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A PROGRAM FOR CALCULATING EXPANSION-TUBE FLOW QUANTITIES FOR REAL-GAS MIXTURES AND COMPARISON WITH EXPERIMENTAL RESULTS

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16. Abstract

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SUMMARY

A computer program written in FORTRAN IV language is presented which determines expansion-tube flow quantities for real test gases CO_2, N_2, O_2, Ar, He, and H_2, or mixtures of these gases, in thermochemical equilibrium. The effects of dissociation and first and second ionization are included. Flow quantities behind the incident shock into the quiescent test gas are determined from the pressure and temperature of the quiescent test gas in conjunction with (1) incident-shock velocity, (2) static pressure immediately behind the incident shock, or (3) pressure and temperature of the driver gas (imperfect hydrogen or helium). The effect of the possible existence of a shock reflection at the secondary diaphragm of the expansion tube is included. Expansion-tube test-section flow conditions are obtained by performing an isentropic unsteady expansion from the conditions behind the incident shock or reflected shock to either the test-region velocity or the static pressure. Both a thermochemical-equilibrium expansion and a frozen expansion are included. Flow conditions immediately behind the bow shock of a model positioned at the test section are also determined. Results from the program are compared with preliminary experimental data obtained in the Langley 6-inch expansion tube.

A listing of the program is presented along with a description of required inputs, a flow chart, and sample data printouts. Some typical solutions are presented for CO_2, Ar, and air and for Mars, Venus, and Jovian atmospheric models.

INTRODUCTION

Several experimental studies to be performed in the Langley 6-inch expansion tube will use various gas mixtures as test media at hypersonic conditions. Before such studies are performed, it is essential to ascertain the theoretical performance of the expansion tube for the gas mixture being tested. The wide range of flow conditions and the very short test times of the expansion tube impose rather stringent requirements on facility instrumentation. Thus, in preparing the facility for a test, it is necessary that the magnitude of the physical quantities to be measured be known to within reasonable limits.

Following a test, it is desirable to have convenient means for determining expansion-tube flow quantities from the measured flow quantities.

Relatively little effort has been directed towards the calculation of expansion-tube flow quantities for arbitrary gas mixtures. One such study, reported in reference 1, is basically a shock-tube program which can generate expansion-tube flow conditions. However, several effects which may markedly alter calculated flow quantities are not included in the program of reference 1. Also, the program of reference 1 requires inputs other than the actual flow quantities measured during a test.

A primary purpose of the present study is to fulfill the need for a convenient, versatile program for determining expansion-tube flow quantities in real gases CO_2, N_2, O_2, Ar, He, and H_2 or mixtures of these gases from several combinations of routinely measured flow quantities. Included in this program are the effect (ref. 2) of an imperfect (intermolecular force) driver gas (helium or hydrogen), the possible existence of a shock reflection at the secondary diaphragm (ref. 3), and the calculation of both a thermochemical-equilibrium expansion and a frozen expansion. Flow quantities immediately behind the bow shock of a test model, including stagnation-point heat-transfer rate, are calculated.

SYMBOLS

The International System of Units (SI) is used for all physical quantities in the present study. Conversion factors relating SI Units to U.S. Customary Units are given in reference 4.

a	speed of sound, m/sec
B	second virial coefficient, m^3/kg
C	third virial coefficient, $(m^3/kg)^2$
c_pW_o/R	nondimensional specific heat at constant pressure
c_vW_o/R	nondimensional specific heat at constant volume
h	specific enthalpy, m^2/sec^2 (J/kg)
h_o	standard heat of formation at $T = 0$ K, J/kmol
M	Mach number, U/a

M_s	incident-shock Mach number, U_s/a
N_{Re}	Reynolds number per meter, $\rho U/\mu$
p	pressure, N/m^2
$\dot{q}$	heat-transfer rate, W/m^2
R	universal gas constant, 8.31434 kJ/kmol-K
r	nose radius, m
sW_o/R	nondimensional specific entropy
T	temperature, K
U	velocity, m/sec
U_s	velocity of incident shock, m/sec
W	molecular weight, kg/kmol
W_o	molecular weight of undissociated gas or gas mixture, kg/kmol
X_i	mole fraction, kmol of species i per kmol of mixture
Y_i	number of kmoles of species i per mass of mixture, kmol of species i per kg of mixture
Z	compressibility factor, $pW_o/\rho RT$
Z^*	number of kmoles of dissociated gas mixture per number of kmoles of undissociated gas mixture, W_o/W
γ	ratio of specific heats
γ_E	isentropic exponent, $\left(\frac{\partial \log p}{\partial \log \rho}\right)_{sW_o/R}$
η_i	parameter defined in equation (25), $kg/m^{3/2}\text{-sec-}(N/m^2)^{1/2}$

μ	viscosity, N-sec/m^2
ρ	density, kg/m^3

Subscripts:

A	denotes region ② for no standing shock at secondary diaphragm or region (2,s) for a standing shock
act	active or available
f	frozen
i	individual species
mix	mixture
perf	perfect-gas behavior
ref	reference state
w	model-wall conditions
1	state of quiescent test gas in front of incident normal shock
2	state of test gas behind incident normal shock in intermediate section
2,s	state of test gas behind shock at secondary diaphragm
3	state of expanded driver gas
4	driver-gas conditions at time of primary-diaphragm rupture
5	state of test gas flow in acceleration section (free-stream conditions)
5,s	static conditions behind bow shock of model positioned at expansion-tube test section
5,t	stagnation conditions behind bow shock of model positioned at expansion-tube test section

10 state of quiescent acceleration gas in front of incident normal shock

20 state of acceleration gas behind incident normal shock in acceleration section

Approximate value is denoted by superscript ~.

ANALYSIS AND PROCEDURE

Before the procedures for determining expansion-tube flow quantities are discussed, a brief description of the Langley 6-inch expansion tube and its operating sequence is given. This facility is basically a cylindrical tube, having a 15.24-cm inside diameter, divided by two diaphragms into three sections (fig. 1(a)). The most-upstream section is the driver or high-pressure section. This section is pressurized at ambient temperature with a gas having a high speed of sound, such as hydrogen or helium. (Greater operation efficiency is realized with gases having high speed of sound.) The pressure and speed of sound of the driver gas may be increased further by heating the gas with a 3-MW resistance heater or by utilizing an arc discharge into the gas from a 10-MJ capacitor bank. The intermediate section is usually referred to as the driven section. This section is evacuated and then filled with the test gas at ambient temperature. The most-downstream section is denoted as the acceleration or expansion section. This section is also evacuated and is generally filled with helium at a low pressure and at ambient temperature. For unheated or resistance heating of the driver gas, the driver and driven sections are separated by a double-diaphragm apparatus capable of withstanding a maximum pressure differential of 68.95 MN/m^2. (By controlling the pressure level in the small chamber between these diaphragms, the time of diaphragm rupture can be controlled.) For arc heating, a single diaphragm is used between the driver and driven sections. A weak, low-pressure diaphragm (secondary diaphragm) separates the driven and acceleration sections. The test section and the model are located at the downstream exit of the acceleration section.

The operating sequence, which is shown schematically in figure 1(a), begins with the rupture of the primary or high-pressure diaphragm. A primary shock wave propagates into the static test gas and an expansion wave propagates into the driver gas. The shock wave then encounters and ruptures the secondary or low-pressure diaphragm. The flow energy lost in rupturing this diaphragm results in an upstream-facing shock wave reflected from the diaphragm (ref. 3). This is shown schematically in figure 1(b). A secondary shock wave propagates into the low-pressure acceleration gas while an upstream-expansion wave moves into the test gas. In passing through this upstream-expansion wave, which is being washed downstream since the shock-heated test gas is supersonic, the test gas undergoes an isentropic unsteady expansion resulting in an increase in the flow velocity (ref. 5). Testing takes place in the flow that has passed through the expansion. This test region is denoted as region ⑤ in figure 1.

Determining Flow Quantities in Region ②

The first step in determining expansion-tube flow conditions is to calculate the flow quantities in region ② (fig. 1). In the Langley 6-inch expansion tube, the quiescent-test-gas pressure p_1 and temperature T_1 (ambient) are known, as is the test-gas composition X_i. The incident-shock velocity $U_{s,1}$ is routinely inferred from microwave measurements and from the response of instrumentation spaced at known intervals along the driven section, and the pressure behind the incident normal shock in the intermediate section p_2 is measured directly. The flow quantities in region ② may be determined by using either $U_{s,1}$ or p_2 as an input, in conjunction with p_1, T_1, and X_i. Also considered is the case where p_4 and T_4 are known for the hydrogen or helium driver gas and are used in conjunction with p_1, T_1, and X_i.

The basic equations required in determining flow quantities in region ② are the conservation relations for mass, momentum, and energy for a normal shock moving through region ①, which are

$$\rho_1 U_{s,1} = \rho_2 \left(U_{s,1} - U_2\right) \tag{1}$$

$$p_1 + \rho_1 U_{s,1}^2 = p_2 + \rho_2 \left(U_{s,1} - U_2\right)^2 \tag{2}$$

$$h_1 + \frac{1}{2} U_{s,1}^2 = h_2 + \frac{1}{2}\left(U_{s,1} - U_2\right)^2 \tag{3}$$

and the equation of state (that is, source of thermodynamic properties for real-gas mixtures). Thermodynamic properties for CO_2, N_2, O_2, Ar, He, and H_2 gases or mixtures of these gases in thermochemical equilibrium are obtained by the procedure of references 6 and 7. The procedure of references 6 and 7 is included in the present study as a subroutine and is referred to herein as ROGO. An iterative-interpolation scheme which enables determination of thermodynamic properties from ROGO, for input combinations of h, p, sW_o/R, and ρ, is also a subroutine and is referred to herein as FIND (I). (See appendix A for a detailed discussion of the source of thermodynamic and transport properties for the arbitrary gas mixtures used in the present study.)

Since p_1 and T_1 are known, the corresponding thermodynamic quantities in region ① (that is, ρ_1 and h_1) appearing on the left sides of equations (1) to (3) are obtained from the perfect-gas relations

$$\rho_1 = \frac{p_1 W_o}{RT_1} \tag{4}$$

and

$$h_1 = \frac{\gamma_1}{\gamma_1 - 1}\frac{R}{W_o}T_1 + \sum_i \frac{X_{i,1}h_{o,i}}{W_o} \tag{5}$$

The corresponding a_1 is obtained from the relation

$$a_1 = \left(\gamma_1 \frac{R}{W_o} T_1\right)^{1/2} \tag{6}$$

where

$$\gamma_1 = \frac{\sum_i X_{i,1}\left(\frac{c_p W_o}{R}\right)_i}{\sum_i X_{i,1}\left(\frac{c_v W_o}{R}\right)_i} \tag{7}$$

For the Langley 6-inch expansion tube, T_1 is the ambient temperature and p_1 is generally less than 1.0 MN/m^2. For these conditions, imperfect-gas effects are negligible. The iterative procedures for determining the quantities in region ② from equations (1) to (3) for inputs $U_{s,1}$, p_2, and p_4 and T_4 are now discussed individually. For all three cases, the flow in region ② is assumed to be in thermochemical equilibrium.

Case where $U_{s,1}$ is known.- When $U_{s,1}$ is known, the terms appearing on the left sides of equations (1) to (3) are known. An initial estimate of $\rho_2 = 10\rho_1$ is made and the corresponding values of U_2, p_2, and h_2 are obtained. The p_2 and h_2 are used as inputs to FIND (2) to obtain a value of ρ_2. This ρ_2 from FIND (2) is compared with the initial guess of ρ_2 and, if it is not within 0.1 percent, the ρ_2 from FIND (2) is used in equations (1) to (3) to obtain upgraded values of U_2, p_2, and h_2. This iterative procedure, commonly referred to as the method of successive approximations, is continued until successive values of ρ_2 are within 0.1 percent.

Case where p_2 is known.- When p_2 is known, an initial estimate of ρ_2 is made. The corresponding $U_{s,1}$ is obtained from equations (1) and (2) in the form

$$U_{s,1} = \left[\frac{p_2 - p_1}{\rho_1\left(1 - \frac{\rho_1}{\rho_2}\right)}\right]^{1/2} \tag{8}$$

U_2 is found from equation (1), and h_2 is found from equation (3). The p_2 and h_2 are used in FIND (2) to obtain a corresponding value of ρ_2. The method of successive approximations is employed on ρ_2 until successive values are within 0.1 percent.

<u>Case where p_4 and T_4 are known.</u>- The thermodynamic properties in region ④ are determined from the imperfect-gas relations of appendix B. The unsteady expansion which occurs from region ④ to region ③ (fig. 1(a)) upon rupture of the primary diaphragm is assumed to be isentropic. An array of thermodynamic properties p, h, Z, a, and ρ is generated in region ③ by varying T_3 from a maximum value (T_4) to a minimum value and by knowing s_3W_3/R $(s_3W_3/R = s_4W_4/R)$. The U_3 corresponding to each value of T_3 is obtained by using the differential equation for a one-dimensional, unsteady expansion. Across an upstream-facing unsteady-expansion wave, the velocity increment is related to the thermodynamic properties by the differential equation (ref. 5)

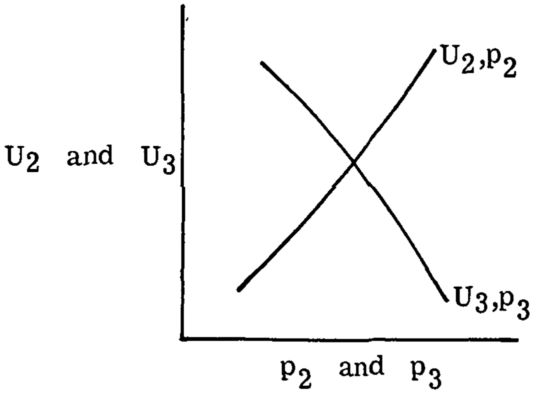
$$dU = -\left(\frac{dh}{a}\right)_{sW_0/R} \tag{9}$$

Integrating equation (9) between regions ③ and ④ gives

$$U_3 = -\int_{h_4}^{h_3}\left(\frac{dh}{a}\right)_{s_4W_4/R} \tag{10}$$

where U_4 is zero. The U_3 is found by performing the integration of equation (10) numerically. Thus, a unique correspondence between U_3 and p_3 at constant s_4W_4/R is obtained.

By varying $U_{s,1}$ over a range, an array of U_2 and p_2 may also be obtained. A solution is found by requiring that p_3 equal p_2 and U_3 equal U_2, as is illustrated in the sketch



The solution is the intersection of the U_2,p_2 curve and the U_3,p_3 curve. The other thermodynamic properties in region ② are obtained from ROGO, where T_2 is obtained by interpolation and $U_{s,1}$ is determined from equation (1).

Determining Flow Quantities in Region (2,s)

As discussed in references 3 and 8, the flow energy lost in the rupture of the secondary diaphragm must result in an upstream-facing shock wave reflected from the diaphragm. In reference 9, this shock-wave reflection is observed to be, for a short period of time, approximately a standing wave, as illustrated in figure 1(b). Therefore, the possible existence of a standing normal shock at the secondary diaphragm, due to shock-wave reflection from this diaphragm, is considered. The conservation relations for this standing shock are

$$\rho_2 U_2 = \rho_{2,s} U_{2,s} \tag{11}$$

$$p_2 + \rho_2 U_2^{\,2} = p_{2,s} + \rho_{2,s} U_{2,s}^{\,2} \tag{12}$$

and

$$h_2 + \frac{1}{2} U_2^{\,2} = h_{2,s} + \frac{1}{2} U_{2,s}^{\,2} \tag{13}$$

Since the quantities in region ② are known (that is, have been calculated previously), equations (11) to (13) are solved by the method of successive approximations to yield the quantities behind the standing normal shock (that is, flow quantities in region (2,s)). As in region ②, the flow in region (2,s) is assumed to be in thermochemical equilibrium.

Determining Flow Quantities in Region ⑤

Upon rupture of the secondary diaphragm, an upstream-expansion wave moves into the test gas. In passing through this upstream-expansion wave, the test gas undergoes an isentropic, unsteady expansion to region ⑤. Integrating equation (9) between regions Ⓐ and ⑤ (where region Ⓐ denotes region ② for no standing shock at the secondary diaphragm or region (2,s) for a standing shock and where the conditions are as yet unknown in region ⑤) gives

$$\Delta U = U_5 - U_A = -\int_{h_A}^{h_5} \left(\frac{dh}{a}\right)_{s_A} W_o/R \tag{14}$$

Since p_5 and U_5 are measured in the Langley 6-inch expansion tube, both quantities are considered, individually, as inputs necessary for the solution of equation (14). As is typical of high-enthalpy facilities, the assumption of thermochemical-equilibrium flow is subject to question. Hence, both equilibrium-flow and frozen-flow cases are considered in the present program.

Thermochemical-equilibrium unsteady expansion.- If the case where U_5 is an input is considered first, then ΔU of equation (14) is known. The expansion in velocity from region Ⓐ to region ⑤ corresponds to a decrease in pressure p between these regions. Thus, with $s_A W_o/R$ and a range of p from an upper limit of p_A to a lower limit of $p_{5,f}$ (calculation of $p_{5,f}$ is discussed subsequently), FIND (3) is used to generate a plot of 1/a against h for the real-gas mixture. The temperature limits, as required by FIND (I), used in generating this plot are T_A as an upper limit and $T_{5,f}$ as a lower limit. Equation (14) is integrated numerically (Simpson's rule) between the known limit h_A and the unknown limit h_5. The h_5 is the value of h which equates the integral of equation (14) to ΔU. The corresponding p_5 and T_5 are obtained by interpolation and the other thermodynamic quantities in region ⑤ are obtained from ROGO.

For the case of an equilibrium expansion where p_5 is an input, $s_A W_o/R$ and p_5 are used as inputs in FIND (3) to obtain the corresponding thermodynamic properties in region ⑤. With the limits of integration known, the integral of equation (14) is evaluated numerically. Once a value for ΔU is obtained and with U_A known, U_5 may be found. Additional free-stream (region ⑤) quantities that are calculated are $M_5 = U_5/a_5$ and $N_{Re,5} = \rho_5 U_5/\mu_5$.

Frozen unsteady expansion.- Frozen flow is defined herein as that in which the vibrational energy and chemistry remain unchanged during the expansion process. In the present program, this freezing of the vibrational energy and chemistry is assumed to occur in region Ⓐ. Hence the energy in region Ⓐ may be viewed as consisting of an active or available part, which provides the energy for flow expansion, and a frozen or nonavailable part. In the frozen expansion, γ_f remains constant and the test-gas mixture behaves as a perfect gas. By using the perfect-gas relation

$$dh = \frac{2}{\gamma_f - 1} a \, da \tag{15}$$

equation (14) may be evaluated in closed form to yield

$$U_{5,f} - U_A = \frac{2}{\gamma_f - 1}\left(a_{A,f} - a_{5,f}\right) \tag{16}$$

By freezing (that is, maintaining constant) the vibrational energy, $c_p W_o/R$ becomes 7/2 for a diatomic molecule and 9/2 for a triatomic molecule. The $c_p W_o/R$ for an atom is 5/2. By using the perfect-gas relation

$$\frac{c_v W_o}{R} = \frac{c_p W_o}{R} - 1 \tag{17}$$

the specific-heat ratio γ_f is obtained from equation (7) as

$$\gamma_f = \frac{\sum_i X_{i,A}\left(\frac{c_p W_o}{R}\right)_i}{\sum_i X_{i,A}\left(\frac{c_v W_o}{R}\right)_i}$$

The speed of sound in region Ⓐ is determined from the relation

$$a_{A,f} = \left(\gamma_f \frac{R}{W_o} Z^*{}_A T_A\right)^{1/2} \tag{18}$$

and the active enthalpy is determined from the relation

$$h_{A,act} = \frac{a_{A,f}{}^2}{\gamma_f - 1} + \frac{\sum_i X_{i,A} h_{o,i}}{W_o} \tag{19}$$

Ionized species in region Ⓐ are not included in the calculation of $h_{A,act}$ from equation (19). The values of h_o for species N, N_2, O, O_2, NO, C, CO, CO_2, and Ar are given in reference 6 and those for He, H, and H_2 are obtained from reference 10. The enthalpy is given by the relation

$$h_{A,f} = h_A - h_{A,act} \tag{20}$$

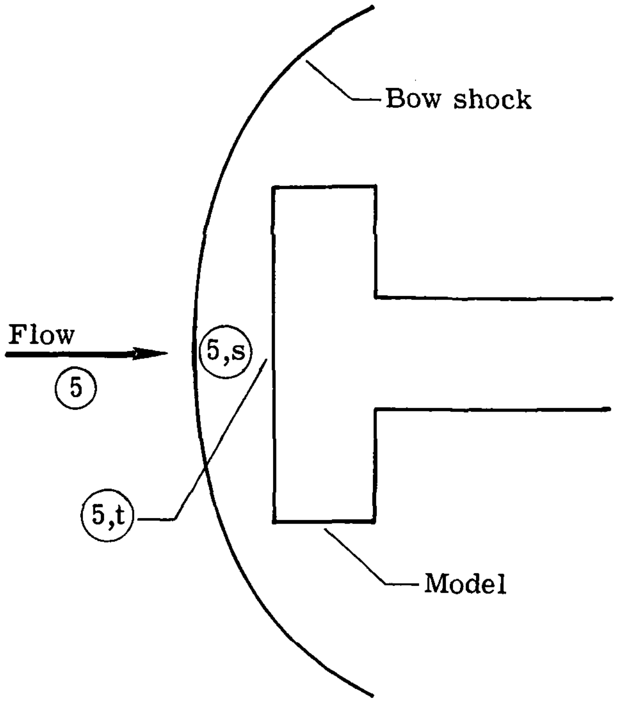
For the case where U_5 $\left(\text{that is, } U_{5,f}\right)$ is known, $a_{5,f}$ may be found from equation (16) and the corresponding frozen-flow thermodynamic quantities in region ⑤ are determined from the isentropic perfect-gas relations of reference 11. For the case where p_5 $\left(\text{that is, } p_{5,f}\right)$ is known, $a_{5,f}$ is determined from the isentropic perfect-gas relation

$$a_{5,f} = a_{A,f}\left(\frac{p_{5,f}}{p_A}\right)^{\gamma_f - 1/2\gamma_f} \tag{21}$$

Corresponding frozen-flow quantities in region ⑤ are determined similarly, and with $a_{5,f}$ known, $U_{5,f}$ may be obtained from equation (16).

Determining Flow Quantities Behind Bow Shock of Test Model

In most tests in the Langley 6-inch expansion tube, a test model (for example, a pitot probe) is positioned at the test section (tube exit). Hence, it is desirable to determine the flow quantities behind the bow shock in front of a blunt test model. In the present study, flow quantities are calculated for the static conditions immediately behind the portion of the bow shock that is essentially a standing normal shock (region (5,s)) and for the stagnation conditions (point (5,t)). These conditions are illustrated in the following sketch:



The conservation relations for a standing normal shock about a blunt body in the expansion-tube test section are given in equations (11) to (13) where the subscripts 2 and 2,s are now replaced by 5 and 5,s. In the present study three combinations concerning the flow chemistry in the free-stream region (region ⑤) and the post-normal-shock region (region (5,s) and point (5,t)) are considered. These combinations are designated cases (1) to (3) as follows:

Case	Region ⑤	Region (5,s) and point (5,t)
(1)	Equilibrium	Equilibrium
(2)	Frozen	Equilibrium
(3)	Frozen	Frozen

For case (1) or (2), where post-normal-shock flow conditions are assumed to be in thermochemical equilibrium and free-stream conditions are either in thermochemical equilibrium or frozen, the conservation relations are solved by iteration for the static conditions immediately behind the shock. In this solution, the flow quantities in region ⑤ are considered known and the initial estimate of $\rho_{5,s}$ is taken to be $10\rho_5$. For the post-normal-shock stagnation conditions, solutions are found by assuming that the flow region from immediately behind the normal shock to the stagnation point is isentropic (that is, $s_{5,t}W_o/R = s_{5,s}W_o/R$). Now, the variations in conditions from immediately downstream of the shock to the stagnation point are relatively small (that is, $\gamma_{E,5,s} \approx \gamma_{E,5,t}$ and $Z^*_{5,s} \approx Z^*_{5,t}$). Thus, the gas in this region may be considered to behave as a perfect gas. The $p_{5,t}$ can be accurately determined from the perfect-gas isentropic relation (ref. 11)

$$p_{5,t} = p_{5,s}\left(1 + \frac{\gamma_{E,5,s} - 1}{2} M_{5,s}^2\right)^{\frac{\gamma_{E,5,s}}{\gamma_{E,5,s} - 1}} \tag{22}$$

Now, for case (1), $h_{5,t}$ is determined from the energy relation (eq. (13)) to be

$$h_{5,t} = h_5 + \frac{1}{2}U_5^2 \tag{23}$$

whereas, for case (2), the energy equation becomes

$$h_{5,t} = h_{5,s} + \frac{1}{2} U_{5,s}^2 = h_{5,f} + h_{A,f} + \frac{1}{2} U_{5,f}^2 \tag{24}$$

that is, for case (2), the nonavailable energy in the expansion process or free stream is made available to the post-normal-shock flow. The $p_{5,t}$ from equation (22) and the $h_{5,t}$ from equation (23) or (24) are used as inputs to FIND (2) to obtain the corresponding thermodynamic properties at the stagnation point. The stagnation-point heat-transfer rate is calculated by using the relation (ref. 12)

$$\dot{q}_{5,t} = \frac{W_o}{\sum_i \frac{X_i W_i}{\eta_i}} \sqrt{\frac{p_{5,t}}{r}} \left(h_{5,t} - h_w\right) \tag{25}$$

where the constants η_i are given in the following table:

Species i	η_i
CO_2	4.3102×10^{-4}
N_2	3.6285
O_2	4.3102
Ar	5.4788
He	2.5038
H_2	1.2786

The values of η_i for CO_2, N_2, Ar, and H_2 are taken directly from table I of reference 12, whereas the value for He is obtained from table II of reference 13. Since a value of η_i for O_2 is not presented in reference 12, the η_i for O_2 is set equal to that for CO_2 in the present study (ref. 13).

For case (3) (both free-stream and post-normal-shock flow conditions frozen), $\gamma_5 = \gamma_{5,s} = \gamma_{5,t}$. Hence, the perfect-gas normal-shock relations of reference 11 are used to determine the properties for static and for stagnation post-normal-shock conditions.

Determining Quiescent-Acceleration-Gas Pressure

An important parameter in the operation of an expansion tube is the quiescent pressure of the acceleration gas p_{10}. For a given condition in region Ⓐ, it is p_{10} and acceleration-gas temperature and molecular weight which determine the extent of the unsteady flow expansion (that is, the velocity obtained in region ⑤); conversely, a particular value of p_{10} is required to obtain a given value of U_5. In most studies in an expansion tube, U_5 is one of the principal flow quantities. Therefore, to generate a desired U_5, the required p_{10} must be known.

The momentum equation for the normal shock moving into region ⑩ is equation (2) where the subscript 10 replaces 1 and the subscript 20 replaces 2. At the interface of the acceleration gas and the test gas, it is required that p_{20} equal p_5 and U_{20} equal U_5. Two cases providing a range of p_{10} are considered. The first is where the incident shock into the acceleration gas is traveling at the same velocity as the interface of the acceleration gas and the test gas (ref. 14). For this case, equation (2) in conjunction with the equation of state (where Z_{10} is unity, because of relatively low values of p_{10}, and T_{10} is equal to T_1) becomes

$$p_{10} = \frac{p_5}{1 + \frac{W_{10}}{RT_1} U_5^2} \tag{26}$$

The second case considered is where (ref. 5)

$$U_{s,10} = \frac{\gamma_{10} + 1}{2} U_5 \tag{27}$$

Now, in the Langley 6-inch expansion tube, helium is generally employed as the acceleration gas. For values of $U_{s,10}$ less than 10 km/sec or so, helium behaves as a perfect gas (ref. 15); hence, the perfect-gas relation of reference 11 gives, for $\gamma_{10} = 5/3$,

$$p_{10} = \frac{4p_5}{5M_{s,10}^2 - 1} \tag{28}$$

where

$$M_{s,10}^2 = \frac{U_{s,10}^2}{a_{10}^2} = \frac{W_{10}U_{s,10}^2}{\gamma_{10}RT_1}$$

At $U_{s,10}$ greater than 10 km/sec, the helium acceleration gas departs from perfect-gas behavior because of ionization, and equation (28) is not valid. For example, at a $M_{s,10}$ of 20, equation (28) yields a value of p_{10} that is approximately 1.2 times the value computed for real helium at a p_{10} of 1 N/m^2. The effects of a real-helium acceleration gas are not included in the present program; hence, for $U_{s,10}$ greater than 10 km/sec, reference 15 should be consulted for more accurate values of p_{10} than those calculated by equation (28).

