PROGRAM AND CHARTS FOR DETERMINING
SHOCK TUBE, EXPANSION TUBE, AND
EXPANSION TUNNEL FLOW QUANTITIES
FOR REAL AIR

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A computer program written in FORTRAN IV language is presented which determines shock tube, expansion tube, and expansion tunnel flow quantities for real-air test gas. This program permits, as input data, a number of possible combinations of flow quantities generally measured during a test. The versatility of the program is enhanced by the inclusion of such effects as a standing or totally reflected shock at the secondary diaphragm, thermochemical-equilibrium flow expansion and frozen flow expansion for the expansion tube and expansion tunnel, attenuation of the flow in traversing the acceleration section of the expansion tube, real air as the acceleration gas, and the effect of wall boundary layer on the acceleration section air flow. Charts which provide a rapid estimation of expansion tube performance prior to a test are included.
A computer program written in FORTRAN IV language is presented which determines shock tube, expansion tube, and expansion tunnel flow quantities for real-air test gas. For the shock tube phase of the program, flow conditions 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 shock reflection at the secondary diaphragm of the expansion tube, resulting in a standing or a totally reflected shock, is included. Expansion tube test-section flow conditions are obtained by performing an isentropic unsteady expansion from conditions behind the incident shock, standing shock, or totally reflected shock to either the test region velocity or static pressure. Expansion tunnel test-section flow conditions are obtained by performing an isentropic steady expansion from expansion tube free-stream conditions to either the nozzle test region velocity or static pressure. Both a thermochemical-equilibrium expansion and a frozen expansion for the expansion tube and expansion tunnel are included. The effect of flow attenuation along the acceleration section of the expansion tube is included for an equilibrium expansion. Flow conditions immediately behind the bow shock of a model positioned at the test section of a shock tube, expansion tube, or expansion tunnel are determined. A listing of the computer program is presented along with a description of inputs required and samples of the data printout. Charts which provide a rapid estimation of expansion tube performance prior to a test are included.

INTRODUCTION

Experimental studies using air as the test gas have been initiated in the Langley 6-inch expansion tube, and a number of studies are expected to be performed in the Langley expansion tunnel. Prior to performing studies in these facilities, it is essential for the investigator to ascertain the theoretical performance of the facility because of the
wide range of flow conditions which may be generated and the very short test times (less than 300 \( \mu \)sec or so) which place stringent requirements on facility instrumentation. Thus, a knowledge of the magnitude of physical quantities to be measured is required. After a test, a convenient means for determining expansion tube and expansion tunnel flow conditions from measured quantities is desirable. Although a number of theoretical studies have been directed toward prediction of expansion tube and expansion tunnel performance with air as the test gas (for example, refs. 1 to 4), these studies were primarily concerned with simulation or duplication of conditions experienced by high-velocity, earth-entry vehicles.

The primary purposes of the present study are (1) to furnish a convenient, versatile, accurate computer program for determining shock tube, expansion tube, and expansion tunnel flow quantities in real air from combinations of measured flow quantities and (2) to provide charts for rapid estimation of facility performance prior to a test. This program is similar to the real-gas mixture study of reference 5; however, a number of differences exist between these two programs. The present program requires much less computer time, with no appreciable sacrifice in accuracy, than the program of reference 5. Such a reduction in computer time is a significant factor in data reduction, since most of the testing in the Langley 6-inch expansion tube is performed with air as the test gas.

Operating experience with the Langley 6-inch expansion tube and operation of this expansion tube as a shock tube demonstrated the desirability for options other than those presented in reference 5. Results included herein, but not in reference 5, are (1) charts illustrating predicted shock tube performance with hydrogen and helium driver gases for a range of driver gas pressure and temperature, (2) a totally reflected shock, as well as a standing shock, at the secondary diaphragm, (3) real air as the acceleration gas, (4) the effect of wall boundary layer on shock tube and acceleration section air flow for laminar (ref. 6) and/or turbulent (ref. 7) boundary layers, (5) the effect of flow attenuation along the acceleration section, (6) imperfect (intermolecular) air effects permitting calculations at higher pressures than permissible with reference 5, (7) determination of expansion tunnel test-section flow conditions from measured nozzle free-stream velocity or static pressure, and (8) charts which provide a convenient means for properly preparing facility instrumentation and determining the level of quiescent test gas and acceleration gas pressures for a test.

