH      ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U   **REAX     5   **
            O2 + H = O + OH    , A = 2.2E14, N = 0.0, B =16.8,    BAULCH 72 (A) 1.5U    **REAX     6   **
            H2 + O = H + OH    , A = 1.8E10, N = -1., B = 8.9,    BAULCH 72 (A) 1.5U    **REAX     7   **
            H2 + OH = H2O + H  , A = 2.2E13, N = 0.0, B =5.15,    BAULCH 72 (A) 2U      **REAX     8   **
            OH + OH = H2O + O  , A = 6.3E12, N = 0.0, B =1.09,    BAULCH 72 (A) 3U
  THIRD BODY REAX RATE RATIOS
  M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
  M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
  M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
  M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
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                    SELECTED SPECIES FOR KINETIC EXPANSION
                               ZONE =  3

       1     AR                    0.13387334E-02     INERT SPECIES
       2     H                     0.36743894E-01
       3     H2                    0.35749605E+00
       4     H2O                   0.57925242E+00
       7     N2                    0.15590010E-03     INERT SPECIES
       8     O                     0.14196864E-02
       9     OH                    0.22612970E-01
      10     O2                    0.92356431E-03



                    DISSOCIATION RECOMBINATION REACTION RATE RATIOS

                                   ZONE =  3
   1       0.10000E+01   0.25000E+02   0.40000E+01   0.10000E+02   0.10000E+01   0.25000E+02
           0.25000E+02   0.15000E+01
   2       0.10000E+01   0.12500E+02   0.50000E+01   0.17000E+02   0.10000E+01   0.12500E+02
           0.12500E+02   0.60000E+01
   3       0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
           0.12500E+02   0.11000E+02
   4       0.10000E+01   0.12500E+02   0.50000E+01   0.50000E+01   0.10000E+01   0.12500E+02
           0.12500E+02   0.50000E+01
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                              INITIAL CONDITIONS   KINETIC EXPANSION

                                   ZONE =  3     O/F =    5.0000

    FLOW PROPERTIES                                   NOZZLE GEOMETRY

    MACH NUMBER                          0.19782001E+00        THROAT RADIUS (FT)             0.16666667E+00
    VELOCITY (FT/SEC)                    0.10733123E+04        THROAT WALL RADIUS DNSTREAM 0.10000000E+01
    PRESSURE (PSIA)                      0.26368848E+03        CONE ANGLE (DEG)               0.15000000E+02
    DENSITY (LB/FT3)                     0.50266068E-01        EXPANSION RATIO                0.20000000E+01
    TEMPERATURE (DEG-R)                  0.57135161E+04        CONTRACTION RATIO              0.30000784E+01
    ENTHALPY     (BTU/LB)               -0.48887775E+03        INLET ANGLE (DEG)              0.30000000E+02
    GAS MOLECULAR WEIGHT                 0.11695736E+02        INLET WALL RADIUS              0.20000000E+01
    HEAT CAPACITY (BTU/LB-DEG-R)         0.97425121E+00        THROAT WALL RADIUS UPSTREAM 0.10000000E+01
    GAMMA                                0.12112339E+01

                                      CHEMICAL COMPOSITION

 NO.  SPECIES          MASS FRACTION   MOLE FRACTION     NO.  SPECIES          MASS FRACTION   MOLE FRACTION

  1    AR              0.45756646E-02  0.13388094E-02     2    H               0.31688218E-02  0.36745980E-01

  3    H2              0.61661471E-01  0.35751635E+00     4    H2O             0.89284354E+00  0.57928526E+00

  5    N2              0.37366056E-03  0.15590896E-03     6    O               0.19433954E-02  0.14197669E-02

  7    OH              0.32904841E-01  0.22614254E-01     8    O2              0.25285168E-02  0.92361670E-03

 STEP SIZE SET TO HMIN AT THROAT, HMIN WAS TOO LARGE AND HAS BEEN RESET FROM  0.50000E-02 TO  0.25882E-03



                                  THROAT CONDITIONS   KINETIC EXPANSION

                                       ZONE =  3     O/F =    5.0000


       FLOW PROPERTIES                                   PERFORMANCE PARAMETERS

       MACH NUMBER                    0.97714138E+00     VACUUM THRUST COEFFICIENT             0.12352805E+01
       PRESSURE (PSIA)                0.15462662E+03     VACUUM SPECIFIC IMPULSE (SEC)         0.29663614E+03
       VELOCITY (FT/SEC)              0.51191938E+04     CHARACTERISTIC VELOCITY (FT/SEC)      0.77261567E+04
       DENSITY (LB/FT3)               0.31627599E-01
       TEMPERATURE (DEG-R)            0.53742822E+04     INTEGRATION PARAMETERS
       ENTHALPY     (BTU/LB)         -0.98919781E+03
       GAS MOLECULAR WEIGHT           0.11802890E+02     STEP SIZE                             0.10352762E-02
       HEAT CAPACITY(BTU/LB-DEG)      0.96414113E+00     AXIAL POSITION                        0.00000000E+00
       GAMMA                          0.12115697E+01     PERCENT ENTHALPY CHANGE               0.68588299E-02
                                                         PERCENT MASS FRACTION CHANGE          0.00000000E+00

                                          CHEMICAL COMPOSITION

    NO.  SPECIES          MASS FRACTION   MOLE FRACTION     NO.  SPECIES          MASS FRACTION   MOLE FRACTION

     1    AR              0.45756646E-02  0.13510754E-02     2    H               0.24232785E-02  0.28358039E-01

     3    H2              0.61514165E-01  0.35992998E+00     4    H2O             0.90647423E+00  0.59351736E+00

     5    N2              0.37366056E-03  0.15733739E-03     6    O               0.10286119E-02  0.75834757E-03

     7    OH              0.22233596E-01  0.15420306E-01     8    O2              0.13767871E-02  0.50752045E-03
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                    EXPANSION CONDITIONS  KINETIC EXPANSION   AREA RATIO      2.000

                                  ZONE =  3     O/F =    5.0000

   FLOW PROPERTIES
                                                    PERFORMANCE PARAMETERS

   MACH NUMBER                   0.20044303E+01
   PRESSURE (PSIA)               0.33545719E+02     VACUUM THRUST COEFFICIENT         0.14652495E+01
   VELOCITY (FT/SEC)             0.94009004E+04     VACUUM SPECIFIC IMPULSE (SEC)     0.35186014E+03
   DENSITY (LB/FT3)              0.86109657E-02
   TEMPERATURE (DEG-R)           0.43445571E+04
   ENTHALPY    (BTU/LB)         -0.22308054E+04     INTEGRATION PARAMETERS
   GAS MOLECULAR WEIGHT          0.11975692E+02
   HEAT CAPACITY(BTU/LB-DEG)     0.92458695E+00     STEP SIZE                         0.33128839E-01
   GAMMA                         0.12187207E+01     AXIAL POSITION                    0.16775185E+01
   CURRENT RO*V*A                0.14128585E+02     PERCENT ENTHALPY CHANGE           0.56242407E-02
                                                    PERCENT MASS FRACTION CHANGE     -0.83446503E-04
                                   CHEMICAL COMPOSITION

 NO.  SPECIES          MASS FRACTION  MOLE FRACTION   NO.  SPECIES       MASS FRACTION  MOLE FRACTION

  1    AR             0.45756646E-02  0.13708560E-02   2    H           0.11136207E-02  0.13222769E-01

  3    H2             0.61593093E-01  0.36566815E+00   4    H2O         0.92614126E+00  0.61527246E+00

  5    N2             0.37366056E-03  0.15964088E-03   6    O           0.13606373E-03  0.10178208E-03

  7    OH             0.58691776E-02  0.41302163E-02   8    O2          0.19835548E-03  0.74189629E-04



                             ODK ISP SUMMARY

                    ZONE     ODK ISP      ZONE MASS FLOW

                     1       335.989       0.33330
                     2       317.818       0.33340
                     3       351.860       0.33330


             MASS AVERAGED ISP =     335.221


             MASS AVERAGED O/F =     6.29744



             DATA FOR ODE/ODK SAVED ON UNIT 15
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 TRANSONIC ANALYSIS SUBPROGRAM

    3   ZONE(S) SPECIFIED


  THROAT UPSTREAM RADIUS OF CURVATURE =   1.00000
 THROAT DOWNSTREAM RADIUS OF CURVATURE =   1.00000
 NUMBER OF POINTS ON INITIAL LINE (MP) =        60

   SINUSOIDAL DISTRIBUTION FOR INITIAL LINE

     ZONE          GAMMA         MASS FLOW THRU ZONE

       1          1.12875            0.33330
       2          1.12153            0.33330
       3          1.16325            0.33340


 **********   CD =   0.99559




                    TWO DIMENSIONAL KINETIC ANALYSIS SUBPROGRAM

               NUMBER OF POINTS ON INITIAL LINE =      59


               CHARACTERISTICS MESH CONTROL PARAMETERS
                 (SEE SECTION 5.9.3 TDK MANUAL)

                 INSERTION CONTROL, STREAMLINE POINT SEPARATION (DS) =      0.150
                 INSERTION CONTROL, NOZZLE END POINT TOLERANCE (EPW) =      0.010
                         INSERTION CONTROL, FLOW ANGLE CHANGE (DTWI) =      2.000
                         INSERTION CONTROL, WALL ANGLE CHANGE (DWWI) =      3.000
                 EDIT CONTROL, CHARACTERISTICS POINT SEPARATION (ES) =      0.000
               EDIT CONTROL, CHARACTERISTICS POINT ANGLE CHANGE (ETHI) =      0.250

               IWALL =  1   OPTION SPECIFIED
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                                 WALL COORDINATES
  1  R/R*     1.00000  1.00000  1.00001  1.00003  1.00005  1.00009  1.00012  1.00017  1.00022  1.00028  1.00034
  1  X/R*     0.00000  0.00262  0.00524  0.00785  0.01047  0.01309  0.01571  0.01832  0.02094  0.02356  0.02618
SLOPE(DEG)             0.07566  0.22437  0.37569  0.52440  0.67573  0.82445  0.97579  1.12453  1.27588  1.42463

 12  R/R*     1.00041  1.00049  1.00058  1.00067  1.00077  1.00088  1.00099  1.00111  1.00124  1.00137  1.00151
 12  X/R*     0.02879  0.03141  0.03403  0.03664  0.03926  0.04188  0.04449  0.04711  0.04972  0.05234  0.05495
SLOPE(DEG)    1.57339  1.72738  1.87356  2.02496  2.17638  2.32260  2.47666  2.62551  2.77439  2.92589  3.07481

 23  R/R*     1.00166  1.00181  1.00197  1.00214  1.00232  1.00250  1.00269  1.00288  1.00308  1.00329  1.00351
 23  X/R*     0.05756  0.06018  0.06279  0.06540  0.06802  0.07063  0.07324  0.07585  0.07846  0.08107  0.08368
SLOPE(DEG)    3.22375  3.37531  3.52429  3.67590  3.82494  3.97401  4.12569  4.27481  4.42654  4.57313  4.72493

 34  R/R*     1.00373  1.00396  1.00420  1.00444  1.00469  1.00494  1.00521  1.00548  1.00576  1.00604  1.00633
 34  X/R*     0.08629  0.08889  0.09150  0.09411  0.09671  0.09932  0.10192  0.10453  0.10713  0.10973  0.11234
SLOPE(DEG)    4.87677  5.02345  5.17534  5.32469  5.47666  5.62348  5.77554  5.92502  6.07455  6.22414  6.37635

 45  R/R*     1.00663  1.00693  1.00724  1.00756  1.00789  1.00822  1.00856  1.00890  1.00925  1.00961  1.00998
 45  X/R*     0.11494  0.11754  0.12014  0.12274  0.12533  0.12793  0.13053  0.13312  0.13572  0.13831  0.14090
SLOPE(DEG)    6.52341  6.67571  6.82546  6.97527  7.12510  7.27496  7.42491  7.57495  7.72494  7.87506  8.02523

 56  R/R*     1.01035  1.01073  1.01111  1.01151  1.01191  1.01231  1.01272  1.01314  1.01357  1.01400  1.01444
 56  X/R*     0.14349  0.14608  0.14867  0.15126  0.15385  0.15643  0.15902  0.16160  0.16419  0.16677  0.16935
SLOPE(DEG)    8.17539  8.32307  8.47600  8.62636  8.77418  8.92468  9.07528  9.22583  9.37397  9.52467  9.67549

 67  R/R*     1.01489  1.01534  1.01580  1.01627  1.01675  1.01723  1.01771  1.01821  1.01871  1.01921  1.01973
 67  X/R*     0.17193  0.17451  0.17708  0.17966  0.18224  0.18481  0.18738  0.18995  0.19252  0.19509  0.19766
SLOPE(DEG)    9.82379  9.97471 10.12569 10.27673 10.42281 10.57652 10.72523 10.87400 11.02545 11.17434 11.32592

 78  R/R*     1.02025  1.02078  1.02131  1.02185  1.02240  1.02295  1.02352  1.02408  1.02466  1.02524  1.02583
 78  X/R*     0.20022  0.20279  0.20535  0.20791  0.21047  0.21303  0.21559  0.21814  0.22070  0.22325  0.22580
SLOPE(DEG)   11.47501 11.62416 11.77592 11.92521 12.07469 12.22411 12.37621 12.52329 12.67560 12.82537 12.97528

 89  R/R*     1.02642  1.02702  1.02763  1.02824  1.02887  1.02949  1.03013  1.03077  1.03142  1.03207  1.03273
 89  X/R*     0.22835  0.23090  0.23345  0.23599  0.23853  0.24108  0.24362  0.24615  0.24869  0.25123  0.25376
SLOPE(DEG)   13.12519 13.27533 13.42546 13.57313 13.72603 13.87386 14.02699 14.17498 14.32320 14.47649 14.62505

100  R/R*     1.03340  1.03407  1.41421  0.00000
100  X/R*     0.25629  0.25882  1.67752  0.00000
SLOPE(DEG)   14.77328 14.92570 15.00000
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   P(PSIA)      RHO(LBM/FT3)    THETA(DEG)    VEL(FT/SEC)        R              X         MASS FLOW RATE
0.13069E+03    0.27351E-01    0.00000E+00    0.58091E+04    0.10000E+01    0.00000E+00    0.00000E+00
0.13132E+03    0.27465E-01    0.88066E-01    0.57906E+04    0.98981E+00    0.55602E-02    0.28126E+00
0.13160E+03    0.27515E-01    0.12655E+00    0.57825E+04    0.98535E+00    0.79807E-02    0.40387E+00
0.13192E+03    0.27573E-01    0.17181E+00    0.57731E+04    0.98008E+00    0.10821E-01    0.54785E+00
0.13229E+03    0.27639E-01    0.22375E+00    0.57624E+04    0.97402E+00    0.14071E-01    0.71277E+00
0.13270E+03    0.27714E-01    0.28224E+00    0.57504E+04    0.96717E+00    0.17719E-01    0.89809E+00
0.13316E+03    0.27796E-01    0.34715E+00    0.57372E+04    0.95953E+00    0.21753E-01    0.11032E+01
0.13365E+03    0.27885E-01    0.41832E+00    0.57228E+04    0.95113E+00    0.26158E-01    0.13275E+01
0.13419E+03    0.27981E-01    0.49559E+00    0.57073E+04    0.94196E+00    0.30920E-01    0.15703E+01
0.13476E+03    0.28083E-01    0.57879E+00    0.56908E+04    0.93204E+00    0.36020E-01    0.18307E+01
0.13536E+03    0.28191E-01    0.66770E+00    0.56733E+04    0.92138E+00    0.41441E-01    0.21079E+01
0.13599E+03    0.28305E-01    0.76215E+00    0.56550E+04    0.90999E+00    0.47165E-01    0.24011E+01
0.13665E+03    0.28423E-01    0.86190E+00    0.56360E+04    0.89788E+00    0.53172E-01    0.27091E+01
0.13733E+03    0.28546E-01    0.96674E+00    0.56162E+04    0.88506E+00    0.59440E-01    0.30311E+01
0.13804E+03    0.28672E-01    0.10764E+01    0.55958E+04    0.87156E+00    0.65949E-01    0.33660E+01
0.13876E+03    0.28801E-01    0.11908E+01    0.55750E+04    0.85738E+00    0.72674E-01    0.37125E+01
0.13950E+03    0.28933E-01    0.13095E+01    0.55538E+04    0.84254E+00    0.79595E-01    0.40696E+01
0.14024E+03    0.29067E-01    0.14323E+01    0.55322E+04    0.82706E+00    0.86686E-01    0.44361E+01
0.14100E+03    0.29201E-01    0.15590E+01    0.55105E+04    0.81095E+00    0.93924E-01    0.48107E+01
0.14175E+03    0.29337E-01    0.16894E+01    0.54887E+04    0.79423E+00    0.10128E+00    0.51921E+01
0.14175E+03    0.36593E-01    0.16894E+01    0.51042E+04    0.79423E+00    0.10128E+00    0.51921E+01
0.14248E+03    0.36759E-01    0.16530E+01    0.50863E+04    0.77747E+00    0.10851E+00    0.56268E+01
0.14327E+03    0.36940E-01    0.16973E+01    0.50668E+04    0.76018E+00    0.11581E+00    0.60661E+01
0.14405E+03    0.37120E-01    0.17403E+01    0.50474E+04    0.74237E+00    0.12315E+00    0.65086E+01
0.14483E+03    0.37300E-01    0.17819E+01    0.50280E+04    0.72407E+00    0.13051E+00    0.69529E+01
0.14561E+03    0.37478E-01    0.18216E+01    0.50089E+04    0.70529E+00    0.13788E+00    0.73977E+01
0.14638E+03    0.37653E-01    0.18594E+01    0.49899E+04    0.68605E+00    0.14522E+00    0.78415E+01
0.14713E+03    0.37826E-01    0.18951E+01    0.49713E+04    0.66638E+00    0.15252E+00    0.82829E+01
0.14787E+03    0.37996E-01    0.19285E+01    0.49531E+04    0.64630E+00    0.15975E+00    0.87207E+01
0.14859E+03    0.38161E-01    0.19595E+01    0.49353E+04    0.62582E+00    0.16689E+00    0.91534E+01
0.14930E+03    0.38321E-01    0.19881E+01    0.49181E+04    0.60498E+00    0.17393E+00    0.95797E+01
0.14997E+03    0.38476E-01    0.20141E+01    0.49015E+04    0.58380E+00    0.18084E+00    0.99984E+01
0.15062E+03    0.38624E-01    0.20376E+01    0.48855E+04    0.56230E+00    0.18760E+00    0.10408E+02
0.15062E+03    0.34692E-01    0.20376E+01    0.53701E+04    0.56230E+00    0.18760E+00    0.10408E+02
0.15140E+03    0.34850E-01    0.19222E+01    0.53508E+04    0.53929E+00    0.19455E+00    0.10825E+02
0.15213E+03    0.34999E-01    0.18723E+01    0.53326E+04    0.51597E+00    0.20130E+00    0.11229E+02
0.15284E+03    0.35144E-01    0.18176E+01    0.53150E+04    0.49240E+00    0.20783E+00    0.11620E+02
0.15352E+03    0.35283E-01    0.17582E+01    0.52980E+04    0.46859E+00    0.21410E+00    0.11995E+02
0.15418E+03    0.35416E-01    0.16941E+01    0.52818E+04    0.44459E+00    0.22012E+00    0.12356E+02
0.15480E+03    0.35543E-01    0.16256E+01    0.52664E+04    0.42042E+00    0.22585E+00    0.12699E+02
0.15539E+03    0.35663E-01    0.15529E+01    0.52517E+04    0.39613E+00    0.23129E+00    0.13025E+02
0.15595E+03    0.35777E-01    0.14763E+01    0.52379E+04    0.37175E+00    0.23643E+00    0.13333E+02
0.15648E+03    0.35883E-01    0.13959E+01    0.52249E+04    0.34731E+00    0.24125E+00    0.13622E+02
0.15697E+03    0.35982E-01    0.13122E+01    0.52129E+04    0.32287E+00    0.24574E+00    0.13891E+02
0.15742E+03    0.36074E-01    0.12254E+01    0.52017E+04    0.29846E+00    0.24990E+00    0.14140E+02
0.15783E+03    0.36159E-01    0.11361E+01    0.51914E+04    0.27413E+00    0.25373E+00    0.14369E+02
0.15821E+03    0.36236E-01    0.10446E+01    0.51821E+04    0.24992E+00    0.25721E+00    0.14577E+02
0.15855E+03    0.36305E-01    0.95132E+00    0.51737E+04    0.22588E+00    0.26034E+00    0.14765E+02
0.15886E+03    0.36366E-01    0.85682E+00    0.51662E+04    0.20208E+00    0.26314E+00    0.14932E+02
0.15913E+03    0.36421E-01    0.76160E+00    0.51596E+04    0.17856E+00    0.26559E+00    0.15079E+02
0.15936E+03    0.36467E-01    0.66621E+00    0.51539E+04    0.15540E+00    0.26772E+00    0.15206E+02
0.15955E+03    0.36507E-01    0.57123E+00    0.51491E+04    0.13268E+00    0.26951E+00    0.15314E+02
0.15971E+03    0.36540E-01    0.47733E+00    0.51451E+04    0.11048E+00    0.27099E+00    0.15402E+02
0.15984E+03    0.36566E-01    0.38522E+00    0.51419E+04    0.88907E-01    0.27217E+00    0.15473E+02
0.15994E+03    0.36585E-01    0.29573E+00    0.51395E+04    0.68109E-01    0.27307E+00    0.15527E+02
0.16001E+03    0.36599E-01    0.20992E+00    0.51378E+04    0.48274E-01    0.27370E+00    0.15564E+02
0.16005E+03    0.36608E-01    0.12926E+00    0.51368E+04    0.29697E-01    0.27410E+00    0.15588E+02
0.16007E+03    0.36612E-01    0.56314E-01    0.51362E+04    0.12932E-01    0.27430E+00    0.15600E+02
0.16008E+03    0.36613E-01    0.00000E+00    0.51361E+04    0.00000E+00    0.27434E+00    0.15603E+02

MASS FLOW RATE (LB/SEC) = 15.6027          CSTAR (FT/SEC) = 6996.46          INITIAL THRUST (LBF) = 4395.54

LRC ID     R          X          MACH   THETA  T (DEG.R)   P (PSI)    DENSITY      VELOCITY   CF       ISP     IT
 0 15   1.00000    0.00000      1.122   0.000   5264.60    130.69    0.27351E-01   5809.73  1.2955  281.716   0
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ZONE
3