DISCUSSION

Flow quantities in region Ⓐ are obtained by using basic measured inputs in the following combinations:

Case (1) p_1, T_1, X_i, and $U_{s,1}$

Case (2) p_1, T_1, X_i, and p_2

Case (3) p_1, T_1, p_4, T_4, W_4, and X_i

For each combination, the option of a standing shock at the secondary diaphragm may be exercised. The values in regions ② and (2,s) for case (1) where $U_{s,1}$ is an input are compared, for several mixtures, to those calculated by using the program of reference 16. This comparison shows excellent agreement (all parameters within 0.5 percent) as expected, since both reference 16 and the present study employ references 6 and 7 as the source of thermodynamic properties. For case (2) where p_2 is an input, the values of p_2 calculated for case (1) where $U_{s,1}$ is an input are in turn used as inputs; this cross-check shows excellent agreement between the results. For case (3) where p_4 and T_4 are inputs, the values in region ② are observed to be in good agreement ($U_{s,1}$ within 0.2 percent) with those of reference 1 for helium driver gas when imperfect-gas effects are negligible.

Combinations of measured input and options for obtaining stagnation-point conditions in region ⑤, when it is assumed that the flow conditions in region Ⓐ are known, are summarized in the following table:

Case	Measured input	Unsteady expansion	Postnormal shock
(1)	U_5 or p_5	Equilibrium	Equilibrium
(2)	U_5 or p_5	Frozen	Equilibrium
(3)	U_5 or p_5	Frozen	Frozen

The flow quantities in region ⑤ for case (1) are compared with those obtained by using the real-air charts of reference 17. For this comparison, a 10-species (e^-, Ar, N, N^+, N_2, O, O^+, O_2, NO, and NO^+) air model is employed in the present program, the air composition by volume being 78.08 percent N_2, 20.95 percent O_2, and 0.97 percent Ar. This comparison shows good agreement between the results obtained from the charts of reference 17 and from the present program. For the case where p_5 is an input, the values of p_5 calculated for the case where U_5 is an input are in turn used as inputs. Results of this cross-check show good agreement. Quantities in regions (5,s) and (5,t) for thermochemical equilibrium are checked by comparing results with those obtained by using the program of reference 18.

The large number of gas mixtures that may be used as test media coupled to the wide range of flow conditions that may be generated with these mixtures in the expansion tube results in an extremely large number of possible flow states. For this reason the present program, which requires relatively long computer times (to be discussed subsequently), has not yet been exercised to generate a family of plots illustrating facility performance for several gases or gas mixtures. Instead, detailed sample calculations are presented.

In performing a test in an expansion tube, the first consideration is to calculate the theoretical flow quantities for the chosen mode of operation. From the experimenter's viewpoint, this is necessary in order to obtain the approximate magnitudes of velocity and pressure in the various regions. Knowledge of these magnitudes is required in the preparation of facility instrumentation for the test. Also, if several gas mixtures are to be used in a study, it may be desirable to determine conditions required to yield the same values of certain quantities for all gases (for example, velocity and/or pressure in the test section, or region ⑤).

As an example, the expansion tube is assumed to be operated in a low-to-moderate performance mode. The driver gas is helium at ambient temperature (T_4 = 300 K) and a pressure of 34.474 MN/m^2. The acceleration gas is also helium at ambient temperature. Three test gases are considered, air (N_2-O_2-Ar mixture), pure CO_2, and pure Ar. The p_1 is varied from 861.9 N/m^2 to 6.895 kN/m^2 for all gases, and the T_1 is ambient. The desired free-stream velocity U_5 is 4.267, 4.877, 5.486, and 6.096 km/sec. For the experimenter, a knowledge is required of the approximate magnitudes of $U_{s,1}$ and p_2 in region ②; p_5, $p_{5,t}$, and $\dot{q}_{5,t}$ in region ⑤; and the p_{10} to produce the desired U_5. As shown in reference 18 a substantial reduction in computer time is realized by judicious selection of the number of species. Now, at such moderate performance, first and second ionization for air and for CO_2 are negligible so that the species considered in the air model may be limited to Ar, N, N_2, O, O_2, and NO and the species considered for the CO_2 are O, O_2, C, CO, and CO_2. For Ar, second ionization is assumed negligible and the species considered are e^-, Ar, and Ar^+. The inputs to the program and the procedure for varying the number of species are discussed in appendix C. The species inputs, in FORTRAN IV language, for the composition of these gases are

	Air	CO_2	Ar
NUMSP	6	5	3
JINDX	3	2	2
IAR	1	0	2
IC	0	3	0
IC0	0	4	0
IC02	0	5	0
IN	2	0	0
IN2	3	0	0
IN0	6	0	0
I0	4	1	0
I02	5	2	0
PC02	0.0	1.0	0.0
PN2	0.78	0.0	0.0
P02	0.21	0.0	0.0
PAR	0.01	0.0	1.0
PMIX	1.0	1.0	1.0

The composition for the air model is $X_{N_2} = 0.78$, $X_{O_2} = 0.21$, and $X_{Ar} = 0.01$. It should be noted that PMIX must satisfy the relation

PMIX = PC02 + PN2 + P02 + PAR

Symbols denoting position in species array (that is, IAR, IC, etc.) that are zero need not be included in the input.

For a given p_1, which in turn corresponds to a given set of flow quantities in region Ⓐ, four values of U_5 are considered in this example; that is, four expansions from the given conditions in region Ⓐ are to be performed. Hence, the inputs (appendix C) for this case are IREP = 1, U5I = 610, and NVEL = 4. For this example, the existence of a standing shock at the secondary diaphragm is assumed (LD = 1) and only a thermochemical-equilibrium expansion from region Ⓐ to region ⑤ is considered (LG = 0).

Pertinent quantities calculated within the present program for the three test gases considered in this example are given in tables I to III.

The results for CO_2 (table II) and for Ar (table III) were obtained on a Control Data 6600 series computer, whereas the results for air (table I) were obtained on the slower

Control Data 6400 series computer. Three cases were also run for a 15-species CO_2 model and the same conditions as in table II for $p_1 = 6.895$ kN/m^2. These cases were run on a Control Data 6600 series computer and the computer times required per case are compared in the following table:

Gas	No. of species	Computer time per case, sec
Ar	3	24
CO_2	5	58
CO_2	15	215

At the moderate velocities in regions ② and ⑤ considered, the computed flow quantities for the 5-species CO_2 model and the 15-species CO_2 model are the same. Therefore, species should be selected judiciously to minimize computer time without sacrificing accuracy in calculated flow quantities.

Cases are also run, at an arbitrary p_1 of 3.447 kN/m^2, for gas mixtures representing atmospheric models of Mars $\left(X_{CO_2} = 0.85 \text{ and } X_{Ar} = 0.15\right)$, Venus $\left(X_{CO_2} = 0.95 \text{ and } X_{N_2} = 0.05\right)$, and Jupiter $\left(X_{He} = X_{H_2} = 0.5\right)$. For the Mars model, the driver conditions are the same as in tables I to III and U_5 is 5.486 km/sec. However, for the Venus model, maximum performance for resistance-heated helium driver gas in the Langley 6-inch expansion tube is utilized. This corresponds to $p_4 = 68.95$ MN/m^2 and $T_4 = 600$ K. The U_5 for this Venus model is 10.97 km/sec. For the Jovian model, maximum performance with resistance-heated hydrogen driver gas $\left(p_4 = 68.95 \text{ MN/m}^2 \text{ and } T_4 = 600 \text{ K}\right)$ is utilized and the U_5 is 12.19 km/sec. Sample data printouts for these cases are presented in appendix C.

For an actual test in an expansion tube, a comparison of the measured flow quantities to the calculated flow quantities is desired. Such a comparison is illustrated in figure 2 where preliminary experimental results for several tests in the Langley 6-inch expansion tube are shown along with calculations from the present program.

For these tests, the test gas is air and the driver gas is unheated helium at a p_4 of approximately 34.474 MN/m^2. For a p_1 of 3.447 kN/m^2, the p_{10} is 37 N/m^2 of helium and, for a p_1 of 1.379 kN/m^2, the p_{10} is 3.3 N/m^2 of argon. In figure 2(a), the ratio p_4/p_1 is plotted against $U_{s,1}$ and the solid line represents the calculated results shown in table I. From figure 2(a), it is observed that the $U_{s,1}$ inferred from the response of ionization gages located in the intermediate section is actually greater than the predicted $U_{s,1}$, being approximately 1.2 times the predicted values for both values of p_1. This trend is consistently observed in the Langley 6-inch expansion tube and is believed to result from a combination of several effects. Among these effects are the following: (1) The cross-sectional area of the driver section is somewhat larger than the intermediate section. The data of figure 2(a) are obtained for a ratio of driver-section cross-sectional area to intermediate-section cross-sectional area equal to 1.173, whereas this ratio is assumed to be unity in the present program. As shown in reference 19, an increase in $U_{s,1}$ is to be expected for an increase in this ratio. (2) The double-diaphragm mode of operation resembles that of a buffered-shock tube. Upon rupture of the upstream diaphragm, a shock wave propagates through the short chamber between the diaphragms. This shock wave heats the gas, contained within this chamber, just prior to rupture of the second diaphragm. Gains in $U_{s,1}$ obtained with buffered-shock tubes are illustrated in reference 19. (3) The relatively long opening times of the steel diaphragms may result in coalescing compressions and accelerating shock waves. It has been shown previously (ref. 20) that the finite opening time of the diaphragm produces faster shock waves for a given p_4/p_1 than simple shock-tube theory predicts.

The p_5 are plotted against U_5 in figures 2(b) and 2(d) for p_1 of 3.447 kN/m^2 and 1.379 kN/m^2, respectively; the $p_{5,t}$ are plotted against U_5 in figures 2(c) and 2(e) for p_1 of 3.447 kN/m^2 and 1.379 kN/m^2, respectively. The solid lines in figures 2(b) and 2(c) represent calculated results shown in table I.

In figures 2(b) and 2(c), the experimental data show best agreement with the results calculated by the method which uses the measured $U_{s,1}$ as an input, includes a standing shock at the secondary diaphragm, and assumes thermochemical equilibrium during the unsteady-expansion process. At the experimental values of p_5 (fig. 2(b)) and $p_{5,t}$ (fig. 2(c)), the calculated velocity from table I is approximately 20 percent less than the measured velocity. This low prediction is expected, because of the difference in $U_{s,1}$ observed between theory and experiment in figure 2(a). The lower-density data of figures 2(d) and 2(e) indicate a departure from an equilibrium expansion; for example, the calculated free-stream static pressure for an equilibrium expansion (fig. 2(d)) is approximately 2.7 times the measured value, but this measured value is about 26 times as high as the calculated value for a frozen expansion (if it is assumed that a standing shock exists at the secondary diaphragm).

CONCLUDING REMARKS

A computer program written in FORTRAN IV language is presented which determines expansion-tube flow quantities for real test gases CO_2, N_2, O_2, Ar, He, and H_2, or mixtures of these gases, in thermochemical equilibrium. This program permits, as input data, a number of possible combinations of flow quantities, which are generally measured during an expansion-tube test. The versatility of the program is enhanced by the inclusion of such effects as imperfect driver gas and shock reflection at the secondary diaphragm and by consideration of both a thermochemical-equilibrium flow expansion and a frozen flow expansion.

The usage of the program in preparing the expansion tube for testing with several gases is illustrated by sample calculations. Results from the program are also compared with preliminary data obtained experimentally in the Langley 6-inch expansion tube. This comparison shows that the measured incident-shock velocity $U_{s,1}$ and the measured interface velocity U_5 are approximately 1.2 times the calculated values, when driver-gas pressure and temperature are inputs. This discrepancy is attributed to several effects believed to be present in the Langley 6-inch expansion tube. Agreement between calculated and measured test-section flow quantities is significantly improved when measured incident-shock velocity is employed as an input.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 2, 1972.

APPENDIX A

THERMODYNAMIC AND TRANSPORT PROPERTIES FOR ARBITRARY GAS MIXTURES

Thermodynamic properties for real gases CO_2, N_2, O_2, Ar, He, and H_2, or mixtures of these gases, are obtained by the procedure of references 6 and 7 and include dissociation and first and second ionization. Basic assumptions used in obtaining these properties are

(1) The mixture is composed of ideal gases

(2) For diatomic species the rigid-rotor harmonic-oscillator model is used with vibrational-rotational corrections for each electronic configuration

(3) Only electronic levels with principal quantum number less than or equal to 5 are included

The procedure of references 6 and 7 is based upon the free-energy-minimization method of reference 21. For a given pressure and temperature, the free energies for individual species are computed from the partition function of statistical mechanics. The equilibrium composition is then obtained by minimization of the free energy. When the composition for a given pressure and temperature is determined, the corresponding thermodynamic properties are computed directly.

The 5 components and 26 species considered in references 6 and 7 are listed in appendix C. These 26 species permit modeling of Earth, Mars, and Venus atmospheres but not of proposed Jovian atmospheres which are believed to consist primarily of helium and hydrogen. Therefore, the components H and He and the species H, H_2, H^+, He, He^+, and He^{++} are also included in the present study. However, no provision is included for combinations of hydrogen with any of the other species. The energy-level constants for the 26 species considered in references 6 and 7 are tabulated in reference 6, whereas the energy-level constants for the 6 additional species are obtained from reference 22.

The procedure of references 6 and 7 is included in the present study as a subroutine and is referred to herein as ROGO. The basic inputs to ROGO, other than the energy-level constants, are pressure, temperature, and initial estimates of the species concentrations. (In the free-energy-minimization method for determining the composition of a gas mixture, the initial estimates of Y_i are somewhat arbitrary.) In the present study, the partial pressures of the quiescent test gas in the intermediate chamber are assumed known. The corresponding mole fractions for these gases are obtained from Dalton's law

$$X_i = \frac{p_i}{p_{mix}} \tag{A1}$$

and the molecular weight is given by

$$W_o = \sum_i X_i W_i \tag{A2}$$

The initial estimates for the species concentrations for CO_2, N_2, O_2, Ar, He, and H_2 are obtained from

$$Y_i = \frac{X_i}{W_o} \tag{A3}$$

For the remaining 26 species the initial estimates for the concentrations are set equal to 10^{-20}. (If Y_i for O_2 is not known, the initial estimate is set equal to 10^{-5}.) Thermodynamic properties obtained from ROGO, for a given p and T, are a, h, sW_o/R, X_i, Z^*, γ_E, and ρ.

Combinations of input thermodynamic properties other than p and T are required in the present study. An iterative-interpolation scheme is derived in reference 18 so as to enable determination of thermodynamic properties from combinations of h, p, sW_o/R, and ρ. This scheme is referred to herein as FIND (I), and the inputs for a given I are as follows:

I	Inputs to FIND (I)
1	p, ρ
2	p, h
3	p, sW_o/R
4	h, ρ

A detailed discussion of FIND (I) is presented in reference 18.

The viscosity μ is calculated by using the expressions presented in reference 18. Since He and H_2 are also included in the present study, expressions for the viscosity of these species are derived. The viscosity for He is obtained by applying a curve fit to the results of references 23 to 25 for temperatures to 5000 K. The resulting expression is

$$\mu = 3.92 \times 10^{-7} T^{0.7} \tag{A4}$$

The expression for Ar is (ref. 18)

$$\mu = 3.33 \times 10^{-7} T^{0.739} \tag{A5}$$

Simple expressions for the viscosity, in the form

$$\mu = \left(b_0 + b_1 T + b_2 T^2\right) \times 10^{-7} \tag{A6}$$

are obtained for the diatomic species N_2 and O_2 and for the triatomic species CO_2 in reference 18. For convenience, the constants of equation (A6) for these species along with those for H_2 obtained from the results of references 25 to 27 are presented in the following table:

Gas	T, K	b_0	b_1	b_2
CO_2	150 to 1000	-9.7303×10^{-1}	5.5222×10^{-1}	-1.6139×10^{-4}
	1000 to 5000	1.5029×10^{2}	2.4890×10^{-1}	-6.1747×10^{-6}
N_2	150 to 1000	2.2992×10^{1}	5.5586×10^{-1}	-1.8436×10^{-4}
	1000 to 5000	1.6388×10^{2}	2.4601×10^{-1}	-7.7388×10^{-6}
O_2	150 to 1000	1.9939×10^{1}	6.6236×10^{-1}	-2.0410×10^{-4}
	1000 to 5000	2.3030×10^{2}	2.5597×10^{-1}	-2.2643×10^{-6}
H_2	150 to 1000	2.3877×10^{1}	2.1918×10^{-1}	-4.4304×10^{-5}
	1000 to 5000	6.3197×10^{1}	1.4093×10^{-1}	-8.6387×10^{-6}

These expressions should provide reasonably accurate (within 10 percent or so) values of μ for T less than 5000 K, with the accuracy decreasing with further increase in T. For T greater than 8000 K, μ is not calculated in the present program.

APPENDIX B

THERMODYNAMIC PROPERTIES FOR IMPERFECT HELIUM AND HYDROGEN

The driver gas for the Langley 6-inch expansion tube is usually helium or hydrogen. For unheated and resistance-heated driver gas, pressures up to 70 MN/m^2 and temperatures from 300 K to 600 K are obtained. For such conditions, the assumption of perfect helium or hydrogen is inadequate because of intermolecular-force effects (for example, see refs. 28 and 29). The relations used to calculate imperfect-gas effects at these driver-gas conditions are taken from reference 28 and are based on the virial form of the equation of state which, where interactions involving four or more molecules are neglected, can be written as

$$p = \rho \frac{R}{W_o} TZ = \rho \frac{R}{W_o} T \left[1 + \rho B(T) + \rho^2 C(T)\right] \tag{B1}$$

For helium, the virial coefficients are given by

$$\begin{aligned} B(T) = {} & 3.3565 \times 10^{-6} (15.8922 - \ln T)^3 \\ & - 2.0085 \times 10^{-3} \exp\left[-\left(3.7156 \times 10^{-3}\right)T\right] \end{aligned} \tag{B2}$$

and

$$C(T) = 5.6330 \times 10^{-12}(15.8922 - \ln T)^6 \tag{B3}$$

These expressions for B(T) and C(T) are employed in the imperfect-helium study of reference 28 for a temperature range of 200 K to 15 000 K.

For hydrogen a curve fit is applied to the second-virial-coefficient results of reference 30. These results include a temperature range of 273 K to 473 K and the curve-fit expression is

$$B(T) = 1.6994 \times 10^{-3} T^{1/4} \tag{B4}$$

Although equation (B4) is obtained for temperatures to only 473 K, this expression is assumed to be valid for temperatures to 600 K. (This temperature represents the maximum value of T_4 considered herein.) To obtain an expression for C(T) for hydrogen, the results of reference 29 are used. In reference 29 compressibility factors are calculated by using the Beattie-Bridgeman equation of state for temperatures from 30 K to 1000 K and for pressures from 10 kN/m^2 to 10^2 MN/m^2. Now, for pressures to 10 MN/m^2, the compressibility factors obtained from equations (B1) and (B4), where $C(T) = 0$, are within 1 percent of the values presented in reference 29 for temperatures from 300 K to 1000 K. However, at higher pressures $\left(10 \text{ MN/m}^2 < p < 10^2 \text{ MN/m}^2\right)$, these compressibility factors are as much as 20 percent less than those of reference 29, since interactions involving three molecules are ignored (that is, $C(T) = 0$). Hence, values of

$C(T)$ are calculated which bring the compressibility factors from equation (B1) into agreement with those of reference 29 for a pressure of 10^2 MN/m^2. For a temperature range of 300 K to 1000 K, these values of $C(T)$ vary from 2.002×10^{-4} to 2.195×10^{-4}. With no appreciable loss of accuracy, $C(T)$ is set equal to the constant 2.1×10^{-4} for the temperature range of 300 K to 600 K. The $B(T)$ of equation (B4) and this constant value of $C(T)$ result in compressibility factors within approximately 1 percent of those of reference 29 for the temperature range of 300 K to 1000 K and the pressure range of 10^2 kN/m^2 to 10^2 MN/m^2.

The thermodynamic relations, in terms of the virial coefficients, for hW_o/RT, sW_o/R, c_vW_o/R, and a^2 are (ref. 28)

$$\frac{hW_o}{RT} = \left(\frac{hW_o}{RT}\right)_{perf} + \rho\left[B(T) - T\frac{dB(T)}{dT}\right] + \frac{\rho^2}{2}\left[2C(T) - T\frac{dC(T)}{dT}\right] \tag{B5}$$

$$\frac{sW_o}{R} = \left(\frac{c_vW_o}{R}\right)_{perf} \ln T - \ln \rho - \rho\left[B(T) + T\frac{dB(T)}{dT}\right] - \frac{\rho^2}{2}\left[C(T) + T\frac{dC(T)}{dT}\right] + \left(\frac{sW_o}{R}\right)_{ref} \tag{B6}$$

$$\frac{c_vW_o}{R} = \left(\frac{c_vW_o}{R}\right)_{perf} - T\left\{\rho\left[2\frac{dB(T)}{dT} + T\frac{d^2B(T)}{dT^2}\right] + \frac{\rho^2}{2}\left[2\frac{dC(T)}{dT} + T\frac{d^2C(T)}{dT^2}\right]\right\} \tag{B7}$$

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_T + \frac{T}{c_v\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho^2 \tag{B8}$$

where, from differentiation of equation (B1),

$$\left(\frac{\partial p}{\partial T}\right)_\rho = \frac{\rho R}{W_o}\left\{1 + \rho\left[B(T) + T\frac{dB(T)}{dT}\right] + \rho^2\left[C(T) + T\frac{dC(T)}{dT}\right]\right\} \tag{B9}$$

and

$$\left(\frac{\partial p}{\partial \rho}\right)_T = \frac{RT}{W_o}\left[1 + 2\rho B(T) + 3\rho^2 C(T)\right] \tag{B10}$$

The $(sW_o/R)_{ref}$ of equation (B6) is obtained for $p = 1.01325 \times 10^2$ kN/m^2 and $T = 300$ K by using reference 10 for both helium and hydrogen. For helium, a value of $(sW_o/R)_{ref} = 4.8024$ is calculated and, for hydrogen, $(sW_o/R)_{ref} = -1.0363$. (It should be noted that $(sW_o/R)_{ref}$ is omitted in reference 28; hence, the values of sW_o/R plotted for helium in reference 28 differ from equation (B6) by a constant $(sW_o/R)_{ref}$.)

In the thermodynamic relations shown in equations (B5) to (B10), the independent variables are T and ρ. Hence, in generating an array of thermodynamic properties in region ③ for a range of T_3 and a known $s_3 W_3/R$ (see section entitled "Determining Flow Quantities in Region ②"), the corresponding ρ_3 must be known. These ρ_3 are determined iteratively from the implicit relation given by equation (B6). With T_3 known and the corresponding ρ_3 determined, corresponding values of Z and p, h, and a may be calculated from equations (B1), (B5), and (B8), respectively.

APPENDIX C

COMPUTER-PROGRAM INPUTS, LISTING, AND FLOW CHART WITH SAMPLE DATA PRINTOUTS

The present program is written in FORTRAN IV language for Control Data 6000 series computers. Minimum machine requirements are 70 000 octal locations of core storage. The FORTRAN NAMELIST capability is used for data input with INP as the NAMELIST name. The units for the inputs which are physical quantities are given in the section entitled "Symbols." The program symbols and a brief description of the inputs necessary to utilize the computer program are listed as follows:

Program symbol	Description
P1	Pressure of quiescent test gas in region ①
T1	Temperature of quiescent test gas in region ①
US1	Incident-shock velocity into region ①
P2	Static pressure in region ②
P4	Driver-gas pressure in region ④
T4	Driver-gas temperature in region ④
U5	Velocity in region ⑤
P5	Static pressure in region ⑤
PC02	Partial pressure of CO_2
PN2	Partial pressure of N_2
P02	Partial pressure of O_2
PAR	Partial pressure of Ar
PHE	Partial pressure of He
PH2	Partial pressure of H_2
PMIX	Mixture pressure
TW	Model surface temperature

Program symbol	Description
BNR	Model nose radius
RUN	Facility test number
NUMSP	Number of species considered (30 maximum)
JINDX	Number of components considered (8 maximum)
IAR	Position in species array of Ar
IC	Position in species array of C
ICØ	Position in species array of CO
ICØ2	Position in species array of CO_2
IN	Position in species array of N
IN2	Position in species array of N_2
INØ	Position in species array of NO
IØ	Position in species array of O
IØ2	Position in species array of O_2
IHE	Position in species array of He
IH	Position in species array of H
IH2	Position in species array of H_2
NDRIV	NDRIV = 0 denotes helium driver gas
	NDRIV = 1 denotes hydrogen driver gas
LB	LB = 0 denotes inputs p_1, T_1, and $U_{s,1}$ used to find region ② quantities
	LB = 1 denotes inputs p_1, T_1, and p_2 used to find region ② quantities
	LB = 2 denotes inputs p_1, T_1, p_4, and T_4 used to find region ② quantities

Program symbol	Description
ISTET	ISTET = 0 denotes only quantities in regions ② and (2,s) determined ISTET = 1 denotes all expansion-tube flow quantities determined
LF	LF = 1 denotes U_5 is basic input in region ⑤ LF = 2 denotes p_5 is basic input in region ⑤
LD	LD = 0 denotes no standing shock at secondary diaphragm LD = 1 denotes existence of standing shock at secondary diaphragm LD = 2 denotes both cases (LD = 0 and LD = 1) are performed
LG	LG = 0 denotes frozen expansion is not performed LG = 1 denotes frozen expansion is performed
IREP	IREP = 0 denotes only a single value of U_5 is of interest for given region Ⓐ quantities IREP = 1 denotes several U_5 of interest for given region Ⓐ quantities
U5I	Velocity increment for IREP = 1
NVEL	Total number of U_5 of interest for IREP = 1 (10 maximum)
NUMUS	Number of $U_{s,1}$ in array for LB = 2

To minimize the number of inputs required for running cases on the computer, inputs are assigned values within the program as follows:

Program symbol	Assigned value
TW	300
BNR	0.0127
RUN	1.0
NDRIV	0

Program symbol	Assigned value
ISTET	1
LD	2
LG	1
IREP	0
U5I	0
NVEL	0
NUMUS	16

These values may be changed from their assigned values by inclusion in the NAMELIST INP. For a given LB, only the basic parameters p_1, T_1, and $U_{s,1}$ (LB = 0), p_2 (LB = 1), or p_4 and T_4 (LB = 2) need be included in INP. Similarly, for a given LF, only U_5 (LF = 1) or p_5 (LF = 2) need be included in INP. Only the partial pressures of the quiescent test gas in region ① need be included in conjunction with PMIX. It should be noted that the condition

$$\text{PMIX} = \text{PCØ2} + \text{PN2} + \text{PØ2} + \text{PAR} + \text{PHE} + \text{PH2}$$

must be satisfied. Along with LB and LF, NUMSP and JINDX must also be specified for each case. However, only the positions in the species array (for example, IAR, IC, ICØ, and so forth) of the species being considered need be included.

The 26 species and 5 components considered in references 6 and 7 and employed in the present program are as follows:

Species

e^-
Ar
Ar^+
Ar^{++}
N
N^+
N^{++}
N_2
N_2^+

O
O^+
O^{++}
O^-
O_2
O_2^+
O_2^-
NO
NO^+

C
C^+
C^{++}
C^-
CO
CO^+
CN
CO_2

Components

e^-
Ar
N
O
C

The thermodynamic data for these species, which are tabulated in reference 6, are read into the computer program from cards. A listing of these cards is presented in reference 18. An additional 6 species and 2 components considered in the present study are as follows:

Species		Components
H	He	He
H^+	He^+	H
H_2	He^{++}	

The thermodynamic data for these species are obtained from reference 22 and are also read into the computer program from cards.