The procedures for determining shock tube, expansion tube, and expansion tunnel flow quantities for real air are incorporated into a single computer program written in FORTRAN IV language. Required program inputs are listed and described in appendix A. A flow chart and a listing of the program are also presented in appendix A along with sample data printouts.
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 8.

\begin{itemize}
  \item \textbf{A} \quad \text{cross-sectional area, m}^2$
  \item \textbf{a} \quad \text{speed of sound, m/sec}$
  \item \textbf{d} \quad \text{shock tube or expansion tube inside diameter, m}$
  \item \textbf{h} \quad \text{specific enthalpy, m}^2/\text{sec}^2 \quad (\text{J/kg})$
  \item \textbf{L}_a \quad \text{length of acceleration section, m}$
  \item \textbf{L}_s \quad \text{distance measured downstream from secondary diaphragm, m}$
  \item \textbf{l} \quad \text{distance between incident shock in region 1 and test-air—driver-gas interface, m (see fig. 1)}$
  \item \textbf{M} \quad \text{Mach number, U/a}$
  \item \textbf{M}_s \quad \text{incident shock Mach number, U}_s/a$
  \item \textbf{N}_{Re} \quad \text{unit Reynolds number, } \rho U/\mu, \text{ m}^{-1}$
  \item \textbf{p} \quad \text{pressure, N/m}^2$
  \item \textbf{q} \quad \text{stagnation point convective heat-transfer rate, W/m}^2$
  \item \textbf{R} \quad \text{universal gas constant, 8.31434 kJ/kmol-K}$
  \item \textbf{r} \quad \text{radius, m}$
  \item \textbf{s} \quad \text{specific entropy, kJ/kg-K}$
  \item \textbf{sW}_u/R \quad \text{nondimensional specific entropy}$
\end{itemize}
T  temperature, K

t  test time, sec

U  velocity, m/sec

U_I  interface velocity, m/sec

U_r  reflected shock velocity, m/sec

U_s  incident shock velocity, m/sec

W  molecular weight, kg/kmol

W_u  molecular weight of undissociated air, 28.967 kg/kmol

X  distance between primary diaphragm station and incident shock in
  region 1, m (see fig. 1)

X_s  distance behind incident shock in region 1, m (see fig. 1)

x  mole fraction

Z  compressibility factor, \( p_{W_u}/\rho RT \)

Z*  number of kmol of dissociated air per number of kmol of undissociated
  air, \( W_u/W \)

\( \gamma \)  ratio of specific heats

\( \gamma_E \)  isentropic exponent, \( \left( \frac{\partial \log p}{\partial \log \rho} \right)_{SW_u/R} \)

\( \alpha \)  defined by \( Z^* = 1 + \alpha \)

\( \delta^* \)  nozzle boundary-layer displacement thickness, m

\( \mu \)  coefficient of viscosity, N-sec/m²
\( \rho \) density, kg/m\(^3\)

\( \tau \) time interval between arrival of incident shock and interface, sec

Subscripts:

A denotes region 2 for no standing shock at secondary diaphragm, region 2s for standing shock, and region 2r for reflected shock (see fig. 1)

a atom

eff effective (based on mass flow considerations)

f frozen

geo geometric

i ideal

k \( k = 2 \) denotes shock tube flow, \( k = 5 \) denotes expansion tube flow, and \( k = 6 \) denotes expansion tunnel flow

m molecule

max maximum

n model nose

\( t,2 \) stagnation conditions behind normal bow shock at shock tube test section

\( t,5 \) stagnation conditions behind normal bow shock at expansion tube test section

\( t,6 \) stagnation conditions behind normal bow shock at expansion tunnel test section

w wall

\( X_s \) distance behind incident shock in region 1, m (see fig. 1)
1 state of quiescent air in front of incident shock in shock tube (intermediate section of expansion tube)

2 state of air behind incident shock in shock tube

2s state of air behind standing shock at secondary diaphragm or normal bow shock at shock tube test section

2r state of air behind reflected shock at secondary diaphragm

3 state of expanded driver gas

4 initial driver gas conditions

5 state of test air in expansion tube test section

5s static conditions behind normal bow shock at expansion tube test section

6 state of test air in expansion tunnel test section

6s static conditions behind normal bow shock at expansion tunnel test section

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

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

Superscript:

* conditions at nozzle throat

FACILITIES, ANALYSIS, AND PROCEDURE

Before the procedures for determining shock tube, expansion tube, and expansion tunnel flow quantities are discussed, a brief description of these facilities is given. Next, the source of imperfect real-air thermodynamic properties is briefly discussed. After these discussions, the procedures for determining free-stream and post-normal-shock flow conditions for the shock tube, expansion tube, and expansion tunnel are presented.
Description of Shock Tube, Expansion Tube, and Expansion Tunnel