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LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  1  1   0.98981   0.00556    1.118  0.088   5267.78   131.32    0.27465E-01   5791.21   0.0000    0.000   0     3
  1  5   1.00001   0.00539    1.130  0.309   5256.82   129.31    0.27105E-01   5850.36   1.2955  281.719   2     3
  1  5   1.00006   0.01083    1.139  0.620   5249.17   127.94    0.26860E-01   5890.66   1.2956  281.728   4     3
MASS FLOW POINT    1 =  2.812945E-01  DELTA FLOWRATE =  1.532142E+01  PERCENT DELTA =  9.819714E+01  AREA RATIO =  1.000117E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  2  1   0.98535   0.00798    1.116  0.127   5269.16   131.60    0.27515E-01   5783.18   0.0000    0.000   0     3
  2  5   1.00012   0.01562    1.147  0.895   5242.62   126.76    0.26648E-01   5925.42   1.2956  281.741   4     3
MASS FLOW POINT    2 =  4.039025E-01  DELTA FLOWRATE =  1.519881E+01  PERCENT DELTA =  9.741134E+01  AREA RATIO =  1.000244E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  3  1   0.98008   0.01082    1.114  0.172   5270.77   131.92    0.27573E-01   5773.77   0.0000    0.000   0     3
  3  5   1.00023   0.02130    1.155  1.220   5234.96   125.38    0.26400E-01   5966.18   1.2957  281.763   4     3
MASS FLOW POINT    3 =  5.478930E-01  DELTA FLOWRATE =  1.505482E+01  PERCENT DELTA =  9.648848E+01  AREA RATIO =  1.000454E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  4  1   0.97402   0.01407    1.112  0.224   5272.61   132.29    0.27639E-01   5763.04   0.0000    0.000   0     3
  4  5   1.00039   0.02786    1.165  1.596   5226.27   123.80    0.26115E-01   6012.51   1.2959  281.795   4     3
MASS FLOW POINT    4 =  7.127798E-01  DELTA FLOWRATE =  1.488993E+01  PERCENT DELTA =  9.543169E+01  AREA RATIO =  1.000776E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  5  1   0.96717   0.01772    1.109  0.282   5274.65   132.70    0.27714E-01   5751.02   0.0000    0.000   0     3
  5  5   1.00062   0.03530    1.177  2.023   5216.42   122.04    0.25796E-01   6064.76   1.2961  281.842   4     3
MASS FLOW POINT    5 =  8.981084E-01  DELTA FLOWRATE =  1.470460E+01  PERCENT DELTA =  9.424390E+01  AREA RATIO =  1.001247E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  6  1   0.95953   0.02175    1.106  0.347   5276.90   133.16    0.27796E-01   5737.79   0.0000    0.000   0     3
  6  5   1.00095   0.04363    1.189  2.501   5205.45   120.10    0.25444E-01   6122.64   1.2964  281.906   4     3
MASS FLOW POINT    6 =  1.103257E+00  DELTA FLOWRATE =  1.449945E+01  PERCENT DELTA =  9.292907E+01  AREA RATIO =  1.001906E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  7  1   0.95113   0.02616    1.103  0.418   5279.34   133.65    0.27885E-01   5723.40   0.0000    0.000   0     3
  7  5   1.00116   0.04823    1.196  2.764   5199.45   119.04    0.25251E-01   6154.12   1.2966  281.947   2     3
  7  5   1.00140   0.05284    1.203  3.029   5193.40   117.98    0.25059E-01   6185.64   1.2968  281.991   3     3
MASS FLOW POINT    7 =  1.327569E+00  DELTA FLOWRATE =  1.427514E+01  PERCENT DELTA =  9.149142E+01  AREA RATIO =  1.002796E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  8  1   0.94196   0.03092    1.100  0.496   5281.95   134.19    0.27981E-01   5707.92   0.0000    0.000   0     3
  8  5   1.00168   0.05786    1.210  3.317   5186.79   116.83    0.24850E-01   6219.89   1.2970  282.044   2     3
  8  5   1.00198   0.06291    1.218  3.607   5180.13   115.69    0.24641E-01   6254.17   1.2973  282.101   3     3
MASS FLOW POINT    8 =  1.570325E+00  DELTA FLOWRATE =  1.403239E+01  PERCENT DELTA =  8.993556E+01  AREA RATIO =  1.003965E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
  9  1   0.93204   0.03602    1.097  0.579   5284.72   134.76    0.28083E-01   5691.42   0.0000    0.000   0     3
  9  5   1.00234   0.06835    1.226  3.919   5172.92   114.46    0.24417E-01   6291.04   1.2976  282.168   2     3
  9  5   1.00273   0.07382    1.234  4.234   5165.64   113.24    0.24193E-01   6327.97   1.2979  282.239   3     3
MASS FLOW POINT    9 =  1.830737E+00  DELTA FLOWRATE =  1.377197E+01  PERCENT DELTA =  8.826655E+01  AREA RATIO =  1.005465E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
 10  1   0.92138   0.04144    1.093  0.668   5287.64   135.36    0.28191E-01   5673.98   0.0000    0.000   0     3
 10  5   1.00318   0.07968    1.243  4.570   5157.79   111.94    0.23954E-01   6367.43   1.2983  282.321   2     3
 10  5   1.00367   0.08557    1.252  4.909   5149.86   110.63    0.23715E-01   6406.98   1.2987  282.409   3     3
MASS FLOW POINT   10 =  2.107963E+00  DELTA FLOWRATE =  1.349475E+01  PERCENT DELTA =  8.648976E+01  AREA RATIO =  1.007350E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
 11  1   0.90999   0.04717    1.089  0.762   5290.69   135.99    0.28305E-01   5655.68   0.0000    0.000   0     3
 11  5   1.00423   0.09184    1.261  5.269   5141.36   109.26    0.23463E-01   6448.96   1.2991  282.508   2     3
 11  5   1.00483   0.09814    1.270  5.632   5132.74   107.88    0.23209E-01   6491.11   1.2996  282.614   3     3
MASS FLOW POINT   11 =  2.401087E+00  DELTA FLOWRATE =  1.320162E+01  PERCENT DELTA =  8.461109E+01  AREA RATIO =  1.009677E+00
LRC ID     R         X         MACH   THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT   ZONE
 12  1   0.89788   0.05317    1.085  0.862   5293.85   136.65    0.28423E-01   5636.60   0.0000    0.000   0     3
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 12  5  1.00551  0.10479  1.280   6.015  5123.56  106.44   0.22944E-01  6535.54  1.3002  282.732  2      3
 12  5  1.00623  0.11149  1.290   6.401  5114.24  105.00   0.22677E-01  6580.20  1.3007  282.857  3      3
MASS FLOW POINT  12 =  2.709148E+00  DELTA FLOWRATE =  1.289356E+01  PERCENT DELTA =  8.263668E+01  AREA RATIO =  1.012507E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 13  1  0.88506  0.05944  1.081   0.967  5297.11  137.33   0.28546E-01  5616.84  0.0000    0.000  0      3
 13  5  1.00705  0.11852  1.301   6.807  5104.35  103.49   0.22399E-01  6627.01  1.3014  282.994  2      3
 13  5  1.00792  0.12560  1.311   7.215  5094.29  101.98   0.22119E-01  6674.16  1.3020  283.139  3      3
MASS FLOW POINT  13 =  3.031123E+00  DELTA FLOWRATE =  1.257159E+01  PERCENT DELTA =  8.057310E+01  AREA RATIO =  1.015901E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 14  1  0.87156  0.06595  1.076   1.076  5300.46  138.04   0.28672E-01  5596.49  0.0000    0.000  0      3
 14  5  1.00888  0.13300  1.322   7.643  5083.67  100.42   0.21830E-01  6723.31  1.3028  283.298  2      3
 14  5  1.00991  0.14044  1.334   8.074  5072.83  98.855   0.21538E-01  6772.86  1.3035  283.464  3      3
MASS FLOW POINT  14 =  3.365937E+00  DELTA FLOWRATE =  1.223677E+01  PERCENT DELTA =  7.842723E+01  AREA RATIO =  1.019921E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 15  1  0.85738  0.07267  1.072   1.191  5303.87  138.76   0.28801E-01  5575.64  0.0000    0.000  0      3
 15  5  1.01104  0.14819  1.345   8.522  5061.44  97.242   0.21238E-01  6824.31  1.3044  283.645  2      3
 15  5  1.01224  0.15599  1.357   8.974  5049.79  95.619   0.20935E-01  6876.26  1.3052  283.833  3      3
MASS FLOW POINT  15 =  3.712483E+00  DELTA FLOWRATE =  1.189023E+01  PERCENT DELTA =  7.620618E+01  AREA RATIO =  1.024631E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 16  1  0.84254  0.07959  1.068   1.309  5307.32  139.50   0.28933E-01  5554.41  0.0000    0.000  0      3
 16  5  1.01355  0.16406  1.370   9.443  5037.62  93.960   0.20625E-01  6929.84  1.3062  284.036  3      3
 16  5  1.01494  0.17220  1.382   9.916  5025.13  92.290   0.20312E-01  6984.09  1.3071  284.247  3      3
MASS FLOW POINT  16 =  4.069514E+00  DELTA FLOWRATE =  1.153320E+01  PERCENT DELTA =  7.391790E+01  AREA RATIO =  1.030098E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 17  1  0.82706  0.08669  1.063   1.432  5310.80  140.24   0.29067E-01  5532.88  0.0000    0.000  0      3
 17  5  1.01644  0.18059  1.395  10.404  5012.11  90.589   0.19993E-01  7039.90  1.3082  284.472  3      3
 17  5  1.01803  0.18905  1.408  10.897  4998.71  88.874   0.19671E-01  7096.49  1.3093  284.706  3      3
MASS FLOW POINT  17 =  4.435881E+00  DELTA FLOWRATE =  1.116683E+01  PERCENT DELTA =  7.156981E+01  AREA RATIO =  1.036390E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 18  1  0.81095  0.09392  1.059   1.559  5314.30  141.00   0.29201E-01  5511.18  0.0000    0.000  0      3
 18  5  1.01888  0.19339  1.415  11.150  4991.81  88.010   0.19508E-01  7125.37  1.3098  284.828  2      3
 18  5  1.02019  0.19993  1.425  11.533  4981.28  86.703   0.19262E-01  7169.06  1.3107  285.017  3      3
 18  5  1.02156  0.20651  1.436  11.918  4970.49  85.386   0.19013E-01  7213.27  1.3116  285.210  3      3
MASS FLOW POINT  18 =  4.810304E+00  DELTA FLOWRATE =  1.079241E+01  PERCENT DELTA =  6.917008E+01  AREA RATIO =  1.043577E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 19  1  0.79423  0.10128  1.054   1.689  5317.78  141.75   0.29337E-01  5489.40  0.0000    0.000  0      3
 19  5  1.02251  0.21099  1.443  12.180  4963.15  84.509   0.18847E-01  7243.18  1.3122  285.344  2      3
 19  5  1.02399  0.21774  1.453  12.577  4951.91  83.179   0.18595E-01  7288.44  1.3131  285.549  3      3
 19  5  1.02554  0.22454  1.464  12.976  4940.39  81.840   0.18341E-01  7334.29  1.3141  285.758  3
MASS FLOW POINT  19 =  5.191622E+00  DELTA FLOWRATE =  1.041109E+01  PERCENT DELTA =  6.672616E+01  AREA RATIO =  1.051723E+00
LRC ID   R        X        MACH   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 20  1  0.79423  0.10128  1.103   1.689  5812.36  141.75   0.36593E-01  5113.63  0.0000    0.000  0      2
 20  1  0.77747  0.10851  1.099   1.653  5814.88  142.48   0.36759E-01  5095.68  0.0000    0.000  0      2
 20  4  0.79473  0.11608  1.119   2.155  5802.15  138.92   0.35942E-01  5184.78  0.0000    0.000  3      2
 20  4  0.79473  0.11608  1.071   2.155  5304.19  138.92   0.28831E-01  5571.97  0.0000    0.000  3      3
 20  5  [illegible] 0.23002  1.473  13.298  4930.51  80.729   0.18130E-01  7372.91  1.3149  285.930  3      3
 20  5  1.02881  0.23830  1.487  13.786  4915.30  79.042   0.17809E-01  7431.63  1.3161  286.194  3      3
 20  5  1.03089  0.24663  1.502  14.278  4899.58  77.342   0.17484E-01  7491.41  1.3173  286.464  4      3
MASS FLOW POINT  21 =  5.627794E+00  DELTA FLOWRATE =  9.974917E+00  PERCENT DELTA =  6.393067E+01  AREA RATIO =  1.062737E+00
LRC ID   R        X        MAC.   THETA   T (DEG.R) P (PSI)  DENSITY      VELOCITY  CF      ISP      IT  ZONE
 21  1  0.76018  0.11581  1.094   1.697  5817.59  143.27   0.36940E-01  5076.26  0.0000    0.000  0      2
 21  4  0.79538  0.13141  1.134   2.675  5793.74  136.35   0.35344E-01  5246.02  0.0000    0.000  5      2
 21  4  0.79538  0.13141  1.087   2.675  5292.39  136.35   0.28369E-01  5645.55  0.0000    0.000  5      3
 21  5  1.03658  0.26819  1.521  15.000  4880.84  75.011   0.17029E-01  7572.72  1.3207  287.186  3      3
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MASS FLOW POINT   22 =  6.068181E+00  DELTA FLOWRATE =  9.534531E+00  PERCENT DELTA =  6.110817E+01  AREA RATIO =  1.074506E+00
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  22  1   0.74237  0.12315   1.090   1.740   5820.29   144.05    0.37120E-01   5056.86   0.0000    0.000  0          ZONE
  22  4   0.79619  0.14720   1.149   3.199   5784.31   133.72    0.34737E-01   5311.10   0.0000    0.000  4           2
  22  4   0.79619  0.14720   1.103   3.199   5280.06   133.72    0.27895E-01   5720.52   0.0000    0.000  4           2
  22  5   1.04241  0.28991   1.521  15.000   4886.93   74.945    0.16998E-01   7572.37   1.3240  287.917  3           3
MASS FLOW POINT   23 =  6.509702E+00  DELTA FLOWRATE =  9.093010E+00  PERCENT DELTA =  5.827840E+01  AREA RATIO =  1.086609E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  23  1   0.72407  0.13051   1.085   1.782   5822.96   144.83    0.37300E-01   5037.55   0.0000    0.000  0          ZONE
  23  4   0.79717  0.16347   1.165   3.736   5774.41   131.06    0.34119E-01   5378.43   0.0000    0.000  3           2
  23  4   0.79717  0.16347   1.119   3.736   5267.04   131.06    0.27415E-01   5797.84   0.0000    0.000  3           2
  23  5   1.04826  0.31178   1.521  15.000   4891.59   74.844    0.16964E-01   7574.04   1.3274  288.656  3           3
MASS FLOW POINT   24 =  6.953610E+00  DELTA FLOWRATE =  8.649102E+00  PERCENT DELTA =  5.543333E+01  AREA RATIO =  1.098859E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  24  1   0.70529  0.13788   1.081   1.822   5825.60   145.61    0.37478E-01   5018.42   0.0000    0.000  0          ZONE
  24  4   0.79834  0.18016   1.182   4.286   5763.92   128.32    0.33484E-01   5448.59   0.0000    0.000  3           2
  24  4   0.79834  0.18016   1.136   4.286   5253.18   128.32    0.26920E-01   5878.11   0.0000    0.000  3           2
  24  5   1.05416  0.33377   1.521  15.000   4894.90   74.698    0.16923E-01   7577.84   1.3308  289.402  3           3
MASS FLOW POINT   25 =  7.398190E+00  DELTA FLOWRATE =  8.204522E+00  PERCENT DELTA =  5.258395E+01  AREA RATIO =  1.111247E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  25  1   0.68605  0.14522   1.076   1.859   5828.20   146.38    0.37653E-01   4999.53   0.0000    0.000  0          ZONE
  25  4   0.79971  0.19727   1.198   4.844   5753.42   125.55    0.32840E-01   5518.33   0.0000    0.000  2           2
  25  4   0.79971  0.19727   1.154   4.844   5238.90   125.55    0.26419E-01   5959.44   0.0000    0.000  2           2
  25  5   1.06008  0.35586   1.522  15.000   4897.08   74.510    0.16877E-01   7583.46   1.3343  290.154  3           3
MASS FLOW POINT   26 =  7.841299E+00  DELTA FLOWRATE =  7.761413E+00  PERCENT DELTA =  4.974400E+01  AREA RATIO =  1.123764E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  26  1   0.66638  0.15252   1.072   1.895   5830.74   147.13    0.37826E-01   4980.95   0.0000    0.000  0          ZONE
  26  4   0.80127  0.21471   1.215   5.404   5742.42   122.76    0.32188E-01   5589.83   0.0000    0.000  2           2
  26  4   0.80127  0.21471   1.172   5.404   5224.00   122.76    0.25913E-01   6042.49   0.0000    0.000  2           2
  26  5   1.06602  0.37806   1.524  15.000   4898.06   74.271    0.16822E-01   7591.36   1.3378  290.911  3           3
MASS FLOW POINT   27 =  8.282604E+00  DELTA FLOWRATE =  7.320107E+00  PERCENT DELTA =  4.691561E+01  AREA RATIO =  1.136406E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  27  1   0.64630  0.15975   1.068   1.929   5833.22   147.87    0.37996E-01   4962.76   0.0000    0.000  0          ZONE
  27  4   0.80304  0.23249   1.233   5.973   5730.96   119.92    0.31524E-01   5663.11   0.0000    0.000  2           2
  27  4   0.80304  0.23249   1.190   5.973   5208.47   119.92    0.25397E-01   6127.35   0.0000    0.000  2           2
  27  5   1.07200  0.40035   1.526  15.000   4898.08   73.989    0.16761E-01   7601.08   1.3413  291.674  3           3
MASS FLOW POINT   28 =  8.720003E+00  DELTA FLOWRATE =  6.882709E+00  PERCENT DELTA =  4.411226E+01  AREA RATIO =  1.149176E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  28  1   0.62582  0.16689   1.064   1.960   5835.63   148.59    0.38161E-01   4945.03   0.0000    0.000  0          ZONE
  28  4   0.80503  0.25059   1.251   6.544   5719.08   117.05    0.30853E-01   5737.94   0.0000    0.000  2           2
  28  4   0.80503  0.25059   1.209   6.544   5192.31   117.05    0.24875E-01   6213.78   0.0000    0.000  2           2
  28  5   1.07800  0.42275   1.528  15.000   4897.16   73.658    0.16692E-01   7612.81   1.3448  292.441  3           3
MASS FLOW POINT   29 =  9.152867E+00  DELTA FLOWRATE =  6.449844E+00  PERCENT DELTA =  4.133797E+01  AREA RATIO =  1.162081E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  29  1   0.60498  0.17393   1.060   1.988   5837.95   149.30    0.38321E-01   4927.84   0.0000    0.000  0          ZONE
  29  4   0.80723  0.26896   1.269   7.117   5706.86   114.17    0.30177E-01   5813.80   0.0000    0.000  2           2
  29  4   0.80723  0.26896   1.228   7.117   5175.65   114.17    0.24349E-01   6301.17   0.0000    0.000  2           2
  29  5   1.08402  0.44522   1.531  15.000   4895.46   73.285    0.16615E-01   7626.18   1.3484  293.211  3           3
MASS FLOW POINT   30 =  9.579399E+00  DELTA FLOWRATE =  6.023313E+00  PERCENT DELTA =  3.860427E+01  AREA RATIO =  1.175099E+00   3
LRC ID    R        X         MACH   THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY   CF       ISP     IT
  30  1   0.58380  0.18084   1.056   2.014   5840.19   149.97    0.38476E-01   4911.24   0.0000    0.000  0          ZONE
  30  4   0.80965  0.28757   1.288   7.694   5694.25   111.28    0.29495E-01   5890.78   0.0000    0.000  2           2
  30  4   0.80965  0.28757   1.247   7.694   5158.44   111.28    0.23819E-01   6389.55   0.0000    0.000  2           2
  30  5   1.09004  0.46770   1.535  15.000   4893.11   72.878    0.16533E-01   7640.88   1.3519  293.982  3           3
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MASS FLOW POINT   31 =  9.998495E+00  DELTA FLOWRATE =  5.604217E+00  PERCENT DELTA =  3.591822E+01  AREA RATIO =  1.188193E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  31  1    0.56230    0.18760    1.052    2.038    5842.33   150.62     0.38624E-01    4895.31  0.0000    0.000   0                2
  31  4    0.81229    0.30646    1.307    8.273    5681.18   108.36     0.28805E-01    5969.21  0.0000    0.000   2                2
  31  4    0.81229    0.30646    1.267    8.273    5140.56   108.36     0.23282E-01    6479.37  0.0000    0.000   2                3
  31  5    1.09610    0.49031    1.539   15.000    4890.06   72.424     0.16442E-01    7657.27  1.3555  294.757   3                3
MASS FLOW POINT   32 =  1.040845E+01  DELTA FLOWRATE =  5.194263E+00  PERCENT DELTA =  3.329077E+01  AREA RATIO =  1.201439E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  32  1    0.56230    0.18760    1.094    2.038    5743.63   150.62     0.34692E-01    5375.42  0.0000    0.000   0                1
  32  1    0.53929    0.19455    1.089    1.922    5746.33   151.40     0.34850E-01    5356.17  0.0000    0.000   0                1
  32  4    0.56294    0.20427    1.108    2.341    5734.58   147.87     0.34125E-01    5442.46  0.0000    0.000   8                1
  32  4    0.56294    0.20427    1.068    2.341    5833.54   147.87     0.37992E-01    4962.36  0.0000    0.000   8                2
  32  4    0.81604    0.33110    1.332    9.007    5663.65   104.57     0.27906E-01    6072.42  0.0000    0.000   2                2
  32  4    0.81604    0.33110    1.294    9.007    5116.39   104.57     0.22583E-01    6597.66  0.0000    0.000   2                3
  32  5    1.10004    0.50501    1.542   15.000    4887.29   72.070     0.16372E-01    7670.23  1.3578  295.260   3                3
  32  5    1.10398    0.51971    1.545   15.000    4884.45   71.717     0.16303E-01    7683.21  1.3601  295.763   3                3
MASS FLOW POINT   34 =  1.082411E+01  DELTA FLOWRATE =  4.778598E+00  PERCENT DELTA =  3.062671E+01  AREA RATIO =  1.218770E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  33  1    0.51597    0.20130    1.085    1.872    5748.88   152.13     0.34999E-01    5337.96  0.0000    0.000   0                1
  33  4    0.56368    0.22127    1.122    2.671    5726.01   145.33     0.33605E-01    5504.94  0.0000    0.000   2                1
  33  4    0.56368    0.22127    1.082    2.671    5825.40   145.33     0.37410E-01    5024.06  0.0000    0.000   2                2
  33  4    0.82002    0.35526    1.357    9.720    5646.16   100.92     0.27040E-01    6173.33  0.0000    0.000   2                2
  33  4    0.82002    0.35526    1.320    9.720    5092.18   100.92     0.21908E-01    6713.05  0.0000    0.000   2                3
  33  5    1.10779    0.53392    1.548   15.000    4881.59   71.375     0.16236E-01    7695.99  1.3623  296.248   3                3
  33  5    1.11159    0.54812    1.551   15.000    4878.68   71.028     0.16167E-01    7708.82  1.3646  296.733   3                3
MASS FLOW POINT   35 =  1.122801E+01  DELTA FLOWRATE =  4.374704E+00  PERCENT DELTA =  2.803810E+01  AREA RATIO =  1.235640E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  34  1    0.49240    0.20783    1.082    1.818    5751.33   152.84     0.35144E-01    5320.37  0.0000    0.000   0                1
  34  4    0.56454    0.23858    1.137    3.005    5716.49   142.71     0.33068E-01    5571.03  0.0000    0.000   4                1
  34  4    0.56454    0.23858    1.097    3.005    5816.47   142.71     0.36809E-01    5088.93  0.0000    0.000   4                2
  34  4    0.82433    0.37952    1.382   10.432    5628.39   97.346     0.26186E-01    6273.91  0.0000    0.000   2                2
  34  4    0.82433    0.37952    1.346   10.432    5067.48   97.346     0.21243E-01    6827.76  0.0000    0.000   2                3
  34  5    1.11537    0.56222    1.554   15.000    4875.64   70.682     0.16099E-01    7721.90  1.3668  297.213   3                3
  34  5    1.11915    0.57631    1.557   15.000    4872.55   70.329     0.16030E-01    7735.03  1.3690  297.692   3                3
MASS FLOW POINT   36 =  1.161917E+01  DELTA FLOWRATE =  3.983541E+00  PERCENT DELTA =  2.553108E+01  AREA RATIO =  1.252490E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  35  1    0.46859    0.21410    1.078    1.758    5753.67   153.52     0.35283E-01    5303.46  0.0000    0.000   0                1
  35  4    0.56552    0.25616    1.152    3.335    5706.92   140.10     0.32530E-01    5636.74  0.0000    0.000   2                1
  35  4    0.56552    0.25616    1.112    3.335    5807.54   140.10     0.36206E-01    5153.07  0.0000    0.000   2                2
  35  4    0.82898    0.40393    1.407   11.141    5610.20   93.817     0.25340E-01    6374.65  0.0000    0.000   2                2
  35  4    0.82898    0.40393    1.372   11.141    5042.15   93.817     0.20584E-01    6942.30  0.0000    0.000   2                3
  35  5    1.12291    0.59035    1.561   15.000    4869.29   69.968     0.15960E-01    7748.60  1.3712  298.168   3                3
  35  5    1.12667    0.60438    1.564   15.000    4865.99   69.604     0.15888E-01    7762.20  1.3733  298.644   3                3
MASS FLOW POINT   37 =  1.199530E+01  DELTA FLOWRATE =  3.607415E+00  PERCENT DELTA =  2.312044E+01  AREA RATIO =  1.269381E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  36  1    0.44459    0.22012    1.074    1.694    5755.91   154.18     0.35416E-01    5287.27  0.0000    0.000   0                1
  36  4    0.56660    0.27397    1.167    3.660    5696.86   137.45     0.31986E-01    5704.46  0.0000    0.000   3                1
  36  4    0.56660    0.27397    1.128    3.660    5798.00   137.45     0.35599E-01    5220.25  0.0000    0.000   3                2
  36  4    0.83398    0.42853    1.432   11.849    5591.54   90.337     0.24502E-01    6475.66  0.0000    0.000   2                2
  36  4    0.83398    0.42853    1.398   11.849    5016.12   90.337     0.19931E-01    7056.88  0.0000    0.000   2                3
  36  5    1.13042    0.61839    1.567   15.000    4862.53   69.232     0.15816E-01    7776.21  1.3755  299.118   3                3
  36  5    1.13417    0.63240    1.571   15.000    4859.04   68.859     0.15743E-01    7790.27  1.3777  299.590   3                3
MASS FLOW POINT   38 =  1.235581E+01  DELTA FLOWRATE =  3.246900E+00  PERCENT DELTA =  2.080984E+01  AREA RATIO =  1.286353E+00

LRC ID      R          X          MACH    THETA   T (DEG.R)   P (PSI)    DENSITY       VELOCITY   CF       ISP     IT              ZONE
  37  1    0.42042    0.22585    1.071    1.626    5758.04   154.80     0.35543E-01    5271.84  0.0000    0.000   0                1
  37  4    0.56781    0.29201    1.182    3.982    5686.85   134.82     0.31442E-01    5771.31  0.0000    0.000   2                1
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  37  4   0.56781   0.29201    1.143    3.982    5788.68  134.82    0.34990E-01   5285.63  0.0000     0.000  2
  37  4   0.83934   0.45331    1.458   12.551    5572.36   86.905   0.23673E-01   6577.17  0.0000     0.000  2             2
  37  4   0.83934   0.45331    1.425   12.551    4989.35   86.905   0.19284E-01   7171.58  0.0000     0.000  2             2
  37  5   1.13793   0.64640    1.574   15.000    4855.34   68.472   0.15667E-01   7804.90  1.3799   300.062  3             3
  37  5   1.14168   0.66040    1.578   15.000    4851.61   68.085   0.15591E-01   7819.56  1.3820   300.532  3             3
MASS FLOW POINT   39 =  1.269941E+01  DELTA FLOWRATE =  2.903298E+00  PERCENT DELTA =  1.860765E+01  AREA RATIO =  1.303427E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  38  1   0.39613   0.23129    1.068    1.553    5760.05  155.39    0.35663E-01   5257.21  0.0000     0.000  0          ZONE
  38  4   0.56913   0.31023    1.197    4.302    5676.53  132.18    0.30896E-01   5838.91  0.0000     0.000  2             1
  38  4   0.56913   0.31023    1.159    4.302    5779.06  132.18    0.34378E-01   5351.74  0.0000     0.000  2             1
  38  4   0.84505   0.47825    1.483   13.240    5552.99   83.565   0.22863E-01   6677.77  0.0000     0.000  2             2
  38  4   0.84505   0.47825    1.452   13.240    4962.18   83.565   0.18652E-01   7285.07  0.0000     0.000  2             2
  38  5   1.14542   0.67438    1.582   15.000    4847.73   67.688   0.15514E-01   7834.62  1.3842   301.000  3             3
  38  5   1.14917   0.68835    1.585   15.000    4843.83   67.293   0.15436E-01   7849.71  1.3863   301.467  3             3
MASS FLOW POINT   40 =  1.302545E+01  DELTA FLOWRATE =  2.577257E+00  PERCENT DELTA =  1.651801E+01  AREA RATIO =  1.320586E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  39  1   0.37175   0.23643    1.065    1.476    5761.94  155.95    0.35777E-01   5243.40  0.0000     0.000  0          ZONE
  39  4   0.57056   0.32859    1.212    4.617    5665.94  129.53    0.30347E-01   5907.26  0.0000     0.000  2             1
  39  4   0.57056   0.32859    1.174    4.617    5769.21  129.53    0.33763E-01   5418.34  0.0000     0.000  2             1
  39  4   0.85110   0.50334    1.508   13.892    5534.16   80.388   0.22088E-01   6774.70  0.0000     0.000  3             2
  39  4   0.85110   0.50334    1.478   13.892    4935.40   80.388   0.18047E-01   7394.75  0.0000     0.000  3             2
  39  5   1.15291   0.70232    1.589   15.000    4839.76   66.886   0.15357E-01   7865.26  1.3885   301.933  3             3
  39  5   1.15665   0.71629    1.593   15.000    4835.66   66.480   0.15277E-01   7880.85  1.3906   302.397  3             3
MASS FLOW POINT   41 =  1.333325E+01  DELTA FLOWRATE =  2.269464E+00  PERCENT DELTA =  1.454531E+01  AREA RATIO =  1.337849E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  40  1   0.34731   0.24125    1.062    1.396    5763.71  156.48    0.35883E-01   5230.46  0.0000     0.000  0          ZONE
  40  4   0.57210   0.34710    1.228    4.930    5655.14  126.88    0.29798E-01   5975.99  0.0000     0.000  2             1
  40  4   0.57210   0.34710    1.190    4.930    5759.15  126.88    0.33148E-01   5485.37  0.0000     0.000  2             1
  40  4   0.85747   0.52854    1.531   14.474    5516.82   77.482   0.21374E-01   6864.44  0.0000     0.000  3             2
  40  4   0.85747   0.52854    1.502   14.474    4910.21   77.482   0.17490E-01   7496.65  0.0000     0.000  3             2
  40  5   1.16413   0.74421    1.601   15.000    4827.12   65.648   0.15115E-01   7912.96  1.3949   303.321  3             3
MASS FLOW POINT   42 =  1.362206E+01  DELTA FLOWRATE =  1.980650E+00  PERCENT DELTA =  1.269427E+01  AREA RATIO =  1.355209E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  41  1   0.32287   0.24574    1.059    1.312    5765.35  156.97    0.35982E-01   5218.39  0.0000     0.000  0          ZONE
  41  4   0.57376   0.36569    1.244    5.239    5644.13  124.24    0.29248E-01   6045.06  0.0000     0.000  2             1
  41  4   0.57376   0.36569    1.204    5.239    5748.89  124.24    0.32533E-01   5552.83  0.0000     0.000  2             1
  41  4   0.86411   0.55383    1.552   14.952    5501.83   74.933   0.20743E-01   6943.87  0.0000     0.000  3             2
  41  4   0.86411   0.55383    1.524   14.952    4887.77   74.933   0.16997E-01   7587.35  0.0000     0.000  3             2
  41  5   1.17161   0.77212    1.609   15.000    4818.15   64.793   0.14947E-01   7946.17  1.3991   304.238  3             3
MASS FLOW POINT   43 =  1.389131E+01  DELTA FLOWRATE =  1.711402E+00  PERCENT DELTA =  1.096862E+01  AREA RATIO =  1.372676E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  42  1   0.29846   0.24990    1.057    1.225    5766.87  157.42    0.36074E-01   5207.22  0.0000     0.000  0          ZONE
  42  4   0.57552   0.38435    1.259    5.545    5632.96  121.62    0.28701E-01   6114.16  0.0000     0.000  2             1
  42  4   0.57552   0.38435    1.222    5.545    5738.51  121.62    0.31920E-01   5620.20  0.0000     0.000  2             1
  42  4   0.87095   0.57913    1.569   15.308    5489.58   72.779   0.20206E-01   7011.51  0.0000     0.000  3             2
  42  4   0.87095   0.57913    1.543   15.308    4868.76   72.779   0.16578E-01   7664.98  0.0000     0.000  3             2
  42  5   1.17908   0.79999    1.618   15.000    4808.84   63.921   0.14776E-01   7980.28  1.4033   305.148  3             3
MASS FLOW POINT   44 =  1.414055E+01  DELTA FLOWRATE =  1.462163E+00  PERCENT DELTA =  9.371210E+00  AREA RATIO =  1.390229E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT
  43  1   0.27413   0.25373    1.055    1.136    5768.26  157.83    0.36159E-01   5196.97  0.0000     0.000  0          ZONE
  43  4   0.57738   0.40305    1.275    5.847    5621.63  119.02    0.28157E-01   6183.26  0.0000     0.000  2             1
  43  4   0.57738   0.40305    1.238    5.847    5727.98  119.02    0.31311E-01   5687.61  0.0000     0.000  2             1
  43  4   0.87792   0.60438    1.584   15.543    5479.99   71.003   0.19760E-01   7067.58  0.0000     0.000  3             2
  43  4   0.87792   0.60438    1.558   15.543    4853.26   71.003   0.16230E-01   7729.66  0.0000     0.000  3             2
  43  5   1.18653   0.82778    1.627   15.000    4799.19   63.035   0.14602E-01   8015.20  1.4074   306.049  3             3
MASS FLOW POINT   45 =  1.436951E+01  DELTA FLOWRATE =  1.233202E+00  PERCENT DELTA =  7.903767E+00  AREA RATIO =  1.407849E+00  3

LRC ID     R         X         MACH    THETA   T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT                ZONE
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  44  1   0.24992   0.25721   1.052   1.045   5769.52  158.21   0.36236E-01   5187.63  0.0000   0.000  0        1
  44  4   0.57935   0.42176   1.291   6.144   5610.17  116.44   0.27616E-01   6252.18  0.0000   0.000  2        1
  44  4   0.57935   0.42176   1.255   6.144   5717.32  116.44   0.30706E-01   5754.91  0.0000   0.000  2        2
  44  4   0.88495   0.62954   1.596  15.670   5472.52  69.550   0.19393E-01   7113.79  0.0000   0.000  3        2
  44  4   0.88495   0.62954   1.571  15.670   4840.83  69.550   0.15943E-01   7783.09  0.0000   0.000  3        3
  44  5   1.19396   0.85551   1.636  15.000   4789.25  62.138   0.14426E-01   8050.82  1.4115 306.941  3        3
MASS FLOW POINT   46 =  1.457803E+01  DELTA FLOWRATE =  1.024679E+00  PERCENT DELTA =  6.567315E+00  AREA RATIO =  1.425536E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  45  1   0.22588   0.26034   1.051   0.951   5770.66  158.55   0.36305E-01   5179.22  0.0000   0.000  0        1
  45  4   0.58140   0.44043   1.307   6.436   5598.58  113.89   0.27082E-01   6320.84  0.0000   0.000  2        1
  45  4   0.58140   0.44043   1.271   6.436   5706.55  113.89   0.30108E-01   5821.99  0.0000   0.000  2        2
  45  4   0.89197   0.65454   1.606  15.710   5466.43  68.350   0.19088E-01   7152.81  0.0000   0.000  2        2
  45  4   0.89197   0.65454   1.582  15.710   4830.82  68.350   0.15704E-01   7827.55  0.0000   0.000  2        3
  45  5   1.20135   0.88311   1.645  15.000   4779.05  61.233   0.14248E-01   8087.02  1.4155 307.820  3        3
MASS FLOW POINT   47 =  1.476592E+01  DELTA FLOWRATE =  8.367891E-01  PERCENT DELTA =  5.363101E+00  AREA RATIO =  1.443248E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  46  1   0.20208   0.26314   1.049   0.857   5771.67  158.86   0.36366E-01   5171.74  0.0000   0.000  0        1
  46  4   0.58355   0.45903   1.323   6.724   5586.93  111.39   0.26555E-01   6388.91  0.0000   0.000  2        1
  46  4   0.58355   0.45903   1.287   6.724   5695.76  111.39   0.29518E-01   5888.34  0.0000   0.000  2        2
  46  4   0.89894   0.67932   1.614  15.687   5461.39  67.339   0.18831E-01   7185.94  0.0000   0.000  2        2
  46  4   0.89894   0.67932   1.591  15.687   4822.58  67.339   0.15502E-01   7865.26  0.0000   0.000  2        3
  46  5   1.20870   0.91052   1.654  15.000   4768.73  60.332   0.14070E-01   8123.35  1.4195 308.687  3        3
MASS FLOW POINT   48 =  1.493324E+01  DELTA FLOWRATE =  6.694727E-01  PERCENT DELTA =  4.290746E+00  AREA RATIO =  1.460949E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  47  1   0.17856   0.26559   1.048   0.762   5772.55  159.13   0.36421E-01   5165.16  0.0000   0.000  0        1
  47  4   0.58577   0.47751   1.338   7.005   5575.22  108.94   0.26037E-01   6456.38  0.0000   0.000  2        1
  47  4   0.58577   0.47751   1.303   7.005   5684.93  108.94   0.28938E-01   5954.06  0.0000   0.000  2        2
  47  4   0.90580   0.70382   1.622  15.621   5456.90  66.459   0.18607E-01   7215.08  0.0000   0.000  2        2
  47  4   0.90580   0.70382   1.599  15.621   4815.47  66.459   0.15325E-01   7898.31  0.0000   0.000  2        3
  47  5   1.21598   0.93770   1.663  15.000   4758.31  59.436   0.13893E-01   8159.74  1.4234 309.539  3        3
MASS FLOW POINT   49 =  1.508026E+01  DELTA FLOWRATE =  5.224562E-01  PERCENT DELTA =  3.348496E+00  AREA RATIO =  1.478606E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  48  1   0.15540   0.26772   1.046   0.666   5773.32  159.36   0.36467E-01   5159.47  0.0000   0.000  0        1
  48  4   0.58806   0.49580   1.354   7.281   5563.55  106.54   0.25530E-01   6522.76  0.0000   0.000  2        1
  48  4   0.58806   0.49580   1.319   7.281   5674.12  106.54   0.28371E-01   6018.79  0.0000   0.000  2        2
  48  4   0.91252   0.72793   1.629  15.529   5452.64  65.668   0.18407E-01   7241.61  0.0000   0.000  2        2
  48  4   0.91252   0.72793   1.606  15.529   4809.05  65.668   0.15166E-01   7928.20  0.0000   0.000  2        3
  48  5   1.22316   0.96450   1.672  15.000   4747.89  58.555   0.13719E-01   8195.82  1.4273 310.371  3        3
MASS FLOW POINT   50 =  1.520722E+01  DELTA FLOWRATE =  3.954868E-01  PERCENT DELTA =  2.534731E+00  AREA RATIO =  1.496123E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  49  1   0.13268   0.26951   1.045   0.571   5773.96  159.55   0.36507E-01   5154.66  0.0000   0.000  0        1
  49  4   0.59041   0.51384   1.369   7.550   5551.92  104.21   0.25035E-01   6587.99  0.0000   0.000  2        1
  49  4   0.59041   0.51384   1.334   7.550   5663.36  104.21   0.27817E-01   6082.39  0.0000   0.000  2        2
  49  4   0.91908   0.75161   1.635  15.422   5448.40  64.934   0.18220E-01   7266.55  0.0000   0.000  2        2
  49  4   0.91908   0.75161   1.613  15.422   4802.94  64.934   0.15018E-01   7956.16  0.0000   0.000  2        3
  49  5   1.23024   0.99090   1.682  15.000   4737.50  57.689   0.13547E-01   8231.55  1.4310 311.183  3        3
MASS FLOW POINT   51 =  1.531470E+01  DELTA FLOWRATE =  2.880116E-01  PERCENT DELTA =  1.845907E+00  AREA RATIO =  1.513478E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
  50  1   0.11048   0.27099   1.044   0.477   5774.49  159.71   0.36540E-01   5150.69  0.0000   0.000  0        1
  50  4   0.59281   0.53159   1.384   7.811   5540.39  101.95   0.24555E-01   6651.80  0.0000   0.000  2        1
  50  4   0.59281   0.53159   1.350   7.811   5652.70  101.95   0.27280E-01   6144.61  0.0000   0.000  2        2
  50  4   0.92545   0.77478   1.641  15.310   5444.10  64.239   0.18045E-01   7290.45  0.0000   0.000  2        2
  50  4   0.92545   0.77478   1.620  15.310   4796.99  64.239   0.14878E-01   7982.82  0.0000   0.000  2        3
  50  5   1.23717   1.01680   1.691  15.000   4727.22  56.845   0.13379E-01   8266.66  1.4346 311.973  3        3
MASS FLOW POINT   52 =  1.540332E+01  DELTA FLOWRATE =  1.993933E-01  PERCENT DELTA =  1.277940E+00  AREA RATIO =  1.530602E+00