A listing of this program, including subroutines, comments, sample input, and thermodynamic data for a mixture of He and H_2, is reproduced in the following pages.

```
JOB•1•0700,070000•1000•        A3731   RGK143                  1250        CENT
USER•MILLER• CHARLES G  III          000605575N 64720
RUN(S)•
SFTINDF• •
LGO•     •
- •
      PROGRAM MILLER(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     DATA REDUCTION PROCEDURE FOR CO2-N2-O2-AR MIXTURES
C     THERMODYNAMIC PROPERTIES OBTAINED FROM PROGRAM OF ALLISON
      DIMENSION TABH(50)• TABA(50)• TABANS(50)• TABP(50)• P5K(50)• P5G(5
     10)• TABT(50)
      DIMENSION RESULT(2)
      DIMENSION TABTI(50)• TABRI(50)• TABPI(50)• TABZI(50)• TABHI(50)
      DIMENSION TABAI(50)• TABUI(50)
      DIMENSION US1I(30)• U2I(30)• P2I(30)• H2I(30)• TABP2I(30)• TABT2I(
     130)
      DIMENSION XSLM(5)• BNON(5)• R2X(5)• U2X(5)• H2X(5)• T2X(5)• P2X(5)
     1• A2X(5)• RXR(5)• RXH(5)• RXU(5)• RXP(5)• RXT(5)• RXA(5)
      DIMENSION XMOLE(30)• SPECIE(30)
      REAL MS1•M2•M5•M5S•MX•MN•MNS•MS•MA•M5F•M5SF•M5SFF
      EXTERNAL FOFX•FOFR•FOFMS
      COMMON /BLK1/ BT4•CT4•RHOG•T1•GAM4•W4•T4•P4•P1•TII•AI•ZI•GI•SR
      COMMON /BLK2/ BTI•CTI•TI•CVRI•S4R•SREF•DBTI•DCTI
      COMMON /BLK3/ LB•LD•LF•LG•NON•LU•NDRIV•ICOUNT•SAR•LCODE•DELU
      COMMON /BLK4/ NUMSP•JINDX•IAR•IN2•IO2•ICO2•BOZ•XAR•XN2•XO2•XCO2
      COMMON /BLK5/ TMAX1•TMAX2•TMIN1•TMIN2•XMOLE•SPECIE
      COMMON /BLK6/ IHE•IH2•IH•XHE•XH2
      COMMON /BLK7/ GE•WO
      NAMELIST /INP/ T1•P1•US1•P2•LB•LD•LF•LG•U5•P5•IREP•U5I•NVEL•P4•T4•
     1RUN•ISTET•NUMUS•NDRIV•TW•BNR•PCO2•PN2•PO2•PAR•PMIX•NUMSP•JINDX•ICO
     22•IN2•IO2•IAR•INO•ICO•IN•IO•IC•IH•IH2•IHE•PHE•PH2
      BOZ=0•
      CALL DAYTIM (RESULT)
C
C     SHOCK TUBE PHASE
C
C     NDRIV=0 DENOTES IMPERFECT HELIUM DRIVER GAS
C     NDRIV=1 DENOTES IMPERFECT HYDROGEN GAS
C
C     LB=0 DENOTES SHOCK TUBE INPUTS P1•T1•US1
C     LB=1 DENOTES SHOCK TUBE INPUTS P1•T1•P2
C     LB=2 DENOTES SHOCK TUBE INPUTS P1•T1•P4•T4
C
C     ISTET DENOTES PHASE(S) CALCULATED
```

```
C     ISTET=0 DENOTES SHOCK TUBE PHASE ONLY                             A  39
C     ISTET=1 DENOTES EXPANSION TUBE PHASE                              A  40
C                                                                       A  41
C     LG=0  FROZEN EXPANSION  NOT  PERFORMED                            A  42
C     LG=1  FROZEN EXPANSION  IS   PERFORMED                            A  43
C                                                                       A  44
C     IREP=0  SINGLE VALUE OF U5 OF INTEREST                            A  45
C     IREP=1  SEVERAL U5 OF INTEREST-FOR SETTING UP EXPANSION TUBE      A  46
C                                                                       A  47
C     U5I IS U5 INCREMENT FOR IREP=1                                    A  48
C     NVEL IS TOTAL NUMBER OF U5 OF INTEREST FOR IREP=1                 A  49
C                                                                       A  50
      RU=8.31434E+3                                                     A  51
      MM=0                                                              A  52
1     US1=P2=P4=T4=U5=P5=U5I=PCO2=PN2=PO2=PAR=PHE=PH2=0.0               A  53
      IAR=IN2=IN=IO2=IO=INO=ICO2=ICO=IC=IHE=IH2=IH=IREP=NVEL=NDRIV=0    A  54
      ISTET=LG=1                                                        A  55
      LD=2
      NUMUS=15                                                          A  56
      RUN=1.                                                            A  57
      TW=300.                                                           A  58
      BNR=.0127                                                         A  59
      READ (5,INP)                                                      A  60
      IF (ENDFILE 5) 58,2                                               A  61
2     CONTINUE                                                          A  62
      PRINT 109, RESULT(1)                                              A  63
      PRINT 70                                                          A  64
      PRINT 71                                                          A  65
      PRINT 72                                                          A  66
      PRINT 73                                                          A  67
      PRINT 74                                                          A  68
      PRINT 75, RUN,P1,T1,US1,P2,P4,T4                                  A  69
      LU=0                                                              A  70
      NN=0                                                              A  71
      XCO2=PCO2/PMIX                                                    A  72
      XN2=PN2/PMIX                                                      A  73
      XO2=PO2/PMIX                                                      A  74
      XAR=PAR/PMIX                                                      A  75
      XHE=PHE/PMIX                                                      A  76
      XH2=PH2/PMIX                                                      A  77
      WO=44.011*XCO2+28.016*XN2+32.*XO2+39.944*XAR+4.003*XHE+2.016*XH2  A  78
      PRINT 76                                                          A  79
      PRINT 75, WO,XCO2,XN2,XO2,XAR,XHE,XH2                             A  80
      ZMIX=1.E+4*(7.2906*XAR+10.2109*XCO2+7.7211*XN2+7.4243*XO2+1.5988*X A  81
```

```
     1HE+1.5767*XH2)/WO
      RHO1=(P1*WO)/(RU*T1)
      HW=(RU*TW*(4.5*XCO2+3.5*(XO2+XN2+XH2)+2.5*(XAR+XHE))/WO)-(3.93146E
     1+8*XCO2/WO)
      H1=(RU*T1*(4.5*XCO2+3.5*(XO2+XN2+XH2)+2.5*(XAR+XHE))/WO)-(3.93146E
     1+8*XCO2/WO)
      CPE=4.5*XCO2+3.5*(XN2+XO2+XH2)+2.5*(XHE+XAR)
      CVE=3.5*XCO2+2.5*(XN2+XO2+XH2)+1.5*(XHE+XAR)
      GE=CPE/CVE
      A1=SQRT(GE*RU*T1/WO)
      PRINT 59
      PRINT 60
      PRINT 79, P1,RHO1,T1,H1,GE,A1
      TMIN2=T1
      IF (LB.EQ.2) GO TO 5
      IF (LB.EQ.1) GO TO 3
      MS1=US1/A1
      GO TO 4
3     MS1=SQRT((.8*P2/P1)+.2)
4     TMAX2=1.05*T1*(2.*GE*MS1**2-GE+1.)*((GE-1.)*MS1**2+2.)/((GE+1.)**2
     1*MS1**2)
      CALL SC (RHO2,U2,P2,H2,RHO1,US1,P1,H1,WO)
      S2R=SR
      T2=TI1
      A2=AI
      Z2=ZI
      GAM2=GI
      M2=U2/A2
      MS1=US1/A1
      RE2=0.
      IF (T2.GT.8000.) GO TO 28
      CALL VISC (T2,VIS2)
      RE2=RHO2*U2/VIS2
      GO TO 28
5     LU=20
      R=8.31434E+3
      IF (NDRIV.EQ.1) GO TO 6
C
C     HELIUM
C
      HWRT=2.5
      CVRI=1.5
      SREF=4.8024
      GAM4=1.66667
```

```
      W4=4.003
      RHOG=(P4*W4)/(R*T4)
      ALOW=.70*RHOG
      GO TO 7
C
C     HYDROGEN
C
6     HWRT=3.5
      CVRI=2.5
      SREF=-1.0363
      GAM4=1.4
      W4=2.016
      RHOG=(P4*W4)/(R*T4)
      ALOW=.50*RHOG
7     AUP=1.05*RHOG
      DELTX=(AUP-ALOW)/100.
      E1=.1E-6
      CALL BDT (BT4,CT4,DBT4,DCT4,D2BT4,D2CT4,T4)
      RHO4=1.2*RHOG
      CALL ITR1 (RHO4,DELTX,FOFX,E1,E1,200,ICODE)
      IF (ICODE) 8,11,8
8     GO TO (9,10,10,10), ICODE
9     PRINT 77
      GO TO 1
10    PRINT 78, ICODE
      GO TO 1
11    Z4=1.+RHO4*BT4+RHO4**2*CT4
      H4=(R*T4/W4)*(HWRT+RHO4*(BT4-T4*DBT4)+(RHO4**2/2.)*(2.*CT4-T4*DCT4
     1))
      S4R=CVRI*ALOG(T4)-ALOG(RHO4)-RHO4*(BT4+T4*DBT4)-(RHO4**2/2.)*(CT4+
     1T4*DCT4)+SREF
      CVR=CVRI-T4*(RHO4*(2.*DBT4+T4*D2BT4)+(RHO4**2/2.)*(2.*DCT4+T4*D2CT
     14))
      PPTR=(RHO4*R/W4)*(1.+RHO4*(BT4+T4*DBT4)+(RHO4**2    )*(CT4+T4*DCT4)
     1)
      PPRT=(T4*R/W4)*(1.+2.*RHO4*BT4+3.*RHO4**2*CT4)
      A4=SQRT(PPRT+((T4*W4)/(CVR*R*RHO4**2))*PPTR**2)
      TABTI(1)=T4
      TABPI(1)=P4
      TABRI(1)=RHO4
      TABZI(1)=Z4
      TABHI(1)=H4
      TABAI(1)=1./A4
      DELT=T4/49.
```

```
      NU=1                                                              A 170
      DO 12 I=2,50                                                      A 171
      TABTI(I)=T4-FLOAT(I-1)*DELT                                       A 172
   12 CONTINUE                                                          A 173
      TABTI(50)=TABTI(50)+4.5                                           A 174
      AUP=1.1*RHO4                                                      A 175
      ALOW=.0001                                                        A 176
      DELR=(AUP-ALOW)/200.                                              A 177
      RI=RHO4                                                           A 178
      DO 19 I=2,50                                                      A 179
      TI=TABTI(I)                                                       A 180
      CALL BDT (BTI,CTI,DBTI,DCTI,D2BTI,D2CTI,TI)                       A 181
      CALL ITR2 (RI,ALOW,AUP,DELR,FOFR,EI,EI,400,ICODE)                 A 182
      IF (ICODE) 13,18,13                                               A 183
   13 GO TO (14,15,15,16), ICODE                                        A 184
   14 PRINT 77                                                          A 185
      GO TO 17                                                          A 186
   15 PRINT 78, ICODE                                                   A 187
      GO TO 17                                                          A 188
   16 PRINT 80, ICODE,RI,DELR                                           A 189
   17 PRINT 61                                                          A 190
      PRINT 62, NU                                                      A 191
   18 TABRI(I)=RI                                                       A 192
      TABZI(I)=1.+RI*BTI+RI**2*CTI                                      A 193
      TABPI(I)=TI*(R/W4)*RI*TABZI(I)                                    A 194
      TABHI(I)=(R*TI/W4)*(HWRT+RI*(BTI-TI*DBTI)+(RI**2/2.)*(2.*CTI-TI*DC A 195
     1TI))                                                              A 196
      CVIR=CVRI-TI*(RI*(2.*DBTI+TI*D2BTI)+(RI**2/2.)*(2.*DCTI+TI*D2CTI)) A 197
      PPTRI=(RI*R/W4)*(1.+RI*(BTI+TI*DBTI)+(RI**2    )*(CTI+TI*DCTI))   A 198
      PPRTI=(TI*R/W4)*(1.+2.*RI*BTI+3.*RI**2*CTI)                       A 199
      TABAI(I)=1./(SQRT(PPRTI+((TI*W4)/(CVIR*R*RI**2))*PPTRI**2))       A 200
      NU=NU+1                                                           A 201
   19 CONTINUE                                                          A 202
      CALL SIMR (TABHI,TABAI,NU,NU,TABANS)                              A 203
      MS=1.4                                                            A 204
      DELS=.2                                                           A 205
      CALL ITR1 (MS,DELS,FOFMS,EI,EI,200,ICODE)                         A 206
      IF (ICODE) 20,23,20                                               A 207
   20 GO TO (21,22,22), ICODE                                           A 208
   21 PRINT 77                                                          A 209
      GO TO 1                                                           A 210
   22 PRINT 78, ICODE                                                   A 211
      GO TO 1                                                           A 212
   23 USMAX=1.1*A1*MS                                                   A 213
```

```
      USMIN=.65*USMAX
      US1I(1)=USMAX
      DEL1=(USMAX-USMIN)/FLOAT(NUMUS)
      MS1=US1I(1)/A1
      TMAX2=1.05*T1*(2.*GE*MS1**2-GE+1.)*((GE-1.)*MS1**2+2.)/((GE+1.)**2
     1*MS1**2)
      DO 24 I=1,NUMUS
      US1I(I)=USMAX-FLOAT(I-1)*DEL1
      CALL SC (RH2I,U2I(I),P2I(I),H2I(I),RHO1,US1I(I),P1,H1,WO)
      TABT2I(I)=TII
      TABP2I(I)=P2I(I)
      TMAX2=TII
   24 CONTINUE
      CALL SOLUT (TABANS,TABPI,U2I,P2I,NU,NUMUS,UR,P)
      P2=P
      U2=UR
      CALL FTLUP (P2,T2,-2,NUMUS,TABP2I,TABT2I)
      P2U=P2/1.01325E+5
      CALL ROGO (P2U,RHO2,H2,S2R,T2,A2,Z2,GAM2,WO)
      US1=U2/(1.-RHO1/RHO2)
      MS1=US1/A1
      M2=U2/A2
      RE2=0.
      IF (T2.GT.8000.) GO TO 25
      CALL VISC (T2,VIS2)
      RE2=RHO2*U2/VIS2
   25 IF (LB.NE.2) GO TO 28
      IF (NDRIV.EQ.0) GO TO 26
      PRINT 81
      GO TO 27
   26 PRINT 82
   27 PRINT 83
      PRINT 84
      PRINT 85, P4,RHO4,T4,H4,S4R,Z4,A4,W4
   28 PRINT 86
      PRINT 87
      PRINT 88, P2,RHO2,T2,H2,S2R,Z2,GAM2,A2,U2,M2,RE2
      RAP=P2/P1
      RARHO=RHO2/RHO1
      RAT=T2/T1
      RAH=H2/H1
      PRINT 89
      PRINT 90
      PRINT 91, RAP,RARHO,RAT,RAH,MS1,US1
```

```
      PRINT 92
      PRINT 93
      DO 29 I=1,NUMSP
      PRINT 94, SPECIE(I),XMOLE(I)
29    CONTINUE
C
C     STANDING SHOCK AT SECOND DIAPHRAGM
C
C     LD=0 DENOTES NO STANDING SHOCK
C     LD=1 DENOTES EXISTENCE OF STANDING SHOCK
C     LD=2 DENOTES BOTH CASES WILL BE RUN
C
      IF (LD.EQ.0.AND.ISTET.EQ.0) GO TO 1
      IF(LD.EQ.0.OR.LD.EQ.2) GO TO 31
111   CALL SHOCK (BSNS2,CSNS2,DSNS2,RHO2,U2,P2,H2)
      RHOA=4.*RHO2
30    UA=BSNS2/RHOA
      PA=CSNS2-BSNS2*UA
      HA=DSNS2-.5*UA**2
      TMIN2=T2
      TMAX2=1.05*T2*(2.*GAM2*M2**2-GAM2+1.)*((GAM2-1.)*M2**2+2.)/((GAM2+
     11.)**2*M2**2)
      CALL FIND (PA,RNEW,HA,SAR,TA,AA,ZA,GAMA,WO,2,2)
      IF (ABS(1.-RNEW/RHOA).LE..001) GO TO 32
      RHOA=RNEW
      GO TO 30
31    PA=P2
      RHOA=RHO2
      TA=T2
      SAR=S2R
      HA=H2
      AA=A2
      UA=U2
      ZA=Z2
      GAMA=GAM2
      REA=RE2
      MA=UA/AA
      GO TO 35
32    RHOA=RNEW
      MA=UA/AA
      REA=0.
      IF (TA.GT.8000.) GO TO 33
      CALL VISC (TA,VISA)
      REA=RHOA*UA/VISA
```

```
   33 PRINT 95                                                          A 301
      PRINT 87                                                          A 302
      PRINT 88, PA,RHOA,TA,HA,SAR,ZA,GAMA,AA,UA,MA,REA                  A 303
      PRINT 96                                                          A 304
      PRINT 93                                                          A 305
      DO 34 I=1,NUMSP                                                   A 306
      PRINT 97, SPECIE(I),XMOLE(I)                                      A 307
   34 CONTINUE                                                          A 308
   35 IF (ISTET.EQ.0) GO TO 1                                           A 309
C                                                                       A 310
C     EXPANSION TUBE PHASE                                              A 311
C                                                                       A 312
C     LF=1 DENOTES U5 IS BASIC INPUT                                    A 313
C     LF=2 DENOTES P5 IS BASIC INPUT                                    A 314
C                                                                       A 315
C                                                                       A 316
C     FROZEN FLOW- EXPANSION TUBE                                       A 317
C                                                                       A 318
      IF (ICO2.NE.0) GO TO 36                                           A 319
      XMOLE(ICO)=XMOLE(IC)=XMOLE(ICO2)=0.                               A 320
   36 IF (IAR.NE.0) GO TO 37                                            A 321
      XMOLE(IAR)=0.                                                     A 322
   37 IF (IN2.NE.0) GO TO 38                                            A 323
      XMOLE(IN2)=XMOLE(INO)=XMOLE(IN)=0.                                A 324
   38 IF (IO2.NE.0) GO TO 39                                            A 325
      XMOLE(IO2)=XMOLE(INO)=XMOLE(IO)=0.                                A 326
   39 IF (IHE.NE.0) GO TO 40                                            A 327
      XMOLE(IHE)=0.                                                     A 328
   40 IF (IH2.NE.0) GO TO 41                                            A 329
      XMOLE(IH2)=XMOLE(IH)=0                                            A 330
   41 ATRO1=XMOLE(IN2)+XMOLE(IO2)+XMOLE(INO)+XMOLE(ICO)+XMOLE(IH2)      A 331
      ATRO2=XMOLE(IAR)+XMOLE(IN)+XMOLE(IO)+XMOLE(IC)+XMOLE(IHE)+XMOLE(IH A 332
     1)                                                                 A 333
      GAMACT=(9.*XMOLE(ICO2)+7.*ATRO1+5.*ATRO2)/(7.*XMOLE(ICO2)+5.*ATRO1 A 334
     1+3.*ATRO2)                                                        A 335
      AACT=SQRT(GAMACT*ZA*RU*TA/WO)                                     A 336
      HOI=1.E+8*(4.70729*XMOLE(IN)+2.46741*XMOLE(IO)+.8986*XMOLE(INO)-3. A 337
     193146*XMOLE(ICO2)-1.13813*XMOLE(ICO)+7.11238*XMOLE(IC)+2.16013*XMO A 338
     2LE(IH))/WO                                                        A 339
      HACT=AACT**2/(GAMACT-1.)+HOI                                      A 340
      HFRO=HA-HACT                                                      A 341
   42 IF (LF.EQ.2) GO TO 44                                             A 342
      U5F=U5                                                            A 343
      A5F=AACT+((GAMACT-1.)/2.)*(UA-U5F)                                A 344
```

```
      IF (A5F.GT.0.) GO TO 43                                           A 345
      PRINT 63                                                          A 346
      TMAX1=TA                                                          A 347
      TMIN1=1.                                                          A 348
      P5F=.1                                                            A 349
      GO TO 47                                                          A 350
   43 P5F=PA*((A5F/AACT)**(2.*GAMACT/(GAMACT-1.)))                      A 351
      GO TO 45                                                          A 352
   44 P5F=P5                                                            A 353
      A5F=AACT*(P5F/PA)**((GAMACT-1.)/(2.*GAMACT))                      A 354
      U5F=2.*(AACT-A5F)/(GAMACT-1.)+UA                                  A 355
   45 M5F=U5F/A5F                                                       A 356
      T5F=TA*(A5F/AACT)**2                                              A 357
      IF (LG.EQ.0) GO TO 46                                             A 358
      RHO5F=P5F*WO/(RU*ZA*T5F)                                          A 359
      S5RF=SAR                                                          A 360
      H5F=HACT*(T5F/TA)                                                 A 361
      Z5F=ZA                                                            A 362
      GAM5F=GAMACT                                                      A 363
      CALL VISC (T5F,VIS5F)                                             A 364
      RE5F=RHO5F*U5F/VIS5F                                              A 365
      PRINT 98                                                          A 366
      PRINT 87                                                          A 367
      PRINT 88, P5F,RHO5F,T5F,H5F,S5RF,Z5F,GAM5F,A5F,U5F,M5F,RE5F       A 368
C                                                                       A 369
C     SHOCK CROSSING - FROZEN EXPANSION - EQUILIBRIUM POST SHOCK        A 370
C                                                                       A 371
      H5FSC=H5F+HFRO                                                    A 372
      TMIN2=TA                                                          A 373
      TMAX2=1.05*T5F*(2.*GAM5F*M5F**2-GAM5F+1.)*((GAM5F-1.)*M5F**2+2.)/(A 374
     1(GAM5F+1.)**2*M5F**2)                                             A 375
      CALL SNS (R5SF,U5SF,P5SF,H5SF,S5SRF,T5SF,A5SF,Z5SF,G5SF,M5SF,RHO5FA 376
     1,U5F,P5F,H5FSC,HT5F,PT5F,RT5F,ST5RF,TT5F,AT5F,ZT5F,GT5F,WO)       A 377
      RR5SF=R5SF/RHO5F                                                  A 378
      PRINT 102                                                         A 379
      PRINT 99                                                          A 380
      PRINT 104                                                         A 381
      PRINT 88, P5SF,R5SF,T5SF,H5SF,S5SRF,Z5SF,G5SF,A5SF,U5SF,M5SF,RR5SFA 382
      PRINT 106                                                         A 383
      PRINT 99                                                          A 384
      PRINT 107                                                         A 385
      QTZOF=(1./ZMIX)*SQRT(PT5F/BNR)*(HT5F-HW)                          A 386
      PRINT 108, PT5F,RT5F,TT5F,HT5F,ZT5F,GT5F,AT5F,QTZOF,BNR           A 387
C                                                                       A 388
```

```
C     SHOCK CROSSING-FROZEN EXPANSION-FROZEN POSTSHOCK                     A 389
C                                                                          A 390
      PRINT 102                                                            A 391
      PRINT 100                                                            A 392
      PRINT 104                                                            A 393
      P5SFF=P5F*(2.*GAMACT*M5F**2-GAMACT+1.)/(GAMACT+1.)                   A 394
      R5SFF=(RHO5F*(GAMACT+1.)*M5F**2)/((GAMACT-1.)*M5F**2+2.)             A 395
      RR5SFF=R5SFF/RHO5F                                                   A 396
      T5SFF=P5SFF*WO/(R5SFF*RU*ZA)                                         A 397
      H5SFF=H5F*T5SFF/T5F                                                  A 398
      G5SFF=GAMACT                                                         A 399
      A5SFF=A5F*SQRT(T5SFF/T5F)                                            A 400
      U5SFF=RHO5F*U5F/R5SFF                                                A 401
      M5SFF=U5SFF/A5SFF                                                    A 402
      S5SRFF=(ALOG(P5SFF/P5F)-GAMACT*ALOG(R5SFF/RHO5F))/(GAMACT-1.)+S5RF   A 403
      Z5SFF=ZA                                                             A 404
      PRINT 88, P5SFF,R5SFF,T5SFF,H5SFF,S5SRFF,Z5SFF,G5SFF,A5SFF,U5SFF,M   A 405
     15SFF,RR5SFF                                                          A 406
      PRINT 106                                                            A 407
      PRINT 100                                                            A 408
      PRINT 107                                                            A 409
      HT5FF=H5F+.5*U5F**2                                                  A 410
      TT5FF=T5SFF*(1.+((GAMACT-1.)*M5SFF**2)/2.)                           A 411
      PT5FF=P5SFF*(1.+((GAMACT-1.)*M5SFF**2)/2.)**(GAMACT/(GAMACT-1.))     A 412
      RT5FF=PT5FF*WO/(TT5FF*ZA*RU)                                         A 413
      ZT5FF=ZA                                                             A 414
      GT5FF=GAMACT                                                         A 415
      AT5FF=A5SFF*SQRT(TT5FF/T5SFF)                                        A 416
      QTZOFF=(1./ZMIX)*SQRT(PT5FF/BNR)*(HT5FF-HW)                          A 417
      PRINT 108, PT5FF,RT5FF,TT5FF,HT5FF,ZT5FF,GT5FF,AT5FF,QTZOFF,BNR      A 418
46    TMAX1=TA                                                             A 419
      TMIN1=T5F                                                            A 420
47    IF (LF.EQ.2) GO TO 50                                                A 421
C                                                                          A 422
C     LF=1 CASE                                                            A 423
C                                                                          A 424
      DELU=U5-UA                                                           A 425
      P5K(1)=PA                                                            A 426
      P5G(1)=ALOG10(PA)                                                    A 427
      DELPG=(P5G(1)-ALOG10(P5F))/49.                                       A 428
48    TABH(1)=HA                                                           A 429
      TABA(1)=1./AA                                                        A 430
      TABP(1)=P5K(1)                                                       A 431
      TABT(1)=TA                                                           A 432
```

```
      DO 49 J=2,50                                                      A 433
      P5G(J)=P5G(J-1)-DELPG                                             A 434
      P5K(J)=10.**P5G(J)                                                A 435
      CALL FIND (P5K(J),RHOK,HK,SAR,TK,AK,ZK,GK,WO,3,1)                 A 436
      TABH(J)=HK                                                        A 437
      TABA(J)=1./AK                                                     A 438
      TABP(J)=P5K(J)                                                    A 439
      TABT(J)=TK                                                        A 440
      TMAX1=TK                                                          A 441
   49 CONTINUE                                                          A 442
      CALL SIMR (TABH,TABA,50,50,TABANS)                                A 443
      IF (LF.EQ.2) GO TO 51                                             A 444
      CALL FTLUP (DELU,H5,2,NON,TABANS,TABH)                            A 445
      CALL FTLUP (H5,P5,-2,50,TABH,TABP)                                A 446
      CALL FTLUP (H5,T5,-2,50,TABH,TABT)                                A 447
      P5U=P5/1.01325E+5                                                 A 448
      CALL ROGO (P5U,R5,H5,S5R,T5,A5,ZZ5,GAM5,WO)                       A 449
      GO TO 52                                                          A 450
C                                                                       A 451
C     LF=2 CASE                                                         A 452
C                                                                       A 453
   50 CALL FIND (P5,R5,H5,SAR,T5,A5,ZZ5,GAM5,WO,3,1)                    A 454
      P5K(1)=PA                                                         A 455
      P5G(1)=ALOG10(PA)                                                 A 456
      DELPG=(P5G(1)-ALOG10(P5))/49.                                     A 457
      GO TO 48                                                          A 458
   51 U5=UA+TABANS(50)                                                  A 459
   52 M5=U5/A5                                                          A 460
      CALL VISC (T5,VIS5)                                               A 461
      RE5=R5*U5/VIS5                                                    A 462
      PRINT 101                                                         A 463
      PRINT 87                                                          A 464
      PRINT 88, P5,R5,T5,H5,SAR,ZZ5,GAM5,A5,U5,M5,RE5                   A 465
      PRINT 64                                                          A 466
      PRINT 93                                                          A 467
      DO 53 I=1,NUMSP                                                   A 468
      PRINT 97, SPECIE(I),XMOLE(I)                                      A 469
   53 CONTINUE                                                          A 470
      IF (IREP.EQ.0) GO TO 54                                           A 471
      PT5ES=.97*R5*U5**2                                                A 472
      HT5ES=H5+.5*U5**2                                                 A 473
      QTZOES=(1./ZMIX)*SQRT(PT5ES/BNR)*(HT5ES-HW)                       A 474
      P100=P5/(1.+(4.003/(RU*T1))*U5**2)                                A 475
      US10=1.333*U5                                                     A 476
```

```
      A10=SQRT((1.6667*RU*T1)/4.003)                                    A 477
      MS10=US10/A10                                                     A 478
      P10=4.*P5/(5.*MS10**2-1.)                                         A 479
      USIC=3.281*USI                                                    A 480
      U5C=3.281*U5                                                      A 481
      P4C=1.45E-4*P4                                                    A 482
      P2C=1.45E-4*P2                                                    A 483
      P1C=1.45E-4*P1                                                    A 484
      P5C=1.45E-4*P5                                                    A 485
      PT5C=1.45E-4*PT5ES                                                A 486
      QTZOEC=QTZOES/1.1349E+4                                           A 487