**Shock tube.** The shock tube is a tube, generally cylindrical, divided by a high-pressure diaphragm into two sections. The upstream section is the driver or high-pressure section. This section is pressurized with a gas having a high speed of sound, such as unheated or heated hydrogen or helium. (Greater operation efficiency is realized with gases having a high speed of sound.) The downstream section is referred to as the driven or low-pressure section and the cross section is constant and generally circular. The driven section is usually evacuated and then filled with the test gas at ambient temperature. As illustrated in figure 1(a), the driver gas at time of diaphragm rupture is designated as region \( \text{\textbullet} \) and the quiescent test gas is designated as region \( \text{\o} \). Upon rupture of the diaphragm, an incident shock wave propagates into region \( \text{\textbullet} \) with velocity \( U_{S,1} \). Flow conditions immediately behind this shock are denoted as region \( \text{\textbullet} \) (fig. 1(b)), and shock tube testing takes place in the flow region from immediately behind this incident shock wave to the test-gas—driver-gas interface. For a blunt model positioned in the driven section, a standing shock is formed at the model, provided flow in region \( \text{\textbullet} \) is supersonic. (See fig. 1(c).) The flow conditions immediately behind this standing shock are designated as region \( \text{\textbullet} \); the model stagnation conditions, as region \( \text{\textbullet} \). When the incident shock wave reaches the end wall (or secondary diaphragm of the expansion tube, to be discussed subsequently), it is reflected back into region \( \text{\textbullet} \). (See fig. 1(d).) Flow conditions behind this reflected shock are designated as region \( \text{\textbullet} \).

**Expansion tube and expansion tunnel.** The expansion tube is basically a shock tube with a section of constant cross section attached to the downstream end. A weak low-pressure diaphragm (secondary diaphragm) separates this section, denoted as the expansion or acceleration section, from the driven section, which is commonly referred to as the intermediate section of the expansion tube. The acceleration section is evacuated and filled with the acceleration gas at a low pressure and ambient temperature. The expansion tunnel is simply an expansion tube with a nozzle added to the downstream end.

The operating sequence of the expansion tunnel includes that for an expansion tube, which, in turn, includes that for a shock tube; the sequence for an expansion tunnel is shown schematically in figure 2. The sequence begins with the rupture of the primary or high-pressure diaphragm separating the driver and driven sections. An incident shock wave propagates into the static test gas and an expansion wave propagates into the driver gas. The shock wave encounters and ruptures the secondary diaphragm. Flow energy lost in rupturing this diaphragm results in an upstream-facing shock wave reflected from the diaphragm. If this shock wave is assumed to be a standing shock, flow conditions behind this standing shock are denoted as region \( \text{\textbullet} \); if a totally reflected shock at the secondary diaphragm is assumed, flow conditions behind this reflected shock are

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Note: The original text contains figures (1 and 2) that are not included in this transcription. The figures are typically included in the full document to provide visual context for the described processes.
denoted as region \( \text{region 2} \). (See fig. 1(d).) A second incident shock wave propagates into the acceleration gas while an upstream expansion wave moves into the test gas. In passing through this upstream expansion wave, the test gas undergoes an isentropic unsteady expansion that results in an increase in flow velocity. Expansion tube testing occurs in the flow that has passed through the expansion and is denoted as region \( \text{region 5} \) in figure 2. Thus, for the expansion tunnel, the test gas is processed first by an incident shock into the quiescent test gas in region \( \text{region 1} \), second, by a shock wave resulting from shock reflection at the secondary diaphragm, third, by an unsteady expansion in the acceleration section, and finally, by an isentropic steady expansion in the nozzle. Expansion tunnel testing takes place in region \( \text{region 6} \) of figure 2.

**Thermodynamic Properties for Real Air**

Thermodynamic properties for imperfect real air in thermochemical equilibrium are obtained from a magnetic tape furnished to the Langley Research Center by the Arnold Engineering Development Center (AEDC). The thermodynamic properties obtained from this tape correspond to the properties tabulated in reference 9 for various values of entropy \( sW_u/R \). The temperature range of the AEDC tape is 100 K to 15,000 K and the \( sW_u/R \) range is 15.6 to 133. A subroutine for searching the real-air tape was also obtained from AEDC and is designated herein as SLOW. An interpolation procedure allowing pressure \( p \) and enthalpy \( h \) as inputs was derived for the study of reference 10 and is referred to herein as SEARCH.