LRC ID    R         X         MACH    THETA  T (DEG.R)  P (PSI)   DENSITY       VELOCITY  CF        ISP    IT    ZONE
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   51  1   0.08891   0.27217   1.044   0.385   5774.92  159.84   0.36566E-01   5147.53  0.0000    0.000  0
   51  4   0.59522   0.54894   1.399   8.063   5528.99  99.772   0.24090E-01   6713.98  0.0000    0.000  2        1
   51  4   0.59522   0.54894   1.365   8.063   5642.19  99.772   0.26759E-01   6205.15  0.0000    0.000  2        1
   51  4   0.93160   0.79734   1.648  15.197   5439.73  63.573   0.17876E-01   7313.65  0.0000    0.000  2        2
   51  4   0.93160   0.79734   1.626  15.197   4791.07  63.573   0.14744E-01   8008.56  0.0000    0.000  2        2
   51  5   1.24395   1.04208   1.699  15.000   4717.09  56.026   0.13216E-01   8300.99  1.4382  312.737  3        3
 MASS FLOW POINT    53 =  1.547390E+01  DELTA FLOWRATE =   1.288071E-01  PERCENT DELTA =  8.255428E-01  AREA RATIO =   1.547407E+00  3
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   52  1   0.06811   0.27307   1.043   0.296   5775.24  159.94   0.36585E-01   5145.13  0.0000    0.000  0        1
   52  4   0.59764   0.56573   1.413   8.305   5517.93  97.698   0.23647E-01   6773.64  0.0000    0.000  2        1
   52  4   0.59764   0.56573   1.379   8.305   5632.00  97.698   0.26264E-01   6263.26  0.0000    0.000  2        2
   52  4   0.93747   0.81905   1.653  15.089   5435.36  62.936   0.17716E-01   7336.01  0.0000    0.000  2        2
   52  4   0.93747   0.81905   1.632  15.089   4785.23  62.936   0.14616E-01   8033.34  0.0000    0.000  2        3
   52  5   1.25048   1.06646   1.708  15.000   4707.27  55.244   0.13060E-01   8334.05  1.4415  313.467  3        3
 MASS FLOW POINT    54 =  1.552747E+01  DELTA FLOWRATE =   7.523823E-02  PERCENT DELTA =  4.822125E-01  AREA RATIO =   1.563700E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   53  1   0.04827   0.27370   1.043   0.210   5775.46  160.01   0.36599E-01   5143.44  0.0000    0.000  0        1
   53  4   0.60003   0.58189   1.427   8.536   5507.18  95.728   0.23225E-01   6830.86  0.0000    0.000  2        1
   53  4   0.60003   0.58189   1.393   8.536   5622.09  95.728   0.25792E-01   6319.02  0.0000    0.000  2        2
   53  4   0.94307   0.83988   1.659  14.985   5431.02  62.325   0.17562E-01   7357.61  0.0000    0.000  2        2
   53  4   0.94307   0.83988   1.638  14.985   4779.44  62.325   0.14493E-01   8057.24  0.0000    0.000  2        3
   53  5   1.25676   1.08989   1.716  15.000   4697.79  54.498   0.12911E-01   8365.79  1.4447  314.163  3        3
 MASS FLOW POINT    55 =  1.556536E+01  DELTA FLOWRATE =   3.734684E-02  PERCENT DELTA =  2.393612E-01  AREA RATIO =   1.579443E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   54  1   0.02970   0.27410   1.043   0.129   5775.61  160.05   0.36608E-01   5142.37  0.0000    0.000  0        1
   54  4   0.60234   0.59709   1.440   8.750   5497.01  93.902   0.22833E-01   6884.39  0.0000    0.000  2        1
   54  4   0.60234   0.59709   1.406   8.750   5612.73  93.902   0.25353E-01   6371.13  0.0000    0.000  2        2
   54  4   0.94828   0.85941   1.665  14.890   5426.82  61.752   0.17417E-01   7378.05  0.0000    0.000  2        2
   54  4   0.94828   0.85941   1.644  14.890   4773.86  61.752   0.14378E-01   8079.83  0.0000    0.000  2        3
   54  5   1.26266   1.11190   1.724  15.000   4688.83  53.803   0.12772E-01   8395.59  1.4477  314.811  3        3
 MASS FLOW POINT    56 =  1.558911E+01  DELTA FLOWRATE =   1.360416E-02  PERCENT DELTA =  8.719102E-02  AREA RATIO =   1.594303E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   55  1   0.01293   0.27430   1.042   0.056   5775.68  160.07   0.36612E-01   5141.85  0.0000    0.000  0        1
   55  4   0.60449   0.61093   1.451   8.944   5487.71  92.264   0.22481E-01   6932.80  0.0000    0.000  2        1
   55  4   0.60449   0.61093   1.418   8.944   5604.18  92.264   0.24959E-01   6418.26  0.0000    0.000  2        2
   55  4   0.95297   0.87712   1.670  14.806   5422.92  61.231   0.17286E-01   7396.72  0.0000    0.000  2        2
   55  4   0.95297   0.87712   1.649  14.806   4768.67  61.231   0.14274E-01   8100.44  0.0000    0.000  2        3
   55  5   1.26801   1.13190   1.731  15.000   4680.69  53.179   0.12646E-01   8422.52  1.4504  315.395  3        3
 MASS FLOW POINT    57 =  1.560079E+01  DELTA FLOWRATE =   1.916885E-03  PERCENT DELTA =  1.228559E-02  AREA RATIO =   1.607861E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   56 13   0.00000   0.27434   1.042   0.000   5775.69  160.08   0.36613E-01   5141.72  0.0000    0.000  0        1
   56  4   0.60620   0.62169   1.460   9.093   5480.46  91.006   0.22210E-01   6970.25  0.0000    0.000  2        1
   56  4   0.60620   0.62169   1.427   9.093   5597.52  91.006   0.24656E-01   6454.71  0.0000    0.000  2        2
   56  4   0.95659   0.89085   1.673  14.742   5419.85  60.826   0.17184E-01   7411.29  0.0000    0.000  2        2
   56  4   0.95659   0.89085   1.653  14.742   4764.56  60.826   0.14193E-01   8116.53  0.0000    0.000  2        3
   56  5   1.27217   1.14742   1.737  15.000   4674.36  52.698   0.12550E-01   8443.36  1.4524  315.845  3        3
 MASS FLOW POINT    58 =  1.560344E+01  DELTA FLOWRATE = -7.247925E-04  PERCENT DELTA = -4.645298E-03  AREA RATIO =   1.618425E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
   57  3   0.00000   0.28236   1.051   0.000   5770.20  158.44   0.36283E-01   5181.81  0.0000    0.000  2        1
   57  4   0.60979   0.64373   1.479   9.392   5465.47  88.475   0.21663E-01   7046.66  0.0000    0.000  2        1
   57  4   0.60979   0.64373   1.445   9.392   5583.79  88.475   0.24045E-01   6529.02  0.0000    0.000  2        2
   57  4   0.96393   0.91886   1.681  14.612   5413.49  60.004   0.16977E-01   7441.18  0.0000    0.000  2        2
   57  4   0.96393   0.91886   1.661  14.612   4755.99  60.004   0.14028E-01   8149.47  0.0000    0.000  2        3
   57  5   1.28068   1.17916   1.748  15.000   4661.23  51.720   0.12353E-01   8486.26  1.4566  316.758  3        3
 MASS FLOW POINT    58 =  1.560351E+01  DELTA FLOWRATE = -7.991791E-04  PERCENT DELTA = -5.122053E-03  AREA RATIO =   1.640140E+00
 LRC ID     R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT      ZONE
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 58  3   0.00000   0.29116   1.061   0.000   5764.36  156.69   0.35926E-01   5224.80  0.0000    0.000  2        1
 58  4   0.61369   0.66694   1.498   9.701   5449.70  85.883   0.21102E-01   7125.99  0.0000    0.000  2        1
 58  4   0.61369   0.66694   1.465   9.701   5569.37  85.883   0.23417E-01   6606.07  0.0000    0.000  2        2
 58  4   0.97154   0.94820   1.690  14.482   5406.70  59.144   0.16760E-01   7472.76  0.0000    0.000  2        2
 58  4   0.97154   0.94820   1.670  14.482   4746.75  59.144   0.13856E-01   8184.28  0.0000    0.000  2        3
 58  4   0.97154   0.94820   1.760  15.000   4647.47  50.715   0.12150E-01   8530.86  1.4610  317.705  3        3
 58  5   1.28961   1.21249
MASS FLOW POINT   58 =  1.560348E+01  DELTA FLOWRATE = -7.696152E-04  PERCENT DELTA = -4.932573E-03  AREA RATIO =  1.663090E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 59  3   0.00000   0.30071   1.071   0.000   5758.17  154.83   0.35548E-01   5270.32  0.0000    0.000  2        1
 59  4   0.61792   0.69127   1.518  10.017   5433.16  83.248   0.20530E-01   7207.80  0.0000    0.000  3        2
 59  4   0.61792   0.69127   1.485  10.017   5554.28  83.248   0.22776E-01   6685.48  0.0000    0.000  3        2
 59  4   0.97940   0.97879   1.699  14.351   5399.48  58.248   0.16534E-01   7505.98  0.0000    0.000  2        3
 59  4   0.97940   0.97879   1.679  14.351   4736.84  58.248   0.13677E-01   8220.86  0.0000    0.000  2        3
 59  5   1.29427   1.22990   1.766  15.000   4640.31  50.199   0.12046E-01   8553.92  1.4633  318.195  3        3
 59  5   1.29894   1.24731   1.772  15.000   4633.07  49.684   0.11942E-01   8577.11  1.4655  318.681  3
MASS FLOW POINT   58 =  1.560343E+01  DELTA FLOWRATE = -7.190704E-04  PERCENT DELTA = -4.608625E-03  AREA RATIO =  1.687242E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 60  3   0.00000   0.31100   1.081   0.000   5751.83  152.92   0.35158E-01   5317.06  0.0000    0.000  2        1
 60  4   0.62247   0.71662   1.539  10.336   5415.93  80.591   0.19950E-01   7291.64  0.0000    0.000  3        2
 60  4   0.62247   0.71662   1.506  10.336   5538.57  80.591   0.22128E-01   6766.82  0.0000    0.000  3        2
 60  4   0.98748   1.01052   1.708  14.222   5391.85  57.320   0.16299E-01   7540.77  0.0000    0.000  2        3
 60  4   0.98748   1.01052   1.689  14.222   4726.27  57.320   0.13491E-01   8259.16  0.0000    0.000  2        3
 60  5   1.30379   1.26541   1.778  15.000   4625.62  49.157   0.11835E-01   8600.92  1.4678  319.184  3        3
 60  5   1.30864   1.28351   1.785  15.000   4618.07  48.632   0.11729E-01   8624.87  1.4701  319.683  3
MASS FLOW POINT   58 =  1.560341E+01  DELTA FLOWRATE = -6.942749E-04  PERCENT DELTA = -4.449707E-03  AREA RATIO =  1.712536E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 61  3   0.00000   0.32202   1.092   0.000   5745.18  150.95   0.34756E-01   5365.57  0.0000    0.000  2        1
 61  4   0.62737   0.74306   1.560  10.656   5398.05  77.926   0.19367E-01   7377.20  0.0000    0.000  3        2
 61  4   0.62737   0.74306   1.527  10.656   5522.31  77.926   0.21475E-01   6849.81  0.0000    0.000  3        2
 61  4   0.99578   1.04343   1.718  14.095   5383.77  56.358   0.16055E-01   7577.19  0.0000    0.000  2        3
 61  4   0.99578   1.04343   1.699  14.095   4715.03  56.358   0.13298E-01   8299.21  0.0000    0.000  2        3
 61  5   1.31368   1.30233   1.791  15.000   4610.30  48.096   0.11619E-01   8649.43  1.4725  320.198  3        3
 61  5   1.31872   1.32115   1.798  15.000   4602.43  47.561   0.11511E-01   8674.15  1.4748  320.709  3
MASS FLOW POINT   58 =  1.560340E+01  DELTA FLOWRATE = -6.904602E-04  PERCENT DELTA = -4.425258E-03  AREA RATIO =  1.739035E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 62  3   0.00000   0.33374   1.103   0.000   5738.23  148.92   0.34340E-01   5415.72  0.0000    0.000  2        1
 62  4   0.63261   0.77051   1.581  10.973   5379.67  75.277   0.18785E-01   7463.75  0.0000    0.000  3        2
 62  4   0.63261   0.77051   1.549  10.973   5505.62  75.277   0.20824E-01   6933.73  0.0000    0.000  3        2
 62  4   1.00428   1.07742   1.728  13.971   5375.31  55.369   0.15804E-01   7615.07  0.0000    0.000  2        3
 62  4   1.00428   1.07742   1.710  13.971   4703.15  55.369   0.13100E-01   8340.86  0.0000    0.000  2        3
 62  5   1.32394   1.34062   1.805  15.000   4594.40  47.019   0.11400E-01   8699.30  1.4772  321.234  3        3
 62  5   1.32916   1.36010   1.812  15.000   4586.26  46.478   0.11290E-01   8724.62  1.4796  321.756  3
MASS FLOW POINT   58 =  1.560336E+01  DELTA FLOWRATE = -6.475449E-04  PERCENT DELTA = -4.150207E-03  AREA RATIO =  1.766670E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 63  3   0.00000   0.34618   1.114   0.000   5731.04  146.84   0.33916E-01   5467.15  0.0000    0.000  2        1
 63  4   0.63823   0.79906   1.603  11.282   5360.84  72.654   0.18206E-01   7551.08  0.0000    0.000  3        2
 63  4   0.63823   0.79906   1.571  11.282   5488.56  72.654   0.20177E-01   7018.35  0.0000    0.000  3        2
 63  4   1.01299   1.11259   1.739  13.851   5366.40  54.349   0.15545E-01   7654.57  0.0000    0.000  2        3
 63  4   1.01299   1.11259   1.721  13.851   4690.57  54.349   0.12895E-01   8384.26  0.0000    0.000  2        3
 63  5   1.33457   1.38029   1.819  15.000   4577.93  45.929   0.11177E-01   8750.43  1.4821  322.292  3        3
 63  5   1.33998   1.40049   1.826  15.000   4569.48  45.382   0.11065E-01   8776.43  1.4845  322.824  3
MASS FLOW POINT   58 =  1.560334E+01  DELTA FLOWRATE = -6.237030E-04  PERCENT DELTA = -3.997401E-03  AREA RATIO =  1.795558E+00
                                                                                                             ZONE
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)  DENSITY       VELOCITY   CF        ISP    IT        1
 64  3   0.00000   0.35932   1.126   0.000   5723.53  144.72   0.33479E-01   5520.18  0.0000    0.000  2        1
 64  4   0.64422   0.82872   1.625  11.578   5341.70  70.076   0.17635E-01   7638.55  0.0000    0.000  3        2
 64  4   0.64422   0.82872   1.593  11.578   5471.27  70.076   0.19538E-01   7103.02  0.0000    0.000  3
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  64  4   1.02191   1.14893   1.750  13.736   5357.05  53.300   0.15278E-01   7695.65  0.0000    0.000  2     2
  64  4   1.02191   1.14893   1.733  13.736   4677.31  53.300   0.12684E-01   8429.38  0.0000    0.000  2     3
  64  5   1.34559   1.42141   1.833  15.000   4560.87  44.829   0.10952E-01   8802.84  1.4871  323.371  3     3
  64  5   1.35119   1.44232   1.840  15.000   4552.13  44.277   0.10839E-01   8829.44  1.4896  323.913  3     3
MASS FLOW POINT   58 =   1.560333E+01  DELTA FLOWRATE = -6.170273E-04  PERCENT DELTA = -3.954616E-03  AREA RATIO =  1.825723E+00
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT    ZONE
  65  3   0.00000   0.37316   1.138   0.000   5715.77  142.54   0.33033E-01   5574.41  0.0000    0.000  2     1
  65  4   0.65061   0.85950   1.647  11.856   5322.41  67.561   0.17076E-01   7725.55  0.0000    0.000  3     1
  65  4   0.65061   0.85950   1.615  11.856   5453.86  67.561   0.18912E-01   7187.24  0.0000    0.000  3     2
  65  4   1.03104   1.18647   1.762  13.626   5347.25  52.224   0.15003E-01   7738.31  0.0000    0.000  2     2
  65  4   1.03104   1.18647   1.745  13.626   4663.33  52.224   0.12467E-01   8476.22  0.0000    0.000  2     3
  65  5   1.35699   1.46396   1.848  15.000   4543.24  43.720   0.10724E-01   8856.44  1.4921  324.470  3     3
  65  5   1.36279   1.48561   1.855  15.000   4534.21  43.164   0.10609E-01   8883.63  1.4946  325.022  3     3
MASS FLOW POINT   58 =   1.560330E+01  DELTA FLOWRATE = -5.865097E-04  PERCENT DELTA = -3.759024E-03  AREA RATIO =  1.857199E+00
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT    ZONE
  66  3   0.00000   0.38771   1.150   0.000   5707.66  140.32   0.32576E-01   5630.32  0.0000    0.000  2     1
  66  4   0.65738   0.89141   1.669  12.110   5303.06  65.126   0.16532E-01   7811.65  0.0000    0.000  2     1
  66  4   0.65738   0.89141   1.637  12.110   5436.41  65.126   0.18304E-01   7270.71  0.0000    0.000  2     2
  66  4   1.04040   1.22521   1.774  13.522   5336.99  51.123   0.14722E-01   7782.53  0.0000    0.000  2     2
  66  4   1.04040   1.22521   1.758  13.522   4648.65  51.123   0.12244E-01   8524.75  0.0000    0.000  2     3
  66  5   1.36879   1.50799   1.863  15.000   4525.03  42.604   0.10494E-01   8911.17  1.4972  325.587  3     3
  66  5   1.37479   1.53037   1.871  15.000   4515.72  42.046   0.10378E-01   8938.93  1.4998  326.148  3     3
MASS FLOW POINT   58 =   1.560329E+01  DELTA FLOWRATE = -5.798340E-04  PERCENT DELTA = -3.716239E-03  AREA RATIO =  1.890036E+00
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT    ZONE
  67  3   0.00000   0.40295   1.163   0.000   5699.31  138.06   0.32110E-01   5687.29  0.0000    0.000  2     1
  67  4   0.66455   0.92451   1.691  12.334   5283.89  62.784   0.16006E-01   7896.11  0.0000    0.000  2     1
  67  4   0.66455   0.92451   1.659  12.334   5419.18  62.784   0.17716E-01   7352.51  0.0000    0.000  2     2
  67  4   1.04998   1.26521   1.787  13.424   5326.29  50.000   0.14434E-01   7828.28  0.0000    0.000  2     2
  67  4   1.04998   1.26521   1.771  13.424   4633.28  50.000   0.12017E-01   8574.91  0.0000    0.000  2     3
  67  5   1.38099   1.55352   1.878  15.000   4506.27  41.484   0.10262E-01   8966.99  1.5025  326.723  3     3
  67  5   1.38719   1.57667   1.886  15.000   4496.66  40.925   0.10146E-01   8995.27  1.5051  327.293  3     3
MASS FLOW POINT   58 =   1.560325E+01  DELTA FLOWRATE = -5.369186E-04  PERCENT DELTA = -3.441188E-03  AREA RATIO =  1.924302E+00
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT    ZONE
  68  3   0.00000   0.41889   1.176   0.000   5690.68  135.76   0.31636E-01   5745.47  0.0000    0.000  2     1
  68  4   0.67210   0.95879   1.712  12.523   5265.07  60.552   0.15503E-01   7978.28  0.0000    0.000  2     1
  68  4   0.67210   0.95879   1.680  12.523   5402.31  60.552   0.17153E-01   7432.05  0.0000    0.000  2     2
  68  4   1.05979   1.30647   1.800  13.331   5315.14  48.857   0.14140E-01   7875.48  0.0000    0.000  2     2
  68  4   1.05979   1.30647   1.785  13.331   4617.22  48.857   0.11785E-01   8626.60  0.0000    0.000  2     3
  68  5   1.39360   1.60059   1.894  15.000   4486.94  40.363   0.10029E-01   9023.82  1.5078  327.877  3     3
  68  5   1.40001   1.62452   1.902  15.000   4477.05  39.803   0.99119E-02   9052.62  1.5104  328.455  3     3
MASS FLOW POINT   58 =   1.560325E+01  DELTA FLOWRATE = -5.359650E-04  PERCENT DELTA = -3.435076E-03  AREA RATIO =  1.960033E+00
LRC ID    R         X        MACH   THETA  T (DEG.R)  P (PSI)   DENSITY      VELOCITY   CF       ISP    IT    ZONE
  69  3   0.00000   0.43554   1.189   0.000   5681.78  133.44   0.31154E-01   5804.77  0.0000    0.000  2     1
  69  4   0.68004   0.99429   1.733  12.671   5246.74  58.436   0.15023E-01   8057.76  0.0000    0.000  2     1
  69  4   0.68004   0.99429   1.701  12.671   5385.94  58.436   0.16617E-01   7508.96  0.0000    0.000  2     2
  69  4   1.06985   1.34906   1.814  13.243   5303.55  47.698   0.13842E-01   7924.09  0.0000    0.000  2     2
  69  4   1.06985   1.34906   1.799  13.243   4600.48  47.698   0.11549E-01   8679.79  0.0000    0.000  2     3
  69  5   1.40664   1.64925   1.911  15.000   4467.04  39.240   0.97945E-02   9081.68  1.5132  329.047  3     3
  69  5   1.41327   1.67399   1.919  15.000   4456.86  38.680   0.96772E-02   9110.99  1.5159  329.633  3     3
```

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                  TDK PERFORMANCE SUMMARY :   3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE


ISP (SEC)               329.633
F (LBF)                 5143.17
MASS FLOW (LB/SEC)      15.6027
CD                     0.995594
C* (FT/SEC)             6996.46
CF                      1.51585
```

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TDK PERFORMANCE SUMMARY :   3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE
          REAL WALL CONTOUR   3 ZONES

                                                   FIRST
                                               TDK SOLUTION

       CHAMBER PRESS   [PSIA]                   300.0000
       CHAMBER TEMP    [R]                      6001.056
       MIXTURE RATIO   [-]                      6.297435
       EP (NOZZLE)     [-]                      2.000000
       H (OXID)        [CAL/MOLE]               -3099.196
       H (FUEL)        [CAL/MOLE]               -2154.000
       HCHAM (ODE)     [BTU/LB]                 -413.8725
       DELH (AVERAGE)  [BTU/LB]                0.0000000E+00
       DELH1  (AV)     [BTU/LB]                0.0000000E+00
       ECRAT           [-]                      3.000000
       RSTAR           [INCHES]                 2.000000
       RWTD            [-]                      1.000000
       RWTU            [-]                      1.000000
       THE             [DEGREES]               0.0000000E+00
       THETA           [DEGREES]                15.00000
       THETAI          [DEGREES]                30.00000
       RI              [-]                      2.000000
       NIT             [-]                      59.00000
       ISP (ODE)       [SECONDS]                335.4859
       ISP (ODF)       [SECONDS]                326.8484
       ISP (ODK)       [SECONDS]                335.2208
       ISP (TDK)       [SECONDS]                329.6333
       THRUST (TDK)    [POUNDS]                 5143.173
       WDOT (TDK)      [LB/SEC]                 15.60271
       CSTAR (TDK)     [FT/SEC]                 6996.465
       CF (TDK)        [-]                      1.515854
       CD              [-]                     0.9955939
       P (AXIS,EXIT)   [PSIA]                  0.0000000E+00
       P (WALL,EXIT)   [PSIA]                   38.67983
       T (WALL,EXIT)   [R]                      4456.856
       V (WALL,EXIT)   [FT/SEC]                 9110.994
       MA (WALL,EXIT)  [-]                      1.918942
       SHOCK STRENGTH  [-]                     0.0000000E+00
       SHOCK (X/R*)    [-]                     0.0000000E+00
       SHOCK (R/R*)    [-]                     0.0000000E+00
       XA (X/R*)       [-]                     0.0000000E+00
       XB (X/R*)       [-]                     0.0000000E+00



*************************************************************************************************************
                      BOUNDARY LAYER MODULE ( BLM )

                 3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE
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INPUT GEOMETRY
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 I      X(FT)         R(FT)         S(FT)       UE(FT/SEC)     TE(DEG. R)   PE(LB-F/FT2)  HSE(FT2/SEC2)
--- ------------ ------------ ------------ ------------ ------------ ------------ ------------