      P10C=7.501E-3*P10                                                 A 488
      P100C=7.501E-3*P100                                               A 489
      PRINT 65                                                          A 490
      PRINT 66                                                          A 491
      PRINT 67                                                          A 492
      PRINT 68                                                          A 493
      PRINT 105, P1C,P4C,P2C,P5C,PT5C,USIC,U5C,QTZOEC,P10C,P100C        A 494
54    TMIN2=TA                                                          A 496
      TMAX2=1.05*T5*(2.*GAM5*M5**2-GAM5+1.)*((GAM5-1.)*M5**2+2.)/((GAM5+A 497
     11.)**2*M5**2)                                                     A 498
      CALL SNS (RHO5S,U5S,P5S,H5S,S5SR,T5S,A5S,Z5S,GAME5S,M5S,R5,U5,P5,HA 499
     15,HT5,PT5,RT5,ST5R,TT5,AT5,ZT5,GAMET5,WO)                         A 500
      PRINT 102                                                         A 501
      PRINT 103                                                         A 502
      PRINT 104                                                         A 503
      RR5S=RHO5S/R5                                                     A 504
      PRINT 88, P5S,RHO5S,T5S,H5S,S5SR,Z5S,GAME5S,A5S,U5S,M5,RR5S       A 505
      PRINT 106                                                         A 506
      PRINT 103                                                         A 507
      PRINT 107                                                         A 508
      QTZO=(1./ZMIX)*SQRT(PT5/BNR)*(HT5-HW)                             A 509
      PRINT 108, PT5,RT5,TT5,HT5,ZT5,GAMET5,AT5,QTZO,BNR                A 510
      PRINT 69                                                          A 511
      PRINT 93                                                          A 512
      DO 55 I=1,NUMSP                                                   A 513
      PRINT 97, SPECIE(I),XMOLE(I)                                      A 514
55    CONTINUE                                                          A 515
56    NN=NN+1                                                           A 516
      IF (IREP.EQ.0.OR.NVEL.EQ.NN) GO TO 57                             A 517
      IF (NN.GT.10) GO TO 57                                            A 518
      U5=U5+U5I                                                         A 519
      GO TO 42                                                          A 520
57    IF(LD.NE.2) GO TO 110
```

```
      U5=U5-(FLOAT(NVEL)-1.)*U5I
      NN=0
      LD=1
      GO TO 111
110   IF (ISTET.EQ.1) GO TO 1                                           A 521
58    STOP                                                              A 522
C                                                                       A 523
C                                                                       A 524
59    FORMAT (//34H 1 CONDITIONS - QUIESCENT TEST GAS)                  A 525
60    FORMAT (/55H    P          RHO         T           H          GAM A 526
     1A)                                                                A 527
61    FORMAT (///26H NUMBER OF P3,T3 IN ARRARY)                         A 528
62    FORMAT (I5)                                                       A 529
63    FORMAT (///45H ASF IS NEGATIVE - FROZEN FLOW NOT CALCULATED)      A 530
64    FORMAT (//27H MOLE FRACTIONS IN REGION 5)                         A 531
65    FORMAT (//45H IMPORTANT PARAMETERS FOR SETTING UP EXP TUBE)       A 532
66    FORMAT (/46H P1,P4,P2,P5,PT5 IN PSI - P10,P100 IN MM OF HG)       A 533
67    FORMAT (36H US1,U5 IN FPS - QT5 IN BTU/FTSQ-SEC)                  A 534
68    FORMAT (/97H    P1         P4          P2          P5         PT5       U A 535
     1S1         U5          QT5         P10         P100)              A 536
69    FORMAT (//28H MOLE FRACTIONS IN REGION T5)                        A 537
70    FORMAT (//50H EXPANSION TUBE PROGRAM OF MILLER FOR GAS MIXTURES)  A 538
71    FORMAT (51H ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012)   A 539
72    FORMAT (//28H SHOCK TUBE PHASE OF PROGRAM)                        A 540
73    FORMAT (//37H MEASURED INPUTS FOR SHOCK TUBE PHASE)               A 541
74    FORMAT (/66H      RUN        P1          T1          US1         P2 A 542
     1 P4         T4)                                                   A 543
75    FORMAT (7E10.3)                                                   A 544
76    FORMAT (/68H      WO         XCO2        XN2         XO2         XAR A 545
     1 XHE        XH2)                                                  A 546
77    FORMAT (20H MAX COUNT EXCEEDED )                                  A 547
78    FORMAT (17H DERIVATIVE = 0. ,I5)                                  A 548
79    FORMAT (6E10.3)                                                   A 549
80    FORMAT (7H ICODE=,I5,5H  RI=,E12.3,7H  DELR=,E12.3)               A 550
81    FORMAT (//30H IMPERFECT HYDROGEN DRIVER GAS)                      A 551
82    FORMAT (//28H IMPERFECT HELIUM DRIVER GAS)                        A 552
83    FORMAT (//13H 4 CONDITIONS)                                       A 553
84    FORMAT (/75H    P          RHO         T           H          S/R        Z A 554
     1          A          W)                                           A 555
85    FORMAT (8E10.3)                                                   A 556
86    FORMAT (//32H 2 CONDITIONS- REAL GAS MIXTURES)                    A 557
87    FORMAT (/106H   P          RHO         T           H          S/R A 558
     1Z         GAME        A           U           M          NRE)     A 559
88    FORMAT (11E10.3)                                                  A 560
```

```
89     FORMAT (//36H RATIO- 2 CONDITIONS TO 1 CONDITIONS)                          A 561
90     FORMAT (/55H    P          RHO         T           H          MS1        US A 562
      11)                                                                          A 563
91     FORMAT (6E10.3)                                                             A 564
92     FORMAT (//27H MOLE FRACTIONS IN REGION 2)                                   A 565
93     FORMAT (/29H  SPECIE          MOLE FRACTION/)                               A 566
94     FORMAT (A10,E16.4)                                                          A 567
95     FORMAT (//33H CONDITIONS BEHIND STANDING SHOCK)                             A 568
96     FORMAT (//43H MOLE FRACTIONS BEHIND SHOCK AT SECOND DIA.)                   A 569
97     FORMAT (A10,E16.4)                                                          A 570
98     FORMAT (//34H 5 CONDITIONS FOR FROZEN EXPANSION)                            A 571
99     FORMAT (41H FROZEN EXPANSION--EQUILIBRIUM POST SHOCK)                       A 572
100    FORMAT (37H FROZEN EXPANSION-- FROZEN POST SHOCK)                           A 573
101    FORMAT (//39H 5 CONDITIONS FOR EQUILIBRIUM EXPANSION)                       A 574
102    FORMAT (//42H STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK)                    A 575
103    FORMAT (46H EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK)                  A 576
104    FORMAT (/109H   P          RHO         T           H          S/R           A 577
      1Z          GAME        A          U           M          R5S/R5)            A 578
105    FORMAT (10E10.3)                                                            A 579
106    FORMAT (//46H STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK)                A 580
107    FORMAT (/85H    P          RHO         T           H          Z           G A 581
      1AME        A          QT          RN)                                       A 582
108    FORMAT (9E10.3)                                                             A 583
109    FORMAT (1H1,A10/)                                                           A 584
       END                                                                         A 585-
       SUBROUTINE VISC (T1,VISMIX)                                                 B   1
       DIMENSION VIS(6), W(6), XMF(6), PHI(6,6), SUM(6,6), SUMM(6)                 B   2
       COMMON /BLK4/ NUMSP,JINDX,IAR,IN2,IO2,ICO2,BOZ,XAR,XN2,XO2,XCO2             B   3
       COMMON /BLK6/ IHE,IH2,IH,XHE,XH2                                            B   4
1      VIS(1)=3.33E-7*T1**.739                                                     B   5
       VIS(5)=3.92E-7*T1**.7                                                       B   6
       IF (T1.GT.950.) GO TO 2                                                     B   7
       VIS(2)=(-.973034+.5522198*T1-1.613866E-4*T1**2)*1.E-7                       B   8
       VIS(3)=(22.99167+.5558644*T1-1.84356E-4*T1**2)*1.E-7                        B   9
       VIS(4)=(19.93933+.6623589*T1-2.04096E-4*T1**2)*1.E-7                        B  10
       VIS(6)=(23.877+.21918*T1-4.4304E-5*T1**2)*1.E-7                             B  11
       GO TO 3                                                                     B  12
2      VIS(2)=(150.2874+.248903*T1-6.174675E-6*T1**2)*1.E-7                        B  13
       VIS(3)=(163.8798+.2460075*T1-7.738745E-6*T1**2)*1.E-7                       B  14
       VIS(4)=(230.3+.2559657*T1-2.264286E-6*T1**2)*1.E-7                          B  15
       VIS(6)=(63.197+.14093*T1-8.6387E-6*T1**2)*1.E-7                             B  16
3      W(1)=39.944                                                                 B  17
       W(2)=44.011                                                                 B  18
       W(3)=28.016                                                                 B  19
```

```
      W(4)=32.                                                          B  20
      W(5)=4.003                                                        B  21
      W(6)=2.016                                                        B  22
      XMF(1)=XAR                                                        B  23
      XMF(2)=XCO2                                                       B  24
      XMF(3)=XN2                                                        B  25
      XMF(4)=XO2                                                        B  26
      XMF(5)=XHE                                                        B  27
      XMF(6)=XH2                                                        B  28
      DO 5 I=1,6                                                        B  29
      DO 5 J=1,6                                                        B  30
      PHI(I,J)=(((1.+SQRT(VIS(I)/VIS(J))*(W(J)/W(I))**.25)**2)/(2.8284*S B  31
     1QRT(1.+W(I)/W(J))))                                               B  32
      IF (XMF(I).EQ.0.) GO TO 4                                         B  33
      SUM(I,J)=PHI(I,J)*XMF(J)/XMF(I)                                   B  34
      GO TO 5                                                           B  35
    4 SUM(I,J)=0.                                                       B  36
    5 CONTINUE                                                          B  37
      DO 6 I=1,6                                                        B  38
      SUMM(I)=SUM(I,1)+SUM(I,2)+SUM(I,3)+SUM(I,4)+SUM(I,5)+SUM(I,6)     B  39
      IF (SUMM(I).NE.0.) GO TO 6                                        B  40
      SUMM(I)=1.                                                        B  41
      VIS(I)=0.                                                         B  42
    6 CONTINUE                                                          B  43
      VISMIX=(VIS(1)/SUMM(1))+(VIS(2)/SUMM(2))+(VIS(3)/SUMM(3))+(VIS(4)/ B  44
     1SUMM(4))+(VIS(5)/SUMM(5))+(VIS(6)/SUMM(6))                        B  45
      RETURN                                                            B  46
      END                                                               B  47-
      SUBROUTINE SHOCK (BN,CN,DN,RN,UN,PN,HN)                           C   1
      BN=RN*UN                                                          C   2
      CN=PN+RN*UN**2                                                    C   3
      DN=HN+.5*UN**2                                                    C   4
      RETURN                                                            C   5
      END                                                               C   6-
      FUNCTION FOFX (RN)                                                D   1
      COMMON /BLK1/ BT4,CT4,RHOG,T1,GAM4,W4,T4,P4,P1,TII,AI,ZI,GI,SR    D   2
      FOFX=RHOG-(BT4*RN**2+CT4*RN**3)                                   D   3
      RETURN                                                            D   4
      END                                                               D   5-
      FUNCTION FOFR (RNI)                                               E   1
      COMMON /BLK2/ BTI,CTI,TI,CVRI,S4R,SREF,DBTI,DCTI                  E   2
      A=CVRI*ALOG(TI)                                                   E   3
      B=BTI+TI*DBTI                                                     E   4
      C=CTI+TI*DCTI                                                     E   5
```

```
      FOFR=A-ALOG(RNI)-(RNI*B)-(RNI**2/2.)*C+SREF-S4R                    E   6
    1 RETURN                                                             E   7
      END                                                                E   8-
      FUNCTION FOFMS (MSN)                                               F   1
      COMMON /BLK1/ BT4,CT4,RHOG,T1,GAM4,W4,T4,P4,P1,T11,AI,ZI,GI,SR     F   2
      COMMON /BLK6/ IHE,IH2,IH,XHE,XH2                                   F   3
      COMMON /BLK7/ GE,WO                                                F   4
      REAL MSN                                                           F   5
      A=P4/P1                                                            F   6
      B=SQRT((GE*W4*T1)/(GAM4*WO*T4))                                    F   7
      C=(GAM4-1.)/(GE+1.)                                                F   8
      D=2.*GAM4/(GAM4-1.)                                                F   9
      E=(1.-B*C*(MSN-1./MSN))**D                                         F  10
      FOFMS=SQRT((A*(GE+1.)*E+GE-1.)/(2.*GE))                            F  11
      RETURN                                                             F  12
      END                                                                F  13-
      SUBROUTINE SIMR (TABX,TABY,N,NMAX,TABANS)                          G   1
      DIMENSION TABX(NMAX), TABY(NMAX), TABANS(NMAX)                     G   2
      DIMENSION NP(4)                                                    G   3
      COMMON /BLK3/ LB,LD,LF,LG,NON,LU,NDRIV,ICOUNT,SAR,LCODE,DELU       G   4
      TABANS(1)=0                                                        G   5
      DEN=2.                                                             G   6
      K=2                                                                G   7
      ICOUNT=0                                                           G   8
      DO 2 J=K,N                                                         G   9
      NON=J                                                              G  10
      DELX=(TABX(J)-TABX(J-1))/DEN                                       G  11
      X=TABX(J-1)+DELX                                                   G  12
      CALL FTLUP (X,Y,2,N,TABX,TABY)                                     G  13
      SUM=(TABY(J-1)+4.*Y+TABY(J))*(ABS(DELX))/3.                        G  14
      TABANS(J)=TABANS(J-1)+SUM                                          G  15
      IF (LU.NE.20) GO TO 1                                              G  16
    1 CONTINUE                                                           G  17
      IF (LF.EQ.2.OR.LU.EQ.20) GO TO 2                                   G  18
      IF (TABANS(J).LT.DELU) GO TO 2                                     G  19
      ICOUNT=ICOUNT+1                                                    G  20
      IF (ICOUNT.GT.3) GO TO 3                                           G  21
    2 CONTINUE                                                           G  22
    3 RETURN                                                             G  23
      END                                                                G  24-
      SUBROUTINE SNS (RX,UX,PX,HX,SX,TX,AX,ZX,GX,MX,R5X,U5X,P5X,H5X,HTX, H   1
     1PTX,RTX,STX,TTX,ATX,7TX,GTX,WO)                                    H   2
      DIMENSION XMOLE(30), SPECIE(30)                                    H   3
      REAL MS1,M2,M5,M5S,MX,MN,MNS                                       H   4
```

```
      COMMON /BLK4/ NUMSP,JINDX,IAR,IN2,IO2,ICO2,BOZ,XAR,XN2,XO2,XCO2
      COMMON /BLK5/ TMAX1,TMAX2,TMIN1,TMIN2,XMOLE,SPECIE
      COMMON /BLK6/ IHE,IH2,IH,XHE,XH2
      CALL SHOCK (BSN,CSN,DSN,R5X,U5X,P5X,H5X)
      RX=10.*R5X
      HTX=DSN
1     UX=BSN/RX
      PX=CSN-BSN*UX
      HX=DSN-.5*UX**2
      CALL FIND (PX,RNEW,HX,SX,TX,AX,ZX,GX,WO,2,2)
      IF (ABS(1.-RX/RNEW).LE..001) GO TO 2
      RX=RNEW
      GO TO 1
2     RX=RNEW
      MX=UX/AX
      PTX=PX*(1.+((GX-1.)/2.)*MX**2)**(GX/(GX-1.))
      CALL FIND (PTX,RTX,HTX,STX,TTX,ATX,ZTX,GTX,WO,2,2)
      RETURN
      END
      SUBROUTINE BDT (BTM,CTM,DBM,DCM,D2BM,D2CM,TM)
      COMMON /BLK3/ LB,LD,LF,LG,NON,LU,NDRIV,ICOUNT,SAR,LCODE,DELU
      IF (NDRIV.EQ.1) GO TO 1
C
C     HELIUM  USED AS DRIVER GAS
C
      AMT1=15.8922-ALOG(TM)
      AMT2=-3.7156E-3*TM
      BTM=3.3565E-6*AMT1**3-2.0085E-3*EXP(AMT2)
      CTM=5.633E-12*AMT1**6
      DBM=(-1.00695E-5/TM)*AMT1**2+7.4628E-6*EXP(AMT2)
      DCM=(-3.3798E-11/TM)*AMT1**5
      D2BM=(2.0139E-5/TM**2)*AMT1+(1.00695E-5/TM**2)*AMT1**2-2.7729E-8*E
     1XP(AMT2)
      D2CM=(1.6899E-10/TM**2)*AMT1**4+(3.3798E-11/TM**2)*AMT1**5
      GO TO 2
C
C     HYDROGEN USED AS DRIVER GAS
C
1     BTM=1.6994E-3*TM**.25
      CTM=2.1E-4
      DBM=4.2485E-4*TM**(-.75)
      DCM=D2CM=0.
      D2BM=-3.1864E-4*TM**(-1.75)
2     RETURN
```

```
      END
      SUBROUTINE SC (R2I,UI,PI,HI,R1I,US,P,H,WO)
      DIMENSION XMOLE(30), SPECIE(30)
      COMMON /BLK1/ BT4,CT4,RHOG,T1,GAM4,W4,T4,P4,P1,TII,AI,ZI,GI,SR
      COMMON /BLK3/ LB,LD,LF,LG,NON,LU,NDRIV,ICOUNT,SAR,LCODE,DELU
      COMMON /BLK4/ NUMSP,JINDX,IAR,IN2,IO2,ICO2,BOZ,XAR,XN2,XO2,XCO2
      COMMON /BLK5/ TMAX1,TMAX2,TMIN1,TMIN2,XMOLE,SPECIE
      COMMON /BLK6/ IHE,IH2,IH,XHE,XH2
      R2I=10.*R1I
      IF (LB.EQ.1) GO TO 2
      CALL SHOCK (B,C,D,R1I,US,P,H)
1     UI=US*(1.-R1I/R2I)
      PI=C-(R2I*(US-UI)**2)
      HI=D-.5*(US-UI)**2
      CALL FIND (PI,RNEW,HI,SR,TII,AI,ZI,GI,WO,2,2)
      IF (ABS(1.-RNEW/R2I).LE..001) GO TO 3
      R2I=RNEW
      GO TO 1
2     US=SQRT((PI-P)/(R1I*(1.-R1I/R2I)))
      UI=US*(1.-R1I/R2I)
      HI=H+.5*(US**2-(US-UI)**2)
      CALL FIND (PI,RNEW,HI,SR,TII,AI,ZI,GI,WO,2,2)
      IF (ABS(1.-RNEW/R2I).LE..001) GO TO 3
      R2I=RNEW
      GO TO 2
3     R2I=RNEW
      RETURN
      END
      SUBROUTINE SOLUT (U3,P3,U2,P2,M,N,UR,P)
      DIMENSION U3(20), P3(20), U2(10), P2(10), U(2)
      FUNCD(PP,UU,R)=PP-UU*R
      FUNAB(P,PP,U,UU)=(P-PP)/(U-UU)
C
C     USE END POINTS FOR FIRST INTERSECTION
C
      MR=1
      NR=1
      IF (P2(1).GT.P2(2)) NR=-NR
      IF (P3(1).GT.P3(2)) MR=-MR
      P31=P3(1)
      P32=P3(M)
      P21=P2(1)
      P22=P2(N)
      U21=U2(1)
```

```
        U22=U2(N)                                                          K  17
        U31=U3(1)                                                          K  18
        U32=U3(M)                                                          K  19
 1      AA=FUNAB(P22,P21,U22,U21)                                          K  20
        BB=FUNAB(P32,P31,U32,U31)                                          K  21
        CC=FUNCD(P21,U21,AA)                                               K  22
        DD=FUNCD(P31,U31,BB)                                               K  23
        UR=(CC-DD)/(BB-AA)                                                 K  24
        PR=CC+UR*AA                                                        K  25
        CALL FTLUP (PR,U(1),NR,N,P2,U2)                                    K  26
        CALL FTLUP (PR,U(2),MR,M,P3,U3)                                    K  27
        IF (ABS((U(1)-U(2))/U(1))-.0001) 3,3,2                             K  28
 2      P31=P32                                                            K  29
        P32=PR                                                             K  30
        P21=P22                                                            K  31
        P22=PR                                                             K  32
        U31=U32                                                            K  33
        U32=U(2)                                                           K  34
        U21=U22                                                            K  35
        U22=U(1)                                                           K  36
        GO TO 1                                                            K  37
 3      P=PR                                                               K  38
        RETURN                                                             K  39
        END                                                                K  40-
        SUBROUTINE FIND (P,RHO,H,SR,T,AM,ZM,GAME,MU,K,L)                   L   1
C                                                                          L   2
C       FIND OBTAINS THERMODYNAMIC PROPERTIES FROM SUBROUTINE ROGO WITH-   L   3
C              (1) PRESSURE AND DENSITY (K=1)                              L   4
C              (2) PRESSURE AND ENTHALPY (K=2)                             L   5
C              (3) PRESSURE AND ENTROPY (K=3)                              L   6
C              (4) DENSITY AND ENTHALPY (K=4)                              L   7
C                                                                          L   8
C                                                                          L   9
C       UPPER LIMIT ON T AS REQUIRED IN ITERATION DENOTED BY L             L  10
C            L=1 DENOTES TUP=TMAX1 FOR FREESTREAM CONDITIONS               L  11
C            L=2 DENOTES TUP=TMAX2 FOR STATIC CONDITIONS BEHIND SHOCK      L  12
C                                                                          L  13
C       IF TMAX1=0. THEN TUP=8000 DEG K                                    L  14
C       IF TMAX2=0. THEN TUP=16,000 DEG K                                  L  15
C                                                                          L  16
        DIMENSION TABT(3), TABR(3), TABH(3), TABSR(3), TABAM(3), TABZM(3), L  17
       1 TABG(3), TABXM(3,30), TABXMO(80), TABFIT(30)                      L  18
        DIMENSION TABPM(3), TABHM(3), TABSRM(3), TABTM(3), TABAMM(3), TABZ L  19
       1MM(3), TABGM(3)                                                    L  20
```

```
      DIMENSION XMOLE(30), SPECIE(30)                                   L  21
      COMMON /BLK4/ NUMSP,JINDX,IAR,IN2,IO2,ICO2,BOZ,XAR,XN2,XO2,XCO2   L  22
      COMMON /BLK5/ TMAX1,TMAX2,TMIN1,TMIN2,XMOLE,SPECIE                L  23
      COMMON /BLK6/ IHE,IH2,IH,XHE,XH2                                  L  24
      REAL MU                                                           L  25
      NN=0                                                              L  26
      IF (K.NE.4) GO TO 10                                              L  27
      II=0                                                              L  28
      MN=0                                                              L  29
      PLOW=.01*RHO*ABS(H)                                               L  30
      PPP=PLOW                                                          L  31
      PUP=.51*RHO*ABS(H)                                                L  32
      P=(PUP-PLOW)/2.+PLOW                                              L  33
    1 DELP=(PUP-PLOW)/2.                                                L  34
      IF (MN.EQ.0) GO TO 2                                              L  35
      P=PUP-DELP                                                        L  36
    2 PN=P/1.01325E+5                                                   L  37
      TLOW=0.                                                           L  38
      IF (L.EQ.1) GO TO 3                                               L  39
      TUP=1.6E+4                                                        L  40
      GO TO 4                                                           L  41
    3 TUP=8.E+3                                                         L  42
    4 MN=MN+1                                                           L  43
      NN=0                                                              L  44
      GO TO 16                                                          L  45
    5 IF (ABS(1.-H/HK).LE..001) GO TO 41                                L  46
      IF (HK.LT.H) GO TO 6                                              L  47
      PUP=P                                                             L  48
      PLOW=P-DELP                                                       L  49
      IF (DELP.GT.PPP) GO TO 1                                          L  50
      TABPM(1)=PUP                                                      L  51
      TABPM(3)=PLOW                                                     L  52
      NNN=-2                                                            L  53
      GO TO 7                                                           L  54
    6 PLOW=P                                                            L  55
      PUP=P+DELP                                                        L  56
      IF (DELP.GT.PPP) GO TO 1                                          L  57
      TABPM(1)=PLOW                                                     L  58
      TABPM(3)=PUP                                                      L  59
      NNN=2                                                             L  60
    7 TABHM(1)=HK                                                       L  61
      TABSRM(1)=SR                                                      L  62
      TABTM(1)=T                                                        L  63
      TABAMM(1)=AM                                                      L  64
```

```
      TABZMM(1)=ZM
      TABGM(1)=GAME
      DELP=(TABPM(3)-TABPM(1))/2•
      TABPM(2)=TABPM(1)+DELP
      DO 9 JK=2•3
      P=TABPM(JK)
      II=1
      GO TO 2
8     TABHM(JK)=HK
      TABSRM(JK)=SR
      TABTM(JK)=T
      TABAMM(JK)=AM
      TABZMM(JK)=ZM
      TABGM(JK)=GAME
9     CONTINUE
      CALL FTLUP (H•SR•NNN,3•TABHM•TABSRM)
      CALL FTLUP (H•AM•NNN,3•TABHM•TABAMM)
      CALL FTLUP (H•ZM•NNN,3•TABHM•TABZMM)
      CALL FTLUP (H•T•NNN•3•TABHM•TABTM)
      CALL FTLUP (H•P•NNN•3•TABHM•TABPM)
      CALL FTLUP (H•GAME•NNN•3•TABHM•TABGM)
      GO TO 41
10    PN=P/1•01325E+5
      IF (L•EQ•2) GO TO 12
      IF (TMAX1•EQ•0•) GO TO 11
      TUP=TMAX1
      GO TO 14
11    TUP=8•E+3
      GO TO 14
12    IF (TMAX2•EQ•0•) GO TO 13
      TUP=TMAX2
      GO TO 14
13    TUP=1•6E+4
14    IF (L•EQ•2) GO TO 15
      TLOW=TMIN1
      GO TO 16
15    TLOW=TMIN2
16    T=(TUP-TLOW)/2•+TLOW
17    DELT=(TUP-TLOW)/2•
      IF (NN•EQ•0) GO TO 18
      T=TUP-DELT
18    CALL ROGO (PN•RHOA•HA•SAR•T•AM•ZM•GAME•MU)
      NN=NN+1
      IF (K•EQ•2) GO TO 23
```

```
      IF (K.EQ.3) GO TO 24
C
C     CONVERGENCE TEST FOR K=1
C
      IF (ABS(1.-RHO/RHOA).LE..001) GO TO 36
      IF (RHO.LT.RHOA) GO TO 21
19    TUP=T
      TLOW=T-DELT
      IF (DELT.GT.250.) GO TO 17
      TABT(1)=TUP
      TABT(3)=TLOW
      IF (K.EQ.1.OR.K.EQ.4) GO TO 20
      N=-2
      GO TO 25
20    N=2
      GO TO 25
21    TLOW=T
      TUP=T+DELT
      IF (DELT.GT.250.) GO TO 17
      TABT(1)=TLOW
      TABT(3)=TUP
      IF (K.EQ.1.OR.K.EQ.4) GO TO 22
      N=2
      GO TO 25
22    N=-2
      GO TO 25
C
C     CONVERGENCE TEST FOR K=2
C
23    IF (ABS(1.-H/HA).LE..001) GO TO 37
      IF (HA.LT.H) GO TO 21
      GO TO 19
C