The relations derived in reference 11 for predicting thermodynamic properties of real air in thermochemical equilibrium are also employed in the present study. These relations were obtained from curve fits and cover a temperature range of 90 K to 15,000 K and an \( sW_u/R \) range of 26 to 126. Imperfect air (intermolecular force) effects are neglected in reference 11. These relations are incorporated into a subroutine designated as SAVE. The sources of thermodynamic properties are discussed in more detail in reference 10 and appendix B.

**Calculation Procedure for Shock Tube**

As in reference 5, three combinations of inputs are considered for determining flow quantities in region \( \text{region 2} \). In all three combinations, the quiescent test air pressure \( p_1 \) and temperature \( T_1 \) are assumed to be known. The quantities (1) incident-shock velocity \( U_{s1} \), (2) pressure behind the incident shock in the driven section \( p_2 \), or (3) the driver gas pressure \( p_4 \) and temperature \( T_4 \) are used in conjunction with \( p_1 \) and \( T_1 \) to determine conditions in region \( \text{region 2} \).
The conservation relations, in a laboratory coordinate system, for mass, momentum, and energy for a normal shock wave moving through region 1 are

\[ \rho_1 U_{s,1} = \rho_2 (U_{s,1} - U_2) \]  
(1)

\[ p_1 + \rho_1 U_{s,1}^2 = p_2 + \rho_2 (U_{s,1} - U_2)^2 \]  
(2)

\[ h_1 + \frac{1}{2} U_{s,1}^2 = h_2 + \frac{1}{2} (U_{s,1} - U_2)^2 \]  
(3)

These relations are solved in conjunction with the equation of state (that is, source of real-air thermodynamic properties) in the form

\[ \rho_2 = \rho_2 (p_2, h_2) \]  
(4)

for the unknown quantities \( \rho_2, \ h_2, \ U_2, \) and \( p_2 \) or \( U_{s,1} \). For the Langley shock tube and expansion tube, \( T_1 \) is ambient and \( p_1 \) is generally less than 1MN/m². At these conditions in region 1, imperfect air effects are negligible and corresponding thermodynamic quantities appearing on the left-hand side of equations (1) to (3) are obtained from perfect air \( (\gamma_1 = 1, \ \gamma_1 = 7/5) \) relations.

Equations (1) to (4) are solved by iteration. The iterative schemes used for inputs \( U_{s,1}, \ p_2, \) or \( p_4 \) and \( T_4 \) are discussed in detail in reference 5. For all three combinations of inputs, the air flow in region 2 is assumed to be in thermochemical equilibrium.

The procedure for determining shock tube performance where \( p_4 \) and \( T_4 \) are inputs is commonly referred to as "simple shock tube theory," since it is based on a simplified one-dimensional, inviscid flow model which assumes instantaneous diaphragm rupture, no shock wave attenuation, and a driver to driven cross-sectional area ratio of unity. Imperfect gas effects in region 4 for helium at 200 K \( \leq T_4 \leq 15000 \) K and hydrogen at 273 K \( \leq T_4 \leq 600 \) K are included.

Two additional shock tube flow regions of interest (fig. 1) are the result of a standing shock in region 2 (region 2s) and a totally reflected shock into region 2 (region 2r). Because of shock reflection at the secondary diaphragm of the expansion tube, these two regions are also considered in the calculation of expansion tube flow quantities and are discussed subsequently.

**Effect of boundary layer on test time.** - Shock tube wall boundary-layer growth behind the incident shock introduces departures from ideal shock tube flow. (See refs. 6
The presence of this boundary layer causes the incident shock to decelerate, the interface to accelerate, and the flow between the incident shock and interface to be non-uniform. When the wall boundary-layer displacement thickness is large in comparison with the tube diameter, the separation distance between the incident shock and the interface and the test time approach limiting maximum values. (Test time is defined as the time interval between arrival of incident shock in region 1 and arrival of the test-gas—driver-gas interface at a given station.) Actual shock tube test times may be considerably less than the values predicted by use of idealized theory. Thus, shock tube test time and flow nonuniformity are considered in the present calculations. Since these flow phenomena are dependent on the character of the shock tube wall boundary layer behind the incident shock, the effect of both laminar and turbulent wall boundary layers are included.