 1  -3.45300E-01  2.88675E-01  0.00000E+00  1.07331E+03  5.71352E+03  3.79711E+04
 2  -3.25315E-01  2.88075E-01  1.99940E-02  1.07911E+03  5.71346E+03  3.79617E+04
 3  -2.42048E-01  2.72280E-01  1.04746E-01  1.21460E+03  5.70943E+03  3.77194E+04
 4  -1.67107E-01  2.37362E-01  1.87423E-01  1.63275E+03  5.69394E+03  3.68027E+04
 5  -1.13816E-01  2.06595E-01  2.48958E-01  2.25131E+03  5.66253E+03  3.50142E+04
 6  -6.71857E-02  1.80808E-01  3.02243E-01  3.24766E+03  5.58988E+03  3.12172E+04
 7  -7.23290E-03  1.66823E-01  3.63805E-01  4.90616E+03  5.40456E+03  2.33375E+04
 8   0.00000E+00  1.66667E-01  3.71040E-01  5.80973E+03  5.26460E+03  1.88189E+04
 9   1.80460E-03  1.66677E-01  3.72844E-01  5.89066E+03  5.24917E+03  1.84234E+04
10   3.54942E-03  1.66705E-01  3.74589E-01  5.96618E+03  5.23496E+03  1.80546E+04
11   4.64293E-03  1.66732E-01  3.75683E-01  6.01251E+03  5.22627E+03  1.78278E+04
12   5.88402E-03  1.66770E-01  3.76925E-01  6.06476E+03  5.21642E+03  1.75739E+04
13   7.27195E-03  1.66825E-01  3..78314E-01  6.12264E+03  5.20545E+03  1.72938E+04
14   8.80657E-03  1.66900E-01  3.79850E-01  6.18564E+03  5.19340E+03  1.69890E+04
15   1.04842E-02  1.66997E-01  3.81531E-01  6.25417E+03  5.18013E+03  1.66592E+04
16   1.23036E-02  1.67122E-01  3.83354E-01  6.32797E+03  5.16564E+03  1.63064E+04
17   1.42620E-02  1.67278E-01  3.85319E-01  6.40698E+03  5.14986E+03  1.59313E+04
18   1.63560E-02  1.67472E-01  3.87422E-01  6.49111E+03  5.13274E+03  1.55353E+04
19   1.85813E-02  1.67705E-01  3.89660E-01  6.58020E+03  5.11424E+03  1.51196E+04
20   2.09335E-02  1.67987E-01  3.92028E-01  6.67416E+03  5.09429E+03  1.46857E+04
21   2.34073E-02  1.68318E-01  3.94524E-01  6.77286E+03  5.07283E+03  1.42351E+04
22   2.59977E-02  1.68707E-01  3.97144E-01  6.87626E+03  5.04979E+03  1.37691E+04
23   2.86995E-02  1.69157E-01  3.99883E-01  6.98409E+03  5.02513E+03  1.32897E+04
24   3.15083E-02  1.69672E-01  4.02738E-01  7.09649E+03  4.99871E+03  1.27979E+04
25   3.44188E-02  1.70260E-01  4.05708E-01  7.21327E+03  4.97049E+03  1.22956E+04
26   3.74235E-02  1.70923E-01  4.08785E-01  7.33429E+03  4.94039E+03  1.17850E+04
27   4.11057E-02  1.71815E-01  4.12573E-01  7.49141E+03  4.89958E+03  1.11373E+04
28   4.46977E-02  1.72763E-01  4.16288E-01  7.57272E+03  4.88084E+03  1.08016E+04
29   6.67243E-02  1.78667E-01  4.39092E-01  7.60108E+03  4.89808E+03  1.06544E+04
30   7.79495E-02  1.81673E-01  4.50713E-01  7.64088E+03  4.89311E+03  1.04944E+04
31   8.66180E-02  1.83997E-01  4.59688E-01  7.68321E+03  4.88445E+03  1.03273E+04
32   9.60525E-02  1.86525E-01  4.69455E-01  7.73503E+03  4.87255E+03  1.01274E+04
33   1.00731E-01  1.87778E-01  4.74298E-01  7.76220E+03  4.86599E+03  1.00230E+04
34   1.05400E-01  1.89028E-01  4.79132E-01  7.79027E+03  4.85904E+03  9.91570E+03
35   1.10067E-01  1.90280E-01  4.83964E-01  7.81956E+03  4.85161E+03  9.80424E+03
36   1.14726E-01  1.91528E-01  4.88787E-01  7.84971E+03  4.84383E+03  9.69018E+03
37   1.19382E-01  1.92775E-01  4.93608E-01  7.88085E+03  4.83566E+03  9.57313E+03
38   1.24035E-01  1.94022E-01  4.98425E-01  7.91296E+03  4.82712E+03  9.45325E+03
39   1.28687E-01  1.95268E-01  5.03240E-01  7.94617E+03  4.81815E+03  9.33019E+03
40   1.33331E-01  1.96513E-01  5.08049E-01  7.98028E+03  4.80884E+03  9.20465E+03
41   1.37964E-01  1.97755E-01  5.12845E-01  8.01520E+03  4.79919E+03  9.07710E+03
42   1.42586E-01  1.98993E-01  5.17630E-01  8.05082E+03  4.78925E+03  8.94790E+03
43   1.47185E-01  2.00225E-01  5.22391E-01  8.08702E+03  4.77905E+03  8.81757E+03
44   1.51754E-01  2.01450E-01  5.27121E-01  8.12335E+03  4.76873E+03  8.68775E+03
45   1.56283E-01  2.02663E-01  5.31810E-01  8.15974E+03  4.75831E+03  8.55877E+03
46   1.60750E-01  2.03860E-01  5.36435E-01  8.19582E+03  4.74789E+03  8.43185E+03
47   1.65150E-01  2.05040E-01  5.40990E-01  8.23155E+03  4.73750E+03  8.30720E+03
48   1.69467E-01  2.06195E-01  5.45459E-01  8.26666E+03  4.72722E+03  8.18564E+03
49   1.73680E-01  2.07325E-01  5.49821E-01  8.30099E+03  4.71709E+03  8.06773E+03
50   1.77743E-01  2.08413E-01  5.54028E-01  8.33405E+03  4.70727E+03  7.95506E+03
51   1.81648E-01  2.09460E-01  5.58070E-01  8.36579E+03  4.69779E+03  7.84771E+03
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                    3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE
INPUT GEOMETRY
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 I       X(FT)         R(FT)         S(FT)       UE(FT/SEC)    TE(DEG. R)   PE(LB-F/FT2)   HSE(FT2/SEC2)
--- ------------- ------------- ------------- ------------- ------------- ------------- -------------