C     CONVERGENCE TEST FOR K=3
C
24    IF (ABS(1.-SR/SAR).LE..0001) GO TO 38
      IF (SAR.LT.SR) GO TO 21
      GO TO 19
C
C     INTERPOLATION FOR DELT LESS THAN 250 DEG K
C
25    TABR(1)=RHOA
      TABH(1)=HA
      TABSR(1)=SAR
```

```
      TABAM(1)=AM                                                       L 153
      TABZM(1)=ZM                                                       L 154
      TABG(1)=GAME                                                      L 155
      DO 26 J=1,NUMSP                                                   L 156
      TABXM(1,J)=XMOLE(J)                                               L 157
   26 CONTINUE                                                          L 158
      DELT=(TABT(3)-TABT(1))/2.                                         L 159
      TABT(2)=TABT(1)+DELT                                              L 160
      DO 28 I=2,3                                                       L 161
      T=TABT(I)                                                         L 162
      CALL ROGO (PN,RHOA,HA,SAR,T,AM,ZM,GAME,MU)                        L 163
      DO 27 J=1,NUMSP                                                   L 164
      TABXM(I,J)=XMOLE(J)                                               L 165
   27 CONTINUE                                                          L 166
      TABR(I)=RHOA                                                      L 167
      TABH(I)=HA                                                        L 168
      TABSR(I)=SAR                                                      L 169
      TABAM(I)=AM                                                       L 170
      TABZM(I)=ZM                                                       L 171
      TABG(I)=GAME                                                      L 172
   28 CONTINUE                                                          L 173
      IJK=0                                                             L 174
      DO 29 I=1,3                                                       L 175
      DO 29 J=1,NUMSP                                                   L 176
      IJK=IJK+1                                                         L 177
      TABXMO(IJK)=TABXM(I,J)                                            L 178
   29 CONTINUE                                                          L 179
      DO 30 J=1,NUMSP                                                   L 180
      TABFIT(J)=J                                                       L 181
   30 CONTINUE                                                          L 182
      IY=3*NUMSP                                                        L 183
      IF (K.EQ.2) GO TO 32                                              L 184
      IF (K.EQ.3) GO TO 34                                              L 185
      CALL FTLUP (RHO,T,N,3,TABR,TABT)                                  L 186
      CALL FTLUP (RHO,HK,N,3,TABR,TABH)                                 L 187
      CALL FTLUP (RHO,SR,N,3,TABR,TABSR)                                L 188
      CALL FTLUP (RHO,AM,N,3,TABR,TABAM)                                L 189
      CALL FTLUP (RHO,ZM,N,3,TABR,TABZM)                                L 190
      CALL FTLUP (RHO,GAME,N,3,TABR,TABG)                               L 191
      DO 31 JJ=1,NUMSP                                                  L 192
      FIT=JJ                                                            L 193
      CALL DISCOT (FIT,RHO,TABFIT,TABXMO,TABR,02,IY,3,XMOLE(JJ))        L 194
   31 CONTINUE                                                          L 195
      IF (K.EQ.1) GO TO 40                                              L 196
```

```
      IF (II.EQ.1) GO TO 8                                              L 197
      GO TO 5                                                           L 198
32    CALL FTLUP (H,T,N,3,TABH,TABT)                                    L 199
      CALL FTLUP (H,RHO,N,3,TABH,TABR)                                  L 200
      CALL FTLUP (H,SR,N,3,TABH,TABSR)                                  L 201
      CALL FTLUP (H,AM,N,3,TABH,TABAM)                                  L 202
      CALL FTLUP (H,ZM,N,3,TABH,TABZM)                                  L 203
      CALL FTLUP (H,GAME,N,3,TABH,TABG)                                 L 204
      DO 33 JJ=1,NUMSP                                                  L 205
      FIT=JJ                                                            L 206
      CALL DISCOT (FIT,H,TABFIT,TABXMO,TABH,02,IY,3,XMOLE(JJ))          L 207
33    CONTINUE                                                          L 208
      GO TO 41                                                          L 209
34    CALL FTLUP (SR,RHO,N,3,TABSR,TABR)                                L 210
      CALL FTLUP (SR,H,N,3,TABSR,TABH)                                  L 211
      CALL FTLUP (SR,T,N,3,TABSR,TABT)                                  L 212
      CALL FTLUP (SR,AM,N,3,TABSR,TABAM)                                L 213
      CALL FTLUP (SR,ZM,N,3,TABSR,TABZM)                                L 214
      CALL FTLUP (SR,GAME,N,3,TABSR,TABG)                               L 215
      DO 35 JJ=1,NUMSP                                                  L 216
      FIT=JJ                                                            L 217
      CALL DISCOT (FIT,SR,TABFIT,TABXMO,TABSR,02,IY,3,XMOLE(JJ))        L 218
35    CONTINUE                                                          L 219
      GO TO 41                                                          L 220
36    IF (K.EQ.4) GO TO 39                                              L 221
      H=HA                                                              L 222
      SR=SAR                                                            L 223
      GO TO 41                                                          L 224
37    RHO=RHOA                                                          L 225
      SR=SAR                                                            L 226
      GO TO 41                                                          L 227
38    H=HA                                                              L 228
      RHO=RHOA                                                          L 229
      GO TO 41                                                          L 230
39    HK=HA                                                             L 231
      SR=SAR                                                            L 232
      GO TO 5                                                           L 233
40    H=HK                                                              L 234
41    RETURN                                                            L 235
      END                                                               L 236-
      SUBROUTINE ROGO (PN,RHOAN,HA,SOR,T,AM,XZ,GAMMAE,MU)               M   1
C                                                                       M   2
C     PROGRAM OF ALLISON(NASA TN D-3538) AND NEWMAN(NASA TN D-3540)     M   3
C     COMPUTES THERMOCHEMICAL EQUILIBRIUM PROPERTIES OF GAS MIXTURES    M   4
```

```
C     REQUIRES INPUTS OF P AND T                                          M   5
C                                                                         M   6
      COMMON /BLK4/ NUMSP,JINDX,IAR,IN2,IO2,ICO2,BOZ,XAR,XN2,XO2,XCO2      M   7
      COMMON /BLK5/ TMAX1,TMAX2,TMIN1,TMIN2,XMOLE,SPECIE                  M   8
      COMMON /BLK6/ IHE,IH2,IH,XHE,XH2                                    M   9
      REAL NO,M,LAMB,LAMBDA,MU,NE,NEGFRT,LOGNE,MASSFR,LMIN                M  10
      REAL INTENE,LGEORT,LGRORE                                           M  11
      INTEGER F(30),V(30,10)                                              M  12
      DIMENSION LB(30), M(30), DELHF(30), BETA(30), NDEBUG(30), IPIVOT(1  M  13
     10), R(10,10), SUMAY(10,1), G(30,30), E(30,30), BE(30,10), ALPHAE(3  M  14
     20,10), OMEGA(30,10), OMEGAX(30,10), XOMEG(30,4), XOMEGX(30,4), Z(3  M  15
     30), SIGMA(10), U(10), DELTA(10), GAMMA(10), XX(10), Q(30), Y(30),   M  16
     4X(30), A(30,9), HORT(30), FORT(30), NEGFRT(30), PI(9,2), XPRIME(30  M  17
     5), MASSFR(30), CAPX(50), YINT(30,5), CSUBP(30), PSI(30,2), CON(10,  M  18
     62), DXDT(30), RR(10,10), O(10,10)                                   M  19
      DIMENSION HEPG(30), DMSFRDT(30)                                     M  20
      DIMENSION XMOLE(30), SPECIE(30)                                     M  21
      H=6.62517E-27                                                       M  22
      XK=1.38044E-16                                                      M  23
      PREF=1.013250E+6                                                    M  24
      NO=6.02322E+23                                                      M  25
      C=2.99793E+10                                                       M  26
      IF (BOZ.EQ.1.) GO TO 3                                              M  27
      BOZ=1.                                                              M  28
      EA=1.E-8                                                            M  29
      ER=1.E-1                                                            M  30
      DO 2 I=1,NUMSP                                                      M  31
      READ (5,76) SPECIE(I),LB(I),F(I),NDEBUG(I),M(I),DELHF(I),BETA(I)    M  32
      IL=LB(I)                                                            M  33
C     IF NDEBUG EQUALS 0, DEBUG                                           M  34
      READ (5,77) (G(I,L),E(I,L),L=1,IL)                                  M  35
      IF (F(I).EQ.0) GO TO 2                                              M  36
      IF (F(I).EQ.2) GO TO 1                                              M  37
      READ (5,78) (BE(I,L),ALPHAE(I,L),OMEGA(I,L),OMEGAX(I,L),V(I,L),L=1  M  38
     1,IL)                                                                M  39
      GO TO 2                                                             M  40
    1 READ (5,77) BE(I,1),ALPHAE(I,1)                                     M  41
      READ (5,77) (XOMEG(I,LW),XOMEGX(I,LW),LW=1,4)                       M  42
    2 CONTINUE                                                            M  43
      READ (5,79) ((A(I,J),J=1,JINDX),I=1,NUMSP)                          M  44
    3 DO 4 I=1,NUMSP                                                      M  45
    4 YINT(I,1)=1.E-20                                                    M  46
      YINT(IO2,1)=1.E-5                                                   M  47
      IF (XAR.EQ.0.) GO TO 5                                              M  48
```

```
      YINT(IAR,1)=XAR/MU
5     IF (XN2.EQ.0.) GO TO 6
      YINT(IN2,1)=XN2/MU
6     IF (XO2.EQ.0.) GO TO 7
      YINT(IO2,1)=XO2/MU
7     IF (XCO2.EQ.0.) GO TO 8
      YINT(ICO2,1)=XCO2/MU
8     IF (XHE.EQ.0.) GO TO 9
      YINT(IHE,1)=XHE/MU
9     IF (XH2.EQ.0.) GO TO 10
      YINT(IH2,1)=XH2/MU
10    RHOO=PREF*MU/(NO*XK*273.15)
      DO 11 I=1,NUMSP
11    IF (YINT(I,1).EQ.0.) YINT(I,1)=1.E-20
      AO=SQRT(1.4*(PREF/RHOO))
      NUMT=NCAPX=1
      LEEBOB=INDEP=0
      IF (INDEP.NE.0) GO TO 13
      DO 12 KP=1,NCAPX
12    CAPX(KP)=ALOG10(PN)
13    DO 75 KI=1,NUMT
      IF (LEEBOB.EQ.1) PUNCH 83, T
      NY=1
      PART=H*C/(XK*T)
      DO 21 I=1,NUMSP
      IL=LB(I)
      IF (F(I).EQ.1) GO TO 15
      IF (F(I).EQ.2) GO TO 18
      QSUM=0.
      FPQSUM=0.
      SPQSUM=0.
      DO 14 L=1,IL
      Z(L)=PART*E(I,L)
      GEZ=G(I,L)*EXP(-Z(L))
      QSUM=QSUM+GEZ
      FPQSUM=FPQSUM+GEZ*Z(L)
14    SPQSUM=SPQSUM+(Z(L)-2.)*GEZ*Z(L)
      FPQSUM=FPQSUM/T
      SPQSUM=SPQSUM/T**2
      QI=(M(I)*T*.32807618)**1.5*QSUM*.13623883*T
      GO TO 20
15    QSUM=0.
      FPQSUM=0.
      SPQSUM=0.
```

```
      DO 17 L=1,IL
      Z(L)=PART*E(I,L)
      SIGMA(L)=PART*(BE(I,L)-.5*ALPHAE(I,L))
      U(L)=PART*(OMEGA(I,L)-2.*OMEGAX(I,L))
      DELTA(L)=ALPHAE(I,L)*1./(BE(I,L)-.5*ALPHAE(I,L))
      GAMMA(L)=(BE(I,L)/OMEGA(I,L))**2*1./(1.-.5*ALPHAE(I,L)/BE(I,L))
      XX(L)=OMEGAX(I,L)/(OMEGA(I,L)-2.*OMEGAX(I,L))
      THREE=0.
      FOUR=0.
      FIVE=0.
      NV=V(I,L)+1
      DO 16 IV=1,NV
      W=IV-1
      CC=(1.-W*DELTA(L))
      AA=SIGMA(L)*CC
      BB=U(L)*(W-XX(L)*W*(W-1.))
      ONE1=1./AA+8.*GAMMA(L)/(AA**2*CC)+.33333333+AA/12.
      TWO2=1./AA+16.*GAMMA(L)/(AA**2*CC)-AA/12.-384.*GAMMA(L)**2/(AA**3*
     1CC**2)
      THREE=THREE+ONE1*EXP(-BB)
      FOUR=FOUR+(BB*ONE1+TWO2)*EXP(-BB)
   16 FIVE=FIVE+((BB**2*ONE1+2.*BB*TWO2+GAMMA(L)/(AA**2*CC)*(48.-3456.*G
     1AMMA(L)/(AA*CC)+46080.*GAMMA(L)**2/(AA**2*CC**2))+2./AA)*EXP(-BB))
      GEZ=G(I,L)*EXP(-Z(L))
      Q(L)=THREE/BETA(I)*GEZ
      QSUM=QSUM+Q(L)
      FPQSUM=FPQSUM+(FOUR+THREE*Z(L))*GEZ
   17 SPQSUM=SPQSUM+(Z(L)*(Z(L)-2.)*THREE+2.*(Z(L)-1.)*FOUR+FIVE)*GEZ
      FPQSUM=FPQSUM/(T*BETA(I))
      SPQSUM=SPQSUM/(T**2*BETA(I))
      QI=(M(I)*T*.32807618)**1.5*QSUM*.13623883*T
      GO TO 20
   18 SIGMA(1)=PART*(BE(I,1)-.5*ALPHAE(I,1))
      PROD=1.
      SUM1=0.
      SUM2=0.
      DO 19 LW=1,4
      U(LW)=PART*(XOMEG(I,LW)-XOMEGX(I,LW))
      PROD=PROD*(1.-EXP(-U(LW)))
      BTM=EXP(U(LW))-1.
      SUM1=SUM1+U(LW)/BTM
   19 SUM2=SUM2+U(LW)**2*EXP(U(LW))/BTM**2
      QSUM=G(I,1)/(BETA(I)*SIGMA(1)*PROD)
      FPQSUM=(1.+SUM1)*QSUM/T
```

```
      SPQSUM=(SUM1**2+SUM2)*QSUM/T**2
      QI=(M(I)*T*.32807618)**1.5*QSUM*.13623883*T
20    HORT(I)=2.5+T/QSUM*FPQSUM+DELHF(I)/(NO*XK*T)
      HEPG(I)=HORT(I)*NO*XK*T/M(I)
      FORT(I)=DELHF(I)/(NO*XK*T)-ALOG(QI)
      NEGFRT(I)=-FORT(I)
21    CSUBP(I)=2.5+2.*T/QSUM*FPQSUM-(T*FPQSUM/QSUM)**2+T**2*SPQSUM/QSUM
      IF (LEEBOB.EQ.1) PUNCH 83, (CSUBP(I),HORT(I),I=1,NUMSP)
      NNN=1
      DO 74 KP=1,NCAPX
      IF (INDEP.EQ.2) SAVERHO=CAPX(KP)
      P=(10.**CAPX(KP))*PREF
      POPO=P/PREF
      DO 22 I=1,NUMSP
22    Y(I)=YINT(I,NY)
      NUMIT=0
      NUMITF=0
      MM=JINDX+1
      DO 24 J=1,JINDX
      O(J,MM)=0.
      DO 23 I=1,NUMSP
23    O(J,MM)=O(J,MM)+A(I,J)*Y(I)
      O(MM,J)=O(J,MM)
24    CONTINUE
      O(MM,MM)=0.
25    CONTINUE
      YBAR=Y(1)
      NUMIT=NUMIT+1
      IF (NUMIT.EQ.201) GO TO 61
      DO 26 I=2,NUMSP
26    YBAR=YBAR+Y(I)
      IF (INDEP.EQ.2) P=NO*XK*T*YBAR*CAPX(KP)
      DO 28 K=1,JINDX
      R(1,K)=0.
      DO 27 I=1,NUMSP
27    R(1,K)=R(1,K)+A(I,1)*A(I,K)*Y(I)
28    CONTINUE
      ICOUNT=1
      JJ=2
      DO 32 J=JJ,JINDX
      DO 30 K=J,JINDX
      R(J,K)=0.
      DO 29 I=1,NUMSP
29    R(J,K)=R(J,K)+A(I,J)*A(I,K)*Y(I)
```

```
30    CONTINUE
      DO 31 K=1,ICOUNT
31    R(J,K)=R(K,J)
      ICOUNT=ICOUNT+1
32    JJ=1+ICOUNT
      DO 33 J=1,MM
      R(J,MM)=O(J,MM)
33    R(MM,J)=O(J,MM)
      DO 34 J=1,MM
      DO 34 K=1,MM
34    RR(J,K)=R(J,K)
      PYBAR=PREF*YBAR
      DO 36 J=1,JINDX
      SUMAY(J,1)=0.
      DO 35 I=1,NUMSP
      THIS=P*Y(I)/PYBAR
      IF (THIS.LE.0.) GO TO 35
      SUMAY(J,1)=SUMAY(J,1)+A(I,J)*Y(I)*(FORT(I)+ALOG(THIS))
35    CONTINUE
36    CONTINUE
      SUMAY(MM,1)=0.
      DO 37 I=1,NUMSP
      THIS=P*Y(I)/PYBAR
      IF (THIS.LE.0.) GO TO 37
      SUMAY(MM,1)=SUMAY(MM,1)+Y(I)*(FORT(I)+ALOG(THIS))
37    CONTINUE
      MN=1
      NMAX=10
      CALL SIMEQ (R,MM,SUMAY,MN,DETERM,IPIVOT,NMAX,ISCALE)
      DO 38 J=1,JINDX
38    PI(J,1)=SUMAY(J,1)
      U=SUMAY(MM,1)
      LMIN=1.
      LCOUNT=0
      DO 45 I=1,NUMSP
      API=0.
      DO 39 J=1,JINDX
39    API=API+A(I,J)*PI(J,1)
      THIS=P*Y(I)/PYBAR
      IF (THIS.LE.0.) GO TO 40
      X(I)=Y(I)*(NEGFRT(I)-ALOG(THIS)+U+1.+API)
      GO TO 41
40    X(I)=0.
41    IF (X(I)) 42,44,45
```

```
42    LAMB=-Y(I)/(X(I)-Y(I))                                                M 225
      IF (LAMB.GT.0.) GO TO 43                                              M 226
      Y(I)=0.                                                               M 227
      GO TO 25                                                              M 228
43    LCOUNT=1                                                              M 229
      LMIN=AMIN1(LMIN,LAMB)                                                 M 230
      GO TO 45                                                              M 231
44    IF (Y(I).EQ.0.) GO TO 45                                              M 232
      LCOUNT=1                                                              M 233
      LAMB=1.                                                               M 234
      LMIN=AMIN1(LMIN,LAMB)                                                 M 235
45    CONTINUE                                                              M 236
      IF (LCOUNT.EQ.0) GO TO 47                                             M 237
      LAMBDA=.999999999999*LMIN                                             M 238
      DO 46 I=1,NUMSP                                                       M 239
      Y(I)=(1.-LAMBDA)*Y(I)+LAMBDA*X(I)                                     M 240
46    IF (Y(I).LT.1.E-100) Y(I)=0.                                          M 241
      GO TO 25                                                              M 242
47    DO 48 I=1,NUMSP                                                       M 243
      IF (Y(I).EQ.0.) GO TO 48                                              M 244
      IF (ABS(X(I)-Y(I))/Y(I).GE.ER.OR.ABS(X(I)-Y(I)).GE.EA) GO TO 49      M 245
48    CONTINUE                                                              M 246
      GO TO 56                                                              M 247
49    XBAR=0.                                                               M 248
      LAMBDA=1.                                                             M 249
      LASTCT=0                                                              M 250
50    DO 51 I=1,NUMSP                                                       M 251
      XPRIME(I)=(1.-LAMBDA)*Y(I)+LAMBDA*X(I)                                M 252
51    XBAR=XBAR+XPRIME(I)                                                   M 253
      DFLAMB=0.                                                             M 254
      DO 52 I=1,NUMSP                                                       M 255
      THIS=P*XPRIME(I)/(PREF*XBAR)                                          M 256
      IF (THIS.LE.1.E-38) GO TO 52                                          M 257
      DFLAMB=DFLAMB+(X(I)-Y(I))*(FORT(I)+ALOG(THIS))                        M 258
52    CONTINUE                                                              M 259
      IF (DFLAMB.GT.0.) GO TO 55                                            M 260
53    DO 54 I=1,NUMSP                                                       M 261
54    Y(I)=XPRIME(I)                                                        M 262
      GO TO 25                                                              M 263
55    LASTCT=LASTCT+1                                                       M 264
      IF (LASTCT.EQ.4) GO TO 53                                             M 265
      LAMBDA=.9*LAMBDA                                                      M 266
      XBAR=0.                                                               M 267
      GO TO 50                                                              M.268
```

```
56    IF (NUMITF.EQ.1) GO TO 58                                    M 269
      NUMITO=0                                                     M 270
      IF (INDEP.NE.2) GO TO 58                                     M 271
      NUMITF=1                                                     M 272
      NUMITO=NUMIT                                                 M 273
      INDEP=1                                                      M 274
      DO 57 I=1,NUMSP                                              M 275
57    Y(I)=X(I)                                                    M 276
      GO TO 25                                                     M 277
58    XBAR=0.                                                      M 278
      ONE=0.                                                       M 279
      TWO=0.                                                       M 280
      DO 59 I=1,NUMSP                                              M 281
      XBAR=XBAR+X(I)                                               M 282
      ONE=ONE+X(I)*HORT(I)                                         M 283
      MASSFR(I)=X(I)*M(I)                                          M 284
      IF (Y(I).EQ.0.) GO TO 59                                     M 285
      TWO=TWO+X(I)*(FORT(I)+ALOG(X(I)))                            M 286
59    CONTINUE                                                     M 287
      RECIPZ=1./(MU*XBAR)                                          M 288
      IF (NUMITF.EQ.1) CAPX(KP)=ALOG10(P/PREF)                     M 289
      IF (NUMITF.EQ.1) INDEP=2                                     M 290
      CAPU=CAPX(KP)+ALOG10(RECIPZ*273.15/T)                        M 291
      CHORT=MU*ONE                                                 M 292
      SOR=CHORT-MU*(XBAR*ALOG(P/(PREF*XBAR))+TWO)                  M 293
      RHO=P/(XBAR*NO*XK*T)                                         M 294
      NE=X(1)*RHO*NO                                               M 295
      IF (X(1).GT.10.**-20) GO TO 60                               M 296
      LOGNE=-0.                                                    M 297
      GO TO 62                                                     M 298
60    LOGNE=ALOG10(NE)                                             M 299
      GO TO 62                                                     M 300
61    WRITE (6,80) P                                               M 301
      GO TO 74                                                     M 302
62    CONTINUE                                                     M 303
      DO 64 I=1,NUMSP                                              M 304
      TEST=X(I)*P/(XBAR*PREF)                                      M 305
      IF (TEST.LT.10.**(-20)) GO TO 63                             M 306
      PSI(I,1)=X(I)/T*(HORT(I)-FORT(I)-ALOG(TEST))                 M 307
      PSI(I,2)=-X(I)                                               M 308
      GO TO 64                                                     M 309
63    PSI(I,1)=0.                                                  M 310
      PSI(I,2)=0.                                                  M 311
64    CONTINUE                                                     M 312
```

```
      DO 66 J=1.JINDX                                                   M 313
      CON(J.1)=A(1.J)*PSI(1.1)                                          M 314
      CON(J.2)=A(1.J)*PSI(1.2)                                          M 315
      DO 65 I=2.NUMSP                                                   M 316
      CON(J.1)=CON(J.1)+A(I.J)*PSI(I.1)                                 M 317
   65 CON(J.2)=CON(J.2)+A(I.J)*PSI(I.2)                                 M 318
   66 CONTINUE                                                          M 319
      CON(MM.1)=PSI(1.1)                                                M 320
      CON(MM.2)=PSI(1.2)                                                M 321
      DO 67 I=2.NUMSP                                                   M 322
      CON(MM.1)=CON(MM.1)+PSI(I.1)                                      M 323
   67 CON(MM.2)=CON(MM.2)+PSI(I.2)                                      M 324
      NC=2                                                              M 325
      CALL SIMEQ (RR.MM.CON.NC.DETERM.IPIVOT.NMAX.ISCALE)               M 326
      DO 68 J=1.MM                                                      M 327
      PI(J.1)=CON(J.1)                                                  M 328
   68 PI(J.2)=CON(J.2)                                                  M 329
      DHDT=0.                                                           M 330
      DO 70 I=1.NUMSP                                                   M 331
      SUMAP=A(I.1)*PI(1.1)                                              M 332
      DO 69 J=2.JINDX                                                   M 333
   69 SUMAP=SUMAP+A(I.J)*PI(J.1)                                        M 334
      DXDT(I)=PSI(I.1)-X(I)*(PI(MM.1)+SUMAP)                            M 335
      DMSFRDT(I)=M(I)*DXDT(I)                                           M 336
   70 DHDT=DHDT+(X(I)*CSUBP(I)+T*HORT(I)*DXDT(I))                       M 337
      DRHODT=T*PI(MM.1)-1.                                              M 338
      DRHODP=1.+PI(MM.2)                                                M 339
      CPOR=MU*DHDT                                                      M 340
      XZ=XBAR*MU                                                        M 341
      CVOR=CPOR-DRHODT**2/DRHODP*XZ                                     M 342
      XGAMMA=CPOR/CVOR                                                  M 343
      GAMMAE=XGAMMA/DRHODP                                              M 344
      RHOR=1./(10.**CAPU)                                               M 345
      HPGRAM=CHORT*NO*XK*T/MU                                           M 346
      TEST=(GAMMAE/1.4*P/PREF*RHOR)                                     M 347
      IF (TEST.LE.0.) WRITE (6.82) CAPX(KP).CAPU.XZ.CHORT.SOR.LOGNE.DRHOM 348
     1DT.DRHODP.CPOR.CVOR.XGAMMA.GAMMAE.AOAO                            M 349
      AOAO=SQRT(TEST)                                                   M 350
      AM=AOAO*AO*.01                                                    M 351
      RHOAN=(10.**CAPU)*RHOO*1.E+3                                      M 352
      HA=CHORT*8.31469E+3*T/MU                                          M 353
      INTENE=((CHORT-XZ)*NO*XK*T+3.93146E+12)/MU                        M 354
      GAMBAR=(INTENE+(P/RHO))/INTENE                                    M 355
      EORTO=INTENE*28.9672/(NO*XK*273.15)                               M 356
```

```
      LGEORT=ALOG10(EORTO)
      RORHOE=RHO/1.29233666E-3
      LGRORE=ALOG10(RORHOE)
      DO 71 I=1,NUMSP
71    XMOLE(I)=MASSFR(I)*MU/(XZ*M(I))
      IF (NNN.EQ.10) GO TO 72
      GO TO 73
72    WRITE (6,81)
      NNN=0
73    NNN=NNN+1
      IF (INDEP.EQ.2) CAPX(KP)=SAVERHO
      IF (LEEBOB.EQ.0) GO TO 74
      IF (KP.EQ.1) PUNCH 84, NCAPX
      PUNCH 83, POPO,CPOR
      PUNCH 85, (XMOLE(I),I=1,NUMSP)
74    CONTINUE
75    CONTINUE
      RETURN
C
C
76    FORMAT (A6,3I5,3E14.8)
77    FORMAT (5E14.8)
78    FORMAT (4E14.8,I5)
79    FORMAT (15E5.0)
80    FORMAT (1X,2HP=E15.8,2X,28H200 ITERATIONS-NONCONVERGENT)
81    FORMAT (/)
82    FORMAT (/F9.4,F10.4,F9.4,F11.4,F10.4,F9.3,F10.3,F10.3,F10.3,F10.3,
     1F8.3,F8.3,F9.3)
83    FORMAT (2E16.8)
84    FORMAT (I5)
85    FORMAT (5E16.8)
      END
- .
 $INP T1=300,T4=600,P4=6.8948E+7,LB=2,LF=1,U5=12192,P1=3447.4,PMIX=1,
 PHE=.5,PH2=.5,NUMSP=7,JINDX=3,IH=5,IH2=7,IHE=2,NDRIV=1$
   E-    1    0    0    54847000-03    00000000+00    00000000+00
  20000000+01    00000000+00
   HE    8    0    0    40026000+01    00000000+00    00000000+00
  10000000+01    00000000+00    30000000+01    15986700+06    13000000+02
  16909900+06    36000000+02    18571700+06    64000000+02    19137100+06
  64000000+02    19388800+06    64000000+02    19524900+06    64000000+02
  19606900+06
  HE+    7    0    0    40026000+01    23719600+14    00000000+00
  20000000+01    00000000+00    80000000+01    32938100+06    14000000+02
```

```
 38999400+06   22000000+02   41152100+06   32000000+02   42161000+06
 44000000+02   42676200+06   58000000+02   42999600+06
HE++    1    0    0   40026000+01   76216100+14   00000000+00
 10000000+01   00000000+00
  H     1    0    0   10080000+01   21602828+13   00000000+00
 10000000+01   00000000+00
  H+    1    0    0   10080000+01   15211700+14   00000000+00
 10000000+00   00000000+00
  H2    1    1    0   20160000+01   00000000+00   20000000+01
 10000000+01   00000000+00
 60800000+02   29930000+01   43953000+04   11790000+03    5
  1    0    0    0    1    0   -1    1    0   -2    1    0    0    0    1
 -1    0    1    0    0    2
$INP T1=300.T4=600.P4=6.8948E+7.LB=2.LF=1,U5=12192.P1=3447.4,PMIX=1.
PHE=.2,PH2=.8,NUMSP=7.JINDX=3.IH=5.IH2=7.IHE=2$
- .
```