Shock tube test times have been treated analytically in reference 6 for laminar boundary layers and in reference 7 for turbulent boundary layers. For a laminar boundary layer, the test time $t$ is obtained from the relation (ref. 6)

$$2t_{\text{max}}(\frac{p_{2}}{p_{1}})^{2} \left[ \log_{e} \left( 1 - \sqrt{\frac{U_{S,1}t}{t_{\text{max}}}} \right) + \sqrt{\frac{U_{S,1}t}{t_{\text{max}}}} \right] + U_{S,1}t = -X$$

where the separation distance between the incident shock in region 1 and the test-gas—driver-gas interface $\ell$ for a given distance $X$ downstream of the diaphragm station is given by (ref. 6)

$$2\ell_{\text{max}}(\frac{p_{2}}{p_{1}})^{2} \left[ \log_{e} \left( 1 - \sqrt{\frac{\ell}{\ell_{\text{max}}}} \right) + \sqrt{\frac{\ell}{\ell_{\text{max}}}} \right] = -X$$

Simple expressions for the maximum separation distance $\ell_{\text{max}}$ in terms of known quantities were obtained from curve fits applied to the real-air results of reference 6 and yielded the expressions

$$\ell_{\text{max}} = p_{1}d^{2} \left( 2.060 - 2.056 \times 10^{-1} M_{S,1} + 8.095 \times 10^{-3} M_{S,1}^{2} \right) \quad (4 < M_{S,1} < 14)$$

$$\ell_{\text{max}} = p_{1}d^{2} \left( 8.723 \times 10^{-1} - 7.488 \times 10^{-3} M_{S,1} \right) \quad (14 < M_{S,1} < 30)$$
The results of figure 6 of reference 6 were extrapolated to a value of \( M_{s,1} \) equal to 30 to obtain equation (7b). As the separation distance approaches this limiting value \( \ell_{\text{max}}' \), the interface velocity approaches the incident shock velocity and is essentially equal to \( U_{s,1} \) at \( \ell_{\text{max}}' \).

The test time for a turbulent boundary layer is obtained from the relation (ref. 7)

\[
\frac{5\ell_{\text{max}}(\rho_2/\rho_1)}{4} \left\{ \log \left[ \frac{1 + \left( \frac{U_{s,1}t}{\ell_{\text{max}}} \right)^{0.2}}{1 - \left( \frac{U_{s,1}t}{\ell_{\text{max}}} \right)^{0.2}} \right] + 2 \tan^{-1} \left( \frac{U_{s,1}t}{\ell_{\text{max}}} \right)^{0.2} - 4 \left( \frac{U_{s,1}t}{\ell_{\text{max}}} \right)^{0.2} \right\} - U_{s,1}t = X
\]

where \( \ell \) is obtained from the relation (ref. 7)

\[
\frac{5\ell_{\text{max}}(\rho_2/\rho_1)}{4} \left\{ \log \left[ \frac{1 - \left( \frac{\ell}{\ell_{\text{max}}} \right)^{0.2}}{1 + \left( \frac{\ell}{\ell_{\text{max}}} \right)^{0.2}} \right] - 2 \tan^{-1} \left( \frac{\ell}{\ell_{\text{max}}} \right)^{0.2} + 4 \left( \frac{\ell}{\ell_{\text{max}}} \right)^{0.2} \right\} = -X
\]

Curve fits to the real-air results of reference 7 yielded the following expressions for \( \ell_{\text{max}}' \):

\[
\ell_{\text{max}}' = p_1^{0.25} d^{1.25} \left( 5.273 - 7.514 \times 10^{-1} M_{s,1} + 3.435 \times 10^{-2} M_{s,1}^2 \right) \quad (4 < M_{s,1} < 10)
\]

(10a)

\[
\ell_{\text{max}}' = p_1^{0.25} d^{1.25} \left( 1.546 - 3.017 \times 10^{-2} M_{s,1} \right) \quad (10 \leq M_{s,1} < 30)
\]

(10b)

For the inviscid case, the "ideal" test time is given by the relation (ref. 12)

\[
t_{1,2} = \frac{\rho_1 X}{\rho_2 U_2}
\]

(11)
Effect of boundary layer on flow nonuniformity.— A method for estimating flow nonuniformity (axial variation of flow quantities) between the incident shock and interface after maximum separation distance is reached is presented in references 6 and 13. In these references, the concept of an equivalent inviscid channel is employed and yields the following continuity equation:

\[
\rho_{2,X_s}(U_{s,1} - U_{2,X_s}) = \rho_{2,X_s=0}(U_{s,1} - U_{2,X_s=0})\left[1 - \left(\frac{X_s}{\ell_{max}}\right)^n\right] \tag{12}
\]

where \( n = 0.5 \) for a laminar boundary layer and \( n = 0.8 \) for a turbulent boundary layer. Additional relations required for solution of flow conditions in the region between the incident shock and interface are the isentropic condition for equivalent inviscid channel flow

\[
\frac{(s_2W_u)}{R}_{X_s} = \frac{(s_2W_u)}{R}_{X_s=0} \tag{13}
\]