  1  -3.45300E-01   2.88675E-01   0.00000E+00   1.07331E+03   5.71352E+03   3.79711E+04
  2  -3.25315E-01   2.88075E-01   1.99940E-02   1.07911E+03   5.71346E+03   3.79617E+04
  3  -2.42048E-01   2.72280E-01   1.04746E-01   1.21460E+03   5.70943E+03   3.77194E+04
  4  -1.67107E-01   2.37362E-01   1.87423E-01   1.63275E+03   5.69394E+03   3.68027E+04
  5  -1.13816E-01   2.06595E-01   2.48958E-01   2.25131E+03   5.66253E+03   3.50142E+04
  6  -6.71857E-02   1.80808E-01   3.02243E-01   3.24766E+03   5.58988E+03   3.12172E+04
  7  -7.23290E-03   1.66823E-01   3.63805E-01   4.90616E+03   5.40456E+03   2.33375E+04
  8   0.00000E+00   1.66667E-01   3.71040E-01   5.80973E+03   5.26460E+03   1.88189E+04
  9   1.80460E-03   1.66677E-01   3.72844E-01   5.89066E+03   5.24917E+03   1.84234E+04
 10   3.54942E-03   1.66705E-01   3.74589E-01   5.96618E+03   5.23496E+03   1.80546E+04
 11   4.64293E-03   1.66732E-01   3.75683E-01   6.01251E+03   5.22627E+03   1.78278E+04
 12   5.88402E-03   1.66770E-01   3.76925E-01   6.06476E+03   5.21642E+03   1.75739E+04
 13   7.27195E-03   1.66825E-01   3.78314E-01   6.12264E+03   5.20545E+03   1.72938E+04
 14   8.80657E-03   1.66900E-01   3.79850E-01   6.18564E+03   5.19340E+03   1.69890E+04
 15   1.04842E-02   1.66997E-01   3.81531E-01   6.25417E+03   5.18013E+03   1.66592E+04
 16   1.23036E-02   1.67122E-01   3.83354E-01   6.32797E+03   5.16564E+03   1.63064E+04
 17   1.42620E-02   1.67278E-01   3.85319E-01   6.40698E+03   5.14986E+03   1.59313E+04
 18   1.63560E-02   1.67472E-01   3.87422E-01   6.49111E+03   5.13274E+03   1.55353E+04
 19   1.85813E-02   1.67705E-01   3.89660E-01   6.58020E+03   5.11424E+03   1.51196E+04
 20   2.09335E-02   1.67987E-01   3.92028E-01   6.67416E+03   5.09429E+03   1.46857E+04
 21   2.34073E-02   1.68318E-01   3.94524E-01   6.77286E+03   5.07283E+03   1.42351E+04
 22   2.59977E-02   1.68707E-01   3.97144E-01   6.87626E+03   5.04979E+03   1.37691E+04
 23   2.86995E-02   1.69157E-01   3.99883E-01   6.98409E+03   5.02513E+03   1.32897E+04
 24   3.15083E-02   1.69672E-01   4.02738E-01   7.09649E+03   4.99871E+03   1.27979E+04
 25   3.44188E-02   1.70260E-01   4.05708E-01   7.21327E+03   4.97049E+03   1.22956E+04
 26   3.74235E-02   1.70923E-01   4.08785E-01   7.33429E+03   4.94039E+03   1.17850E+04
 27   4.11057E-02   1.71815E-01   4.12573E-01   7.49141E+03   4.89958E+03   1.11373E+04
 28   4.46977E-02   1.72763E-01   4.16288E-01   7.57272E+03   4.88084E+03   1.08016E+04
 29   6.67243E-02   1.78667E-01   4.39092E-01   7.60108E+03   4.89808E+03   1.06544E+04
 30   7.79495E-02   1.81673E-01   4.50713E-01   7.64088E+03   4.89311E+03   1.04944E+04
 31   8.66180E-02   1.83997E-01   4.59688E-01   7.68321E+03   4.88445E+03   1.03273E+04
 32   9.60525E-02   1.86525E-01   4.69455E-01   7.73503E+03   4.87255E+03   1.01274E+04
 33   1.00731E-01   1.87778E-01   4.74298E-01   7.76220E+03   4.86599E+03   1.00230E+04
 34   1.05400E-01   1.89028E-01   4.79132E-01   7.79027E+03   4.85904E+03   9.91570E+03
 35   1.10067E-01   1.90280E-01   4.83964E-01   7.81956E+03   4.85161E+03   9.80424E+03
 36   1.14726E-01   1.91528E-01   4.88787E-01   7.84971E+03   4.84383E+03   9.69018E+03
 37   1.19382E-01   1.92775E-01   4.93608E-01   7.88085E+03   4.83566E+03   9.57313E+03
 38   1.24035E-01   1.94022E-01   4.98425E-01   7.91296E+03   4.82712E+03   9.45325E+03
 39   1.28687E-01   1.95268E-01   5.03240E-01   7.94617E+03   4.81815E+03   9.33019E+03
 40   1.33331E-01   1.96513E-01   5.08049E-01   7.98028E+03   4.80884E+03   9.20465E+03
 41   1.37964E-01   1.97755E-01   5.12845E-01   8.01520E+03   4.79919E+03   9.07710E+03
 42   1.42586E-01   1.98993E-01   5.17630E-01   8.05082E+03   4.78925E+03   8.94790E+03
 43   1.47185E-01   2.00225E-01   5.22391E-01   8.08702E+03   4.77905E+03   8.81757E+03
 44   1.51754E-01   2.01450E-01   5.27121E-01   8.12335E+03   4.76873E+03   8.68775E+03
 45   1.56283E-01   2.02663E-01   5.31810E-01   8.15974E+03   4.75831E+03   8.55877E+03
 46   1.60750E-01   2.03860E-01   5.36435E-01   8.19582E+03   4.74789E+03   8.43185E+03
 47   1.65150E-01   2.05040E-01   5.40990E-01   8.23155E+03   4.73750E+03   8.30720E+03
 48   1.69467E-01   2.06195E-01   5.45459E-01   8.26666E+03   4.72722E+03   8.18564E+03
 49   1.73680E-01   2.07325E-01   5.49821E-01   8.30099E+03   4.71709E+03   8.06773E+03
 50   1.77743E-01   2.08413E-01   5.54028E-01   8.33405E+03   4.70727E+03   7.95506E+03
 51   1.81648E-01   2.09460E-01   5.58070E-01   8.36579E+03   4.69779E+03   7.84771E+03
```

INPUT GEOMETRY

I	X(FT)	R(FT)	S(FT)	UE(FT/SEC)	TE(DEG. R)	PE(LB-F/FT2)	HSE(FT2/SEC2)
52	1.85317E-01	2.10443E-01	5.61868E-01	8.39559E+03	4.68883E+03	7.74763E+03	
53	1.88650E-01	2.11335E-01	5.65319E-01	8.42252E+03	4.68069E+03	7.65778E+03	
54	1.96527E-01	2.13447E-01	5.73474E-01	8.48626E+03	4.66123E+03	7.44772E+03	
55	2.02082E-01	2.14935E-01	5.79224E-01	8.53086E+03	4.64747E+03	7.30300E+03	
56	2.07885E-01	2.16490E-01	5.85232E-01	8.57711E+03	4.63307E+03	7.15454E+03	
57	2.13918E-01	2.18107E-01	5.91479E-01	8.62487E+03	4.61807E+03	7.00308E+03	
58	2.20192E-01	2.19787E-01	5.97973E-01	8.67415E+03	4.60243E+03	6.84881E+03	
59	2.26683E-01	2.21527E-01	6.04694E-01	8.72462E+03	4.58626E+03	6.69289E+03	
60	2.33415E-01	2.23330E-01	6.11663E-01	8.77643E+03	4.56948E+03	6.53507E+03	
61	2.40387E-01	2.25198E-01	6.18881E-01	8.82944E+03	4.55213E+03	6.37589E+03	
62	2.47602E-01	2.27132E-01	6.26350E-01	8.88363E+03	4.53421E+03	6.21562E+03	
63	2.55062E-01	2.29132E-01	6.34074E-01	8.93893E+03	4.51572E+03	6.05460E+03	
64	2.62778E-01	2.31198E-01	6.42062E-01	8.99527E+03	4.49666E+03	5.89316E+03	
65	2.70753E-01	2.33335E-01	6.50318E-01	9.05262E+03	4.47705E+03	5.73157E+03	
66	2.78998E-01	2.35545E-01	6.58855E-01	9.11099E+03	4.45686E+03	5.56989E+03	

GAS PROPERTIES TABLES

I	T DEG R	HS FT2/SEC2	MU LBM/FT-SEC	K LBM-FT/S3-DEGR	CP FT2/SEC2-DEGR	GAMMA	RGAS LBF-FT/LBM-DEGR
1	1.0000E+02	-1.4180E+08	3.2758E-06	9.0999E-02	1.5915E+04	1.3501E+00	1.2803E+02
2	6.0000E+02	-1.3385E+08	1.1773E-05	3.2705E-01	1.5915E+04	1.3501E+00	1.2803E+02
3	8.0000E+02	-1.3064E+08	1.4458E-05	4.0778E-01	1.6159E+04	1.3422E+00	1.2804E+02
4	1.0000E+03	-1.2738E+08	1.6955E-05	4.8903E-01	1.6525E+04	1.3321E+00	1.2804E+02
5	1.2000E+03	-1.2403E+08	1.9312E-05	5.7095E-01	1.6938E+04	1.3214E+00	1.2804E+02
6	1.4000E+03	-1.2060E+08	2.1559E-05	6.5441E-01	1.7391E+04	1.3104E+00	1.2804E+02
7	1.6000E+03	-1.1707E+08	2.3715E-05	7.3981E-01	1.7872E+04	1.2996E+00	1.2804E+02
8	1.8000E+03	-1.1345E+08	2.5796E-05	8.2715E-01	1.8371E+04	1.2891E+00	1.2804E+02
9	2.0000E+03	-1.0972E+08	2.7811E-05	9.1795E-01	1.8910E+04	1.2786E+00	1.2804E+02
10	2.2000E+03	-1.0589E+08	2.9769E-05	1.0090E+00	1.9417E+04	1.2693E+00	1.2804E+02
11	2.4000E+03	-1.0196E+08	3.1677E-05	1.1001E+00	1.9897E+04	1.2611E+00	1.2804E+02
12	2.6000E+03	-9.7930E+07	3.3540E-05	1.1918E+00	2.0358E+04	1.2538E+00	1.2804E+02
13	2.8000E+03	-9.3814E+07	3.5363E-05	1.2849E+00	2.0816E+04	1.2470E+00	1.2805E+02
14	3.0000E+03	-8.9606E+07	3.7148E-05	1.3810E+00	2.1298E+04	1.2405E+00	1.2805E+02
15	3.2000E+03	-8.5301E+07	3.8900E-05	1.4831E+00	2.1843E+04	1.2339E+00	1.2807E+02
16	3.4000E+03	-8.0886E+07	4.0621E-05	1.5954E+00	2.2501E+04	1.2269E+00	1.2809E+02
17	3.6000E+03	-7.6341E+07	4.2313E-05	1.7233E+00	2.3333E+04	1.2193E+00	1.2813E+02
18	3.8000E+03	-7.1635E+07	4.3978E-05	1.8733E+00	2.4404E+04	1.2111E+00	1.2821E+02
19	4.0000E+03	-6.6732E+07	4.5619E-05	2.0526E+00	2.5778E+04	1.2023E+00	1.2832E+02
20	4.2000E+03	-6.1593E+07	4.7236E-05	2.2678E+00	2.7506E+04	1.1932E+00	1.2849E+02
21	4.4000E+03	-5.6175E+07	4.8831E-05	2.5250E+00	2.9625E+04	1.1842E+00	1.2872E+02
22	4.6000E+03	-5.0443E+07	5.0406E-05	2.8284E+00	3.2148E+04	1.1758E+00	1.2903E+02
23	4.8000E+03	-4.4369E+07	5.1961E-05	3.1796E+00	3.5058E+04	1.1682E+00	1.2942E+02
24	5.0000E+03	-3.7937E+07	5.3497E-05	3.5773E+00	3.8310E+04	1.1617E+00	1.2990E+02
25	5.2000E+03	-3.1150E+07	5.5017E-05	4.0169E+00	4.1829E+04	1.1564E+00	1.3047E+02
26	5.4000E+03	-2.4020E+07	5.6519E-05	4.4905E+00	4.5518E+04	1.1523E+00	1.3112E+02
27	5.6000E+03	-1.6576E+07	5.8006E-05	4.9882E+00	4.9267E+04	1.1493E+00	1.3184E+02
28	5.8000E+03	-8.8673E+06	5.9478E-05	5.4959E+00	5.2939E+04	1.1473E+00	1.3263E+02
29	5.9000E+03	-9.1460E+05	6.0935E-05	6.0066E+00	5.6474E+04	1.1461E+00	1.3348E+02
30	[illegible]	7.2304E+06	6.2378E-05	6.5082E+00	5.9774E+04	1.1457E+00	1.3437E+02
31	[illegible]	1.5526E+07	6.3808E-05	6.9923E+00	6.2781E+04	1.1458E+00	1.3529E+02
32	6.6000E+03	2.3935E+07	6.5226E-05	7.4524E+00	6.5458E+04	1.1465E+00	1.3624E+02
33	6.8000E+03	3.2423E+07	6.6631E-05	7.8844E+00	6.7792E+04	1.1475E+00	1.3721E+02
34	7.0000E+03	4.0960E+07	6.8024E-05	8.2855E+00	6.9781E+04	1.1488E+00	1.3818E+02

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35      7.2000E+03    4.9523E+07    6.9406E-05    8.6547E+00    7.1439E+04    1.1504E+00    1.3915E+02
36      7.4000E+03    5.8091E+07    7.0777E-05    8.9921E+00    7.2787E+04    1.1521E+00    1.4011E+02
37      7.6000E+03    6.6646E+07    7.2138E-05    9.2985E+00    7.3847E+04    1.1540E+00    1.4107E+02
38      7.8000E+03    7.5176E+07    7.3488E-05    9.5754E+00    7.4649E+04    1.1561E+00    1.4202E+02
39      8.0000E+03    8.3670E+07    7.4829E-05    9.8245E+00    7.5219E+04    1.1582E+00    1.4295E+02
40      8.2000E+03    9.2119E+07    7.6160E-05    1.0048E+01    7.5584E+04    1.1604E+00    1.4386E+02
41      8.4000E+03    1.0052E+08    7.7481E-05    1.0247E+01    7.5770E+04    1.1626E+00    1.4475E+02
42      8.6000E+03    1.0886E+08    7.8794E-05    1.0425E+01    7.5800E+04    1.1648E+00    1.4563E+02
43      8.8000E+03    1.1714E+08    8.0098E-05    1.0583E+01    7.5699E+04    1.1670E+00    1.4648E+02
THERMO DATA
-----------
RMUI(LB-MASS/FT-SEC) =   5.89525E-05   TI   (DEGREE R)       =   5.72839E+03
PR  (CONSTANT)       =   5.72909E-01   OMEGA(CONSTANT)       =   7.13970E-01
                         ---------- * ----------
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BOUNDARY CONDITIONS (IHFLAG = 1)
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 I     X(FT)          R(FT)          S(FT)       UE(FT/SEC)    TE(DEG. R)  PE(LB-F/FT2) HSE(FT2/SEC2) QW(BTU/IN2/S) CQW(LBM/FT2/SEC)
------------------------------------------------------------------------------------------------------------------------------------

 1  -0.34530       0.28868       0.00000E+00  1.07331E+03  5.71352E+03  3.79711E+04 -1.22003E+07  0.00000E+00  0.00000E+00
 2  -0.33886       0.28848       6.44534E-03  1.07518E+03  5.71350E+03  3.79681E+04 -1.22011E+07  0.00000E+00  0.00000E+00
 3  -0.33757       0.28844       7.73441E-03  1.07555E+03  5.71350E+03  3.79674E+04 -1.22012E+07  0.00000E+00  0.00000E+00
 4  -0.33435       0.28835       1.09571E-02  1.07649E+03  5.71349E+03  3.79659E+04 -1.22016E+07  0.00000E+00  0.00000E+00
 5  -0.32791       0.28815       1.74024E-02  1.07836E+03  5.71347E+03  3.79629E+04 -1.22024E+07  0.00000E+00  0.00000E+00
 6  -0.31259       0.28566       3.29427E-02  1.09981E+03  5.71284E+03  3.79247E+04 -1.22264E+07  0.00000E+00  0.00000E+00
 7  -0.30612       0.28443       3.95313E-02  1.11034E+03  5.71253E+03  3.79058E+04 -1.22385E+07  0.00000E+00  0.00000E+00
 8  -0.29965       0.28321       4.61198E-02  1.12088E+03  5.71222E+03  3.78870E+04 -1.22505E+07  0.00000E+00  0.00000E+00
 9  -0.29317       0.28198       5.27084E-02  1.13141E+03  5.71190E+03  3.78682E+04 -1.22626E+07  0.00000E+00  0.00000E+00
10  -0.28670       0.28075       5.92969E-02  1.14194E+03  5.71159E+03  3.78493E+04 -1.22747E+07  0.00000E+00  0.00000E+00
11  -0.28023       0.27952       6.58855E-02  1.15248E+03  5.71128E+03  3.78305E+04 -1.22868E+07  0.00000E+00  0.00000E+00
12  -0.27375       0.27829       7.24740E-02  1.16301E+03  5.71096E+03  3.78116E+04 -1.22988E+07  0.00000E+00  0.00000E+00
13  -0.26728       0.27707       7.90626E-02  1.17354E+03  5.71065E+03  3.77928E+04 -1.23109E+07  0.00000E+00  0.00000E+00
14  -0.26081       0.27584       8.56511E-02  1.18407E+03  5.71034E+03  3.77740E+04 -1.23230E+07  0.00000E+00  0.00000E+00
15  -0.25434       0.27461       9.22396E-02  1.19461E+03  5.71002E+03  3.77551E+04 -1.23351E+07  0.00000E+00  0.00000E+00
16  -0.24786       0.27338       9.88282E-02  1.20514E+03  5.70971E+03  3.77363E+04 -1.23471E+07  0.00000E+00  0.00000E+00
17  -0.24144       0.27200       1.05417E-01  1.21799E+03  5.70930E+03  3.77119E+04 -1.23628E+07  0.00000E+00  0.00000E+00
18  -0.23547       0.26921       1.12005E-01  1.25132E+03  5.70807E+03  3.76389E+04 -1.24104E+07  0.00000E+00  0.00000E+00
19  -0.22950       0.26643       1.18594E-01  1.28464E+03  5.70684E+03  3.75658E+04 -1.24580E+07  0.00000E+00  0.00000E+00
20  -0.22352       0.26365       1.25182E-01  1.31796E+03  5.70560E+03  3.74928E+04 -1.25056E+07  0.00000E+00  0.00000E+00
21  -0.21755       0.26087       1.31771E-01  1.35128E+03  5.70437E+03  3.74197E+04 -1.25531E+07  0.00000E+00  0.00000E+00
22  -0.21158       0.25808       1.38359E-01  1.38461E+03  5.70313E+03  3.73467E+04 -1.26007E+07  0.00000E+00  0.00000E+00
23  -0.20561       0.25530       1.44948E-01  1.41793E+03  5.70190E+03  3.72736E+04 -1.26483E+07  0.00000E+00  0.00000E+00
24  -0.19964       0.25252       1.51537E-01  1.45125E+03  5.70066E+03  3.72006E+04 -1.26959E+07  0.00000E+00  0.00000E+00
25  -0.19366       0.24974       1.58125E-01  1.48457E+03  5.69943E+03  3.71275E+04 -1.27434E+07  0.00000E+00  0.00000E+00
26  -0.18769       0.24695       1.64714E-01  1.51790E+03  5.69819E+03  3.70544E+04 -1.27910E+07  0.00000E+00  0.00000E+00
27  -0.18172       0.24417       1.71302E-01  1.55122E+03  5.69696E+03  3.69814E+04 -1.28386E+07  0.00000E+00  0.00000E+00
28  -0.17575       0.24139       1.77891E-01  1.58454E+03  5.69573E+03  3.69083E+04 -1.28862E+07  0.00000E+00  0.00000E+00
29  -0.16977       0.23860       1.84479E-01  1.61786E+03  5.69449E+03  3.68353E+04 -1.29337E+07  0.00000E+00  0.00000E+00
30  -0.16395       0.23554       1.91068E-01  1.66939E+03  5.69208E+03  3.66967E+04 -1.30267E+07  0.00000E+00  0.00000E+00
31  -0.15824       0.23225       1.97656E-01  1.73562E+03  5.68872E+03  3.65052E+04 -1.31563E+07  0.00000E+00  0.00000E+00
32  -0.15254       0.22895       2.04245E-01  1.80185E+03  5.68535E+03  3.63137E+04 -1.32859E+07  0.00000E+00  0.00000E+00
33  -0.14683       0.22566       2.10833E-01  1.86808E+03  5.68199E+03  3.61222E+04 -1.34156E+07  0.00000E+00  0.00000E+00
34  -0.14113       0.22236       2.17422E-01  1.93431E+03  5.67863E+03  3.59307E+04 -1.35452E+07  0.00000E+00  0.00000E+00
35  -0.13542       0.21907       2.24011E-01  2.00054E+03  5.67526E+03  3.57393E+04 -1.36748E+07  0.00000E+00  0.00000E+00
36  -0.12971       0.21577       2.30599E-01  2.06677E+03  5.67190E+03  3.55478E+04 -1.38044E+07  0.00000E+00  0.00000E+00
37  -0.12401       0.21248       2.37188E-01  2.13299E+03  5.66854E+03  3.53563E+04 -1.39340E+07  0.00000E+00  0.00000E+00
38  -0.11830       0.20919       2.43776E-01  2.19922E+03  5.66517E+03  3.51648E+04 -1.40637E+07  0.00000E+00  0.00000E+00
39  -0.11258       0.20591       2.50365E-01  2.27762E+03  5.66061E+03  3.49139E+04 -1.42395E+07  0.00000E+00  0.00000E+00
40  -0.10682       0.20273       2.56953E-01  2.40082E+03  5.65163E+03  3.44444E+04 -1.45858E+07  0.00000E+00  0.00000E+00
41  -0.10105       0.19954       2.63542E-01  2.52401E+03  5.64265E+03  3.39749E+04 -1.49320E+07  0.00000E+00  0.00000E+00
42  -0.09529       0.19635       2.70130E-01  2.64721E+03  5.63366E+03  3.35054E+04 -1.52782E+07  0.00000E+00  0.00000E+00
43  -0.08952       0.19316       2.76719E-01  2.77040E+03  5.62468E+03  3.30360E+04 -1.56244E+07  0.00000E+00  0.00000E+00
44  -0.08376       0.18997       2.83307E-01  2.89360E+03  5.61570E+03  3.25665E+04 -1.59706E+07  0.00000E+00  0.00000E+00
45  -0.07799       0.18678       2.89896E-01  3.01679E+03  5.60671E+03  3.20970E+04 -1.63168E+07  0.00000E+00  0.00000E+00
46  -0.07222       0.18359       2.96485E-01  3.13999E+03  5.59773E+03  3.16275E+04 -1.66601E+07  0.00000E+00  0.00000E+00
47  -0.06638       0.18062       3.03073E-01  3.27003E+03  5.58738E+03  3.11109E+04 -1.70453E+07  0.00000E+00  0.00000E+00
48  -0.05996       0.17912       3.09662E-01  3.44753E+03  5.56755E+03  3.02676E+04 -1.77836E+07  0.00000E+00  0.00000E+00
49  -0.05354       0.17763       3.16250E-01  3.62502E+03  5.54771E+03  2.94243E+04 -1.85218E+07  0.00000E+00  0.00000E+00
50  -0.04713       0.17613       3.22839E-01  3.80252E+03  5.52788E+03  2.85810E+04 -1.92601E+07  0.00000E+00  0.00000E+00
51  -0.04071       0.17463       3.29427E-01  3.98002E+03  5.50805E+03  2.77377E+04 -1.99983E+07  0.00000E+00  0.00000E+00
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ORIGINAL PAGE IS
OF POOR QUALITY

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BOUNDARY CONDITIONS (IHFLAG = 1)
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  I    X(FT)       R(FT)        S(FT)      UE(FT/SEC)   TE(DEG. R)  PE(LB-F/FT2) HSE(FT2/SEC2) QW(BTU/IN2/S) CQW(LBM/FT2/SEC)
------------------------------------------------------------------------------------------------------------------
 52  -0.03430     0.17314     3.36016E-01  4.15751E+03  5.48821E+03  2.68944E+04 -2.07366E+07  0.00000E+00  0.00000E+00
 53  -0.02788     0.17164     3.42604E-01  4.33501E+03  5.46838E+03  2.60511E+04 -2.14748E+07  0.00000E+00  0.00000E+00
 54  -0.02146     0.17014     3.49193E-01  4.51251E+03  5.44855E+03  2.52078E+04 -2.22131E+07  0.00000E+00  0.00000E+00
 55  -0.01505     0.16865     3.55781E-01  4.69000E+03  5.42871E+03  2.43645E+04 -2.29513E+07  0.00000E+00  0.00000E+00
 56  -0.00863     0.16715     3.62370E-01  4.86750E+03  5.40888E+03  2.35212E+04 -2.36896E+07  0.00000E+00  0.00000E+00
 57  -0.00208     0.16671     3.68959E-01  5.54981E+03  5.30486E+03  2.01187E+04 -2.74116E+07  0.00000E+00  0.00000E+00
 58   0.00451     0.16673     3.75547E-01  6.00675E+03  5.22735E+03  1.78560E+04 -3.01746E+07  0.00000E+00  0.00000E+00
 59   0.01109     0.16704     3.82136E-01  6.27865E+03  5.17532E+03  1.65422E+04 -3.19871E+07  0.00000E+00  0.00000E+00
 60   0.01765     0.16761     3.88724E-01  6.54296E+03  5.12197E+03  1.52934E+04 -3.37977E+07  0.00000E+00  0.00000E+00
 61   0.02419     0.16844     3.95313E-01  6.80398E+03  5.06590E+03  1.40949E+04 -3.57009E+07  0.00000E+00  0.00000E+00
 62   0.03068     0.16952     4.01901E-01  7.06354E+03  5.00646E+03  1.29420E+04 -3.77182E+07  0.00000E+00  0.00000E+00
 63   0.03714     0.17086     4.08490E-01  7.32269E+03  4.94328E+03  1.18339E+04 -3.97613E+07  0.00000E+00  0.00000E+00
 64   0.04353     0.17245     4.15078E-01  7.54623E+03  4.88694E+03  1.09110E+04 -4.15727E+07  0.00000E+00  0.00000E+00
 65   0.04989     0.17416     4.21667E-01  7.57941E+03  4.88491E+03  1.07669E+04 -4.16383E+07  0.00000E+00  0.00000E+00
 66   0.05626     0.17586     4.28255E-01  7.58760E+03  4.88989E+03  1.07244E+04 -4.14781E+07  0.00000E+00  0.00000E+00
 67   0.06262     0.17757     4.34844E-01  7.59580E+03  4.89487E+03  1.06818E+04 -4.13179E+07  0.00000E+00  0.00000E+00
 68   0.06898     0.17927     4.41433E-01  7.60909E+03  4.89708E+03  1.06222E+04 -4.12468E+07  0.00000E+00  0.00000E+00
 69   0.07535     0.18098     4.48021E-01  7.63166E+03  4.89426E+03  1.05314E+04 -4.13374E+07  0.00000E+00  0.00000E+00
 70   0.08171     0.18268     4.54610E-01  7.65926E+03  4.88935E+03  1.04218E+04 -4.14954E+07  0.00000E+00  0.00000E+00
 71   0.08808     0.18439     4.61198E-01  7.69122E+03  4.88261E+03  1.02964E+04 -4.17121E+07  0.00000E+00  0.00000E+00
 72   0.09444     0.18609     4.67787E-01  7.72618E+03  4.87458E+03  1.01615E+04 -4.19702E+07  0.00000E+00  0.00000E+00
 73   0.10080     0.18780     4.74375E-01  7.76265E+03  4.86588E+03  1.00213E+04 -4.22501E+07  0.00000E+00  0.00000E+00
 74   0.10717     0.18950     4.80964E-01  7.80138E+03  4.85622E+03  9.87344E+03 -4.25606E+07  0.00000E+00  0.00000E+00
 75   0.11353     0.19121     4.87552E-01  7.84199E+03  4.84582E+03  9.71937E+03 -4.28951E+07  0.00000E+00  0.00000E+00
 76   0.11990     0.19291     4.94141E-01  7.88440E+03  4.83471E+03  9.55986E+03 -4.32522E+07  0.00000E+00  0.00000E+00
 77   0.12626     0.19462     5.00729E-01  7.92885E+03  4.82283E+03  9.39436E+03 -4.36345E+07  0.00000E+00  0.00000E+00
 78   0.13263     0.19632     5.07318E-01  7.97510E+03  4.81025E+03  9.22373E+03 -4.40388E+07  0.00000E+00  0.00000E+00
 79   0.13899     0.19803     5.13907E-01  8.02310E+03  4.79698E+03  9.04844E+03 -4.44601E+07  0.00000E+00  0.00000E+00
 80   0.14535     0.19973     5.20495E-01  8.07260E+03  4.78311E+03  8.86947E+03 -4.48814E+07  0.00000E+00  0.00000E+00
 81   0.15172     0.20144     5.27084E-01  8.12306E+03  4.76881E+03  8.68878E+03 -4.53157E+07  0.00000E+00  0.00000E+00
 82   0.15808     0.20315     5.33672E-01  8.17427E+03  4.75411E+03  8.50767E+03 -4.57621E+07  0.00000E+00  0.00000E+00
 83   0.16445     0.20485     5.40261E-01  8.22583E+03  4.73916E+03  8.32717E+03 -4.62162E+07  0.00000E+00  0.00000E+00
 84   0.17081     0.20656     5.46849E-01  8.27760E+03  4.72399E+03  8.14805E+03 -4.66770E+07  0.00000E+00  0.00000E+00
 85   0.17717     0.20826     5.53438E-01  8.32942E+03  4.70865E+03  7.97086E+03 -4.71430E+07  0.00000E+00  0.00000E+00
 86   0.18354     0.20997     5.60026E-01  8.38114E+03  4.69318E+03  7.79617E+03 -4.76129E+07  0.00000E+00  0.00000E+00
 87   0.18990     0.21167     5.66615E-01  8.43265E+03  4.67760E+03  7.62439E+03 -4.80861E+07  0.00000E+00  0.00000E+00
 88   0.19627     0.21338     5.73203E-01  8.48415E+03  4.66187E+03  7.45468E+03 -4.85636E+07  0.00000E+00  0.00000E+00
 89   0.20263     0.21508     5.79792E-01  8.53523E+03  4.64611E+03  7.28898E+03 -4.90424E+07  0.00000E+00  0.00000E+00
 90   0.20899     0.21679     5.86381E-01  8.58589E+03  4.63031E+03  7.12670E+03 -4.95221E+07  0.00000E+00  0.00000E+00
 91   0.21536     0.21849     5.92969E-01  8.63618E+03  4.61448E+03  6.96768E+03 -5.00030E+07  0.00000E+00  0.00000E+00
 92   0.22172     0.22020     5.99558E-01  8.68605E+03  4.59862E+03  6.81205E+03 -5.04824E+07  0.00000E+00  0.00000E+00
 93   0.22809     0.22190     6.06146E-01  8.73542E+03  4.58276E+03  6.66000E+03 -5.09368E+07  0.00000E+00  0.00000E+00
 94   0.23445     0.22361     6.12735E-01  8.78430E+03  4.56690E+03  6.51143E+03 -5.13914E+07  0.00000E+00  0.00000E+00
 95   0.24081     0.22531     6.19323E-01  8.83265E+03  4.55107E+03  6.36639E+03 -5.18453E+07  0.00000E+00  0.00000E+00
 96   0.24718     0.22702     6.25912E-01  8.88045E+03  4.53526E+03  6.22502E+03 -5.22983E+07  0.00000E+00  0.00000E+00
 97   0.25354     0.22872     6.32500E-01  8.92767E+03  4.51949E+03  6.08739E+03 -5.27504E+07  0.00000E+00  0.00000E+00
 98   0.25991     0.23043     6.39089E-01  8.97430E+03  4.50375E+03  5.95324E+03 -5.32014E+07  0.00000E+00  0.00000E+00
 99   0.26627     0.23213     6.45677E-01  9.02038E+03  4.48807E+03  5.82240E+03 -5.36508E+07  0.00000E+00  0.00000E+00
100   0.27263     0.23384     6.52266E-01  9.06594E+03  4.47244E+03  5.69469E+03 -5.40988E+07  0.00000E+00  0.00000E+00
101   0.27900     0.23555     6.58855E-01  9.11099E+03  4.45686E+03  5.56989E+03 -5.45454E+07  0.00000E+00  0.00000E+00
                             ---------- * ----------
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ORIGINAL PAGE IS OF POOR QUALITY

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OUTPUT DATA ( SEGMENT   1)
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NX    X          X/R*        DELT*       THETA         H           CF        R DELT*        REX          TW          DF          SQW
      FT                     FT          FT                                                            DEG R        LBF        BTU/SEC
--- --------- --------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ---------- ----------

 1 -0.34530   -2.07180  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  0.0000E+00  5.7276E+03  0.0000E+00  0.0000E+00
 2 -0.33886   -2.03315  1.4563E-04  5.6108E-05  2.5955E+00  8.6546E-03  1.3368E+02  5.9167E+03  5.7253E+03 -9.8341E+00  0.0000E+00
 3 -0.33757   -2.02541  1.5925E-04  6.1444E-05  2.5918E+00  7.9279E-03  1.4624E+02  7.1024E+03  5.7251E+03 -1.0752E+01  0.0000E+00
 4 -0.33435   -2.00609  1.8549E-04  7.3380E-05  2.5278E+00  7.0346E-03  1.7047E+02  1.0070E+04  5.7249E+03 -1.2512E+01  0.0000E+00
 5 -0.32791   -1.96743  2.1621E-04  9.5636E-05  2.2608E+00  7.2411E-03  1.9904E+02  1.6020E+04  5.7249E+03 -1.4512E+01  0.0000E+00
 6 -0.31259   -1.87556  2.7954E-04  1.4393E-04  1.9422E+00  7.5660E-03  2.6225E+02  3.0905E+04  5.7252E+03 -1.8242E+01  0.0000E+00
 7 -0.30612   -1.83672  3.0732E-04  1.6294E-04  1.8861E+00  7.3029E-03  2.9096E+02  3.7426E+04  5.7253E+03 -1.9905E+01  0.0000E+00
 8 -0.29965   -1.79788  3.3353E-04  1.8077E-04  1.8451E+00  7.0424E-03  3.1864E+02  4.4061E+04  5.7253E+03 -2.1473E+01  0.0000E+00
 9 -0.29317   -1.75904  3.5821E-04  1.9765E-04  1.8124E+00  6.8481E-03  3.4530E+02  5.0809E+04  5.7253E+03 -2.2926E+01  0.0000E+00
10 -0.28670   -1.72020  3.8188E-04  2.1368E-04  1.7872E+00  6.6458E-03  3.7140E+02  5.7669E+04  5.7253E+03 -2.4298E+01  0.0000E+00
11 -0.28023   -1.68137  4.0411E-04  2.2893E-04  1.7652E+00  6.4888E-03  3.9648E+02  6.4642E+04  5.7252E+03 -2.5563E+01  0.0000E+00
12 -0.27375   -1.64253  4.2527E-04  2.4358E-04  1.7459E+00  6.3415E-03  4.2089E+02  7.1728E+04  5.7252E+03 -2.6744E+01  0.0000E+00
13 -0.26728   -1.60369  4.4536E-04  2.5768E-04  1.7284E+00  6.2211E-03  4.4459E+02  7.8926E+04  5.7252E+03 -2.7844E+01  0.0000E+00
14 -0.26081   -1.56485  4.6475E-04  2.7130E-04  1.7130E+00  6.1059E-03  4.6792E+02  8.6237E+04  5.7252E+03 -2.8886E+01  0.0000E+00
15 -0.25434   -1.52601  4.8327E-04  2.8448E-04  1.6988E+00  6.0037E-03  4.9071E+02  9.3660E+04  5.7252E+03 -2.9862E+01  0.0000E+00
16 -0.24786   -1.48717  5.0008E-04  2.9682E-04  1.6848E+00  5.9447E-03  5.1205E+02  1.0119E+05  5.7251E+03 -3.0641E+01  0.0000E+00
17 -0.24144   -1.44864  5.0260E-04  3.0259E-04  1.6610E+00  6.2237E-03  5.1986E+02  1.0904E+05  5.7251E+03 -2.9510E+01  0.0000E+00
18 -0.23547   -1.41281  4.8931E-04  2.9929E-04  1.6349E+00  6.5208E-03  5.1915E+02  1.1884E+05  5.7249E+03 -2.7125E+01  0.0000E+00
19 -0.22950   -1.37697  4.7573E-04  2.9443E-04  1.6158E+00  6.6302E-03  5.1737E+02  1.2898E+05  5.7247E+03 -2.5977E+01  0.0000E+00
20 -0.22352   -1.34114  4.6729E-04  2.9136E-04  1.6038E+00  6.6433E-03  5.2056E+02  1.3946E+05  5.7245E+03 -2.5134E+01  0.0000E+00
21 -0.21755   -1.30531  4.6205E-04  2.8969E-04  1.5949E+00  6.6211E-03  5.2692E+02  1.5027E+05  5.7243E+03 -2.4476E+01  0.0000E+00
22 -0.21158   -1.26948  4.5924E-04  2.8917E-04  1.5881E+00  6.5724E-03  5.3580E+02  1.6143E+05  5.7241E+03 -2.3956E+01  0.0000E+00
23 -0.20561   -1.23364  4.5829E-04  2.8961E-04  1.5824E+00  6.5092E-03  5.4671E+02  1.7291E+05  5.7240E+03 -2.3537E+01  0.0000E+00
24 -0.19964   -1.19781  4.5885E-04  2.9089E-04  1.5774E+00  6.4368E-03  5.5937E+02  1.8473E+05  5.7238E+03 -2.3197E+01  0.0000E+00
25 -0.19366   -1.16198  4.6069E-04  2.9289E-04  1.5729E+00  6.3588E-03  5.7362E+02  1.9689E+05  5.7237E+03 -2.2922E+01  0.0000E+00
26 -0.18769   -1.12615  4.6364E-04  2.9555E-04  1.5687E+00  6.2753E-03  5.8933E+02  2.0937E+05  5.7235E+03 -2.2699E+01  0.0000E+00
27 -0.18172   -1.09031  4.6753E-04  2.9880E-04  1.5647E+00  6.1901E-03  6.0639E+02  2.2218E+05  5.7233E+03 -2.2518E+01  0.0000E+00
28 -0.17575   -1.05448  4.7228E-04  3.0258E-04  1.5608E+00  6.1041E-03  6.2473E+02  2.3532E+05  5.7232E+03 -2.2373E+01  0.0000E+00
29 -0.16977   -1.01865  4.7067E-04  3.0328E-04  1.5519E+00  6.2027E-03  6.3472E+02  2.4878E+05  5.7230E+03 -2.1661E+01  0.0000E+00
30 -0.16395   -0.98370  4.5381E-04  2.9537E-04  1.5364E+00  6.4997E-03  6.2958E+02  2.6507E+05  5.7226E+03 -1.9961E+01  0.0000E+00
31 -0.15824   -0.94946  4.3142E-04  2.8323E-04  1.5232E+00  6.6942E-03  6.1965E+02  2.8390E+05  5.7221E+03 -1.8276E+01  0.0000E+00
32 -0.15254   -0.91523  4.1323E-04  2.7247E-04  1.5166E+00  6.7280E-03  6.1360E+02  3.0328E+05  5.7216E+03 -1.7039E+01  0.0000E+00
33 -0.14683   -0.88099  4.0100E-04  2.6475E-04  1.5146E+00  6.6846E-03  6.1473E+02  3.2321E+05  5.7211E+03 -1.6090E+01  0.0000E+00
34 -0.14113   -0.84676  3.9290E-04  2.5941E-04  1.5146E+00  6.6096E-03  6.2105E+02  3.4368E+05  5.7207E+03 -1.5334E+01  0.0000E+00
35 -0.13542   -0.81252  3.8802E-04  2.5603E-04  1.5155E+00  6.5134E-03  6.3166E+02  3.6467E+05  5.7203E+03 -1.4721E+01  0.0000E+00
36 -0.12971   -0.77829  3.8568E-04  2.5426E-04  1.5168E+00  6.4053E-03  6.4589E+02  3.8618E+05  5.7198E+03 -1.4217E+01  0.0000E+00
37 -0.12401   -0.74405  3.8543E-04  2.5385E-04  1.5183E+00  6.2797E-03  6.6334E+02  4.0821E+05  5.7194E+03 -1.3796E+01  0.0000E+00
38 -0.11830   -0.70982  3.8433E-04  2.5339E-04  1.5168E+00  6.2510E-03  6.7909E+02  4.3074E+05  5.7189E+03 -1.3362E+01  0.0000E+00
39 -0.11258   -0.67551  3.7026E-04  2.4565E-04  1.5073E+00  6.5400E-03  6.7373E+02  4.5557E+05  5.7181E+03 -1.2491E+01  0.0000E+00
40 -0.10682   -0.64091  3.4733E-04  2.3182E-04  1.4983E+00  6.7784E-03  6.5905E+02  4.8756E+05  5.7169E+03 -1.1199E+01  0.0000E+00
41 -0.10105   -0.60632  3.2849E-04  2.1944E-04  1.4969E+00  6.8107E-03  6.4818E+02  5.2002E+05  5.7156E+03 -1.0070E+01  0.0000E+00
42 -0.09529   -0.57172  3.1698E-04  2.1110E-04  1.5016E+00  6.7300E-03  6.4880E+02  5.5291E+05  5.7145E+03 -9.2293E+00  0.0000E+00
43 -0.08952   -0.53713  3.1024E-04  2.0574E-04  1.5079E+00  6.6197E-03  6.5719E+02  5.8618E+05  5.7133E+03 -8.5652E+00  0.0000E+00
44 -0.08376   -0.50254  3.0727E-04  2.0268E-04  1.5161E+00  6.4723E-03  6.7220E+02  6.1978E+05  5.7121E+03 -8.0305E+00  0.0000E+00
45 -0.07799   -0.46794  3.0664E-04  2.0150E-04  1.5218E+00  6.3424E-03  6.9144E+02  6.5368E+05  5.7110E+03 -7.5671E+00  0.0000E+00
46 -0.07222   -0.43335  3.0770E-04  2.0147E-04  1.5272E+00  6.2242E-03  7.1383E+02  6.8782E+05  5.7098E+03 -7.2195E+00  0.0000E+00
47 -0.06638   -0.39826  3.0251E-04  1.9809E-04  1.5271E+00  6.3390E-03  7.2151E+02  7.2285E+05  5.7082E+03 -7.0457E+00  0.0000E+00
48 -0.05996   -0.35976  2.9068E-04  1.9011E-04  1.5290E+00  6.4750E-03  7.1542E+02  7.6214E+05  5.7059E+03 -6.4668E+00  0.0000E+00
49 -0.05354   -0.32127  2.8159E-04  1.8334E-04  1.5359E+00  6.4679E-03  7.1283E+02  8.0058E+05  5.7035E+03 -5.7272E+00  0.0000E+00
50 -0.04713   -0.28277  2.7754E-04  1.7917E-04  1.5490E+00  6.3810E-03  7.2042E+02  8.3801E+05  5.7011E+03 -5.1400E+00  0.0000E+00
51 -0.04071   -0.24427  2.7597E-04  1.7698E-04  1.5593E+00  6.2972E-03  7.3241E+02  8.7428E+05  5.6987E+03 -4.6153E+00  0.0000E+00
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OUTPUT DATA ( SEGMENT   1)
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 NX    X        X/R*       DELT*       THETA         H           CF        R DELT*       REX          TW           DF          SQW
       FT                   FT          FT                                                          DEG R         LBF        BTU/SEC
--- --------- -------- ----------- ----------- ----------- ----------- ----------- ----------- ----------- ----------- -----------
 52 -0.03430  -0.20577  2.7699E-04  1.7638E-04  1.5705E+00  6.2070E-03  7.4954E+02  9.0925E+05  5.6964E+03 -4.1507E+00  0.0000E+00
 53 -0.02788  -0.16728  2.8013E-04  1.7705E-04  1.5822E+00  6.0991E-03  7.7083E+02  9.4275E+05  5.6940E+03 -3.7269E+00  0.0000E+00
 54 -0.02146  -0.12878  2.8492E-04  1.7877E-04  1.5938E+00  5.9960E-03  7.9523E+02  9.7462E+05  5.6916E+03 -3.3278E+00  0.0000E+00
 55 -0.01505  -0.09028  2.9120E-04  1.8139E-04  1.6054E+00  5.8906E-03  8.2231E+02  1.0047E+06  5.6890E+03 -2.9457E+00  0.0000E+00
 56 -0.00863  -0.05178  2.7368E-04  1.7135E-04  1.5972E+00  6.6066E-03  7.7998E+02  1.0328E+06  5.6835E+03 -2.3409E+00  0.0000E+00
 57 -0.00208  -0.01248  2.4965E-04  1.5264E-04  1.6355E+00  7.1628E-03  7.1867E+02  1.0621E+06  5.6684E+03 -8.2395E-01  0.0000E+00
 58  0.00451   0.02704  2.4946E-04  1.4786E-04  1.6871E+00  6.8687E-03  7.0842E+02  1.0665E+06  5.6564E+03 -1.2292E-01  0.0000E+00
 59  0.01109   0.06653  2.6486E-04  1.5270E-04  1.7345E+00  6.4401E-03  7.4131E+02  1.0695E+06  5.6520E+03  2.1265E-01  0.0000E+00
 60  0.01765   0.10591  2.8305E-04  1.5927E-04  1.7772E+00  6.2368E-03  7.7736E+02  1.0676E+06  5.6472E+03  5.5208E-01  0.0000E+00
 61  0.02419   0.14512  3.0100E-04  1.6591E-04  1.8142E+00  6.1135E-03  8.0769E+02  1.0608E+06  5.6416E+03  9.0102E-01  0.0000E+00
 62  0.03068   0.18411  3.1757E-04  1.7279E-04  1.8378E+00  6.0690E-03  8.2908E+02  1.0492E+06  5.6355E+03  1.2751E+00  0.0000E+00
 63  0.03714   0.22281  3.4108E-04  1.8060E-04  1.8886E+00  5.9478E-03  8.6270E+02  1.0332E+06  5.6293E+03  1.5827E+00  0.0000E+00
 64  0.04353   0.26117  3.7216E-04  1.9255E-04  1.9328E+00  5.6172E-03  9.1232E+02  1.0175E+06  5.6253E+03  1.8930E+00  0.0000E+00
 65  0.04989   0.29936  4.0494E-04  2.0722E-04  1.9541E+00  5.1586E-03  9.8554E+02  1.0263E+06  5.6279E+03  2.0370E+00  0.0000E+00
 66  0.05626   0.33754  4.3707E-04  2.2195E-04  1.9692E+00  4.8647E-03  1.0600E+03  1.0386E+06  5.6324E+03  2.1643E+00  0.0000E+00
 67  0.06262   0.37572  4.6577E-04  2.3550E-04  1.9778E+00  4.6884E-03  1.1255E+03  1.0508E+06  5.6349E+03  2.2953E+00  0.0000E+00
 68  0.06898   0.41391  4.9172E-04  2.4803E-04  1.9825E+00  4.5788E-03  1.1837E+03  1.0627E+06  5.6366E+03  2.4386E+00  0.0000E+00
 69  0.07535   0.45209  5.0970E-04  2.5966E-04  1.9629E+00  4.5327E-03  1.2219E+03  1.0740E+06  5.6376E+03  2.6704E+00  0.0000E+00
 70  0.08171   0.49028  5.3286E-04  2.7063E-04  1.9690E+00  4.4804E-03  1.2713E+03  1.0846E+06  5.6382E+03  2.8360E+00  0.0000E+00
 71  0.08808   0.52846  5.6060E-04  2.8111E-04  1.9942E+00  4.3936E-03  1.3304E+03  1.0945E+06  5.6383E+03  2.9478E+00  0.0000E+00
 72  0.09444   0.56665  5.7610E-04  2.9105E-04  1.9794E+00  4.3691E-03  1.3595E+03  1.1039E+06  5.6381E+03  3.1957E+00  0.0000E+00
 73  0.10080   0.60483  5.9638E-04  3.0066E-04  1.9835E+00  4.3477E-03  1.3990E+03  1.1128E+06  5.6379E+03  3.3864E+00  0.0000E+00
 74  0.10717   0.64302  6.1651E-04  3.1002E-04  1.9886E+00  4.3114E-03  1.4371E+03  1.1211E+06  5.6376E+03  3.5811E+00  0.0000E+00
 75  0.11353   0.68120  6.3613E-04  3.1909E-04  1.9936E+00  4.2876E-03  1.4729E+03  1.1288E+06  5.6371E+03  3.7814E+00  0.0000E+00
 76  0.11990   0.71938  6.5533E-04  3.2790E-04  1.9986E+00  4.2654E-03  1.5065E+03  1.1360E+06  5.6364E+03  3.9871E+00  0.0000E+00
 77  0.12626   0.75757  6.7424E-04  3.3649E-04  2.0038E+00  4.2512E-03  1.5383E+03  1.1424E+06  5.6357E+03  4.1981E+00  0.0000E+00
 78  0.13263   0.79575  6.9289E-04  3.4486E-04  2.0092E+00  4.2349E-03  1.5682E+03  1.1482E+06  5.6348E+03  4.4136E+00  0.0000E+00
 79  0.13899   0.83394  7.1133E-04  3.5308E-04  2.0146E+00  4.2291E-03  1.5965E+03  1.1534E+06  5.6338E+03  4.6346E+00  0.0000E+00
 80  0.14535   0.87212  7.2978E-04  3.6119E-04  2.0205E+00  4.2188E-03  1.6234E+03  1.1579E+06  5.6327E+03  4.8589E+00  0.0000E+00
 81  0.15172   0.91030  7.4856E-04  3.6920E-04  2.0275E+00  4.2131E-03  1.6500E+03  1.1618E+06  5.6316E+03  5.0822E+00  0.0000E+00
 82  0.15808   0.94849  7.6763E-04  3.7718E-04  2.0352E+00  4.2034E-03  1.6761E+03  1.1653E+06  5.6305E+03  5.3069E+00  0.0000E+00
 83  0.16445   0.98667  7.8679E-04  3.8512E-04  2.0430E+00  4.1955E-03  1.7013E+03  1.1683E+06  5.6293E+03  5.5333E+00  0.0000E+00
 84  0.17081   1.02486  8.0611E-04  3.9305E-04  2.0509E+00  4.1860E-03  1.7259E+03  1.1708E+06  5.6281E+03  5.7616E+00  0.0000E+00
 85  0.17717   1.06304  8.2559E-04  4.0097E-04  2.0590E+00  4.1792E-03  1.7498E+03  1.1730E+06  5.6269E+03  5.9907E+00  0.0000E+00
 86  0.18354   1.10123  8.4531E-04  4.0890E-04  2.0673E+00  4.1693E-03  1.7732E+03  1.1747E+06  5.6257E+03  6.2212E+00  0.0000E+00
 87  0.18990   1.13941  8.6522E-04  4.1683E-04  2.0757E+00  4.1629E-03  1.7961E+03  1.1762E+06  5.6244E+03  6.4520E+00  0.0000E+00
 88  0.19627   1.17759  8.8537E-04  4.2477E-04  2.0844E+00  4.1542E-03  1.8184E+03  1.1773E+06  5.6232E+03  6.6829E+00  0.0000E+00
 89  0.20263   1.21578  9.0573E-04  4.3273E-04  2.0931E+00  4.1466E-03  1.8404E+03  1.1781E+06  5.6219E+03  6.9150E+00  0.0000E+00
 90  0.20899   1.25396  9.2635E-04  4.4072E-04  2.1019E+00  4.1367E-03  1.8621E+03  1.1787E+06  5.6207E+03  7.1467E+00  0.0000E+00
 91  0.21536   1.29215  9.4718E-04  4.4873E-04  2.1108E+00  4.1281E-03  1.8834E+03  1.1791E+06  5.6194E+03  7.3785E+00  0.0000E+00
 92  0.22172   1.33033  9.6823E-04  4.5676E-04  2.1198E+00  4.1189E-03  1.9042E+03  1.1791E+06  5.6182E+03  7.6101E+00  0.0000E+00
 93  0.22809   1.36852  9.8948E-04  4.6481E-04  2.1288E+00  4.1109E-03  1.9246E+03  1.1790E+06  5.6169E+03  7.8413E+00  0.0000E+00
 94  0.23445   1.40670  1.0110E-03  4.7288E-04  2.1379E+00  4.1018E-03  1.9446E+03  1.1786E+06  5.6157E+03  8.0719E+00  0.0000E+00
 95  0.24081   1.44489  1.0331E-03  4.8096E-04  2.1479E+00  4.0938E-03  1.9651E+03  1.1781E+06  5.6145E+03  8.2978E+00  0.0000E+00
 96  0.24718   1.48307  1.0602E-03  4.8920E-04  2.1673E+00  4.0789E-03  1.9946E+03  1.1775E+06  5.6132E+03  8.4858E+00  0.0000E+00
 97  0.25354   1.52125  1.0788E-03  4.9744E-04  2.1687E+00  4.0747E-03  2.0071E+03  1.1768E+06  5.6119E+03  8.7483E+00  0.0000E+00
 98  0.25991   1.55944  1.1020E-03  5.0572E-04  2.1792E+00  4.0692E-03  2.0277E+03  1.1759E+06  5.6107E+03  8.9730E+00  0.0000E+00
 99  0.26627   1.59762  1.1256E-03  5.1404E-04  2.1897E+00  4.0600E-03  2.0480E+03  1.1748E+06  5.6095E+03  9.1959E+00  0.0000E+00
100  0.27263   1.63581  1.1494E-03  5.2239E-04  2.2003E+00  4.0520E-03  2.0680E+03  1.1735E+06  5.6083E+03  9.4178E+00  0.0000E+00
101  0.27900   1.67399  1.1734E-03  5.3076E-04  2.2108E+00  4.0424E-03  2.0875E+03  1.1721E+06  5.6071E+03  9.6385E+00  0.0000E+00
                                                  ---------- * ----------

MEAN FREE PATH (FT) = 0.1493001E-05   RELIMINARIZATION PARAMETER (KE AND KW)= 0.4218829E-06 0.6351738E-06
KNUDSEN NUMBER      = 0.1272339E-02   MASS FLOW (LBM/SEC) =  15.60270         DELTA ISP (SEC)  = 0.6177459
```

```
                    NEW VALUES OF NOZZLE GEOMETRY PARAMETERS
                              (NEGATIVE DISPLACEMENT)

RSI =    1.9970 INCH  RWTU =    1.0030  RWTD =    1.0030  EPS =    1.9841  THE =    14.800 DEG

                                      SLOPE(DEG)
  N      R/R*          X/R*            15.000
  1    1.034176     0.2595955          14.208
  2    1.054212     0.3387269          14.765
  3    1.074391     0.4152935          14.819
  4    1.094643     0.4918421          14.814
  5    1.114889     0.5683912          14.822
  6    1.135145     0.6449372          14.829
  7    1.155410     0.7214797          14.839
  8    1.175689     0.7980213          14.842
  9    1.195971     0.8745610          14.832
 10    1.216242     0.9511083          14.831
 11    1.236510       1.027650         14.832
 12    1.256779       1.104194         14.828
 13    1.277043       1.180739         14.820
 14    1.297296       1.257285         14.816
 15    1.317544       1.333833         14.812
 16    1.337786       1.410382         14.788
 17    1.357997       1.486941         14.820
 18    1.378251       1.563488         14.791
 19    1.398467       1.640051         14.800
 20    1.408579       1.678324




          TDK PERFORMANCE SUMMARY :   3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE


                                                T D K / B L M
           T D K
                                  329.633      DISP(BLM)        0.617748
   ISP (SEC)                      5143.17      DF OPT(BLM)       18.9816
   F (LBF)                        15.6027      'DF(BLM)          9.63854
   MASS FLOW (LB/SEC)            0.995594      ISP(TDK-BLM)      329.016
   CD                             6996.46      F  (TDK-BLM)      5133.53
   C* (FT/SEC)                    1.51585      CF (TDK-BLM)       1.5130
   CF
```

```
TDK PERFORMANCE SUMMARY :   3 ZONES TDK TEST CASE,LOX/GH2 - TDK MANUAL TEST CASE
         REAL WALL CONTOUR   3 ZONES ADIABATIC

                                              FIRST
                                         TDK/BLM SOLUTION
       CHAMBER PRESS   [PSIA]              300.0000
       CHAMBER TEMP    [R]                 6001.056
       MIXTURE RATIO   [-]                 6.297435
       EP (NOZZLE)     [-]                 2.000000
       H (OXID)        [CAL/MOLE]          -3099.196
       H (FUEL)        [CAL/MOLE]          -2154.000
       HCHAM (ODE)     [BTU/LB]            -413.8725
       DELH (AVERAGE)  [BTU/LB]            0.0000000E+00
       DELH1  (AV)     [BTU/LB]            0.0000000E+00
       ECRAT           [-]                 3.000000
       RSTAR           [INCHES]            2.000000
       RWTD            [-]                 1.000000
       RWTU            [-]                 1.000000
       THE             [DEGREES]           0.0000000E+00
       THETA           [DEGREES]           15.00000
       THETAI          [DEGREES]           30.00000
       RI              [-]                 2.000000
       NIT             [-]                 59.00000
       ISP (ODE)       [SECONDS]           335.4859
       ISP (ODF)       [SECONDS]           326.8484
       ISP (ODK)       [SECONDS]           335.2208
       ISP (TDK)       [SECONDS]           329.6333
       THRUST (TDK)    [POUNDS]            5143.173
       WDOT (TDK)      [LB/SEC]            15.60271
       CSTAR (TDK)     [FT/SEC]            6996.465
       CF (TDK)        [-]                 1.515854
                       [-]                 0.9955939
       P (AXIS,EXIT)   [PSIA]              0.0000000E+00
       P (WALL,EXIT)   [PSIA]              38.67983
       T (WALL,EXIT)   [R]                 4456.856
       V (WALL,EXIT)   [FT/SEC]            9110.994
       MA (WALL,EXIT)  [-]                 1.918942
       SHOCK STRENGTH  [-]                 0.0000000E+00
       SHOCK (X/R*)    [-]                 0.0000000E+00
       SHOCK (R/R*)    [-]                 0.0000000E+00
       XA (X/R*)       [-]                 0.0000000E+00
       XB (X/R*)       [-]                 0.0000000E+00
       DFOPT (BLME)    [POUNDS]            18.98157
       DF (BLME)       [POUNDS]            9.638544
       DISP (BLME)     [SECONDS]           0.6177480
       THET (EXIT)     [FEET]              0.5307631E-03
       DEL* (EXIT)     [FEET]              0.1173430E-02
       EP (REGEN)      [-]                 0.0000000E+00
       SODOT (REGEN)   [BTU/SEC]           0.0000000E+00
       SODOT (LOSS)    [BTU/SEC]           0.0000000E+00
       THRUST (TC)     [POUNDS]            5133.535
       ISP (TC)        [SECONDS]           329.0155
       CF (TC)         [ ]                 1.513014
FORTRAN STOP
  LANH         job terminated at 26-OCT-1985 04:11:30.46

  Accounting information:
  Buffered I/O count:           120
  Direct I/O count:            1087      Peak working set size:     500
  Page faults:                 3758      Peak page file size:      2331
  Elapsed CPU time:     0 00:11:03.34    Mounted volumes:             0
                                         Elapsed time:      0 00:11:30.37
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7.2 PRATT AND WHITNEY TEST ENGINE FOR RL-10 OTV PROPULSION

This engine uses a hydrogen expander cycle with oxygen preheating and a nozzle that is regeneratively cooled with hydrogen. A flow schematic for the engine which was taken from Reference 25 is shown in Figure 7-1. The engine is sized to produce a nominal vacuum thrust of 15,500 pounds when operated at a chamber pressure of 394 psia and an expansion ratio of 205:1. Complete input for the case is presented in Table 7-2. This input has been prepared by SEA, Inc. from data provided by NASA MSFC. The complete output for the case is rather lengthy and is not given here. It is available from SEA, Inc. However, the output summary table is given in Table 7-3.

The calculations were carried out using the TDK shock option (SHOCK=1). An induced shock wave was found that originated from the wall inflection point just downstream of the throat. The shock was found to be weak, $(P_2 - P_1)/P_1 = .03$, within the domain of influence for the nozzle wall.

The sequence of calculations is as follows:

1) ODE calculation with the system enthalpy set at the propellant tank values, i.e., liquid oxygen and liquid hydrogen at their normal boiling points.

2) ODK calculation starting from the above ODE results at a chamber contraction ratio of 3.98, corresponding to the chamber diameter.

3) TDK calculation using the above ODE and ODK results.

4) BLM calculation using the above ODE, ODK, and TDK results. A new wall geometry is calculated by displacing the wall inward a distance of δ^* normal to the real wall. This new wall defines the boundary of the invisid core flow. BLM calculated that 5288 BTU/LBM were picked up through the wall by the regen cooling circuit. Since the nozzle mass flow was found by TDK to be 33.82 lb/sec, the propellant enthalpy was increased by 156.3 BTU/LB.

5) ODE calculation with the increased propellant enthalpy. The expansion ratio of the invisid core flow is automatically placed in the ODE output schedule.

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6) ODK calculation using the above ODE results, including the new expansion ratio.

7) TDK calculation using the above ODE and ODK results, including the new wall contour.

8) Output summary table.

The total number of flow field points computed by the MOC was more than 65,000 for each pass. Computer execution time for the case was 2 hours and 50 minutes using a DEC PDP 11/750 VAX computer system.

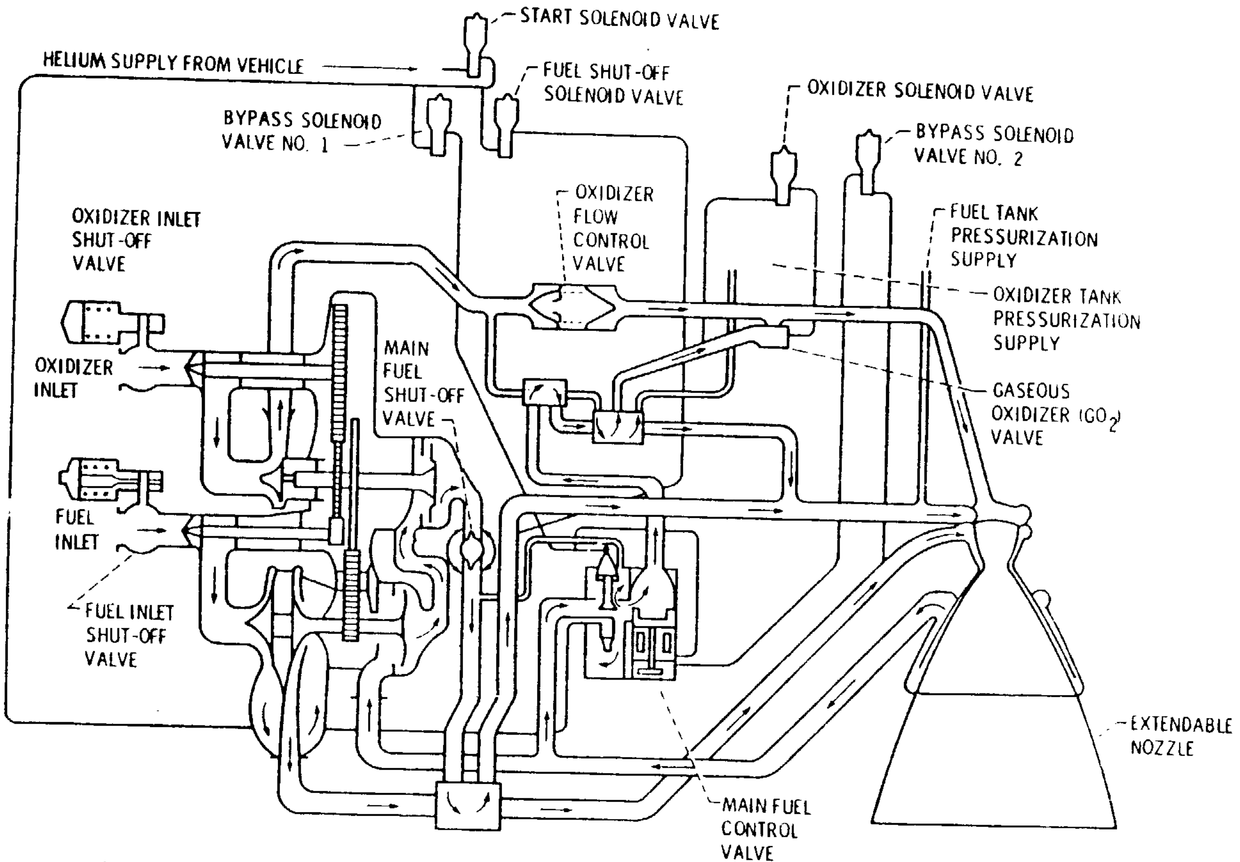

Figure 7-1. Flow schematic; Pratt & Whitney advanced OTV propulsion concept.

Table 7-2. TDK Input for the RL-10 OTV Test Engine.