The basic subroutines of this program are as follows:

(1) ROGO – computes thermodynamic quantities a, h, sW_0/R, X_i, Z^*, γ_E, and ρ for given p, T, and W_0

(2) FIND – iterative-interpolation procedure for obtaining thermodynamic quantities from ROGO with combinations:

1. p and ρ
2. p and h
3. p and sW_0/R
4. h and ρ

(3) VISC – computes μ for given T and X_i

(4) BDT – computes B and C for helium or hydrogen for given T

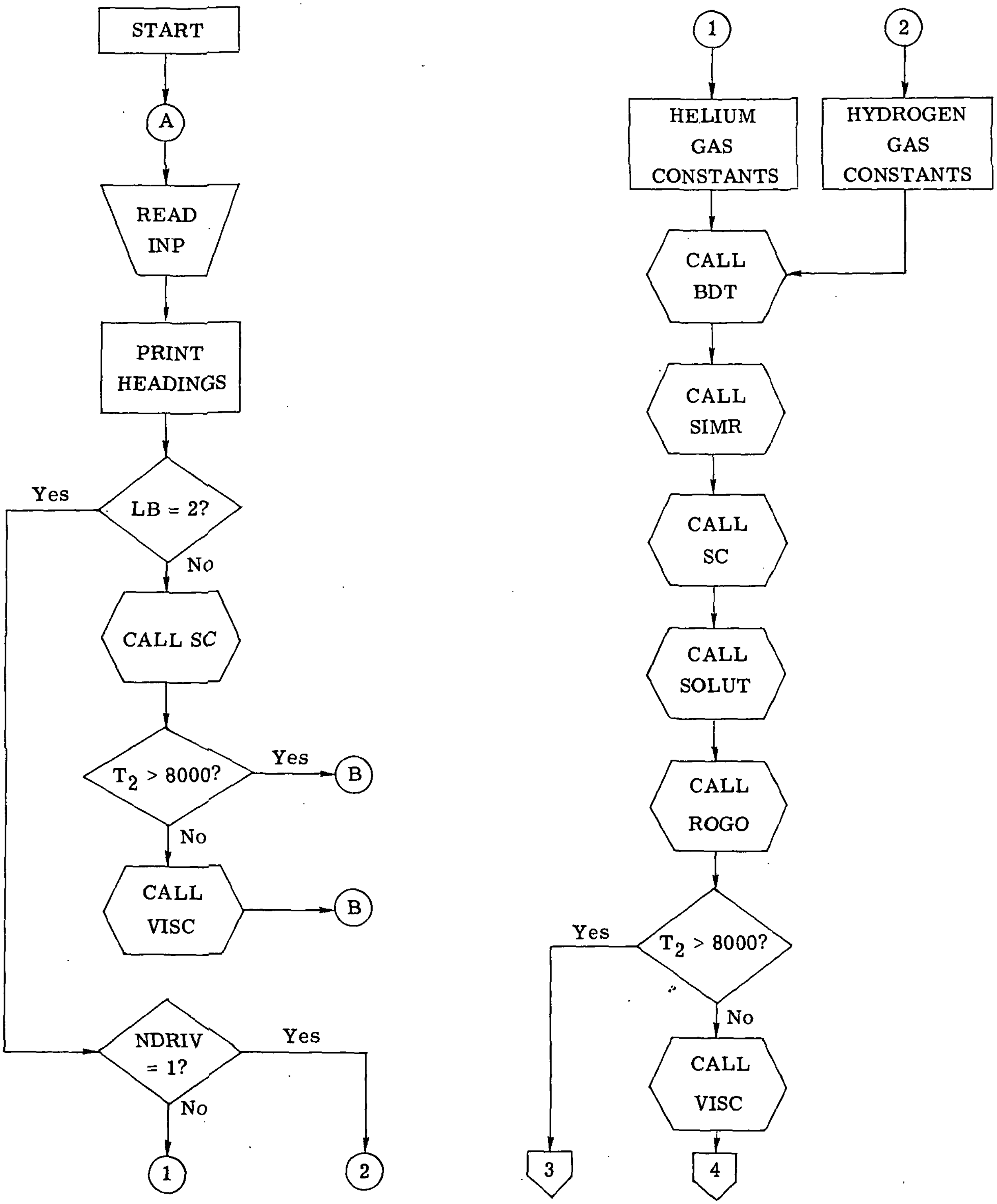
(5) SOLUT – given (p_2,U_2) and (p_3,U_3), finds solution to curves

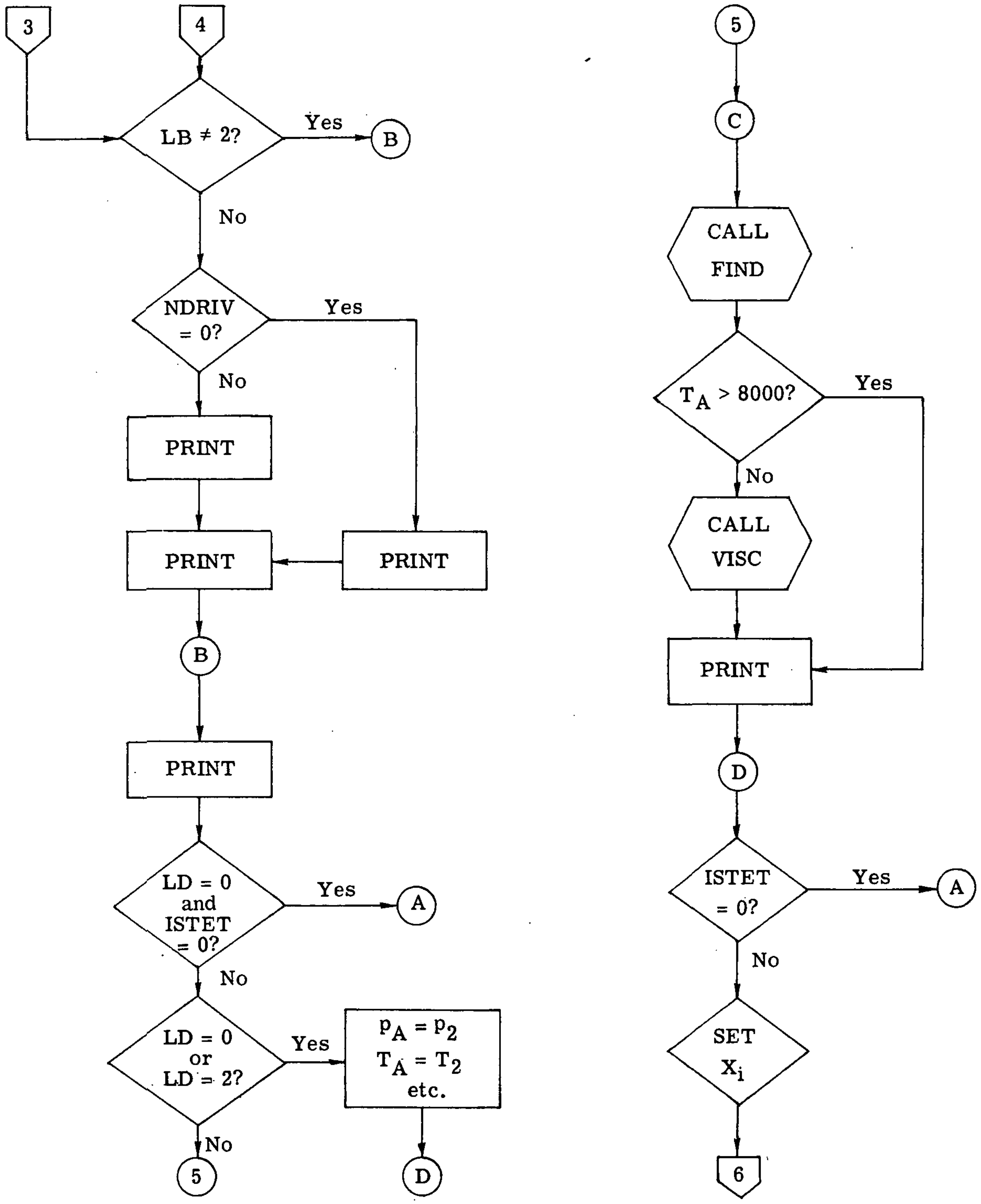
(6) SC – iterative procedure for solving conservation relations for a moving normal shock

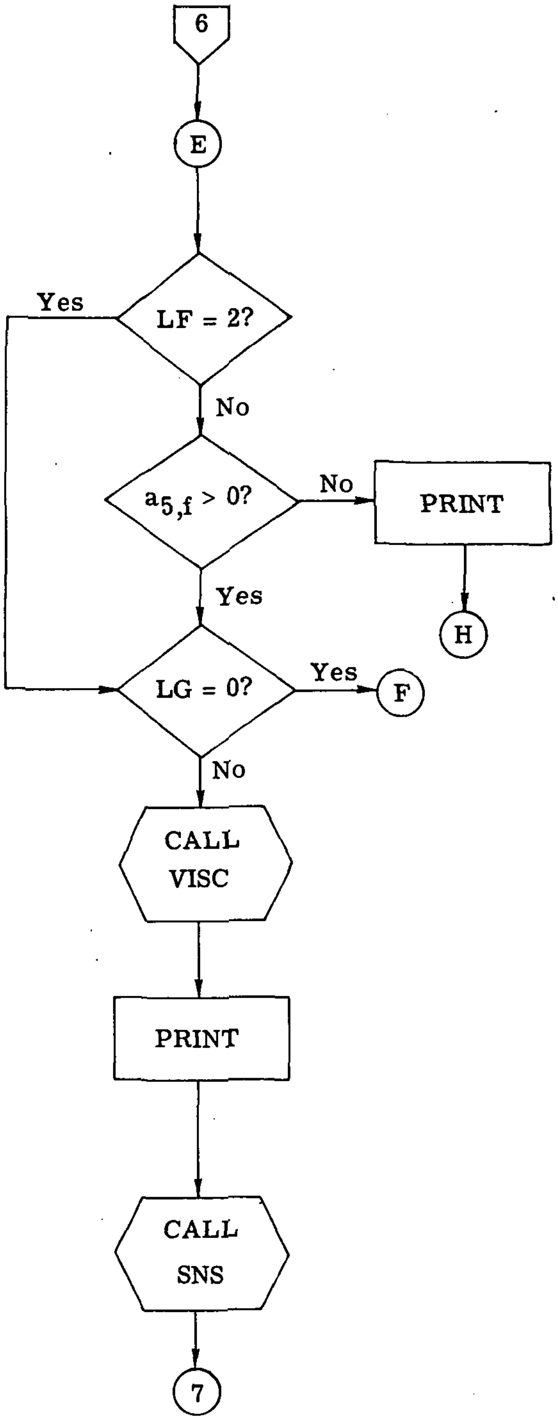
(7) SNS – iterative procedure for solving conservation relations for a standing normal shock

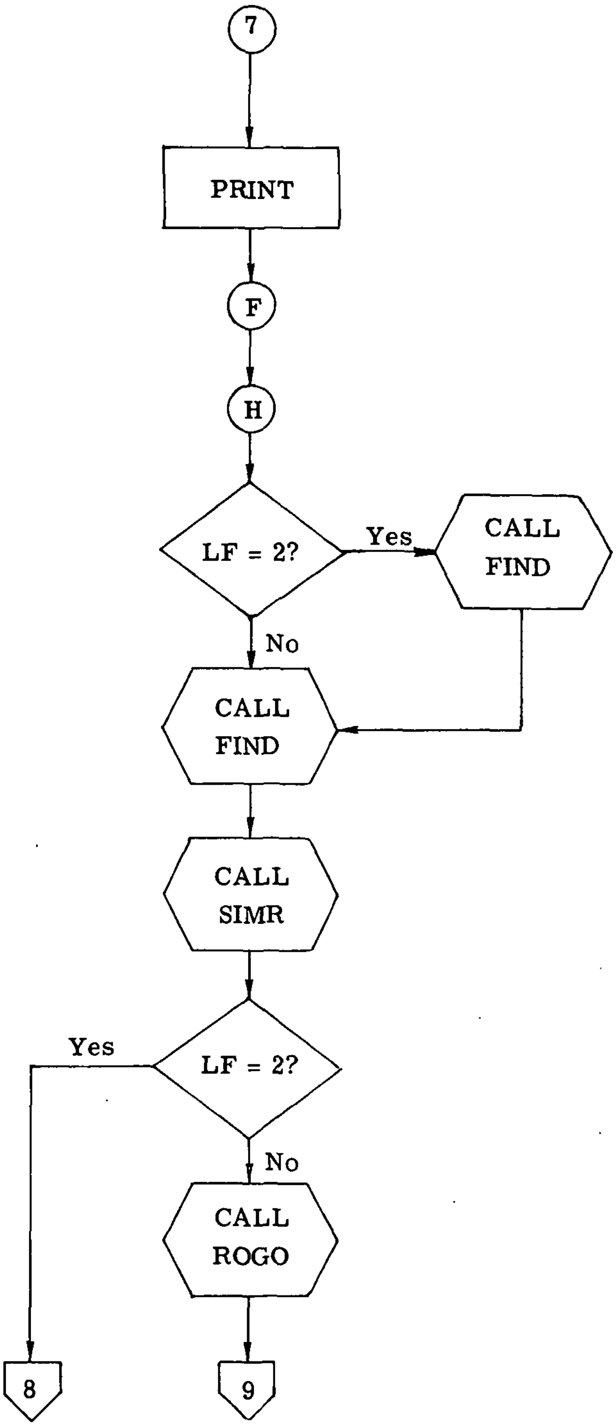
(8) SIMR – computes $\int\left(\frac{dh}{a}\right)_{sW_0/R}$ by Simpson's rule

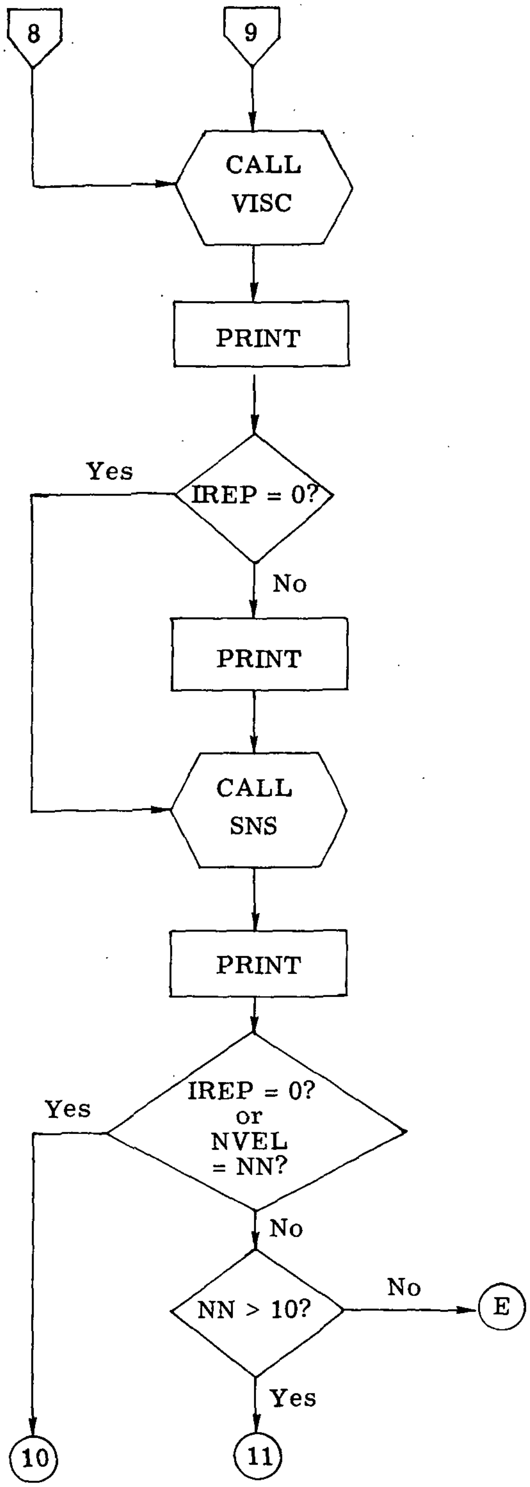
A flow chart of this program is given in the following pages.

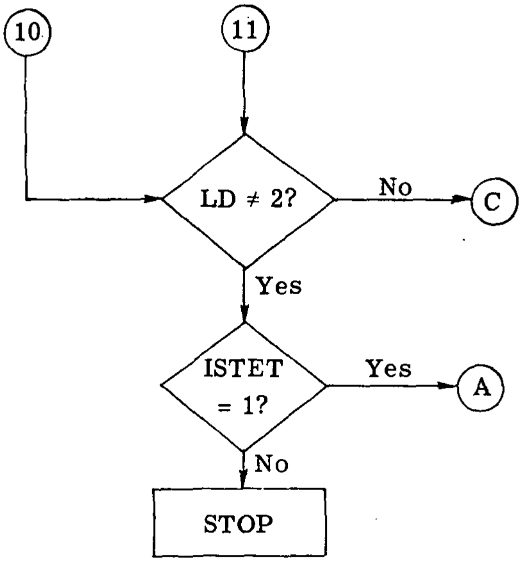

START
A
READ INP
PRINT HEADINGS
LB = 2?
Yes
No
CALL SC
T₂ > 8000?
Yes
B
No
CALL VISC
B
NDRIV = 1?
Yes
No
1
2
1
2
HELIUM GAS CONSTANTS
HYDROGEN GAS CONSTANTS
CALL BDT
CALL SIMR
CALL SC
CALL SOLUT
CALL ROGO
T₂ > 8000?
Yes
No
CALL VISC
3
4


3
4
LB ≠ 2?
Yes
B
No
NDRIV = 0?
Yes
No
PRINT
PRINT
PRINT
B
PRINT
LD = 0 and ISTET = 0?
Yes
A
No
LD = 0 or LD = 2?
Yes
$p_A = p_2$
$T_A = T_2$
etc.
No
5
D
5
C
CALL FIND
$T_A > 8000?$
Yes
No
CALL VISC
PRINT
D
ISTET = 0?
Yes
A
No
SET X_i
6


6
E
LF = 2?
Yes
No
$a_{5,f} > 0$?
No
PRINT
H
Yes
LG = 0?
Yes
F
No
CALL VISC
PRINT
CALL SNS
7


7
PRINT
F
H
LF = 2?
Yes
CALL FIND
No
CALL FIND
CALL SIMR
LF = 2?
Yes
No
CALL ROGO
8
9


8
9
CALL VISC
PRINT
IREP = 0?
Yes
No
PRINT
CALL SNS
PRINT
IREP = 0? or NVEL = NN?
Yes
No
NN > 10?
No
E
Yes
10
11


10
11
LD ≠ 2?
No
C
Yes
ISTET = 1?
Yes
A
No
STOP

The procedure for running a program with all 26 species for CO_2, N_2, O_2, and Ar is discussed in detail in reference 18. Also, modifications required when the number of species is varied are illustrated by example in reference 18. For convenience, an additional example is now presented. A mixture of CO_2 and Ar, which may represent the Mars atmospheric model, is considered with second ionization neglected. Now, the number of atoms of a particular component per particle of a species A(I,J) must be designated. For electrons, a charge constraint is used instead of a mass constraint. Constructing a table of A(I,J) for this CO_2-Ar mixture gives

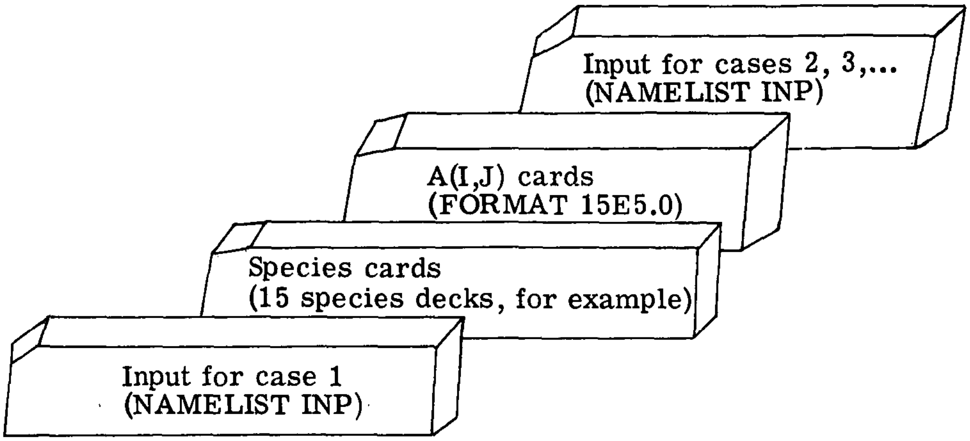
		1	2	3	4
	Component (J) Species (I)	e^-	Ar	O	C
1	e^-	1	0	0	0
2	Ar	0	1	0	0
3	Ar^+	-1	1	0	0
4	O	0	0	1	0
5	O^+	-1	0	1	0
6	O^-	1	0	1	0
7	O_2	0	0	2	0
8	O_2^+	-1	0	2	0
9	O_2^-	1	0	2	0
10	C	0	0	0	1
11	C^+	-1	0	0	1
12	C^-	1	0	0	1
13	CO	0	0	1	1
14	CO^+	-1	0	1	1
15	CO_2	0	0	2	1

The sequence 0, 1, 0, 0 for species Ar denotes that the only component contained in this species is Ar. (A zero denotes that a particular component does not appear in that species.) In the sequence -1, 1, 0, 0 for Ar^+, the -1 denotes that Ar^+ is a positive ion, and so forth. For this mixture, NUMSP = 15, JINDX = 4, IAR = 2, IC = 10, ICØ = 13, ICØ2 = 15, IØ = 4, and IØ2 = 7.

Only the species decks for the 15 species considered are included, and these are placed in the order that they appear in the A(I,J) table. The A(I,J) are read in as illustrated by the following listing:

```
1    0    0    0    0    1    0    0   -1    1    0    0    0    0    1
0   -1    0    1    0    1    0    1    0    0    0    2    0   -1    0
2    0    1    0    2    0    0    0    0    1   -1    0    0    1    1
0    0    1    0    0    1    1   -1    0    1    1    0    0    2    1
```

The first four numbers represent the A(I,J) sequence, from the A(I,J) table, for e$^-$; the next four numbers represent the A(I,J) sequence for Ar; and so forth. The sequence of cards following the main program and subroutine is as follows:



Sample data printouts are included that illustrate program usage for hypothetical tests in an expansion tube with a Mars model atmosphere at moderate velocity and with Venus and Jovian model atmospheres at high velocity.