and either the energy relation

\[
h_{2,X_s} + \frac{1}{2}(U_{s,1} - U_{2,X_s})^2 = h_{2,X_s=0} + \frac{1}{2}(U_{s,1} - U_{2,X_s=0})^2 \tag{14a}
\]

if the AEDC real-air tape is used as the source of thermodynamic properties \((\rho = \rho(h, sW_u/R))\), or the momentum relation

\[
p_{2,X_s} + \rho_{2,X_s}(U_{s,1} - U_{2,X_s})^2 = p_{2,X_s=0} + \rho_{2,X_s=0}(U_{s,1} - U_{2,X_s=0})^2 \tag{14b}
\]

if the AEDC real-air curve fit expressions are used \((\rho = \rho(p, sW_u/R))\). This system of equations is solved for the unknowns \( \rho_{2,X_s}, U_{2,X_s}, \) and \( p_{2,X_s} \), in conjunction with the equation of state, by iteration on \( \rho_{2,X_s} \) for a given value of \( X_s/\ell_{max} \). As discussed in reference 6, equation (12) is less accurate for the case where the maximum separation distance has not been obtained. This inaccuracy is due to entropy variations (associated with nonuniform shock motion) and the unsteady nature of the flow between the incident shock and the interface. Since the accuracy of equation (12) decreases as \( \ell/\ell_{max} \) decreases from its limiting value near unity, the effect of flow nonuniformity is determined herein only when the condition \( \ell/\ell_{max} \geq 0.9 \) is satisfied.
Calculation Procedure for Expansion Tube

As discussed in reference 14, the flow energy lost in rupture of the secondary diaphragm must result in an upstream-facing shock wave reflected from this diaphragm. When the diaphragm ruptures, the resulting expansion fan overtakes and weakens the reflected shock. It is sometimes assumed that the reflected shock has been weakened to a standing shock by the time it processes the flow which eventually becomes the test flow. Therefore, the possible existence of a standing normal shock at the secondary diaphragm (region 2s) was considered in reference 5.

Recently, tests were performed in the Langley expansion tube with helium as the test gas. (See ref. 15.) The primary reason for employing helium was to divorce possible effects of flow chemistry on test-section flow quantities from the gas dynamics or fluid mechanics of the flow and, thereby, to provide an approximate model of the expansion tube fluid mechanics. These helium tests indicated the existence of a totally reflected shock at the secondary diaphragm (region 2r). Hence, the effects of a reflected shock, as well as those of a standing shock, at the secondary diaphragm are considered herein.

As in region 2, flow quantities in regions 2s and 2r are assumed to be in thermochemical equilibrium. In computing flow quantities in regions 2s and 2r, flow quantities in region 2 are assumed to be uniform.

Standing shock at secondary diaphragm. - The conservation relations for a standing shock at the secondary diaphragm are

\[ \rho_2 U_2 = \rho_{2s} U_{2s} \] (15)
\[ p_2 + \rho_2 U_2^2 = p_{2s} + \rho_{2s} U_{2s}^2 \] (16)
\[ h_2 + \frac{1}{2} U_2^2 = h_{2s} + \frac{1}{2} U_{2s}^2 \] (17)

Since the conditions in region 2 are assumed to be known (that is, calculated previously), equations (15) to (17) are solved in conjunction with the equation of state, by iteration, to yield conditions behind the standing shock (region 2s). (It should be noted that the flow conditions in region 2s are the same as those immediately behind a normal bow shock wave on a model positioned in the shock tube test section.)

Totally reflected shock at secondary diaphragm. - For a totally reflected shock wave at the secondary diaphragm, the conservation relations are

\[ \rho_2(U_2 + U_r) = \rho_{2r} U_r \] (18)
\[
p_2 + \rho_2 (U_2 + U_r)^2 = p_{2r} + \rho_{2r} U_r^2
\]

\[
h_2 + \frac{1}{2} (U_2 + U_r)^2 = h_{2r} + \frac{1}{2} U_r^2
\]

(19)

(20)

Again, the conditions in region \( \bar{2} \) are assumed to be known. Equations (18) to (20) are solved by iteration for the thermodynamic properties in region \( \bar{2r} \) and the reflected shock velocity \( U_r \).