```
TITLE 1 ZONE RL-10 (WITH SHOCK SIMULATION)
DATA
 $DATA
 ODE=1, ODK=1, NZONES=1, TDK=1, BLM=1, IRPEAT=1,
 SHOCK=1,
 PFGOPT=0,
 ECRAT=3.98,ASUB=10.089,5.845,4.538,3.234,3.982,NASUB=5,
 ASUP = 40.,56.9,100.,197.8,205.03, NASUP=5,
 ASUB = 4,3.982,2,1.5,1.25, NASUB = 5,
 RSI=2.57,RWTU=2.0623,RWTD=.190,THETAI=26.25,RI=1.7899,
 IWALL=4, THE=11.56, THETA=30,
 NWS=29,
 RS = .0, 1.0967, 1.3149, 1.6292, 2.2540, 3.2560, 4.1825, 4.8385,
          5.5335, 6.3720, 7.0654, 7.2630, 7.8181, 8.0758, 9.6218,
          9.8795,10.3681,10.6064,11.7979,12.0362,
         12.1807,12.1990,12.2166,12.2337,12.2501,
         12.4710,12.6755,
         14.1073,14.3190,
  ZS = .0,  .2198,  .5787, 1.0747, 2.1000, 3.9424, 5.9743, 7.6537,
          9.7136,12.6486,15.5584,16.4883,19.0000,20.0000,26.0000,
         27.0000,29.0000,30.0000,35.0000,36.0000,
         36.6064,36.6846,36.7629,36.8413,36.9199,
         38.0000,39.0000,
         46.0000,47.0350,
  EPS=205.03376,
  IOFF=3,
  $END
 REACTANTS
 H 2.                                               100.     -2154.L   20.56F .0709
 O 2.                                               100.     -3102.L   90.110 1.149

 NAMELISTS
  $ODE
  RKT=.TRUE.,
  P(1)=394.3,PSIA=.TRUE.,XP=1.,
  OFSKED(1)=5.035244,
  $END
 REACTIONS
 H + H = H2      ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U
 H + OH = H2O    ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U
 O + O = O2      ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U
 O + H = OH      ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U
 END TBR REAX
 O2 + H = O + OH      , A = 2.2E14, N = 0.0, B =16.8,   BAULCH 72 (A) 1.5U
 H2 + O = H + OH      , A = 1.8E10, N = -1., B = 8.9,   BAULCH 72 (A) 1.5U
 H2 + OH = H2O + H    , A = 2.2E13, N = 0.0, B =5.15,   BAULCH 72 (A) 2U
 OH + OH = H2O + O    , A = 6.3E12, N = 0.0, B =1.09,   BAULCH 72 (A) 3U
 LAST REAX
 THIRD BODY REAX RATE RATIOS
 M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
 M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
 M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
 M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
 LAST CARD
  [illegible]
   [illegible] 2,
  [illegible]205,
  $END
  $TRANS
  MP=200, XM=1,
  $END
  $MOC
  NC=0,ISHCK=2,
```

Table 7-2. (Continued).

```
$END
$BLM
IPRNT=0,
XINO = -4.28, -3.89, -3.50,
RINO = 3*1.995,
UEO  = 190, 380, 570,
TEO  = 5917, 5915, 5913,
PEO  = 393, 392, 391,
OFC = 2, DISTRB = 0,
XCO = -4.28,
XCE = 18.1,
IHFLAG = 0,
NTQW = 14,
XTQW = -3, -1, 0, 1, 2, 4, 6, 8, 10, 12, 14, 18, 19, 47,
TQW  = 1800, 2000, 2200, 1500, 1300, 1200, 1050, 800, 650, 500,
        425,  350,  750,  800,

NSEGS=10,
APROF=75,150,200, NPROF=0,
KDTPLT=0,KMTPLT=0,KTWPLT=0,
$END
```

Table 7-3. TDK Performance Summary: RL10 Engine.

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TDK PERFORMANCE SUMMARY : 1 ZONE RL-10 (WITH SHOCK SIMULATION)
REAL WALL CONTOUR 1 ZONES WALL TEMP
INDUCED SHOCK AFTER XA

		FIRST TDK/BLM SOLUTION	SECOND TDK/BLM SOLUTION
CHAMBER PRESS	[PSIA]	394.3000	394.3000
CHAMBER TEMP	[R]	5815.918	5892.477
MIXTURE RATIO	[-]	5.035244	5.035244
EP (NOZZLE)	[-]	205.0338	194.0614
H (OXID)	[CAL/MOLE]	-3102.000	-3102.000
H (FUEL)	[CAL/MOLE]	-2154.000	-2154.000
HCHAM (ODE)	[BTU/LB]	-464.2563	-307.9082
DELH (AVERAGE)	[BTU/LB]	0.0000000E+00	0.0000000E+00
DELH1 (AV)	[BTU/LB]	0.0000000E+00	156.3460
ECRAT	[-]	3.980000	3.969802
RSTAR	[INCHES]	2.570000	2.573304
RWTD	[-]	0.1900000	0.1884720
RWTU	[-]	2.062300	2.058368
THE	[DEGREES]	11.56000	10.65555
THETA	[DEGREES]	30.00000	30.00000
THETAI	[DEGREES]	26.25000	26.25000
RI	[-]	1.789900	1.789900
NIT	[-]	196.0000	196.0000
ISP (ODE)	[SECONDS]	477.5184	483.3437
ISP (ODF)	[SECONDS]	456.1371	459.4965
ISP (ODK)	[SECONDS]	474.4465	479.8922
ISP (TDK)	[SECONDS]	469.6459	475.5385
THRUST (TDK)	[POUNDS]	15885.27	15972.03
WDOT (TDK)	[LB/SEC]	33.82393	33.58724
CSTAR (TDK)	[FT/SEC]	7782.584	7857.594
CF (TDK)	[-]	1.941564	1.952167
CD	[-]	0.9963781	0.9989328
P (AXIS,EXIT)	[PSIA]	0.0000000E+00	0.0000000E+00
P (WALL,EXIT)	[PSIA]	0.7859458E-01	0.8903214E-01
T (WALL,EXIT)	[R]	1177.088	1257.314
V (WALL,EXIT)	[FT/SEC]	14947.51	15101.62
MA (WALL,EXIT)	[-]	5.909647	5.784453
SHOCK STRENGTH	[-]	0.3437161E-01	0.9015918E-02
SHOCK (X/R*)	[-]	8.749036	9.098541
SHOCK (R/R*)	[-]	1.110723	1.162930
XA (X/R*)	[-]	0.9500000E-01	0.9500000E-01
XB (X/R*)	[-]	0.0000000E+00	0.0000000E+00
DFOPT (BLME)	[POUNDS]	412.6425	436.4781
DF (BLME)	[POUNDS]	395.3395	417.3250
DISP (BLME)	[SECONDS]	11.68816	12.42511
THET (EXIT)	[FEET]	0.4160833E-01	0.4160833E-01
DEL* (EXIT)	[FEET]	0.8098879E-01	0.8098879E-01
E- (REGEN)		57.88868	57.88868
SQDOT (REGEN)	[BTU/SEC]	5288.230	5288.230
SQDOT (LOSS)	[BTU/SEC]	1214.000	1214.000
THRUST (TC)	[POUNDS]	15489.93	15554.70
ISP (TC)	[SECONDS]	457.9577	463.1133
CF (TC)	[-]	1.893244	1.901160

7.3 ROCKETDYNE PROTOTYPE ADVANCED SPACE ENGINE FOR OTV PROPULSION

This engine uses a hydrogen expander cycle with oxygen preheating and a nozzle that is regeneratively cooled with hydrogen. A flow schematic for the engine which was taken from Reference 25 is shown in Figure 7-2. The engine is sized to produce a nominal vacuum thrust of 22,500 pounds when operated at a chamber pressure of 2300 psia and an expansion ratio of 400:1.

Complete input for the case is given in Table 7-4. This input has been prepared by SEA, Inc., from data provided by NASA MSFC. The complete output for the case is lengthy and is not given here. It is available from SEA, Inc.. However, the output summary table is given in Table 7-5.

As with the RL-10 engine discussed in the previous subsection, 7.2, the calculations were carried out using the TDK shock option (SHOCK=1). The sequence of calculations is the same as given in subsection 7.1. An induced shock wave was found that originated from the wall inflection point just downstream of the throat. The shock strength at the last left running characteristic surface inside the nozzle (i.e., on the boundary of the domain of influence for the nozzle wall) was found to be $(P_2 - P_1)/ P_1 = .12$.

The total number of flow field points computed by the MOC was more than 95,000 for each pass. Computer execution time for the case was 3 hours and 38 minutes using a DEC PDP 11/750 VAX computer system.

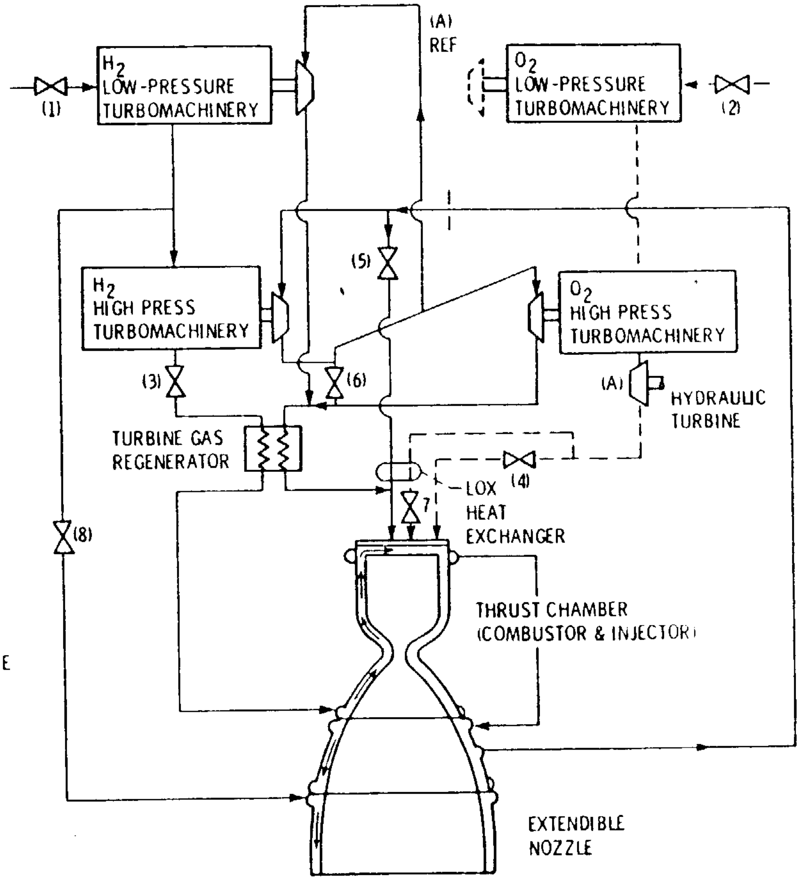
The ASE engine was also run using the TDE option (no shocks allowed); i.e., the two-dimensional expansion was assumed to be in a state of chemical equilibrium. A complete input data listing for the case is presented in Table 7-6. The boundary layer plots given in Section 6.8.5 were obtained for this case by input of APROF = 400, NPROF = 1, KDTPLT = 1, KMTPLT = 1, and KTWPLT = 1 in $BLM. The sequence of calculations for TDE is as follows:

1) ODE calculation with the system enthalpy set at the propellant tank values, i.e., liquid oxygen and liquid hydrogen at their normal boiling points.
2) ODE calculation to generate the TDE gas tables (see Table 7-7 for this output), and the BLM gas tables.
3) TDE calculation using the TDE gas tables.
4) BLM calculations using the above ODE, TDE results. A new wall geometry is calculated by displacing the wall inwards a distance of δ^* normal to the real wall. This new wall defines the boundary of the invisid core flow. BLM calculated that a total of 10592.2 BTU/sec. were conducted through the nozzle wall. Of this amount a total of 8333.8 BTU/sec. were picked up by the two regen cooling circuits, the remainder being lost from the system. Since the nozzle mass flow was found by TDE to be 47.75 llm/sec, the propellant enthalpy was increased by 174.5 BTU/lbm.
5) ODE calculation with the increased propellant enthalpy. The expansion ratio of the invisid core flow is automatically placed in the ODE output schedule.
6) ODE calculation to generate the TDE gas tables.
7) TDE calculation using the above ODE results, including the new wall contour.
8) Output summary table, see Table 7-8.

With the TDE option the flow field is constructed using a left running characteristics procedure, and shock waves from the wall are suppressed. Results obtained from the calculations are given in the output summary table, Table 7-8. These results can be compared with those given in Table 7-5 for the same engine but with full kinetics and shock tracing. The difference in predicted specific impulse is

$$I_{sp_{\substack{TDE\\TC}}} - I_{sp_{\substack{TDK\\TC}}} = 475.6 - 474.1 = 1.5 \text{ sec.}$$

Computer execution time for this case was 39 minutes using a DEC PDP 11/750 VAX computer system.



ENGINE CONTROLS

(1) IFV	-	INLET FUEL VALVE
(2) IOV	-	INLET OXIDIZER VALVE
(3) MFV	-	MAIN FUEL VALVE
(4) MOV	-	MAIN OXIDIZER VALVE
(5) TBV	-	TURBINE BYPASS VALVE
(6) OTBV	-	OXIDIZER TURBINE BYPASS VALVE
(7) GOV	-	GASEOUS OXIDIZER VALVE
(8) DFV	-	DUMP FUEL VALVE
(A)		FULL FLOW HYDRAULIC TURBINE FOR LOW PRESSURE LOX PUMP

Figure 7-2. Flow schematic; Rocketdyne advanced OTV propulsion concept.

Table 7-4. TDK Input for the ASE OTV Test Engine.

```
TITLE 1 ZONE ASE (WITH SHOCK SIMULATION)
DATA
 $DATA
 ODE=1, ODK=1, NZONES=1, TDK=1, BLM=1, IRPEAT=1, IRSTRT=0,
 SHOCK = 1,
 ECRAT=3.6629,
 ASUB=10,5,4,3.6629,3,2,1.5,
 NASUB=7,
 ASUP = 2,4,6,8,10,15,20,25,30,40,50,75,100,125,150,175,200,
        225,250,275,300,325,350,375,400,400.7148,
 NASUP=26,
 RSI=1.254,RWTU=1,RWTD=.3429,THETAI=17,RI=8.3732,
 IWALL=4, THE=6.5036, THETA=41,
 NWS=14,
 RS = .0, 2.1934, 3.3462, 5.0972, 6.7240, 8.4642, 9.7250,11.0935,
        12.5699,14.1654,15.8849,18.6739,21.6611,25.1027,
 ZS = .0, 1.2654, 2.6315, 4.9818, 7.5269,10.6702,13.2392,16.3252,
        20.0311,24.5243,30.0103,40.6593,55.3049,79.7103,
 RZNORM=1.254,
 EPS=400.7248,
 IOFF=4,
 $END
REACTANTS
H 2.                                        100.     -2154.L   20.27F .0709
O 2.                                        100.     -3102.L   90.180 1.149

NAMELISTS
 $ODE
 RKT=.TRUE.,
 P(1)=2287,PSIA=.TRUE.,XP=1.,
 OFSKED(1)=6.3780,
 $END
REACTIONS
H + H = H2     ,M1, A = 6.4E17, N = 1.0, B = 0.0, (AR) BAULCH 72 (A) 30U
H + OH = H2O   ,M2, A = 8.4E21, N = 2.0, B = 0.0, (AR) BAULCH 72 (A) 10U
O + O = O2     ,M3, A = 1.9E13, N = 0.0, B =-1.79,(AR) BAULCH 76 (A) 10U
O + H = OH     ,M7, A =3.62E18, N = 1.0, B = 0.0, (AR) JENSEN 78 (B) 30U
END TBR REAX
O2 + H = O + OH    , A = 2.2E14, N = 0.0, B =16.8,   BAULCH 72 (A) 1.5U
H2 + O = H + OH    , A = 1.8E10, N = -1., B = 8.9,   BAULCH 72 (A) 1.5U
H2 + OH = H2O + H  , A = 2.2E13, N = 0.0, B =5.15,   BAULCH 72 (A) 2U
OH + OH = H2O + O  , A = 6.3E12, N = 0.0, B =1.09,   BAULCH 72 (A) 3U
LAST REAX
THIRD BODY REAX RATE RATIOS
M1 = 25*H,4*H2,10*H2O,25*O,25*OH,1.5*O2,
M2 = 12.5*H,5*H2,17*H2O,12.5*O,12.5*OH,6*O2,
M3 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,11*O2,
M7 = 12.5*H,5*H2,5*H2O,12.5*O,12.5*OH,5*O2,
LAST CARD
 $ODK
 JPRNT=2,EP=400.7148,
 $END
 $TRANS
 MP=200,
 XM(1)=1.,
 $END
 $MOC
 NC=0,
 ISHCK=2,
 $END
 $BLM
 IPRNT=0,
 XINO = -5.778, -5.582, -5.183, -4.749,
```

Table 7-4. (Continued).

```
RINO = 4*1.9138,
UEO  = 309, 533, 689, 856,
PEO  = 2282, 2273, 2264, 2251,
TEO  = 6661, 6658, 6655, 6651,
OFC = 2,2,
DISTRB=0,0,
XCO = -6.7780,3.1901,
XCE = 3.1901,25.9644,
IHFLAG = 0,
NTQW = 11,
XTQW = -6.7780, -5.1834, -1.9936, -.7974, -.4785, -.3987, -.1595,
        2.3928,  3.9872, 25.3589, 25.9968, 63.5649,
TQW  = 910, 1200, 1020, 1210, 1210, 1230, 1210, 430,1180, 1080,
       818,  657,
NSEGS=7,
APROF=2,10,50,100,200,300,390,400, NPROF=0,
KDTPLT=0,KMTPLT=0,KTWPLT=0,
$END
```

Table 7-5. TDK Performance Summary: ASE Engine.

TDK PERFORMANCE SUMMARY : 1 ZONE ASE (WITH SHOCK SIMULATION)
REAL WALL CONTOUR 1 ZONES WALL TEMP
INDUCED SHOCK AFTER XA

		FIRST TDK/BLM SOLUTION	SECOND TDK/BLM SOLUTION
CHAMBER PRESS	[PSIA]	2287.000	2287.000
CHAMBER TEMP	[R]	6556.935	6642.703
MIXTURE RATIO	[-]	6.378000	6.378000
EP (NOZZLE)	[-]	400.7248	384.4752
H (OXID)	[CAL/MOLE]	-3102.000	-3102.000
H (FUEL)	[CAL/MOLE]	-2154.000	-2154.000
HCHAM (ODE)	[BTU/LB]	-411.5210	-236.9780
DELH (AVERAGE)	[BTU/LB]	0.0000000E+00	0.0000000E+00
DELH1 (AV)	[BTU/LB]	0.0000000E+00	174.5418
ECRAT	[-]	3.662900	3.646226
RSTAR	[INCHES]	1.254000	1.256817
RWTD	[-]	0.3429000	0.3398899
RWTU	[-]	1.000000	0.9955171
THE	[DEGREES]	6.503600	6.029917
THETA	[DEGREES]	41.00000	41.00000
THETAI	[DEGREES]	17.00000	17.00000
RI	[-]	8.373200	8.373200
NIT	[-]	196.0000	196.0000
ISP (ODE)	[SECONDS]	485.5364	491.9677
ISP (ODF)	[SECONDS]	457.5597	461.1883
ISP (ODK)	[SECONDS]	484.1301	490.3438
ISP (TDK)	[SECONDS]	481.4474	487.9469
THRUST (TDK)	[POUNDS]	22981.83	23173.47
WDOT (TDK)	[LB/SEC]	47.73488	47.49179
CSTAR (TDK)	[FT/SEC]	7615.182	7688.589
CF (TDK)	[-]	2.034106	2.051068
CD	[-]	0.9896481	0.9940407
P (AXIS,EXIT)	[PSIA]	0.1151442E-01	0.1154842E-01
P (WALL,EXIT)	[PSIA]	0.4545023	0.4803083
T (WALL,EXIT)	[R]	1690.341	1780.143
V (WALL,EXIT)	[FT/SEC]	15046.61	15231.09
MA (WALL,EXIT)	[-]	5.594438	5.527072
SHOCK STRENGTH	[-]	0.1198294	0.4595399E-02
SHOCK (X/R*)	[-]	17.87842	18.09883
SHOCK (R/R*)	[-]	4.474361	4.548824
XA (X/R*)	[-]	0.2249627	0.2249627
XB (X/R*)	[-]	0.0000000E+00	0.0000000E+00
DFOPT (BLME)	[POUNDS]	683.8337	691.0768
DF (BLME)	[POUNDS]	650.9324	656.9037
DISP (BLME)	[SECONDS]	13.63641	13.83194
THET (EXIT)	[FEET]	0.1998608E-01	0.1998608E-01
DEL* (EXIT)	[FEET]	0.3850399E-01	0.3850399E-01
[illegible]	[illegible]	175.4796	175.4796
[illegible]	[BTU/SEC]	8331.736	8331.736
SQDOT (LOSS)	[BTU/SEC]	2289.264	2289.264
THRUST (TC)	[POUNDS]	22330.90	22516.57
ISP (TC)	[SECONDS]	467.8110	474.1150
CF (TC)	[-]	1.976493	1.992926

Table 7-6. TDK Input for the ASE OTV Test Engine.