The headings for the various flow regions correspond to those in the section entitled "SYMBOLS." The units of these flow quantities are as given in the definitions of the symbols, except where explicitly specified in the printout. The sample printouts are as follows:

```
02/15/72
                                                                   MARS

EXPANSION TUBE PROGRAM OF MILLER FOR GAS MIXTURES
ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012

SHOCK TUBE PHASE OF PROGRAM

MEASURED INPUTS FOR SHOCK TUBE PHASE

    RUN        P1        T1       US1        P2        P4        T4
1.000E+00 3.447E+03 3.000E+02 0.        0.        3.447E+07 3.000E+02

     WO      XCO2       XN2       XO2       XAR       XHE       XH2
4.340E+01 8.500E-01 0.        0.        1.500E-01 0.        0.

1 CONDITIONS - QUIESCENT TEST GAS

      P       RHO         T         H       GAM         A
3.447E+03 5.958E-02 3.000E+02-7.458E+06 1.313E+00 2.746E+02

IMPERFECT HELIUM DRIVER GAS

4 CONDITIONS

      P       RHO         T         H       S/R         Z         A         W
3.447E+07 4.758E+01 3.000E+02 1.665E+06 9.261E+00 1.153E+00 1.160E+03 4.003E+00

2 CONDITIONS- REAL GAS MIXTURES

      P       RHO         T         H       S/R         Z      GAME         A         U         M       NRE
2.518E+05 5.907E-01 2.195E+03-5.178E+06 3.566E+01 1.014E+00 1.134E+00 6.953E+02 1.928E+03 2.774E+00 1.620E+07

RATIO- 2 CONDITIONS TO 1 CONDITIONS

      P       RHO         T         H       MS1       US1
7.303E+01 9.847E+00 7.316E+00 6.942E-01 7.815E+00 2.146E+03
```

MARS

```
MOLE FRACTIONS IN REGION 2

 SPECIE        MOLE FRACTION

    A          1.4797E-01
    O          1.9085E-04
   O2          1.3354E-02
    C          1.2842E-17
   CO          2.6043E-02
  CO2          8.1244E-01


CONDITIONS BEHIND STANDING SHOCK

   P         RHO        T          H         S/R        Z          GAME        A          U          M          NRE
2.065E+06 3.385E+00 2.943E+03-3.375E+06 3.711E+01 1.082E+00 1.120E+00 8.266E+02 3.366E+02 4.072E-01 1.303E+07


MOLE FRACTIONS BEHIND SHOCK AT SECOND DIA.

 SPECIE        MOLE FRACTION

    A          1.3862E-01
    O          5.4200E-03
   O2          7.0475E-02
    C          1.3032E-12
   CO          1.4557E-01
  CO2          6.3992E-01


5 CONDITIONS FOR FROZEN EXPANSION

   P         RHO        T          H         S/R        Z          GAME        A          U          M          NRE
5.174E-05 3.815E-08 6.542E+00-8.249E+02 3.711E+01 1.082E+00 1.334E+00 4.253E+01 5.486E+03 1.290E+02 6.520E+02


STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

   P         RHO        T          H         S/R        Z          GAME        A          U          M        R5S/R5
1.074E+00 5.919E-07 4.413E+03 1.531E+07 8.771E+01 2.147E+00 1.079E+00 1.399E+03 3.537E+02 2.528E-01 1.551E+01


STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK
```

```
  P          RHO         T           H           Z          GAME         A           QT          RN
1.112E+00 6.112E-07 4.419E+03 1.538E+07 2.149E+00 1.079E+00 1.401E+03 9.489E+04 1.270E-02
```

MARS

```
STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION-- FROZEN POST SHOCK

  P          RHO         T           H          S/R          Z          GAME         A           U           M          R5S/R5
9.841E-01 2.666E-07 1.780E+04-2.245E+07 5.886E+01 1.082E+00 1.334E+00 2.219E+03 7.850E+02 3.538E-01 6.989E+00

STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION-- FROZEN POST SHOCK

  P          RHO         T           H           Z          GAME         A           QT          RN
1.069E+00 2.837E-07 1.818E+04 1.504E+07 1.082E+00 1.334E+00 2.242E+03 9.167E+04 1.270E-02

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

  P          RHO         T           H          S/R          Z          GAME         A           U           M           NRE
2.389E+02 1.275E-03 9.775E+02-6.816E+06 3.711E+01 1.000E+00 1.205E+00 4.751E+02 5.486E+03 1.155E+01 1.724E+05

MOLE FRACTIONS IN REGION 5

 SPECIE        MOLE FRACTION

     A          1.4993E-01
     O          3.3572E-11
    O2          4.3383E-04
     C          4.2866E-46
    CO          2.3280E-08
   CO2          8.4963E-01

STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P          RHO         T           H          S/R          Z          GAME         A           U           M          R5S/R5
3.634E+04 2.150E-02 4.783E+03 8.181E+06 5.958E+01 1.845E+00 1.352E+00 1.512E+03 3.254E+02 1.155E+01 1.686E+01

STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK
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    P         RHC         T          H          Z         GAME        A          QT         RN
3.749E+04 2.200E-02 4.821E+03 8.234E+06 1.845E+00 1.354E+00 1.519E+03 1.197E+07 1.270E-02

MOLE FRACTIONS IN REGION T5

 SPECIE        MOLE FRACTION

     A         8.1293E-02
     O         4.5554E-01
    O2         2.5091E-03
     C         1.0558E-04
    CO         4.5987E-01
   CO2         6.8025E-04
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MARS

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03/03/72

EXPANSION TUBE PROGRAM OF MILLER FOR GAS MIXTURES
ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012                VENUS

SHOCK TUBE PHASE OF PROGRAM

MEASURED INPUTS FOR SHOCK TUBE PHASE

   RUN        P1         T1         US1        P2         P4         T4
1.000E+00  3.447E+03  3.000E+02  0.         0.         6.895E+07  6.000E+02

   WO         XCO2       XN2        XO2        XAR        XHE        XH2
4.321E+01  9.500E-01  5.000E-02  0.         0.         0.         0.

1 CONDITIONS - QUIESCENT TEST GAS

  P          RHO        T          H          GAM        A
3.447E+03  5.972E-02  3.000E+02-8.386E+06  1.290E+00  2.729E+02

IMPERFECT HELIUM DRIVER GAS

4 CONDITIONS

  P          RHO        T          H          S/R        Z          A          W
6.895E+07  4.858E+01  6.000E+02  3.318E+06  1.040E+01  1.139E+00  1.613E+03  4.003E+00

2 CONDITIONS- REAL GAS MIXTURES

  P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
4.874E+05  8.272E-01  2.792E+03-4.042E+06  4.042E+01  1.097E+00  1.107E+00  8.076E+02  2.742E+03  3.395E+00  2.844E+07

RATIO- 2 CONDITIONS TO 1 CONDITIONS

  P          RHO        T          H          MS1        US1
1.414E+02  1.385E+01  9.307E+00  4.820E-01  1.083E+01  2.955E+03

MOLE FRACTIONS IN REGION 2
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VENUS

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SPECIE        MOLE FRACTICN
-------------------------------
   E-          9.9109E-1C
   A           1.1821E-18
   A+          1.4651E-35
  A++          1.3877E-74
   N           3.1053E-C7
   N+          2.3632E-22
-------------------------------
  N++          3.3090E-65
   N2          4.2888E-02
  N2+          4.0451E-19
   O           6.7022E-03
   O+          4.6853E-17
  O++          2.5384E-69
-------------------------------
   O-          3.6017E-11
   O2          7.8751E-C2
  O2+          8.0586E-13
  O2-          1.6275E-1C
   NO          5.4072E-C3
  NO+          1.1890E-C9
-------------------------------
   C           4.5055E-13
   C+          8.2381E-23
  C++          7.7964E-57
   C-          9.7942E-22
   CO          1.6882E-C1
  CO+          9.3975E-16
-------------------------------
   CN          1.3376E-11
  CO2          6.9743E-01

CONDITIONS BEHIND STANDING SHCCK
-----------------------------------------------------------------------------------------------------------------------
    P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
5.890E+06 6.308E+00 3.791E+C3-3.482E+05 4.335E+01 1.280E+00 1.134E+00 1.029E+03 3.596E+02 3.495E-01 2.257E+07

MOLE FRACTIONS BEHIND SHCCK AT SECCND DIA.
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VENUS

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 SPECIE        MOLE FRACTION

    E-           9.2727E-08
     A           1.0126E-18
    A+           6.7632E-31
   A++          -2.6005E-58
     N           1.7939E-05
    N+           1.5273E-16
   N++          -2.4764E-46
    N2           3.0123E-02
   N2+           1.3661E-14
     O           5.0589E-02
    O+           1.7404E-12
   O++          -5.9480E-49
    O-           2.8406E-08
    O2           1.5937E-01
   O2+           1.5586E-09
   O2-           5.9187E-08
    NO           1.7847E-02
   NO+           1.7874E-07
     C           2.7466E-09
    C+           1.3460E-16
   C++          -2.9732E-40
    C-           6.9447E-16
    CO           3.8651E-01
   CO+           1.7564E-11
    CN           1.2612E-08
   CO2           3.5554E-01


A5F IS NEGATIVE - FROZEN FLOW NOT CALCULATED

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

    P         RHO        T         H         S/R        Z        GAME       A          U          M         NRE
1.556E-01 1.195E-06 6.765E+02-8.050E+06 4.335E+01 1.000E+00 1.209E+00 3.968E+02 1.097E+04 2.765E+01 4.375E+02

MOLE FRACTIONS IN REGION 5

 SPECIE        MOLE FRACTION
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VENUS

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   E-         6.2308E-55
   A          1.2958E-18
   A+         2.6673E-74
   A++        0.
   N          7.0939E-32
   N+         7.5299E-79
   N++        0.
   N2         4.9978E-02
   N2+        7.1814E-57
   O          1.3441E-15
   O+         2.1215E-56
   O++        0.
   O-         1.0380E-65
   O2         4.3192E-04
   O2+        6.6382E-33
   O2-        2.3622E-57
   NO         2.1880E-09
   NO+        5.1831E-18
   C          2.4817E-69
   C+         1.9305E-92
   C++        0.
   C-         0.
   CO         1.8813E-13
   CO+        1.1911E-56
   CN         8.4516E-56
   CO2        9.4959E-01

STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P         RHO        T         H         S/R        Z         GAME       A          U          M         R5S/R5
1.375E+02 2.688E-05 7.847E+03 5.200E+07 1.126E+02 3.388E+00 1.147E+00 2.422E+03 4.875E+02 2.765E+01 2.250E+01

STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P         RHO        T         H         Z         GAME       A          QT         RN
1.407E+02 2.743E-05 7.864E+03 5.212E+07 3.391E+00 1.147E+00 2.426E+03 2.729E+06 1.270E-02

MOLE FRACTIONS IN REGION T5
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VENUS

SPECIE	MOLE FRACTION
E-	1.2986E-01
A	3.7866E-19
A+	3.6284E-21
A++	2.0861E-31
N	2.8883E-02
N+	6.0619E-04
N++	8.4244E-16
N2	1.7803E-07
N2+	1.2332E-09
O	5.5125E-01
O+	9.2424E-03
O++	1.3228E-17
O-	1.5704E-07
O2	9.3945E-08
O2+	2.9507E-08
O2-	4.1198E-14
NO	1.3768E-07
NO+	5.7027E-07
C	1.6008E-01
C+	1.2001E-01
C++	9.5579E-11
C-	3.1327E-08
CO	6.6521E-05
CO+	2.9096E-06
CN	1.2830E-07
CO2	2.8311E-12

JOVIAN

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03/06/72

EXPANSION TUBE PROGRAM OF MILLER FOR GAS MIXTURES
ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012

SHOCK TUBE PHASE OF PROGRAM

MEASURED INPUTS FOR SHOCK TUBE PHASE

   RUN       P1         T1         US1        P2         P4         T4
1.000E+00 3.447E+03 3.000E+02 0.         0.         6.895E+07 6.000E+02

   WO        XCO2       XN2        XO2        XAR        XHE        XH2
3.009E+00 0.         0.         0.         0.         5.000E-01 5.000E-01

1 CONDITIONS - QUIESCENT TEST GAS

   P         RHO        T          H          GAM        A
3.447E+03 4.159E-03 3.000E+02 2.486E+06 1.500E+00 1.115E+03

IMPERFECT HYDROGEN DRIVER GAS

4 CONDITIONS

   P         RHO        T          H          S/R        Z          A          W
6.895E+07 2.173E+01 6.000E+02 9.245E+06 1.160E+01 1.282E+00 2.402E+03 2.016E+00

2 CONDITIONS- REAL GAS MIXTURES

   P         RHO        T          H          S/R        Z          GAME       A          U          M          NRE
1.542E+05 2.086E-02 2.657E+03 2.422E+07 2.266E+01 1.007E+00 1.306E+00 3.107E+03 5.387E+03 1.734E+00 1.705E+06

RATIO- 2 CONDITIONS TO 1 CONDITIONS

   P         RHO        T          H          MS1        US1
4.473E+01 5.016E+00 8.857E+00 9.740E+00 6.034E+00 6.728E+03

MOLE FRACTIONS IN REGION 2
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```
 SPECIE           MOLE FRACTION

    E-            6.8683E-14
    HE            4.9660E-01
   HE+            5.3516E-32                                              JOVIAN
  HE++            0.
     H            1.3606E-02
    H+            6.8683E-14
    H2            4.8980E-01


CONDITIONS BEHIND STANDING SHOCK

    P         RHO         T          H          S/R         Z          GAME        A          U          M          NRE
5.209E+05 5.288E-02 3.433E+03 3.647E+07 2.287E+01 1.038E+00 1.233E+00 3.484E+03 2.124E+03 6.096E-01 1.432E+06


MOLE FRACTIONS BEHIND SHOCK AT SECOND DIA.

 SPECIE           MOLE FRACTION

    E-            9.4645E-11
    HE            4.8148E-01
   HE+            6.2390E-25
  HE++           -5.5034E-91
     H            7.4080E-02
    H+            9.4645E-11
    H2            4.4444E-01


5 CONDITIONS FOR FROZEN EXPANSION

    P         RHO         T          H          S/R         Z          GAME        A          U          M          NRE
7.559E+02 7.063E-04 3.730E+02 3.729E+06 2.287E+01 1.038E+00 1.514E+00 1.273E+03 1.219E+04 9.577E+00 5.064E+05


STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

    P         RHO         T          H          S/R         Z          GAME        A          U          M         R5S/R5
9.437E+04 6.511E-03 4.123E+03 7.933E+07 2.886E+01 1.272E+00 1.206E+00 4.181E+03 1.322E+03 3.161E-01 9.218E+00


STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

    P         RHO         T          H          Z         GAME        A          QT         RN
1.002E+05 6.843E-03 4.153E+03 8.021E+07 1.276E+00 1.208E+00 4.206E+03 4.138E+07 1.270E-02
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STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK                          JOVIAN
FROZEN EXPANSION-- FROZEN POST SHOCK

   P         RHO        T         H         S/R        Z         GAME        A          U          M         R5S/R5
8.336E+04 3.313E-03 8.771E+03 8.768E+07 2.747E+01 1.038E+00 1.514E+00 6.173E+03 2.600E+03 4.211E-01 4.690E+00

STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
FROZEN EXPANSION-- FROZEN POST SHOCK

   P         RHO        T         H          Z         GAME        A         QT         RN
9.506E+04 3.613E-03 9.171E+03 7.805E+07 1.038E+00 1.514E+00 6.312E+03 3.919E+07 1.270E-02

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P         RHO        T         H         S/R        Z         GAME        A          U          M          NRE
3.630E+03 1.416E-03 9.278E+02 7.684E+06 2.287E+01 1.000E+00 1.489E+00 1.954E+03 1.219E+04 6.241E+00 5.354E+05

MOLE FRACTIONS IN REGION 5

 SPECIE         MOLE FRACTION

   E-           9.5169E-63
   HE           5.0000E-01
  HE+           1.5027E-69
 HE++           0.
    H           5.2877E-10
   H+           9.0285E-20
   H2           5.0000E-01

STATIC(5S) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

   P         RHO        T         H         S/R        Z         GAME        A          U          M         R5S/R5
1.903E+05 1.251E-02 4.337E+03 8.105E+07 2.811E+01 1.270E+00 1.218E+00 4.304E+03 1.380E+03 6.241E+00 8.833E+00

STAGNATION(T5) CONDITIONS BEHIND NORMAL SHOCK
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

   P         RHO        T         H          Z         GAME        A         QT         RN
2.025E+05 1.316E-02 4.373E+03 8.201E+07 1.273E+00 1.220E+00 4.332E+03 6.019E+07 1.270E-02

MOLE FRACTIONS IN REGION T5

 SPECIE         MOLE FRACTION
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JOVIAN

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     E-          6.8156E-08
     HE          3.9264E-01
    HE+          2.3530E-19
   HE++          4.0286E-72
      H          4.2944E-01
     H+          6.8156E-08
     H2          1.7792E-01
```

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TABLE I.- CALCULATED EXPANSION-TUBE FLOW QUANTITIES FOR SIX-SPECIES AIR MODEL IN THERMOCHEMICAL EQUILIBRIUM

[78% N_2, 21% O_2, 1% Ar, by volume; $p_4 = 34.474$ MN/m^2;
$T_4 = T_1 = T_{10} = 300$ K; $W_4 = W_{10} = 4.003$ kg/kmol;
$W_1 = 28.97$ kg/kmol]

<table>
<tr><th>U_5, km/sec</th><th>p_5, kN/m^2</th><th>T_5, K</th><th>Z^*_5</th><th>$\gamma_{E,5}$</th><th>M_5</th><th>$N_{Re,5}$, m^{-1}</th><th>$p_{5,t}$, kN/m^2</th><th>$\dot{q}_{5,t}$, MW/m^2</th><th>p_{10}, N/m^2</th></tr>
<tr><td colspan="10">$p_1 = 861.9$ N/m^2; $p_2 = 58.25$ kN/m^2; $T_2 = 2766$ K; $Z^*_2 = 1.013$; $U_{s,1} = 2.579$ km/sec;
$U_2 = 2.223$ km/sec; $p_{2,s} = 326.2$ kN/m^2; $T_{2,s} = 3680$ K; $Z^*_{2,s} = 1.071$</td></tr>
<tr><td>4.267</td><td>3.727</td><td>1924</td><td>1.000</td><td>1.271</td><td>5.094</td><td>4.547 $\times 10^5$</td><td>119.2</td><td>12.74</td><td>120.2 to 123.3</td></tr>
<tr><td>4.877</td><td>1.396</td><td>1545</td><td>1.000</td><td>1.301</td><td>6.420</td><td>2.803</td><td>72.62</td><td>12.03</td><td>31.20 to 35.65</td></tr>
<tr><td>5.486</td><td>.4560</td><td>1184</td><td>1.000</td><td>1.323</td><td>8.183</td><td>1.587</td><td>39.18</td><td>10.64</td><td>7.476 to 9.248</td></tr>
<tr><td>6.096</td><td>.1229</td><td>852.1</td><td>1.000</td><td>1.349</td><td>10.61</td><td>.8080</td><td>18.12</td><td>8.663</td><td>2.016 to 2.028</td></tr>
<tr><td colspan="10">$p_1 = 3.447$ kN/m^2; $p_2 = 190.4$ kN/m^2; $T_2 = 2495$ K; $Z^*_2 = 1.002$; $U_{s,1} = 2.345$ km/sec;
$U_2 = 1.991$ km/sec; $p_{2,s} = 940.4$ kN/m^2; $T_{2,s} = 3450$ K; $Z^*_{2,s} = 1.028$</td></tr>
<tr><td>4.267</td><td>5.871</td><td>1305</td><td>1.000</td><td>1.315</td><td>6.079</td><td>13.59 $\times 10^5$</td><td>276.8</td><td>18.03</td><td>189.4 to 194.2</td></tr>
<tr><td>4.877</td><td>1.706</td><td>962.5</td><td>1.000</td><td>1.339</td><td>8.019</td><td>7.316</td><td>142.5</td><td>15.97</td><td>38.11 to 43.55</td></tr>
<tr><td>5.486</td><td>.3869</td><td>652.9</td><td>1.000</td><td>1.370</td><td>10.83</td><td>3.536</td><td>60.29</td><td>12.71</td><td>6.343 to 7.847</td></tr>
<tr><td>6.096</td><td>.05869</td><td>386.8</td><td>1.000</td><td>1.396</td><td>15.48</td><td>1.475</td><td>19.06</td><td>8.656</td><td>.9621 to .9679</td></tr>
<tr><td colspan="10">$p_1 = 6.895$ kN/m^2; $p_2 = 335.9$ kN/m^2; $T_2 = 2291$ K; $Z^*_2 = 1.001$; $U_{s,1} = 2.207$ km/sec;
$U_2 = 1.861$ km/sec; $p_{2,s} = 1.559$ MN/m^2; $T_{2,s} = 3243$ K; $Z^*_{2,s} = 1.013$</td></tr>
<tr><td>4.267</td><td>6.016</td><td>1002</td><td>1.000</td><td>1.336</td><td>6.885</td><td>21.20 $\times 10^5$</td><td>369.4</td><td>20.11</td><td>194.1 to 199.0</td></tr>
<tr><td>4.877</td><td>1.415</td><td>688.3</td><td>1.000</td><td>1.366</td><td>9.389</td><td>10.52</td><td>165.2</td><td>16.79</td><td>31.62 to 36.13</td></tr>
<tr><td>5.486</td><td>.2283</td><td>416.1</td><td>1.000</td><td>1.394</td><td>13.45</td><td>4.541</td><td>55.82</td><td>12.04</td><td>3.742 to 4.630</td></tr>
<tr><td>6.096</td><td>.01908</td><td>205.1</td><td>1.000</td><td>1.401</td><td>21.23</td><td>1.481</td><td>11.69</td><td>6.712</td><td>.3129 to .3148</td></tr>
</table>

TABLE II.- CALCULATED EXPANSION-TUBE FLOW QUANTITIES FOR FIVE-SPECIES PURE CO_2 IN THERMOCHEMICAL EQUILIBRIUM

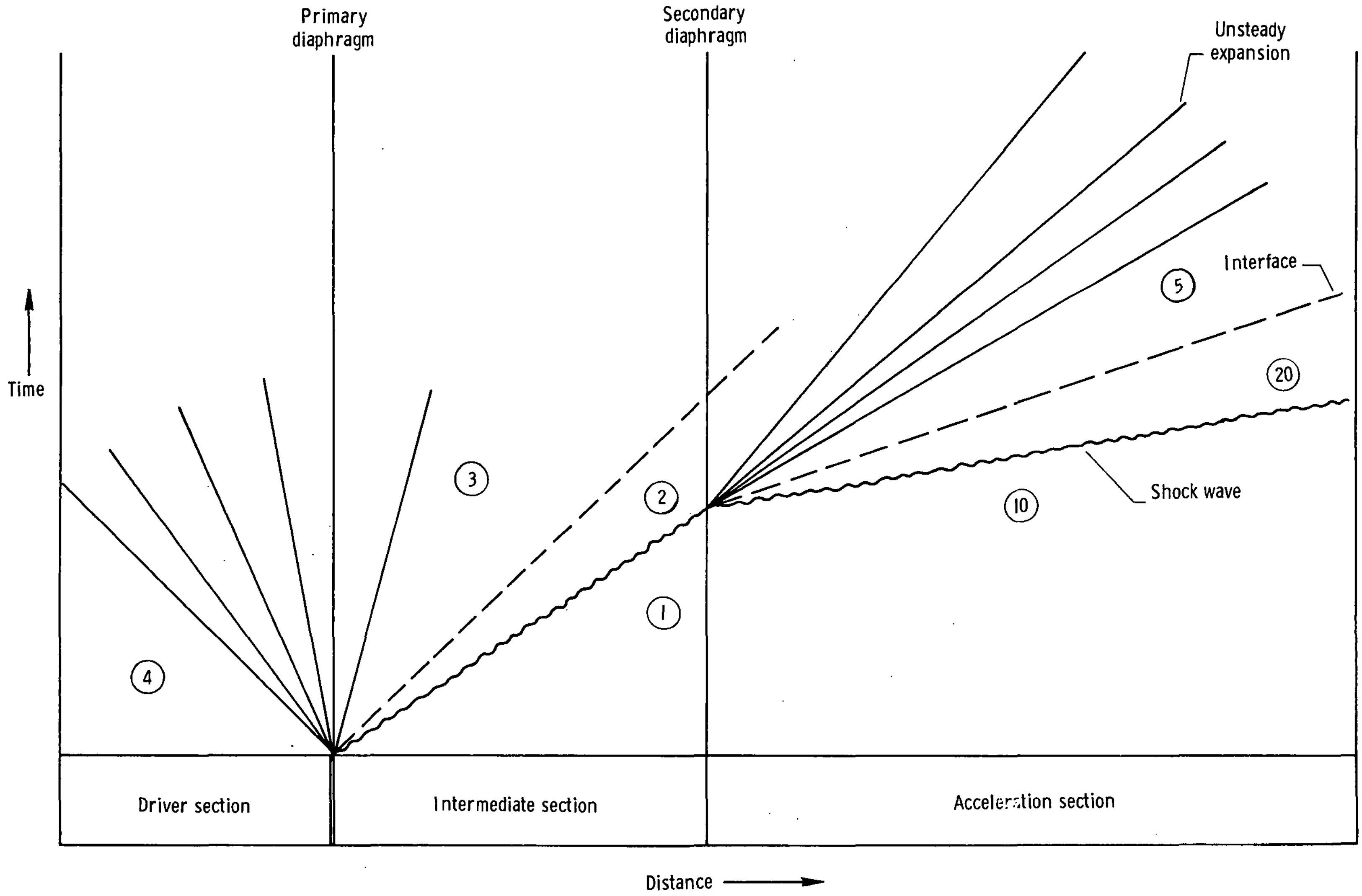
$[p_4 = 34.474\ MN/m^2;\ T_4 = T_1 = T_{10} = 300\ K;\ W_4 = W_{10} = 4.003\ kg/kmol;$
$W_1 = 44.011\ kg/kmol]$

<table>
<tr><th>U_5, km/sec</th><th>p_5, kN/m^2</th><th>T_5, K</th><th>Z^*_5</th><th>$\gamma_{E,5}$</th><th>M_5</th><th>$N_{Re,5}$, m^{-1}</th><th>$p_{5,t}$, kN/m^2</th><th>$\dot{q}_{5,t}$, MW/m^2</th><th>p_{10}, N/m^2</th></tr>
<tr><td colspan="10">$p_1 = 861.9\ N/m^2;\ p_2 = 79.10\ kN/m^2;\ T_2 = 2275\ K;\ Z^*_2 = 1.032;\ U_{s,1} = 2.371\ km/sec;$
$U_2 = 2.169\ km/sec;\ p_{2,s} = 797.9\ kN/m^2;\ T_{2,s} = 2990\ K;\ Z^*_{2,s} = 1.138$</td></tr>
<tr><td>4.267</td><td>2.131</td><td>1933</td><td>1.019</td><td>1.107</td><td>6.649</td><td>4.016 $\times 10^5$</td><td>101.2</td><td>13.71</td><td>68.75 to 70.51</td></tr>
<tr><td>4.877</td><td>.7220</td><td>1749</td><td>1.008</td><td>1.122</td><td>7.977</td><td>1.864</td><td>49.99</td><td>11.70</td><td>16.13 to 18.44</td></tr>
<tr><td>5.486</td><td>.2251</td><td>1534</td><td>1.002</td><td>1.147</td><td>9.506</td><td>.8214</td><td>22.62</td><td>9.478</td><td>3.689 to 4.565</td></tr>
<tr><td>6.096</td><td>.06330</td><td>1291</td><td>1.001</td><td>1.169</td><td>11.41</td><td>.3428</td><td>9.352</td><td>7.272</td><td>1.038 to 1.044</td></tr>
<tr><td colspan="10">$p_1 = 3.447\ kN/m^2;\ p_2 = 253.2\ kN/m^2;\ T_2 = 2084\ K;\ Z^*_2 = 1.009;\ U_{s,1} = 2.130\ km/sec;$
$U_2 = 1.927\ km/sec;\ p_{2,s} = 2.230\ MN/m^2;\ T_{2,s} = 2844\ K;\ Z^*_{2,s} = 1.070$</td></tr>
<tr><td>4.267</td><td>3.336</td><td>1479</td><td>1.001</td><td>1.162</td><td>7.485</td><td>10.08 $\times 10^5$</td><td>210.7</td><td>18.33</td><td>107.6 to 110.4</td></tr>
<tr><td>4.877</td><td>.9050</td><td>1226</td><td>1.000</td><td>1.173</td><td>9.352</td><td>4.267</td><td>90.07</td><td>14.80</td><td>20.22 to 23.10</td></tr>
<tr><td>5.486</td><td>.2127</td><td>985.6</td><td>1.000</td><td>1.182</td><td>11.69</td><td>1.608</td><td>33.33</td><td>11.00</td><td>3.486 to 4.313</td></tr>
<tr><td>6.096</td><td>.04114</td><td>759.3</td><td>1.000</td><td>1.197</td><td>14.71</td><td>.5373</td><td>10.33</td><td>7.390</td><td>.6744 to .6784</td></tr>
<tr><td colspan="10">$p_1 = 6.895\ kN/m^2;\ p_2 = 441.6\ kN/m^2;\ T_2 = 1929\ K;\ Z^*_2 = 1.003;\ U_{s,1} = 1.993\ km/sec;$
$U_2 = 1.793\ km/sec;\ p_{2,s} = 3.634\ MN/m^2;\ T_{2,s} = 2713\ K;\ Z^*_{2,s} = 1.042$</td></tr>
<tr><td>4.267</td><td>3.300</td><td>1185</td><td>1.000</td><td>1.175</td><td>8.321</td><td>14.41 $\times 10^5$</td><td>260.3</td><td>19.61</td><td>106.5 to 109.2</td></tr>
<tr><td>4.877</td><td>.7534</td><td>946.4</td><td>1.000</td><td>1.184</td><td>10.60</td><td>5.447</td><td>97.17</td><td>14.96</td><td>16.84 to 19.24</td></tr>
<tr><td>5.486</td><td>.1405</td><td>722.3</td><td>1.000</td><td>1.200</td><td>13.56</td><td>1.800</td><td>30.05</td><td>10.23</td><td>2.304 to 2.850</td></tr>
<tr><td>6.096</td><td>.01944</td><td>511.0</td><td>1.000</td><td>1.227</td><td>17.71</td><td>.5133</td><td>7.255</td><td>6.105</td><td>.3188 to .3206</td></tr>
</table>