Thermochemical-equilibrium unsteady expansion. - Region \( \bar{A} \) is defined as being region \( \bar{2} \) for the case of no shock reflection at the secondary diaphragm, region \( \bar{2s} \) for a standing shock, and region \( \bar{2r} \) for a totally reflected shock. As discussed previously, the expansion tube flow undergoes an isentropic, unsteady expansion from region \( \bar{A} \) to region \( \bar{5} \). Across an upstream-facing unsteady expansion wave, the velocity increment is related to the thermodynamic properties by the integral expression (ref. 1)

\[
\Delta U = U_5 - U_A = - \int_{h_A}^{h_5} \left( \frac{dh}{\dot{a}} \right) s_A W_u/R
\]

(21)

Either free-stream pressure or test-air—acceleration-gas interface velocity \( U_5 \) is considered, individually, as inputs necessary for the solution of equation (21). As is typical of high-enthalpy facilities, the assumption of thermochemical-equilibrium air flow is subject to question. Hence, limiting cases are obtained by performing both a thermochemical-equilibrium expansion and a frozen expansion.

For an equilibrium expansion where the quantity \( U_5 \) is an input, the \( \Delta U \) of equation (21) is known. If the AEDC real-air tape is to be used as the source of thermodynamic properties, the enthalpy is decreased from a maximum value of \( h_A \) in given increments. Since an isentropic \( \left( s_A W_u/R = s_5 W_u/R \right) \) expansion is assumed, subroutine SLOW

\[ \left( \text{inputs } h \text{ and } s_A W_u/R \right) \]

is used to generate corresponding values of the inverse of the speed of sound \( a^{-1} \). If the AEDC real-air curve-fit relations are to be used instead of the AEDC tape, pressure is decreased in given increments from a maximum value of \( p_A \). These values of pressure are used in the subroutine SAVE with constant entropy \( s_A W_u/R \) to generate corresponding values of enthalpy (the maximum value being \( h_A \)) and the inverse of the speed of sound. Equation (21) is integrated numerically between the known limit \( h_A \) and the unknown limit \( h_5 \). The value of \( h \) which equates the integral of equation (21) to \( \Delta U \) is the desired value of \( h_5 \). Corresponding thermodynamic quantities in region \( \bar{5} \) are obtained from the real-air source, since the quantities \( s_5 W_u/R \)
and $h_5$ or $p_5$ are now known. When $p_5$ is an input, the thermodynamic quantities in region $5$ are obtained directly from the real-air source since $s_5W_u/R$ and $p_5$ are known. With the limits of integration known, the integral in equation (21) is evaluated numerically to give $\Delta U$, and hence $U_5$.

Additional conditions in region 5 that are of interest are free-stream Mach number $M_5$ and free-stream unit Reynolds number $N_{Re,5}$. For values of $T_5$ less than or equal to 1500 K, the free-stream viscosity $\mu_5$ required in determining $N_{Re,5}$ is calculated from Sutherland's viscosity law (ref. 10), whereas for values of $T_5$ greater than 1500 K, $\mu_5$ is obtained by use of the results of reference 16.

Frozen unsteady expansion.- Frozen flow is defined herein as flow in which the vibrational energy and chemistry remain unchanged during the expansion of the test air. For the expansion tube, this freezing of the vibrational energy and chemistry is assumed to occur in region A. Hence, the energy in region A may be viewed as consisting of an active or available part which provides the energy for flow expansion and a frozen or nonavailable part. Since the energy associated with vibration and chemistry is constant for a frozen expansion, the ratio of specific heats $\gamma$ will be constant and the test air behaves as a perfect gas. To obtain an estimate of the ratio of frozen specific heats $\gamma_f$ for dissociated but unionized air, it is assumed that the dissociated air may be modeled by atoms (O and N) and molecules ($N_2$, $O_2$, and NO). It is further assumed that the atoms are not distinguishable and the molecules are not distinguishable. This is a reasonable assumption since $W_O$ is approximately equal to $W_N$, $W_{O_2}$, $W_{N_2}$, and $W_{NO}$ are approximately equal. The molecular weight for this composition is given by the relation

$$W = x_a W_a + x_m W_m \approx W_a \left(2 - x_a\right)$$

where the sum of the mole fractions is unity ($x_a + x_m = 1$) and the molecular weight of a molecule ($O_2$, $N_2$, NO) is approximately twice that of an atom (O, N). From the relation $Z^*$ equal to $W_u/W$, where $W_u$ is approximately $W_m$, the expression

$$Z^* = \frac{2}{2 - x_a}$$

is obtained. By letting the quantity $Z^*$ be defined as $1 + \alpha$, it can be shown that

$$\gamma_f = \frac{7 + 3\alpha}{5 + \alpha}$$

Since the quantity $Z_A^*$ is assumed to be known, values of $\alpha$, and hence $\gamma_f$, may be obtained.
For a frozen (perfect) gas, equation (21) may be evaluated in closed form to yield

\[ U_{5,f} - U_A = \frac{2}{\gamma_f - 1}(a_{A,f} - a_{5,f}) \]  