```
TITLE 1 ZONE ASE - TDE OPTION
DATA
 $DATA
 ODE=1, ODK=0, NZONES=1, TDE=1, BLM=1, IRPEAT=1,
 ECRAT=3.6629,
 ASUB=10,5,4,3.6629,3,2,1.5,
 NASUB=7,
 ASUP = 2,4,6,8,10,15,20,25,30,40,50,75,100,125,150,175,200,
        225,250,275,300,325,350,375,400,400.7148,
 NASUP=26,
 RSI=1.254,RWTU=1,RWTD=.3429,THETAI=17,RI=8.3732,
 IWALL=4, THE=6.5036, THETA=41,
 NWS=14,
 RS = .0, 2.1934, 3.3462, 5.0972, 6.7240, 8.4642, 9.7250,11.0935,
        12.5699,14.1654,15.8849,18.6739,21.6611,25.1027,
 ZS = .0, 1.2654, 2.6315, 4.9818, 7.5269,10.6702,13.2392,16.3252,
        20.0311,24.5243,30.0103,40.6593,55.3049,79.7103,
 RZNORM=1.254,
 EPS=400.7248,
 IOFF=4,
 $END
REACTANTS
H 2.                                          100.      -2154.L   20.27F .0709
O 2.                                          100.      -3102.L   90.180 1.149

NAMELISTS
 $ODE
 RKT=.TRUE.,
 P(1)=2287,PSIA=.TRUE.,XP=1.,
 OFSKED(1)=6.3780,
 $END
 $TRANS
 MP=200,
 XM(1)=1.,
 $END
 $MOC
 NC=0,
 ISHCK=2,
 $END
 $BLM
 IPRNT=0,
 XINO = -5.778, -5.582, -5.183, -4.749,
 RINO = 4*1.9138,
 UEO  = 309, 533, 689, 856,
 PEO  = 2282, 2273, 2264, 2251,
 TEO  = 6661, 6658, 6655, 6651,
 OFC = 2,2,
 DISTRB=0,0,
 XCO = -6.7780,3.1901,
 XCE = 3.1901,25.9644,
 IHFLAG = 0,
 NTOW = 11,
 XTOW = -5.778, -5.1934, 1.9936, -.7974, -.4785, -.3987, -.1595,
        2.3929, 3.9872, 25.3589, 25.9968, 63.5649,
 TOW  = 910, 1200, 1020, 1210, 1210, 1230, 1210, 430,1180, 1080,
        818, 657,
 NSEGS=7,
 APROF=2,10,50,100,200,300,390,400, NPROF=0,
 KDTPLT=0,KMTPLT=0,KTWPLT=0,
 $END
```

Table 7-7. Gas Properties Table Prepared for TDE.

```
************************************************************************************************
                         TDE GAS TABLES FOR ZONE  1
************************************************************************************************

 I      PRESSURE        MOL WT         GAMMA       TEMPERATURE      ENTHALPY         MACH NO
         (PSI)                                       (DEG R)       (FT2/SEC2)

 1      2287.000        14.14817      1.141751      6556.935     -0.1030305E+08    0.0000000E+00
 2      1317.704        14.30514      1.141197      6192.129     -0.2259110E+08    1.000000
 3      1142.505        14.34392      1.141336      6100.000     -0.2564447E+08    1.127213
 4      976.4395        14.38510      1.141634      6000.000     -0.2892166E+08    1.253724
 5      833.8527        14.42552      1.142116      5900.000     -0.3216584E+08    1.371666
 6      711.2675        14.46485      1.142796      5800.000     -0.3536805E+08    1.482871
 7      606.2949        14.50296      1.143696      5700.000     -0.3852501E+08    1.588694
 8      516.4310        14.53959      1.144831      5600.000     -0.4163028E+08    1.689988
 9      374.2011        14.60774      1.147869      5400.000     -0.4766850E+08    1.881458
10      271.4484        14.66821      1.152025      5200.000     -0.5345665E+08    2.060988
11      197.2862        14.71997      1.157297      5000.000     -0.5897009E+08    2.230871
12      143.8113        14.76264      1.163571      4800.000     -0.6420190E+08    2.393127
13      56.45561        14.84074      1.185546      4200.000     -0.7834301E+08    2.855202
14      21.80071        14.86745      1.205911      3600.000     -0.9075598E+08    3.328062
15      7.756236        14.87303      1.223118      3000.000     -0.1021462E+09    3.868471
16      2.376307        14.87359      1.242535      2400.000     -0.1127972E+09    4.533237
17      0.5785754       14.87360      1.270487      1800.000     -0.1226660E+09    5.420125
18      0.9463301E-01   14.87360      1.305148      1200.000     -0.1316647E+09    6.806742
19      0.5593139E-02   14.87360      1.339089      600.0000     -0.1398936E+09    9.820318
20      0.5423629E-05   14.87360      1.349951      100.0000     -0.1463893E+09    24.55089
```

Table 7-8. TDK Performance Summary: ASE Engine (TDE).

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TDK PERFORMANCE SUMMARY : 1 ZONE ASE - TDE OPTION
REAL WALL CONTOUR 1 ZONES WALL TEMP

		FIRST TDK/BLM SOLUTION	SECOND TDK/BLM SOLUTION
CHAMBER PRESS	[PSIA]	2287.000	2287.000
CHAMBER TEMP	[R]	6556.935	6642.690
MIXTURE RATIO	[-]	6.378000	6.378000
EP (NOZZLE)	[-]	400.7248	384.2064
H (OXID)	[CAL/MOLE]	-3102.000	-3102.000
H (FUEL)	[CAL/MOLE]	-2154.000	-2154.000
HCHAM (ODE)	[BTU/LB]	-411.5210	-237.0014
DELH (AVERAGE)	[BTU/LB]	0.0000000E+00	0.0000000E+00
DELH1 (AV)	[BTU/LB]	0.0000000E+00	174.5199
ECRAT	[-]	3.662900	3.646455
RSTAR	[INCHES]	1.254000	1.256778
RWTD	[-]	0.3429000	0.3399320
RWTU	[-]	1.000000	0.9955798
THE	[DEGREES]	6.503600	5.728948
THETA	[DEGREES]	41.00000	41.00000
THETAI	[DEGREES]	17.00000	17.00000
RI	[-]	8.373200	8.373200
NIT	[-]	192.0000	192.0000
ISP (ODE)	[SECONDS]	485.5364	491.9593
ISP (ODF)	[SECONDS]	457.5597	461.1822
ISP (ODK)	[SECONDS]	0.0000000E+00	0.0000000E+00
ISP (TDE)	[SECONDS]	482.9971	489.6729
THRUST (TDE)	[POUNDS]	23064.45	23248.76
WDOT (TDE)	[LB/SEC]	47.75277	47.47814
CSTAR (TDE)	[FT/SEC]	7612.330	7690.318
CF (TDE)	[-]	2.041418	2.057731
CD	[-]	0.9894340	0.9937611
P (AXIS,EXIT)	[PSIA]	0.0000000E+00	0.0000000E+00
P (WALL,EXIT)	[PSIA]	0.4573059	0.5004708
T (WALL,EXIT)	[R]	1711.442	1820.351
V (WALL,EXIT)	[FT/SEC]	15082.84	15258.59
MA (WALL,EXIT)	[-]	5.582643	5.488873
SHOCK STRENGTH	[-]	0.0000000E+00	0.0000000E+00
SHOCK (X/R*)	[-]	0.0000000E+00	0.0000000E+00
SHOCK (R/R*)	[-]	0.0000000E+00	0.0000000E+00
XA (X/R*)	[-]	0.0000000E+00	0.0000000E+00
XB (X/R*)	[-]	0.0000000E+00	0.0000000E+00
DFOPT (BLME)	[POUNDS]	681.5857	705.2800
DF (BLME)	[POUNDS]	647.8039	668.9509
DISP (BLME)	[SECONDS]	13.56579	14.08966
THET (EXIT)	[FEET]	0.1994434E-01	0.1994434E-01
[illegible] (EXIT)	[FEET]	0.3928238E-01	0.3928238E-01
E- (REGEN)	[-]	175.4854	175.4854
SQDOT (REGEN)	[BTU/SEC]	8333.813	8333.813
SQDOT (LOSS)	[BTU/SEC]	2258.387	2258.387
THRUST (TC)	[POUNDS]	22416.64	22579.80
ISP (TC)	[SECONDS]	469.4313	475.5832
CF (TC)	[-]	1.984082	1.998522

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7.4 DISCUSSION OF SUMMARY OUTPUT

At the end of each computer run, the TDK program prints a table of summary output. Examples of this output are given in Table 7-1, and Tables 7-3, 7-5, and 7-8. As can be seen from Table 7-8, the first item printed is the title

TDK PERFORMANCE SUMMARY: (title)

where the title is taken from the input data last title card (see Table 7-2, first card image).

Next, performance parameters summarizing the results of the calculations are printed in three columns. The left hand column identifies each item to be printed and its units. The first column of results is for the first MOC/BLM solution, and second column of results is for the second MOC/BLM solution.

The items labeled ISP(TDK), THRUST(TDK), WDOT(TDK), CD, CSTAR(TDK), and CF(TDK) are defined as:

Name	Units	Definition
ISP(TDK)	sec	Specific Impulse, $I_{sp,2D}$
THRUST(TDK)	lbf	Thrust, F_{2D}
WD0T(TDK)	lbm/sec	Mass Flow, $\dot{m}_{2D}$
CD	-	Flow coefficient, $C_{D,2D}$
CSTAR(TDK)	ft/sec	Characteristic Velocity, C^*_{2D}
CF(TDK)	-	Thrust coefficient, $C_{F,2D}$

If a TDF or TDE calculation was made rather than TDK, then these items will be relabeled.

The values given for $I_{sp,2D}$ and m_{2D} are obtained by evaluating the integrals discussed in the documentation for MOC module subroutine CHAR. The mass flow integral is evaluated across the MOC initial data line. The I_{sp} integral is evaluated across the initial data line, plus the integral of the axial component of wall pressure from the initial data line to the nozzle end point. The thrust is

$$F_{2D} = I_{sp,2D} \, \dot{m}_{2D}$$

The nozzle flow coefficient is calculated as

$$C_{D,2D} = \dot{m}_{2D} / \dot{m}_{1D}$$

where

$$\dot{m}_{1D} = \rho^*_{1D} \, V^*_{1D} \, A^*$$

is obtained from ODE. A^* is the geometric throat area.

The characteristic velocity, C^*, is calculated as

$$C^*_{2D} = I_{sp,2D} \, g / C_{F,2D}$$

where the thrust coefficient, C_F, is defined by

$$C_{F,2D} = F_{2D} \, / \, P_c \, A^*$$

Again, A^*, is the geometric throat area.

The items labeled DISP(BLME), DFOPT(BLME), DF(BLME), ISP(TC), THRUST(TC), and CF(TC) are defined as follows:

Name	Units	Definition
DISP(BLME)	sec	$\Delta I_{sp,BLM}$
DFOPT(BLME)	lbf	ΔF_{BLM} for $P_e = P_{amb}$
DF(BLME)	lbf	ΔF_{BLM}

Name	Units	Definition
ISP(TC)	sec	$I_{sp,2D,BLM}$
THRUST(TC)	lbf	$F_{2D,BLM}$
CF(TC)	-	$C_{F,2D,BLM}$

In the above, the thrust loss calculated by the BLM is given by the following relation:

$$\Delta F_{BLM} = 2\pi r_e \cos \alpha_e * \rho_e U_e^2 \theta_{BLM}$$
$$- 2\pi r_e \cos \alpha_e * (P_e - P_{amb}) \delta^*_{BLM}$$

The additional items, printed are

$\Delta I_{sp,BLM} = \Delta F_{BLM} / \dot{m}_{2D}$

$I_{sp,2D,BLM} = (F_{2D} - \Delta F_{BLM}) / \dot{m}_{2D}$

$F_{2D,BLM} = F_{2D} - \Delta F_{BLM}$

$C_{F,2D,BLM} = F_{2D,BLM} / P_c A^*$

Performance parameters summarizing the results of the second MOC/BLM calculation differ from the first set printed as follows:

1) The TDK and ODE results are for the second (invisid core) run have a modified wall contour, throat area, and expansion ratio. Note that the system enthalpy is different than used in the first run if the BLM wall calculation is not adiabatic.

2) The BLM results are re-calculated using edge conditions from the second TDK run. BLM itself is not re-run, and the values of δ^* and θ are not changed.

The equations used are the same as given above.

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8. ERROR DIAGNOSTICS

8.1 DISCUSSION OF PROGRAM USAGE

Error diagnostics* are printed by the program when it has either found an input card error or is unable to continue with its computations because it has obtained an impossible result. The analysis performed by the computer program is limited by the physical assumptions used in its development and by the numerical methods used. Consequently, an understanding of these assumptions and of the numerical methods that have been applied is necessary in order to correctly run cases using the computer program. Although the computer program contains many error diagnostics, it is not possible to diagnose all errors.

Input values given for the sample cases (see Section 7) can be used as a guide in preparing data for similar calculations. Special care must be taken, however, to avoid errors of the type given below:

8.1.1 The computer program will not give valid results if the input kinetic reaction rate parameters are unrealistic. A common mistake is to input an implied third body reaction rate backwards; which gives a very large error. Tables 6-10 and 6-11 can be used as guides in preparing reaction rate data. It should be remembered that the computer program automatically calculates equilibrium constants from the input JANAF thermochemical data.

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* Error diagnostics can also be given by the computer system subroutines. These vary with the operating system and are not discussed here.

8.1.2 Although the 0DK and TDK calculations allow condensed phases to be present in the flow, no mass transfer between phases is allowed.

8.1.3 A common mistake in using the computer program is to input inlet and throat geometry parameters that are physically impossible when compared with Figure 6-1.

8.1.4 A value RWTU > .5 should be used because of inaccuracies which can occur as a result of the transonic method of solution[9].

8.1.5 For some chemical systems (e.g., H-F) it is possible that the two-dimensional throat Mach number will be subsonic as a result of the kinetic process. In this case the initial data line can be displaced downstream, increasing the Mach number, by use of the input parameter ALI (see Section 6.6). If ALI is input greater than zero, a symmetric throat is required and it is necessary that RWTD be set to the same value as RWTU.

8.1.6 An important consideration in preparing data for all but 0DE calculations concerns input of the nozzle wall. The derivative of the wall contour has an important effect on the nozzle flow field and it is required that wall derivatives vary slowly with respect to the local characteristic mesh spacing. In this respect the TDK program is no different than any other method of characteristics calculation. Usually the most satisfactory method of specifying a nozzle wall contour is through the use of the spline fit contour option (IWALL=4). Too many points should not be input when using this option since a bad derivative could result. Never place points close together. Although the initial section of the contour is assumed to be a circular arc, a small value of THETA can be used if necessary.

In case of difficulty with the method of characteristics calculations, a useful procedure is to plot the (r,x) coordinates of mesh points in the region of difficulty. A plot of this type will frequently locate the cause of the problem. For this purpose it is necessary to print each calculated mesh point (i.e., N1=1 and N2=1).

8.2 LISTING OF ERROR DIAGNOSTICS

Errors printed by the program are listed in Table 8-1 in alphabetical order. The subroutine printing the error message is listed in Table 8-1 in parenthesis at the right of each message. Table 8-2 and the write-up for the subroutine printing the error message should be referred to when the message is encountered.

Suggested corrective action for some of the errors listed in Table 8-1 is given in Table 8-2.

Error diagnostics consist of two types: fatal errors and nonfatal errors. A fatal error will terminate the case being executed and the program will proceed to the next case. The case may not be immediately terminated. For example, in processing input data cards the program will attempt to find as many input card errors as possible before terminating the case. A nonfatal error serves only as a warning and the program will continue the case. If the error diagnostic is of the nonfatal type the symbol (NF) appears in the explanation.

TABLE 8-1: LIST OF ERROR DIAGNOSTICS

```
3 PHASES OF A CONDENSED SPECIES ARE OUT OF ORDER  (EQLBRM)
35 ITERATIONS DID NOT SATISFY CONVERGENCE REQUIREMENTS FOR THE POINT (EQLBRM)
ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN .0000005 FOR ALL ASSIGNED CONDITIONS (OUT1)
ALL REACTION RATE RATIOS INPUT AS 1.0 (PACK)
BLM MODULE COULD NOT FIND DATA FROM ODE MODULE -- WILL ASSUME DATA TO BE READ IN $BLM (READAT)
CALCULATIONS WERE STOPPED BECAUSE NEXT POINT IS MORE THAN 50 DEG BELOW TEMP RANGE OF A CONDENSED SPECIES (ROCKET)
CANNOT FIND POINT 4 FOR 2ND RRS CALCULATION (SHCKA)
CANNOT FIND POINT 4 FOR LRS CALCULATION (CNTR13)
CANNOT FIND POINT 4 FOR RRS CALCULATION (CNTR12)
CANNOT FIND POINT 4 FOR RRS CALCULATION (CNTR14)
CANNOT FIND POINT 4 FOR RRS CALCULATION (CNTR22)
CANNOT FIND POINT 4 FOR RRS CALCULATION (CNTR24)
CANNOT FIND POINT 5 FOR 2ND RRS (CNTR22)
CANNOT FIND POINT 5 FOR 2ND RRS (SHCKA)
CANNOT FIND THETA FOR WALL OPTION 5 - RUN ABORTED IN ODKINP (ODKINP)
CANT FIND MATCHING PHASE FOR  TMELT=   0.00000000E+00 CURRENT TEMP=   0.00000000E+00 (MAIN1D)
COMPUTED HS =   0.000000E+00  AT J =   0  IS OUT OF GIVEN RANGE. (COEF1)
CONDENSED REACTANTS NOT PERMITTED IN DETN OR SHOCK PROBLEMS (ODES)
CONSERVATION EQNS WERE NOT SATISFIED IN 8 ITERATIONS (DETON)
COULD NOT LOCATE PRES  0.000000E+00  FOR ZONE  0  AND POINT   0  IN ODK GENERATED TRANSONIC TABLES (GETIL)
DATA FROM  MODULE OUT OF ORDER IN MODULE BLM. CARD     0 HAS SEQ. NO.     0 (READAT)
DERIVATIVE MATRIX SINGULAR  (EQLBRM)
DID NOT CONVERGE FOR AREA RATIO =   0.00000 (ROCKET)
DID NOT CONVERGE FOR U1=    0.00   ANSWERS PROBABLY NOT RELIABLE  SOLUTION MAY NOT EXIST (SHCK)
DID NOT CONVERGE ON ELECTRON BALANCE (EQLBRM)
DIMENSIONS IN/SPECIES/TOO SMALL TO CONSIDER (SEARCH)
END OF FILE ENCOUNTERED WHILE READING PROFILE PLOT FILE IN BLPLTS - RUN CONTINUES (BLPLTS)
END OF LRC CONSTRUCTION FROM CNTR41 (CNTR41)
END OF NOZZLE DETECTED (CNTR91)
END OF RRC CONSTRUCTION FROM CNTR21 (CNTR31)
ENTIRE TRANSONIC TABLE FILE HAS BEEN READ (GETIL)
EP NOT REACHED (MAIN1D)
ERROR - THE WALL TEMPERATURE/HEAT FLUX TABLE MUST CONTAIN AT LEAST 4 POINTS WHEN CUBIC INTERPOLATION IS USED (INPUTB)
ERROR DETECTED DURING INPUT PROCESSING (REAXIN)
ERROR DETECTED DURING TRANSONIC CALC (TRAN)
ERROR DURING LOW T THERMO EVAL, T=      0.0000000 E+00 (SKPB1)
ERROR DURING LOW T THERMO EVAL, T=      0.0000000 E+00 (THERM)
ERROR DURING LOW T THERMO EVAL, T=      0.00000000E+00 (CPHS)
ERROR FOR SKEWED PARABOLA OPTION - STOP (SKPB1)
ERROR FROM BANDI-  (BANDI)
ERROR IN ABOVE CARD.  CONTENTS IGNORED. (ODES)
ERROR IN ATSHCK (ATSHCK)
ERROR IN BLW WHILE READING LINKAGE DATA (BLTK)
ERROR IN BLW WHILE READING LINKAGE DATA (BLW)
ERROR IN BLW, NWS EXCEEDS 50 (BLW)
ERROR IN CNTR21, CROSSING OF RRC SHOULD HAVE BEEN TERMINATED IN CNTRL1 (CNTR21)
ERROR IN CNTR21, CROSSING OF RRC SHOULD HAVE BEEN TERMINATED IN CNTRL1 (CNTR31)
ERROR IN CNTR91- END OF RRC AND NO SHOCK OR END OF NOZZLE DETECTED (NTR91)
ERROR IN CNTRL1, INSERTION TABLE EXCEEDS MAXIMUM (CNTRL1)
ERROR IN CNTRL1, INSERTION TABLE EXCEEDS MAXIMUM (CNTRL2)
ERROR IN CNTRL1, IP=         0 EXCEEDS MAXIMUM=         0 (CNTR21)
ERROR IN CNTRL1, IP=         0 EXCEEDS MAXIMUM=         0 (CNTR31)
ERROR IN CNTRL1, IP=         0 EXCEEDS MAXIMUM=         0 (CNTRL1)
ERROR IN CNTRL1, IP=         0 EXCEEDS MAXIMUM=         0 (CNTRL2)
ERROR IN FINDT (FINDT)
ERROR IN GAUELM. UNABLE TO FIND PIVOT FOR LINE   0 EPSILON=0.00E+00 (GAUELM)
ERROR IN GETPT, ID=  0 (GETPT)
ERROR IN GETPT- POINT NOT PREVIOUSLY WRITTEN (GETPT)
ERROR IN IVPL, NP EXCEEDS NPT (IVPL)
ERROR IN ODWALL, IWALL=  0 RUN ABORTED (ODWALL)
ERROR IN ORDER OF CARDS FOR (TTAPE)
ERROR IN RBL WHILE READING FILE  0 (RBL)
ERROR IN REACTANT CARDS (ODES)
```

TABLE 8-1: CONTINUED

```
ERROR IN SAVPT, ID=    0 (SAVPT)
ERROR IN SHCKA, ITERATION FOR REFLECTED SHOCK ANGLE FAILED, DLT3A=      0.0000 DLT3B=      0.0000 DEG (SHCKA)
ERROR IN SHCKW, ITERATION FOR REFLECTED SHOCK ANGLE FAILED, DLT3A=      0.0000 DLT3B=      0.0000 DEG (SHCKW)
ERROR IN THE CALCULATION OF 2ND SHOCK, X3 = 0.00000E+00 X4 = 0.00000E+00 (CNTR16)
ERROR MESSAGE  FROM BLTABL - THE REQUESTED TABLE SIZE OF    0 EXCEEDED THE INTERNAL DIMENSIONS OF    0 (BLTABL)
ERROR OCCURS WHILE POSITIONING BLM TAPE FOR RESTART (READAT)
ERROR TYPE=  0 IN CNTR12 (CNTR12)
ERROR TYPE=  0 IN CNTR13 (CNTR13)
ERROR(  ) .... (ERRORZ)
ERROR( 2) OR ( 4)           THE PROGRAM IS ATTEMPTING TO INSERT AN EXCESSIVE NUMBER OF FLOWFIELD POINTS. (ERRORZ)
ERROR( 6)                   THE LRC INSERTION TABLE HAS OVERFLOWED. (ERRORZ)
ERROR( 7)                   THE MAXIMUM NO. OF POINTS FOR A LRC HAS BEEN EXCEEDED. (ERRORZ)
ERROR( 8)                   THE PROGRAM IS ATTEMPTING TO LOCATE A WALL POINT UPSTREAM
                            OF THE 1ST POINT IN THE WALL TABLE. (ERRORZ)
ERROR( 9) OR (10)           THE PROGRAM IS UNABLE TO LOCATE POINT 1 IN SUBROUTINE INPT (ERRORZ)
ERROR(11) OR (12)           THE PROGRAM IS UNABLE TO LOCATE POINT 1 IN SUBROUTINE DSPT  (ERRORZ)
ERROR(50)                   AN IMPROPER INITIAL LINE POINT IS SOUGHT. (ERRORZ)
ERROR(13)                   THE CALCULATION FOR THE LAST POINT EXCEEDED MAXIMUM ITERATIONS (ERRORZ)
ERROR(14)                   NO MORE THAN 275 POINTS MAY BE INPUT ON INITIAL LINE (ERRORZ)
ERROR(15)                   SUM OF INPUT SPECIES CONCENTRATIONS FOR ABOVE POINTS NOT ONE. (ERRORZ)
ERROR(16)                   WALL TABLE VIOLATES INSERTION ANGLE CRITERION  (ERRORZ)
ERROR(17)                   INCOMPLETE TDK INITIAL LINE HAS BEEN GENERATED (ERRORZ)
EXIT PLANE OPTION REQUIRES GREATER WALL EXTENSION (CNTRL)
EXIT PLANE OPTION REQUIRES LARGER NCHMXE,NPTMXE (CNTRL)
FAILED TO CONVERGE IN IVPL (IVPL)
FATAL ERROR ENCOUNTERED DURING REACTION PROCESSING DUE TO ABOVE CARD (REAXIN)
FATAL ERROR ENCOUNTERED WHILE PROCESSING THIRD BODY REACTION RATE RATIOS - ERROR ON ABOVE CARD (REAXIN)
FIND* VAR OUTSIDE TABLE (FIND)
FROZEN DID NOT CONVERGE IN 8 ITERATIONS (FROZEN)
ILL-CONDITIONED MATRIX IN ROUTINE SKPB    ERROR =   0.00000E+00   -STOP- (SKPB1)
INERT      NOT IN MASTER SPECIES TABLE (SEARCH)
INERT SPECIES (SEARCH)
INERTS FOUND IN TDK PROBLM, INERTS NOT SPECIFIED, CANNOT USE RELATIVE
    SELECTION CRITERION FOR TDK CASE (SELECT)
INFINITELY WEAK SHOCK BT1 M1 M1*ABS(SIN(BT1))=  0.000000E+00  0.000000E+00  0.000000E+00 (SHOCK)
INLET GEOMETRY INCOMPATIBLE WITH INITIAL CONDITIONS (PRES)
INTERNAL SEQ NUM (REAXIN)
ITERATIONS EXCEEDED ITMAX (BLSEG)
KIN EXPN CODE DIMENSIONED FOR MAX. OF 40 SPECIES, CURRENT CASE USES (SELECT)
LOW T THERMO EXTENSION AT T=      DEG-K (THERM)
LOW TEMPERATURE IMPLIES CONDENSED SPECIES SHOULD HAVE BEEN INCLUDED ON AN INSERT CARD, RESTART (EQLBRM)
LRS PT IS OUTSIDE THE NOZZLE (CNTR13)
MACH NUMBER CONVERGENCE FAILED, ZONE=  0  CONV CRIT =  0.00E+00   CONV OBTAINED =  0.00E+00 (PRINT)
MACH NUMBER CONVERGENCE FAILED, ZONE=  0  CONV CRIT =  0.00E+00   CONV OBTAINED =  0.00E+00 (PRINTS)
MASS FRACTION SUM NOT 1. (OUT1)
MASS OF MOLE FRACTIONS NOT SPECIFIED MASS FRACTIONS ASSUMED (REAXIN)
MAXIMUM ITERATION REACHED- RUN IS TERMINATED (PRINTS)
MORE THAN 12 CHARACTERS SPECIFIED FOR AN INERT SPECIES NAME (REAXIN)
NE DID NOT CONVERGE (PRES)
NO $ODE VALUE GIVEN FOR OF,ECRAT,FA,OR FPCT (ODES)
NO ECRAT SPECIFIED FOR ODK START-RUN ABORTED (ODES)
NO LINKAGE DATA FOUND, EXPECT MANUAL INPUT (READAT)
NO MATCH FOR SPECIES NAME  (REAXIN)
NO MATCH FOUND FOR SPECIES NAME  (STORNU)
NON-NUMERIC ENCOUNTERED IN ECNV WHILE DECODING...     (ECNV)
NONCONVERGENCE IN ENCALC, T1 T11= 0.0000000E+00 0.0000000E+00 (ENCALC)
NONCONVERGENCE IN TSCALC, T P S S0= 0.0000000E+00 0.0000000E+00 0.0000000E+00 0.0000000E+00 (TSCALC)
NOT ENOUGH POINTS FOR SECOND SPLINE (WALL)
NOZZLE PWZS COORDINATES NOT MONOTONIC INCREASING AT PT    0 (PACK)
NP EXCEEDED NPT -- PROGRAM TERMINATED (BLMAIN)
NUMBER OF SHOCK REFLECTIONS EXCEEDS MAXIMUM=  0 (CNTR91)
NUMBER OF SPECIES TOO LARGE FOR TABLES, MUST REDIMENSION (REAXIN)
NUMBER OF TEMP VALUES OUTSIDE RANGE (LTCPHS)
```

TABLE 8-1: CONTINUED