TABLE III.- CALCULATED EXPANSION-TUBE FLOW QUANTITIES FOR THREE-SPECIES PURE Ar IN THERMOCHEMICAL EQUILIBRIUM

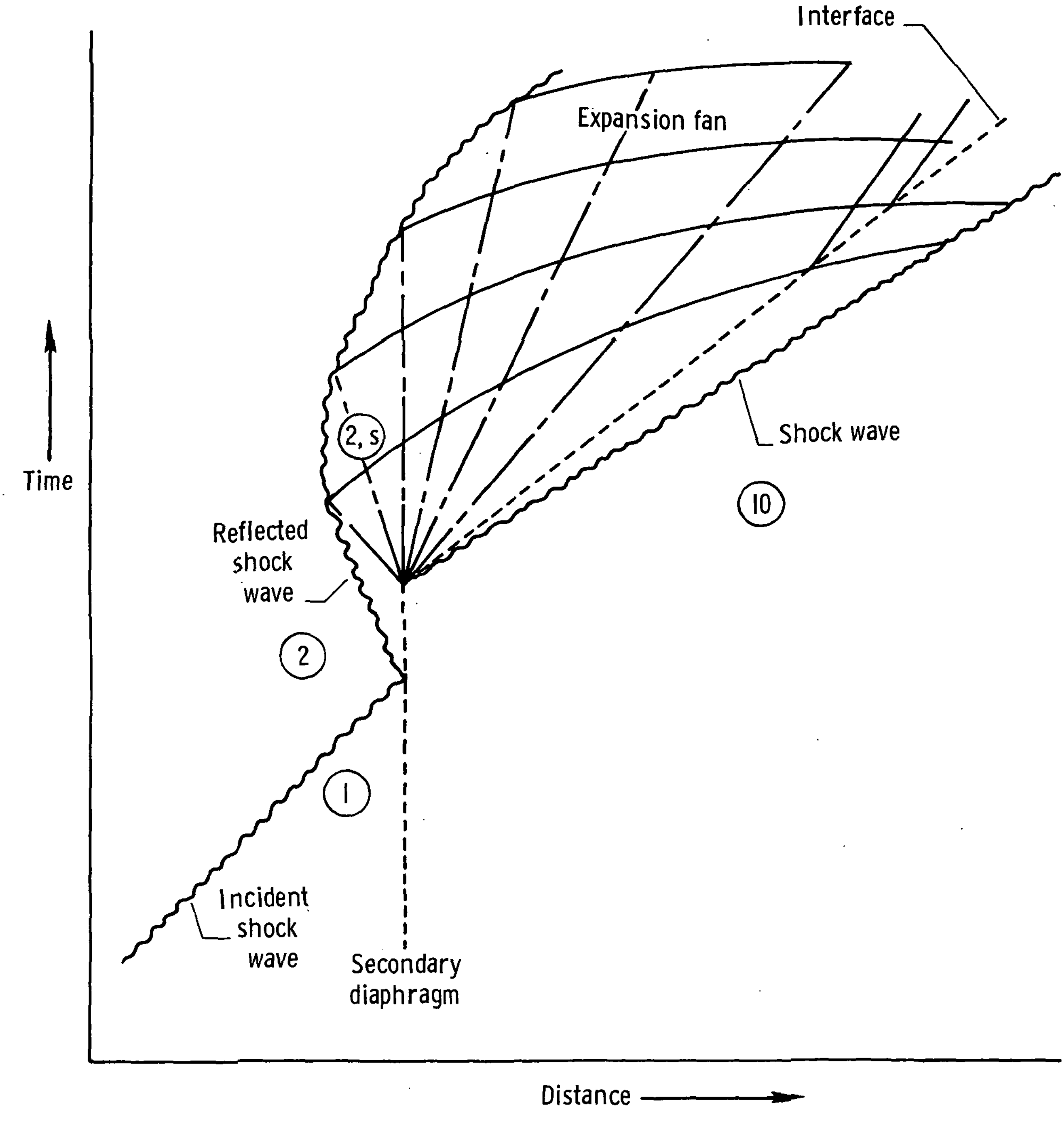
$\left[p_4 = 34.474\ \text{MN/m}^2;\ T_4 = T_1 = T_{10} = 300\ \text{K};\ W_4 = W_{10} = 4.003\ \text{kg/kmol};\ W_1 = 39.944\ \text{kg/kmol}\right]$

<table>
<tr><th>U_5, km/sec</th><th>p_5, N/m^2</th><th>T_5, K</th><th>Z^*_5</th><th>$\gamma_{E,5}$</th><th>M_5</th><th>$N_{Re,5}$, m^{-1}</th><th>$p_{5,t}$, kN/m^2</th><th>$\dot{q}_{5,t}$, MW/m^2</th><th>p_{10}, N/m^2</th></tr>
<tr><td colspan="10">$p_1 = 861.9$ N/m^2; $p_2 = 86.82$ kN/m^2; $T_2 = 7723$ K; $Z^*_2 = 1.001$; $U_{s,1} = 2.893$ km/sec;
$U_2 = 2.153$ km/sec; $p_{2,s} = 192.9$ kN/m^2; $T_{2,s} = 9779$ K; $Z^*_{2,s} = 1.012$</td></tr>
<tr><td>4.267</td><td>5602</td><td>2659</td><td>1.000</td><td>1.667</td><td>4.443</td><td>3.820 $\times 10^5$</td><td>178.8</td><td>21.23</td><td>180.6 to 185.3</td></tr>
<tr><td>4.877</td><td>1706</td><td>1653</td><td>1.000</td><td>1.667</td><td>6.440</td><td>3.041</td><td>114.4</td><td>20.71</td><td>38.13 to 43.57</td></tr>
<tr><td>5.486</td><td>357.6</td><td>884.7</td><td>1.000</td><td>1.667</td><td>9.903</td><td>2.125</td><td>56.70</td><td>17.77</td><td>5.863 to 7.254</td></tr>
<tr><td>6.096</td><td>36.36</td><td>354.6</td><td>1.000</td><td>1.667</td><td>17.38</td><td>1.177</td><td>17.76</td><td>12.05</td><td>.5961 to .5997</td></tr>
<tr><td colspan="10">$p_1 = 3.447$ kN/m^2; $p_2 = 275.4$ kN/m^2; $T_2 = 6267$ K; $Z^*_2 = 1.000$; $U_{s,1} = 2.583$ km/sec;
$U_2 = 1.907$ km/sec; $p_{2,s} = 518.2$ kN/m^2; $T_{2,s} = 8065$ K; $Z^*_{2,s} = 1.001$</td></tr>
<tr><td>4.267</td><td>6245</td><td>1389</td><td>1.000</td><td>1.667</td><td>6.146</td><td>13.17 $\times 10^5$</td><td>381.4</td><td>29.04</td><td>201.4 to 206.6</td></tr>
<tr><td>4.877</td><td>1106</td><td>695.1</td><td>1.000</td><td>1.667</td><td>9.931</td><td>8.884</td><td>176.3</td><td>24.70</td><td>24.70 to 28.22</td></tr>
<tr><td>5.486</td><td>76.52</td><td>238.8</td><td>1.000</td><td>1.667</td><td>19.06</td><td>4.433</td><td>44.94</td><td>15.48</td><td>1.255 to 1.552</td></tr>
<tr><td>6.096</td><td>.1675</td><td>20.61</td><td>1.000</td><td>1.667</td><td>72.08</td><td>.7637</td><td>1.407</td><td>3.362</td><td>.002746 to .002762</td></tr>
<tr><td colspan="10">$p_1 = 6.895$ kN/m^2; $p_2 = 477.2$ kN/m^2; $T_2 = 5469$ K; $Z^*_2 = 1.000$; $U_{s,1} = 2.405$ km/sec;
$U_2 = 1.771$ km/sec; $p_{2,s} = 871.6$ kN/m^2; $T_{2,s} = 6999$ K; $Z^*_{2,s} = 1.000$</td></tr>
<tr><td>4.267</td><td>4775</td><td>873.0</td><td>1.000</td><td>1.667</td><td>7.754</td><td>22.59 $\times 10^5$</td><td>464.1</td><td>31.14</td><td>154.0 to 158.0</td></tr>
<tr><td>4.877</td><td>476.8</td><td>347.3</td><td>1.000</td><td>1.667</td><td>14.05</td><td>12.80</td><td>152.1</td><td>22.60</td><td>10.65 to 12.17</td></tr>
<tr><td>5.486</td><td>5.837</td><td>59.69</td><td>1.000</td><td>1.667</td><td>38.13</td><td>3.770</td><td>13.72</td><td>8.498</td><td>.09569 to .1184</td></tr>
<tr><td>6.096</td><td>.07358</td><td>10.37</td><td>1.000</td><td>1.667</td><td>101.6</td><td>1.108</td><td>1.229</td><td>3.141</td><td>.001206 to .001213</td></tr>
</table>



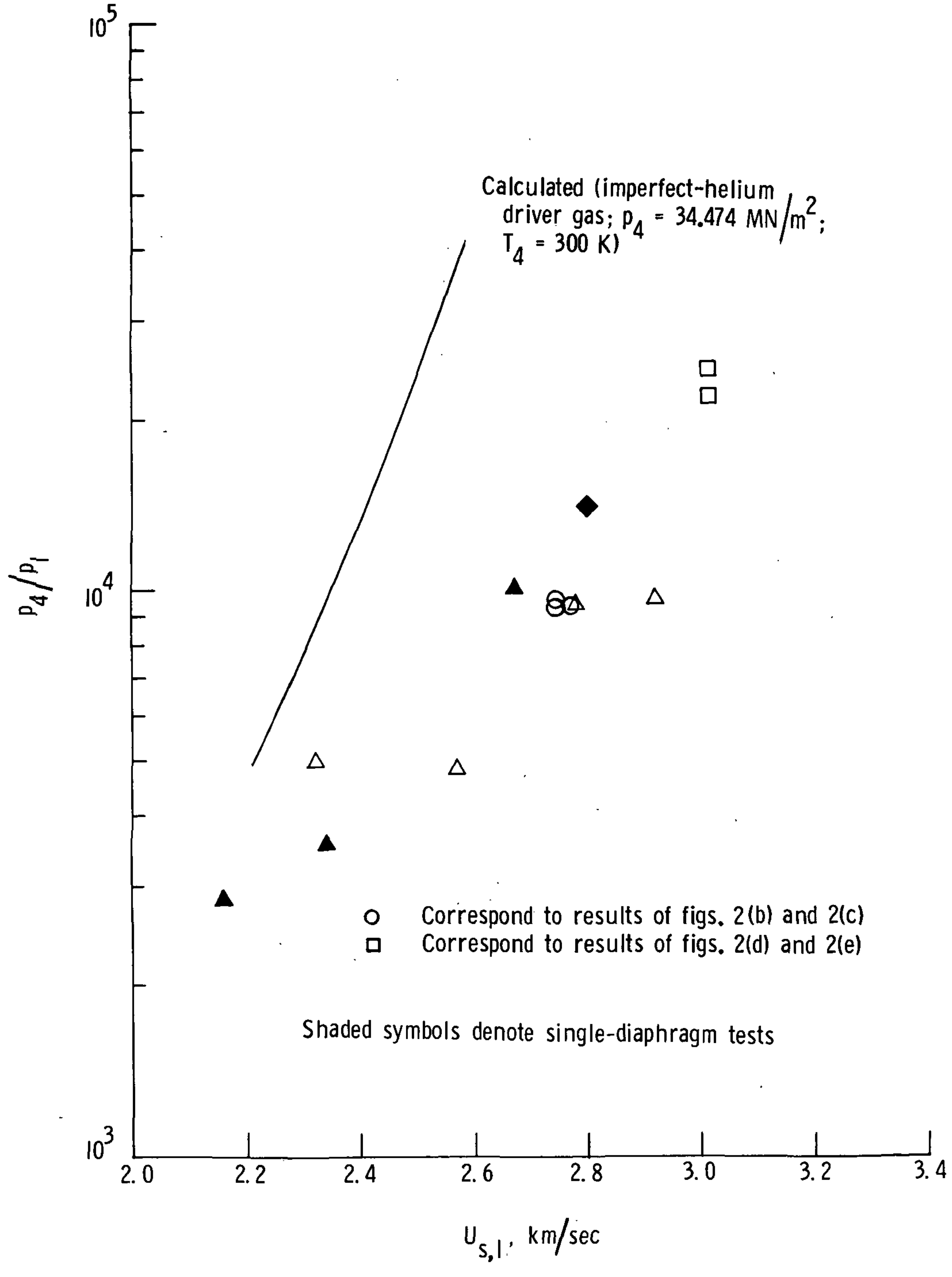
(a) No reflected shock at secondary diaphragm.

Figure 1.- Schematic diagram of expansion-tube flow sequence.



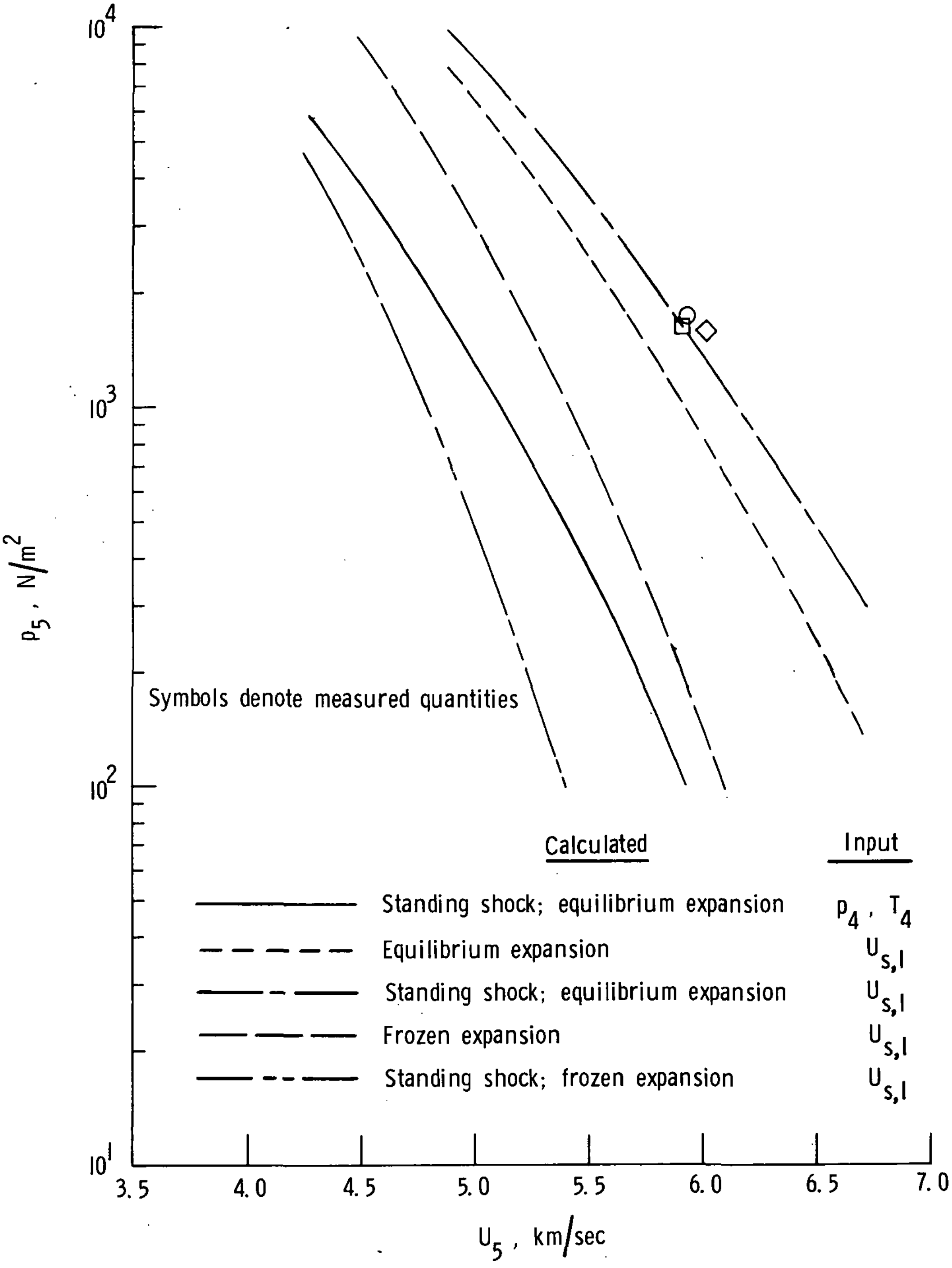
(b) Reflected shock at secondary diaphragm.

Figure 1.- Concluded.



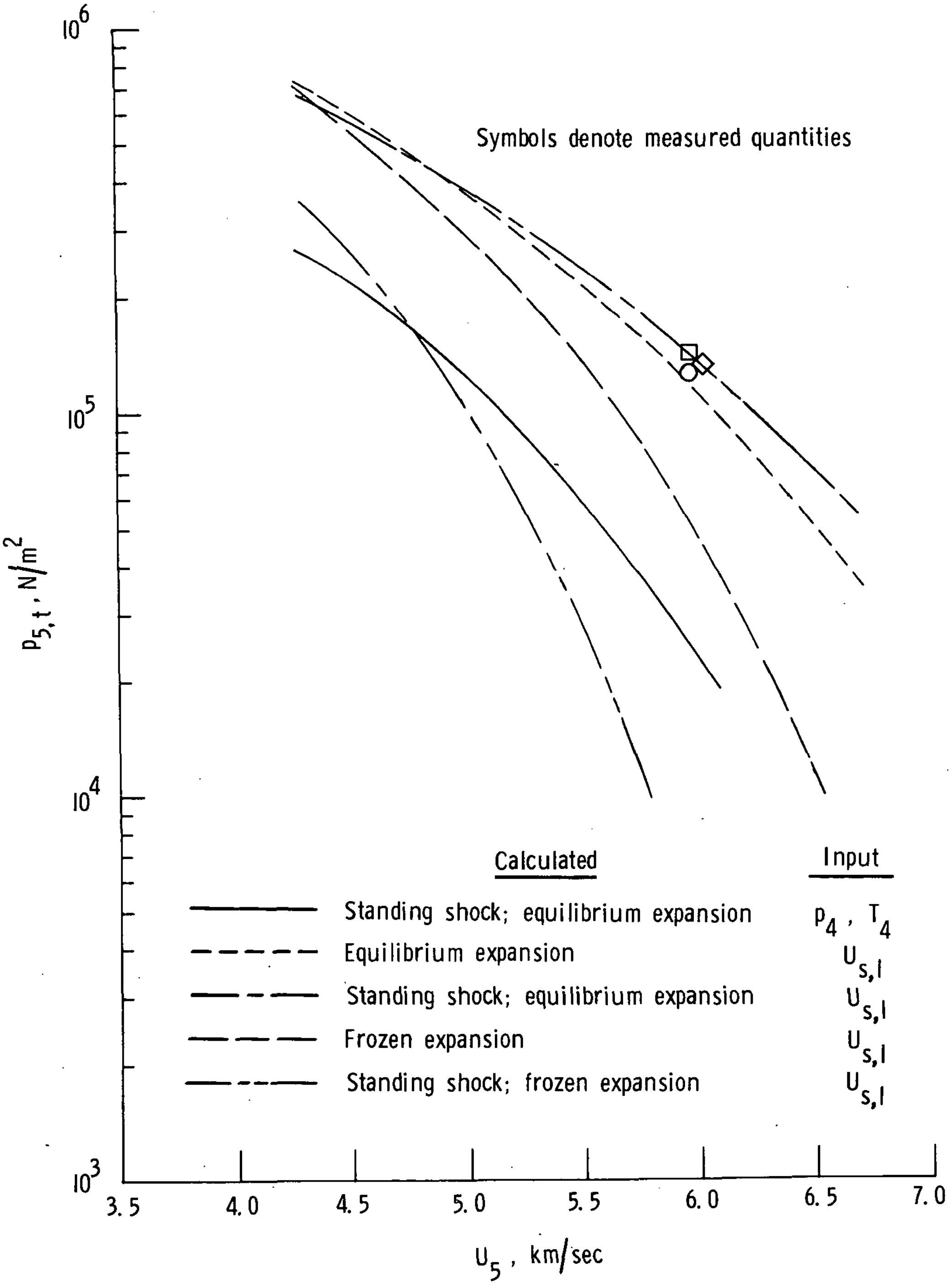
(a) Incident-shock velocity as function of pressure ratio across primary diaphragm.

Figure 2.- Comparison of calculated and measured expansion-tube flow quantities for unheated helium driver gas and air test gas.



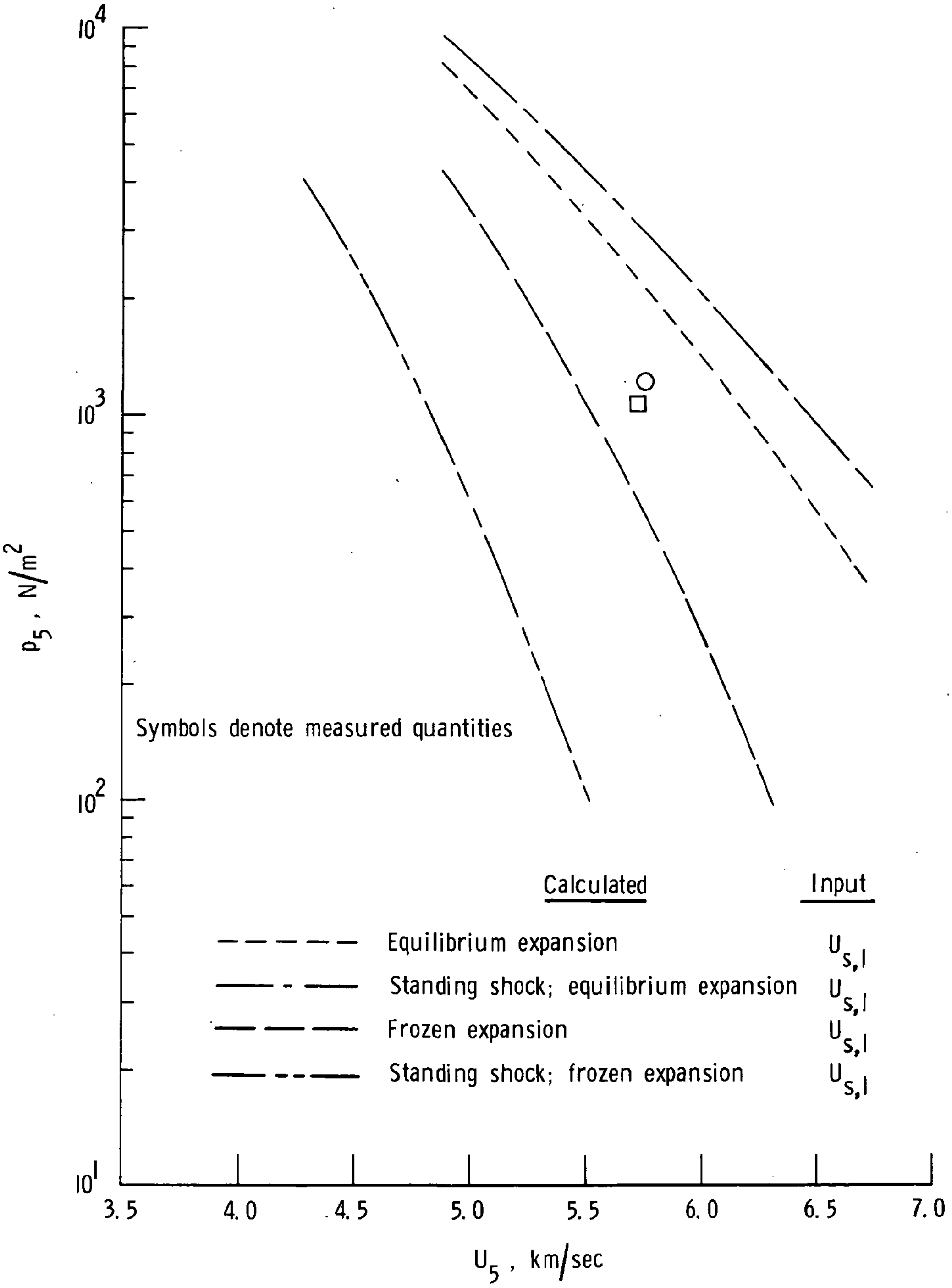
(b) Free-stream static pressure as function of free-stream velocity; $p_1 = 3.447$ kN/m^2.

Figure 2.- Continued.



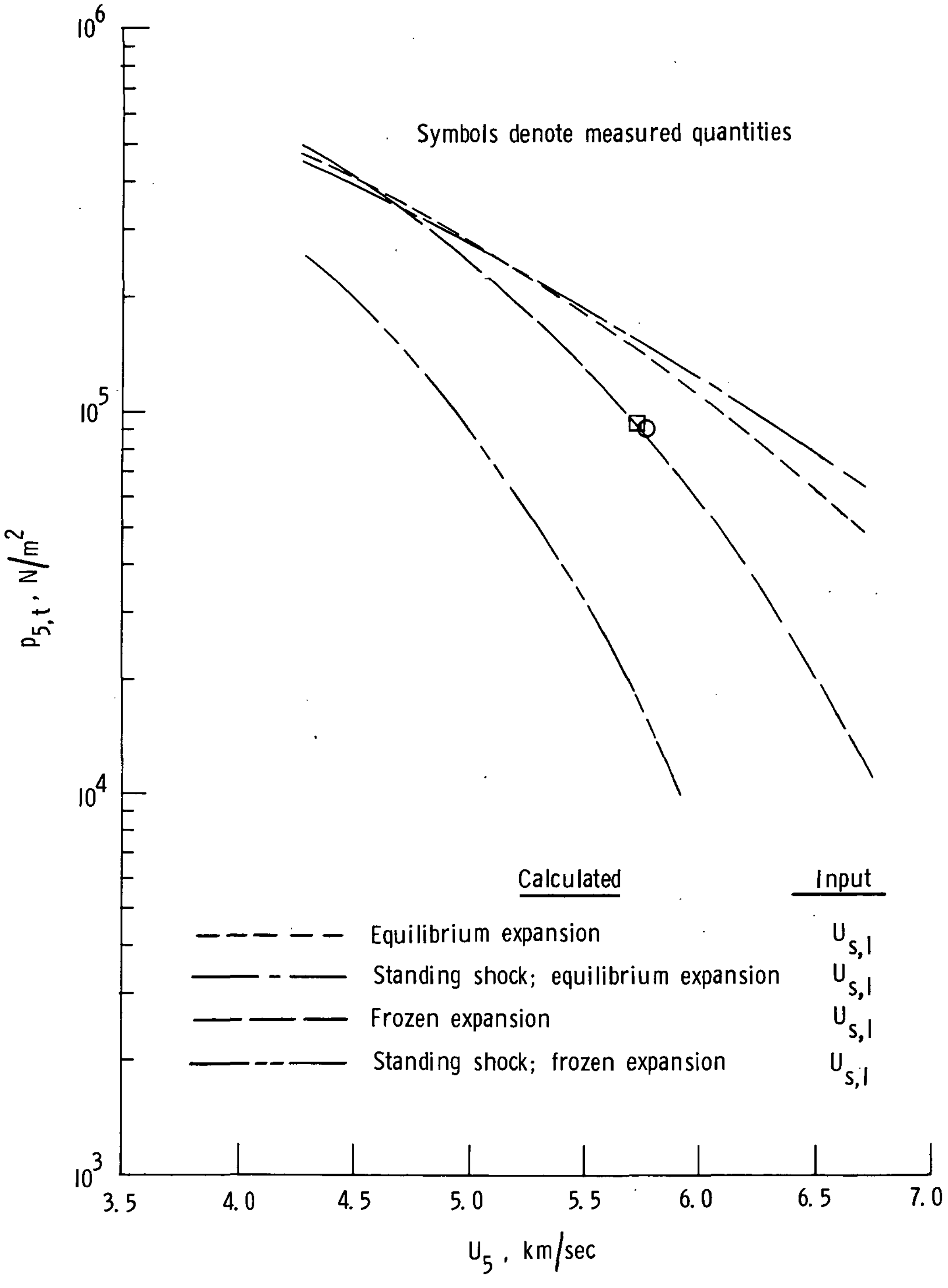
(c) Pitot pressure as function of free-stream velocity; $p_1 = 3.447$ kN/m^2.

Figure 2.- Continued.



(d) Free-stream static pressure as function of free-stream velocity; $p_1 = 1.379$ kN/m^2.

Figure 2.- Continued.



(e) Pitot pressure as function of free-stream velocity; $p_1 = 1.379$ kN/m^2.

Figure 2.- Concluded.

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