```
POOR CONVERGENCE - STOP - (SKPB1)
PRESSURE = 0.0000000E+00 IS OUT OF RANGE FOR STREAMLINE = 0 (FINDT)
PROG NOT DIMENSIONED FOR    0   POINTS AND    0   ZONES (XPIL)
PTB( 0)= 0.0000000E+00, DID NOT CONVERGE (PRES)
REACTANT 0 IS NOT IN THERMO DATA (HCALC)
REACTANT TEMPERATURE OUT OF RANGE OF THERMO DATA  (HCALC)
REACTION    0  HAS MASS IMBALANCE OF      0.00000000E+00 (PACK)
REACTION CARDS (REAXIN)
REACTION EXTENDS BEYOND CARD COL 80 (REAXIN)
REGULAR REFLECTION IS NOT POSSIBLE (CNTR12)
REGULAR REFLECTION IS NOT POSSIBLE (CNTR14)
REGULAR REFLECTION IS NOT POSSIBLE (CNTR22)
REGULAR REFLECTION IS NOT POSSIBLE (CNTR24)
REGULAR REFLECTION NOT POSSIBLE (CNTR12)
REGULAR REFLECTION NOT POSSIBLE (CNTR22)
REGULAR REFLECTION NOT POSSIBLE (SHCKA)
REQ AREA RATIO    0      0.00000000E+00   DELETED (ODKINP)
RESTART (EQLBRM)
RIGHT RUNNING SHOCK DETECTED (CNTR31)
RIGHT RUNNING SHOCK DETECTED (CNTR41)
RRS PT IS OUTSIDE THE NOZZLE (CNTR12)
RRS PT IS OUTSIDE THE NOZZLE (CNTR14)
RRS PT IS OUTSIDE THE NOZZLE (CNTR22)
RRS PT IS OUTSIDE THE NOZZLE (CNTR24)
SHOCK DETECTED ON RRC FROM INITIAL LINE (CNTR11)
SHOCK DETECTED ON RRC FROM INITIAL LINE (CNTR21)
SHOCK DETECTED ON RRC FROM INITIAL LINE (CNTR31)
SHOCK-SHOCK INTERSECTION DETECTED- RUN ABORTED (CNTR22)
SHOCK-SHOCK INTERSECTION DETECTED- RUN ABORTED (SHCKA)
SHOCKED GAS (2)--INCIDENT--EQUILIBRIUM (SHCK)
SHOCKED GAS (2)--INCIDENT--FROZEN (SHCK)
SHOCKED GAS (5)--REFLECTED--EQUILIBRIUM (SHCK)
SHOCKED GAS (5)--REFLECTED--FROZEN (SHCK)
SINGULAR MATRIX (EQLBRM)
SINGULARITY, K,A(K,K)    0      0.00000000E+00 (LESK)
SINGULARITY, N,A(N,N)    0      0.00000000E+00 (LESK)
SPECIES      REQUIRES ELEMENT    THIS ELEMENT IS NOT IN ELEMENT TABLE (PACK)
SPECIES NO.   0       NOT CONTAINED IN MASTER EQUILIBRIUM SPECIES TABLE (SEARCH)
SPECIES NOT ON THERMO TAPE (PACK)
SUM OF INPUT MOLE OR MASS FRACTIONS NOT ONE.  THE SUM IS =       0.00000000E+00  NO. SPECIES =  0 (ODKINP)
TEMPERATURE IS OUT OF RANGE OF THE THERMO DATA (SHCK)
THE FOLLOWING CARD WAS IGNORED (REAXIN)
THE REPEAT OPTION SHOULD NOT BE USED WITH A POTENTIAL WALL (PROBLM)
THE SUM OF THE STOICHIOMETRIC COEFFICIENTS FOR THE REACTANTS OR/AND PRODUTS EXCEEDS 10     (PREAX)
THE TEMPERATURE=   IS OUT OF RANGE FOR POINT (EQLBRM)
THIRD BODY REAX RATE RATIOS ENCOUNTERED BEFORE LAST REAX CARD (REAXIN)
TRY REMOVING CONDENSED SPECIES (EQLBRM)
UNEXPECTED END DURING INERTS PROCESSING LAST CARD ENCOUNTERED BEFORE END SPECIFICATION (REAXIN)
WALL TABLE ERROR ON 2ND SPLINE ... (R,X)=    0.00000E+00    0.00000E+00 (WALL)
WALL TABLE ERROR... (R,X)=    0.00000E+00    0.00000E+00 (WALL)
WALL TABLE REQUIRES TOO MANY PTS ON 2ND SPLINE (WALL)
WALL TABLE REQUIRES TOO MANY PTS. (WALL)
WARNING CARD SEQUENCE ERRORS (LTCPHS)
WARNING IN INTEXT, Z1 ZEXIT Z2=  0.0000000E+00 0.0000000E+00 0.0000000E+00 (INTEXT)
WARNING IN RBL, XFIRST = 0.0000000E+00     XI = 0.0000000E+00 (RBL)
WARNING IN RBL, XLAST = 0.0000000E+00     XI = 0.0000000E+00 (RBL)
WARNING, TBL TABLES EXCEED THEIR DIMENSIONS IN OUT1 (OUT1)
WARNING, UNABLE TO POSITION BLM TAPE FOR RESTART (READAT)
WEIGHT FLOW DID NOT CONVERGE (CHAR)
XTEST=0.000000E+00  ERROR IN TCALC, RUN ABORTED (TCALC)
Z OUTSIDE NOZZLE WALL TABLE, Z AND JNOZ ARE      0.00000000E+00    0 (FLU)
Z OUTSIDE PRESSURE TABLE (FLU)
```

TABLE 8-2: ERROR MESSAGES, POSSIBLE CORRECTIVE ACTION

DIAGNOSTIC	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
ALL REACTION RATE RATIOS INPUT AS 1.0	(NF) Informative, no action necessary.	PACK
AN IMPROPER INITIAL LINE POINT IS SOUGHT	Check input of nozzle throat geometry.	ERRORZ
CALCULATIONS WERE STOPPED BECAUSE NEXT POINT IS MORE THAN 50 DEG. BELOW TEMP. RANGE OF A CONDENSED SPECIES	(NF)ØDE frozen calculation can not be continued. No action required.	RØCKET
CONDENSED REACTANTS NOT PERMITTED IN DETN OR SHOCK PROBLEMS	Only gaseous reactants are permitted (see Ref. 3, pg. 70).	ØDES
CONSERVATION EQNS WERE NOT SATISFIED IN 8 ITERATIONS	On detonation option convergence is usually obtained in 3 or 4 iterations (see Ref. 3, pg 70).	DETØN
COULD NOT LOCATE PRES_____ FOR ZONE_____ AND POINT_____ IN ØDK GENERATED TRANSONIC TABLES	Check nozzle throat geometry and the initial line flow MACH number.	GETIL
DID NOT CONVERGE FOR AREA RATIO=_______	(NF) The area ratio is probably too close to 1.0 the usual number of iterations is less than 6. Here it exceeded 10. (see Ref. 3, pg. 71).	RØCKET
DID NOT CONVERGE FOR U1=_____ ANSWERS PROBABLY NOT RELIABLE SOLUTION MAY NOT EXIST	U1 was probably less than the minimum value required for shock to occur (see Ref. 3, pg. 71).	SHCK
DID NOT CONVERGE ON ELECTRON BALANCE	Check input charge balance.	EQLBRM

TABLE 8-2: CONTINUED

DIAGNOSTIC	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
DIMENSIONS IN/SPECIES/TOO SMALL TO CONSIDER	Too many species are possible for the system being input. Use OMIT cards or recompile program dimensions.	SEARCH
ENTIRE TRANSONIC TABLE FILE HAS BEEN READ	Occurs while constructing initial line for the method of characteristics. Check throat geometry.	GETIL
EP NOT REACHED	Refer to section 6.5.3.1 and discussion of EP	MAIN1D
ERRØR DETECTED DURING INPUT PROCESSING	Check input for bad reaction card.	REAXIN
ERRØR DURING LOW T THERMO EVAL, T=____	Low temperature out of range. Check LØW T CPHS input if used (see section 6.1.1).	THERM
ERRØR IN ABOVE CARD. CONTENTS IGNORED	A card is missing, extraneous, or in error (see Ref. 3, pg. 71).	ØDES
ERRØR IN ORDER OF CARDS FOR ____ ____ ____	THERMØ data cards for this species are out of order (see Ref. 3, pg. 71).	TTAPE
ERRØR IN REACTANT CARDS	Chemical symbol not left-justified, or not included in BLØCK DATA program (see Ref. 3, pg. 71).	ØDES
EXIT PLANE OPTION REQUIRES GREATER WALL EXTENSION	Check nozzle wall input, section 6.3.[illegible].	CNTRL

TABLE 8-2: CONTINUED

DIAGNOSTIC	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
FATAL ERRØR ENCOUNTERED WHILE PROCESSING PROBLEM CARD-PROCESSED TO NEXT CASE	Correct bad problem card.	DRIVER
FIND VAR OUTSIDE TABLE	Interpolation was requested outside of the range of the input tables. Check input tables for range of independent variable.	FIND
FRØZEN DID NOT CONVERGE IN 8 ITERATIONS	ØDE could not converge in frozen calculations. If desired add more area and/or pressure ratios (see Ref. 3, pg. 71).	FRØZEN
INCOMPLETE TDK INITIAL LINE HAS BEEN GENERATED	Check $TRANS input, section 6.6.	ERRØRZ
INERT____ NOT IN MASTER SPECIES TABLE	Species not in thermo file, check species name and correct.	SELECT
INERTS FOUND IN TDK PROBLEM, INERTS NOT SPECIFIED, CAN NOT USE RELATIVE SELECTION CRITERION FOR TDK CASE	See section 6.5.3.4 for explanation of species selection.	SELECT
INLET GEOMETRY INCOMPATIBLE WITH INITIAL CONDITIONS	$\sqrt{EC} < 1+(R_u+R_i)\ (1-\cos\theta_i)$ see 5.3.25.	PRES
35 ITERATIONS DID NOT SATISFY CONVERGENCE REQUIREMENTS FOR THE POINT ____	Check output for cause of non-convergence. If not obvious, re-run with intermidiate output (see Ref. 3, pg. 73).	EQLBRM
KIN EXPN CODE DIMENSIONED FOR MAX. OF 40 SPECIES, CURRENT CASE USES____	More than 40 species found. Check input	SELECT
LOW T THERMO EXTENSION AT T=___ DEG-K	(NF) LØW T CPHS input is being used, section 6.1.1.	THERM
LOW TEMPERATURE IMPLIES CONDENSED SPECIES SHOULD HAVE BEEN INCLUDED ON AN INSERT CARD, RESTART	An important condensed species has been omitted causing unrealistically low combustion temperature (see Ref. 3, pg. 72).	EQLBRM
MASS FRACTION SUM NOT 1	$\left\|1-\Sigma c_i\right\| < .01$ the ØDK output subroutine has detected an error in mass conservation.	ØUTPUT

TABLE 8-2: CONTINUED

DIAGNOSTIC	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
MASS OR MOLE FRACTIONS NOT SPECIFIED, MASS FRACTIONS ASSUMED	(NF) Informative - mass or mole fractions not specified on species card.	REAXIN
MORE THAN 12 CHARACTERS SPECIFIED FOR AN INERT SPECIES NAME	Check inert species names (see section 6.5.2.2).	REAXIN
NE DID NOT CONVERGE	Unable to find an expansion coefficient, N_e, when generating ØDK pressure table (see section 5.3.2.5)	PRES
NØ ECRAT SPECIFIED FOR ØDK START-RUN ABORTED	Initial contraction ratio must be input (see section 5.3.2.5).	ØDES
NØ MORE THAN 275 POINTS MAY BE INPUT ON INITIAL LINE	Check input initial line and modify for 275 or less points.	ERRØRZ
NØ $ØDE VALUE GIVEN FOR OF, EQRAT, FA, OR FPCT	Input the desired value as true in $ØDE.	ØDES
NON-NUMERIC ENCOUNTERED IN ECNV WHILE DECODING. . . ____	Fatal error,correct bad number in data field.	ECNV
NOZZLE PWZS COORDINATES NOT MONOTONIC INCREASING AT PT____	Check input of nozzle wall and correct error (see section 6.3.3.1).	PACK
NUMBER OF SPECIES TOO LARGE FOR TABLES, MUST REDIMENSION	The ØDK program allows only 40 species per reaction. If possible omit unimportant species. Check input. If program is to be modified to allow more species various arrays must be redimensioned.	REAXIN
NUMBER OF TEMP VALUES OUTSIDE RANGE	Temperature below range specified in LØW T CPHS input, section 6.1.1.	LTCPHS
PRØG NOT DIMENSIONED FOR ___ POINTS AND ____ ZONES	The maximum number of initial line points (275) and/or mixture ratio zones (50) has been exceeded.	XPIL
PTB (___) =____ DID NOT CONVERGE	Unable to calculate P/P_e vs. area table entry in ØDK. See 5.3.[illegible].	PRES

TABLE 8-2: CONTINUED

DIAGNOSTIC	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
REACTANT ____ IS NOT IN THERMØDATA	Enthalpy can be computed only for those reactants included as reaction species in thermodynamic data (see Ref. 3, pg. 72).	HCALC
REACTANT TEMPERATURE OUT OF RANGE OF THERMØ DATA	Assigned temperature is more than 20% beyond temperature range over which thermodynamic data have been fitted (see Ref. 3, pg. 72).	HCALC
REACTION ____ HAS MASS IMBALANCE OF ____	Fatal error: either stoichiometric coeffients do not match cr a reaction or molecular weight input in-correctly in thermo data.	PACK
REACTION EXTENDS BEYOND CARD COL. 80	Ending comma left out of a reaction card.	REAXIN
SINGULARITY ____	(NF) Numerical singularity in matrix solution of Ax=b. Solution may be in error.	LESK, NESK
SINGULAR MATRIX	Assign a slightly modified equivalence ratio or O/F ratio (see Ref. 3 pg. 73).	EQLBRM
SPECIES NO. ____ ____ NOT CONTAINED IN MASTER EQUILIBRIUM SPECIES TABLE	Check reaction species names against thermo-dynamic data species names.	SELECT
____ SPECIES NOT ON THERMØ TAPE	Check reaction species names against thermo-dynamic data species names.	PACK
SPECIES ____ REQUIRES ELEMENT ____ THIS ELEMENT IS NOT IN ELEMENT TABLE	Check input for misspelled species or element name.	PACK
SUM OF INPUT SPECIES CONCENTRATIONS FOR ABOVE POINTS NOT ONE	If INLINF option was input in $TDK, check input data for MOC initial data line points.	ERRØRZ
SUM OF MOLE FRACTIONS OF SELECTED SPECIES NOT ONE, THEIR SUM IS= ____	See detailed discussion in section 6.5.3.4.	SELECT
TEMPERATURE IS OUT OF RANGE OF THE THERMØ DATA	Converged temperature for a shock problem is beyond TLØW/1.5 > T > 1.25* THIGH. Results may be inaccurate (see Ref. pg. 73).	SHCK

TABLE 8-2: CONTINUED

DIAGNOSTICS	EXPLANATION OR POSSIBLE CORRECTIVE ACTION	SUBROUTINE
THE CALCULATION FOR THE LAST POINT EXCEEDED MAXIMUM ITERATIONS	Check MOC output to see if run is in error. If no input errors are found and run is to be continued either increase IMAX and/or set IMAXF=0 (see 6.7.1).	ERRØRZ
THE FOLLOWING CARD WAS IGNORED _____	(NF) Check this card for error.	REAXIN
THE LRC INSERTION TABLE HAS OVERFLOWED	The calculation has inserted more than 20 left running characteristics. Try more points on the initial line (see section 6.6).	ERRØRZ
THE MAXIMUM NO. OF POINTS FOR A LRC HAS BEEN EXCEEDED	More than 275 points are on the initial data line. Reduce by modifying $TRANS input (see section 6.6).	ERRØRZ
THE PROGRAM IS ATTEMPTING TO INSERT AN EXCESSIVE NUMBER OF FLOWFIELD POINTS	Probable cause is too few points on the initial line upstream of the region being computed. Try more points or a redistirbution of points on the intital line (see section 6.6).	ERRØRZ
THE PROGRAM IS ATTEMPTING TO LOCATE A WALL POINT UPSTREAM OF THE 1ST POINT IN THE WALL TABLE	Check input of intial line (see section 6.6) and nozzle wall (see section 6.3.3.1).	ERRØRZ
THE PROGRAM IS UNABLE TO LOCATE POINT 1 IN SUBROUTINE DSPT	Check input to be sure a value given in XM is not too small. If XM value is < .05, eliminate this zone and adjust mixture ratios.	ERRØRZ
THE PROGRAM IS UNABLE TO LOCATE POINT 1 IN SUBROUTINE INPT	Error in MOC. All $TRANS and $MOC input should be checked.	ERRØRZ
THE TEMPERATURE=_____ IS OUT OF RANGE FOR POINT_____	Converged temperature input on card following THERMØ card is beyond the allowed range: TLØW/1.5 > T > 1.25*THIGH (see Ref. 3, pg. 73).	EQLBRM
THIRD BODY REAX RATE RATIOS BEFORE END OF REAX	LAST REAX card was left out. Check for a mistake in reaction order.	REAXIN
THREE PHASES OF A CONDENSED SPECIES ARE OUT OF ORDER	THERMØ data for condensed species must be in either increasing or decreasing order depending on their temperature intervals (see Table 6-2).	EQLBRM
TRY REMOVING CONDENSED SPECIES	Use ØMIT cards on trace condensed species.	EQLBRM

TABLE 8-2: CONTINUED

DIAGNOSTIC	EXPLANATION OR POSSIBLE OR CORRECTIVE	SUBROUTINE
UNEXPECTED END DURING INERTS PROCESSING LAST CARD ENCOUNTERED BEFORE END SPECIFICATION	Self explanatory, check reaction input.	REAXIN
WALL TABLE VIOLATES INSERTION ANGLE CRITERION	The program calculates wall angles from point to point and prints them and the wall table points. (e.g. see pg 7-29). If the difference of any adjacent slopes exceed DWWI this error is printed. Modify the wall input .	ERRØRZ
WARNING CARD SEQUENCE ERRORS	(NF) Check input LØW T CPHS cards for proper order (see section 6.1.1).	LTCPHS
WEIGHT FLOW DID NOT CONVERGE XMDØT=_____ PEST=_____ WFLØW=_____ ERRØR OF _____ PERCENT	Specified weight flow option. Input value estimated by the program for chamber pressure, PEST, into P(1) of $ØDE and rerun (unless run is obviously in error).	CHAR

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APPENDIX A

REACTION RATE DATA

NOVEMBER 1984

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REACTION RATE DATA

Reactions and reaction rates for determining loss in performance due to chemical kinetics are presented in Reference 1, which is CPIA 246, the JANNAF Rocket Engine Performance and Evaluation Manual (see Section 6.2, titled Reaction Rate Data.) The reactions and reaction rates presented in CPI 246 were revised by Kushida in Reference 2 in 1976. Until the present time, no further revisions have been made.

A literature review through June 1984 has now been carried out by SEA, Inc. The review includes the systems discussed by Kushida, i.e. those containing the elements CHNO and FHN. The result of this study shows almost no change in the CHNO system and minor changes in the FHN system. A revised uncertainty factor, U, is given for each rate coefficient such that k x U and k/U provide probable approximate upper and lower bounds respectively to k for temperatures within the range 250 to 3000 °K.

Tables 1 and 2 give reactions and rates for the CHNO system, and correspond to Tables I and II of Reference 2 except that the species HO_2 and N_2O have been deleted. These species are not considered important for engine performance prediction. Although there are no changes in the rate data, new information regarding some of the reactions have been obtained that suggest a change in the form of the rate expression.

For certain reactions involving the OH radical, in particular the reactions,

$$OH + H_2 = H_2O + H \qquad (1)$$

$$OH + OH = H_2O + O \qquad (2)$$

$$CO + OH = CO_2 + H \qquad (3)$$

The rate data do not conform to an Arrhenius plot[3]. For reaction (3), the experimental results are now numerous and precise enough to confirm the deviation from the Arrhenius form at low and high temperature. The form that fits the data adequately over the temperature range 250-2500 °K is,

$$\log_{10} k = 10.83 + 3.94 \times 10^{-4} T.$$

The present form of the rate data,

$$k = 1.5 \times 10^{7} T^{1.3} \exp (765./RT).$$

is in close agreement with the above expression up to 2000 °K. In addition, it is necessary for use in the existing computer programs.

Tables 3 and 4 give reactions and rates for the FHN system, and correspond to Tables III and IV of Reference 2.

For the two reactions,

$$F + F + M = F_2 + M$$

$$H + F + M = HF + M$$

the rate coefficient expressions are completely different than those listed in Table III of Reference 2. These new expressions give a much higher rate at low temperature, but about the same value in the high temperature range.

As in Reference 2, the tables given here define the rates in the form accepted by the TDK computer program, i.e, the constants A, N, and B are given for the expression

$$k = AT^{-N} e^{-(1000B/RT)}$$; in units of cc, °K, mole, sec.

The reference for each reaction is listed in the tables, e.g. BAULCH 72 is Reference 7. The uncertainty estimate is also given; e.g. 30 U is an uncertainty factor of 30.

TABLE 1. Reaction Rate Data for the CHON System:

For Chemical Reactions between species, CO, CO_2, H, H_2, H_2O, N, NO, N_2, O, OH, and O_2 in initial equilibrium expanding through an adiabatic nozzle.

$k = A\,T^{-N} \exp(-1000B/RT)$; in units of cc,°K,mole,sec.

REACTIONS

$H + H = H_2$	A = 6.4E17,	N = 1.0,	B = 0.0 ,	M = AR,	BAULCH 72	(A)	30U
$H + OH = H_2O$	A = 8.4E21,	N = 2.0,	B = 0.0 ,	M = AR,	BAULCH 72	(A)	10U
$O + O = O_2$	A = 1.9E13,	N = 0.0,	B =-1.79 ,	M = AR,	BAULCH 76	(A)	10U
$N + O = NO$	A = 6.4E16,	N = 0.5,	B = 0.0 ,	M = N2,	BAULCH 73	(C)	10U
$N + N = N_2$	A = 3.0E14,	N = 0.0,	B = -.99 ,	M = N2,	BAULCH 73	(C)	10U
$CO + O = CO_2$	A = 1.0E14,	N = 0.0,	B = 0.0 ,	M = AR,	BAULCH 76	(B)	30U
$O + H = OH$	A = 3.62E18,	N = 1.0,	B = 0.0. ,	M = AR,	JENSEN 78	(B)	30U

END TBR REAX

$O_2 + H = O + OH$	A = 2.2E14,	N = 0.0,	B = 16.8 ,	BAULCH 72	(A)	1.5U
$H_2 + O = H + OH$	A = 1.8E10,	N =-1. ,	B = 8.9 ,	BAULCH 72	(A)	1.5U
$H_2 + OH = H_2O + H$,	A = 2.2E13,	N = 0.0,	B = 5.15,	BAULCH 72	(A)	2 U
$OH + OH = H_2O + O$,	A = 6.3E12,	N = 0.0,	B = 1.0,	BAULCH 72	(A)	3 U
$CO + OH = CO_2 + H$,	A = 1.5E7 ,	N =-1.3,	B =-.765,	BAULCH 74	(A)	3 U
$N_2 + O = NO + N$	A = 7.6E13,	N = 0.0,	B = 75.5,	BAULCH 73	(C)	3 U
$O_2 + N = NO + O$	A = 6.4E9 ,	N =-1.0,	B = 6.25,	BAULCH 73	(C)	2 U
$CO + O = CO_2$	A = 2.5E6 ,	N = 0.0,	B = 3.18,	BAULCH 76	(B)	2 U
$CO_2 + O = CO + O_2$,	A = 1.7E13,	N = 0.0,	B = 52.7,	BAULCH 76	(B)	3 U

LAST REAX

TABLE 2. Third Body Recombination Efficiency Ratio for CHON System:
(as recommended by Kushida, Reference 2)

Species	H + H	H + OH	O + O	N + O	N + N	CO + O	O + H
AR	1.	1.	1.	.8	1.	1.	1.
CO	1.5	3.	4.	1.	1.	1.	4.
CO_2	6.4	4.	8.	3.	2.	5.	5.
H	25.	12.5	12.5	10.	10.	1.	12.5
H_2	4.	5.	5.	2.	2.	1.	5.
H_2O	10.	17.	5.	7.	3.	1.	5.
N	1.	1.	10.	10.	10.	1.	1.
NO	1.5	3.	4.	1.	1.	1.	4.
N_2	1.5	3.	4.	1.	1.	2.	4.
O	25.	12.5	12.5	10.	10.	1.	12.5
OH	25.	12.5	12.5	10.	10.	1.	12.5
O_2	1.5	6.	11.	1.	1.	25.	5.

TABLE 3. Recommended Reaction Data (HFN System): For chemcial reactions between species F, F_2, H, HF, H_2, N, and N_2 in initial equilibrium expand through an adiabatic nozzle.

$k = AT^{-N} e^{(-1000B/RT)}$; in units of cc, °K, mole, sec.

REACTIONS:

$H + H = H_2$, A = 6.4E17, N = 1.0, B = 0. , BAULCH 72, M= AR (A) 30 U

$F + F = F_2$, A = 3.25E8, N =-1.0, B =-6.38, BAULCH 81, M = AR (A) 10 U

$H + F = HF$, A = 7.5E12, N = 0.0, B =-35.13, BAULCH 81, M = AR (A) 30 U

$N + N = N_2$, A = 3.0E14, N = 0.0, B = -.99, BAULCH 73, M = N_2 (A) 10 U

END TBR REAX

$F + H_2 = HF + H$, A = 9.2E13, N = 0.0 B = 1.08, FOON 75 , (A) 30 U

$H + F_2 = HF + F$, A = 8.8E13, N = 0.0, B = 2.40, BAULCH 81, (A) 10 U

LAST REAX

TABLE 4. Third Body Reaction Rate Ratios (H F N System)

(as recommended by Kushida, Reference 2)

REACTION		H + H	F + F	H + F	N + N
SPECIES	H_2,	4.	1.	8.	2.
SPECIES	F_2,	1.	2.4	1.	1.
SPECIES	HF,	2.	1.	2.	1.
SPECIES	N_2,	1.5	1.	2.8	1.
SPECIES	N ,	1.	1.	1.	10.
SPECIES	F ,	4.	2.4	4.	1.
SPECIES	H ,	25.	1.	20.	10.

Other Elemental Systems

Consideration was given to expanding the reaction set of Reference 2 to other elemental systems. Tables 5 and 6 have been prepared to indicate liquid propellant rocket engine systems of possible interest. This approach leads to 11 combinations of the elements C, $C\ell$, F, H, N, and O, which are listed alphabetically in Table 6. Sets 3, 4, 7, 8, 10, and 11 are covered by the reactions presented in Tables 1 through 4. There is presently a lack interest the oxidizer/fuel combinations that require sets 1, 2, 5, 6, and 9. However, screening studies, such as References 4, 5, and 6, have indicated the species and reactions that control these systems. The additional species required are: $C\ell$, $C\ell_2$, $C\ell F$, $HC\ell$. The additional reactions required are presented in Table 7.

Many of the rates given in Table 7 are estimates rather than measured values. The reaction set given in Table 7 must be considered preliminary.

The reaction numbers used in Reference 1 are indicated in Table 7. For example, the first three reactions in Table 7 are the reactions numbered 13, 12, and 11 in Reference 1.

Good measured data are now available for the $C\ell$ + $C\ell$ recombination reaction. The reaction rate for the reaction $H + C\ell + M = HC\ell + M$ is obtained from the data for the reverse reaction and the equilibrium constant. The third body efficiencies for the reactions listed in Table 7 are given in Table 8. For the reaction $C\ell + C\ell + M = C\ell_2 + M$ with $M = C\ell_2$ an efficiency ratio of about 5 is reported from 4 sets of experiments. A value of unity is used for the other third body efficiencies because of a lack of data.

Measured data was found for reactions 29 and 31 of Reference 1. Reaction 30 of Reference 1, i.e.

$$H_2 + C\ell_2 = HC\ell + HC\ell$$

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Table 5. Oxidizers and Fuels for Liquid Rocket Propellants Containing Elements C, Cl, F, H, N, O

Oxidizers Containing Elements Cl, F, H, N, O Formula, Name	Fuels Containing Elements C, H, N Formula, Name
ClF_3, Chlorine Trifluoride	CH_4, Methane
ClO_3F, Perchloryl Flouride	C_2H_2, Acetylene
F_2, Flourine	C_2H_4, Ethylene
HNO_3, Nitric Acid	C_2H_6, Ethane
N_2O_4, Nitrogen Tetroxide	C_3H_8, Propane
O_2, Oxygen	C_7H_{16}, Heptane
OF_2, Oxygen Difluoride	$(CH_2)_n$, RP-1 or JP-4
	CH_6N_2, Monomethyl - Hydrazine
	$C_2H_8N_2$, Unsymmetrical Dimethyl - Hydrazine (UDMH)
	H_2, Hydrogen
	NH_3, Ammonia
	N_2H_4, Hydrazine

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Table 6. Elemental Compositions for Oxidizer/Fuel Combinations used in Liquid Rocket Engines

	Elemental Composition	Example Propellants
1.	C, F, H, N	F_2/CH_6N_2, $F_2/C_2H_8N_2$
2.	C, F, H, N, O	$OF_2/N_2H_4-C_2H_8N_2$
3.	C, H, O	O_2/RP-1, O_2/CH_4, O_2/C_3H_8
4.	C, H, N, O	N_2O_4/CH_6N_2, $N_2O_4/C_2H_8N_2$
5.	Cl, F, H, N	ClF_3/N_2H_4
6.	Cl, F, H, N, O	ClO_3F/N_2H_4
7.	F, H	F_2/H_2
8.	F, H, N	F_2/N_2H_4
9.	F, H, N, O	OF_2/N_2H_4
10.	H, N, O	N_2O_4/N_2H_4
11.	H, O	O_2/H_2

was deleted as unimportant. Reactions 11, 32, 33, 34, 35, 36, 37, 38, 39, 40, 52, and 53 with their estimated rates, were taken from Reference 1.

There are some scattered data reported for the reactions 32, 33, and 34, i.e.

$HCl + F = Cl + HF$
$Cl_3 + F = Cl + ClF$
$Cl + F_2 = F + ClF$

These data are within a factor of 10 of the estimated values. No other data was found for these reactions.

Two reactions were added to the system that did not appear in Reference 1, but are believed to be important (for example see References 4, 5, and 6). Measured data is available for these reactions, which are:

$Cl + OH = HCl + O$

and

$HCl + OH = H_2O + Cl.$

TABLE 7. Additional Chemical Reactions of Importance in C, Cℓ, F, H, N, O Systems

$k = AT^{-N}e^{(-1000B/RT)}$;in units of cc,°K,mole,sec.

REACTIONS

Cl + Cl = Cl_2,	A = 2.23E14 ,	N=0 ,	B=-1.81,	M = AR	13/BAULCH 81	10U
H + Cl = HCl,	A = 2.6E13 ,	N=0 ,	B=-19.9,	M = AR	12/BAULCH 81	5U
Cl + F = ClF,	A = 3. E16 ,	N=.5 ,	B= 0,	M = AVE	11/CPIA246	25U

END TBR REAX

Cl_2 + H = HCl + Cl,	A= 8.6E13,	N=0 ,	B = 1.2 ,	29/BAULCH 81	10U
Cl + H_2 = HCl + H ,	A= 1.45E13,	N=0 ,	B = 4.4 ,	31/BAULCH 81	10U
HCl+ F = HF + Cl,	A= 1.9E12 ,	N=-.68,	B = .6 ,	32/CPIA246,	25U
Cl_2+ F = Cl + ClF,	A= 6.2E12 ,	N=-.68,	B = .5 ,	33/CPIA246,	25U
Cl + F_2 = F + ClF,	A= 7.6E12,	N=-.68,	B= .3 ,	34/CPIA246,	25U
ClF+ H = HF + Cl,	A= 1.8E12,	N=-.58,	B= 3.2 ,	35/CPIA246,	25U
ClF+ H = HCl + F,	A= 5.6E12,	N=-.68,	B= 1.9 ,	36/CPIA246,	25U
ClF+ H_2 = HCl + HF,	A= 1.8E10,	N=- .5,	B=46.34 ,	37/CPIA246	1000U
F_2 + HCl= HF + ClF,	A= 1.8E10,	N=- .5,	B=39.43 ,	38/CPIA246	1000U
ClF+ HCl= HF + Cl_2,	A= 1.8E10,	N=- .5,	B=46.03 ,	39/CPIA246	1000U
F_2 + Cl_2= ClF + ClF,	A= 1.8E10,	N=- .5,	B=26.76 ,	40/CPIA246	1000U
OH + F = HF + O ,	A= 2.9E12,	N=-.68,	B= .2 ,	52/CPIA246	25U
H_2O+ F = HF + OH ,	A= 1.4E10,	N=-.68,	B= .6 ,	53/CPIA246	25U
Cl +OH = HCl + O ,	A= 5.9E12,	N= 0 ,	B= 5.72 ,	BAULCH 81	10U
HCl+OH = H_2O+Cl ,	A= 2.25E12,	N= 0 ,	B= 1.02 ,	BAULCH 81	10U

LAST REAX

TABLE 8. Third Body Reaction Rate Ratio

REACTION		H + Cl	Cl + Cl
SPECIES	Ar	1	1
SPECIES	HCl	1	1
SPECIES	Cl_2	1	5
SPECIES	Cl	1	1

APPENDIX A -- REFERENCES

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