(25)

If a value of \( U_{5,f} \) is known, the frozen free-stream speed of sound \( a_{5,f} \) follows from equation (25) and the corresponding frozen thermodynamic quantities in region 5 are determined from the isentropic perfect gas relations of reference 17. (See ref. 5.) For the case where a value of \( p_{5,f} \) is known, the quantity \( a_{5,f} \) is determined from the isentropic perfect gas relation (ref. 17)

\[ a_{5,f} = a_{A,f} \left( \frac{p_{5,f}}{p_A} \right)^{\frac{\gamma_f - 1}{2\gamma_f}} \]  

(26)

Corresponding frozen quantities in region 5 are determined similarly, and \( U_{5,f} \) is obtained from equation (25).

The ideal test time for the expansion tube (test time is defined as the time interval between arrival of the acceleration-gas—test-air interface and the expansion fan (ref. 1) is given by the relation

\[ t_{i,5} = L_a \left( \frac{1}{U_5 - a_5} - \frac{1}{U_5} \right) \]  

(27)

The actual test time may be somewhat less than this ideal test time because of the early arrival of a downstream expansion wave. (See ref. 14.) The time of arrival of this downstream expansion wave for real air is not determined in the present study.

Flow attenuation.- The air-test-gas—helium-acceleration-gas interface velocity in the acceleration section of the Langley pilot model expansion tube was observed (ref. 14) to decrease in traversing the acceleration section. A decrease in flow velocity along the acceleration section was also observed in recent tests (ref. 15) performed in the Langley 6-inch expansion tube with air test gas and air acceleration gas. Thus, the effect of flow attenuation on calculated flow quantities in region 5 and on the post-normal-shock region of a test model subjected to flow in region 5 is considered herein.

A method for determining the effect of flow attenuation on thermodynamic quantities in region 5 is discussed in reference 14. To illustrate this method, consider a thermodynamic quantity in region 5, such as \( p_5 \), plotted as a function of interface velocity \( U_5 \).
at the exit of the acceleration section. Application of the method of reference 14 is equivalent to a shift of point \( P_5, U_5 \) for no flow attenuation to point \( P_5, U_5 - 2\Delta U_5 \) with flow attenuation. The quantity \( \Delta U_5 \) is the difference between the maximum and minimum (that is, acceleration section exit) values of interface velocity observed along the acceleration section. In the present program, the unsteady expansion is performed to the acceleration section exit (region 5) and the interface velocity \( U_5 \) changed to \( U_5 - 2\Delta U_5 \) to account for flow attenuation. Post-normal-shock flow quantities (regions 5 and 15) are calculated by the shock crossing procedure to be discussed subsequently, where the free-stream velocity is equal to \( U_5 - 2\Delta U_5 \). The effect of flow attenuation is included for an equilibrium expansion only.

**Acceleration-gas flow quantities and quiescent pressure.** An important parameter in the operation of an expansion tube is the initial pressure of the acceleration gas \( p_{10} \). This pressure is the controlling factor in determining the degree of expansion in the acceleration section. In reference 5, a range of \( p_{10} \) was determined for each \( U_5 \) with helium acceleration gas. Only helium was considered in reference 5, since helium was used exclusively as the acceleration gas in the Langley pilot model expansion tube. (See ref. 14.) However, more recent tests in the Langley 6-inch expansion tube (ref. 15) have indicated the desirability of using the same gas for both test gas and acceleration gas.

In the present study, the conditions in region 5 are determined prior to calculating the corresponding value of \( p_{10} \) required. Since the values of \( p_{10} \) are relatively low and since the quiescent acceleration air temperature \( T_{10} \) is ambient, thermodynamic conditions in region 10 obey ideal air relations. At the interface of the acceleration air and test air, it is required that \( p_{20} \) equal \( p_5 \) and \( U_{20} \) equal \( U_5 \). Hence, the conservation relations for an incident shock wave into region 10, excluding the effect of boundary-layer growth along the tube wall, are

\[
\frac{W_{10}}{RT_{10}} p_{10} U_{s,10} = \rho_{20} (U_{s,10} - U_5) \tag{28}
\]

\[
p_{10} \left(1 + \frac{W_{10}}{RT_{10}} U_{s,10}^2\right) = p_5 + \rho_{20} (U_{s,10} - U_5)^2 \tag{29}
\]

\[
\frac{7}{2} \frac{R}{W_{10}} T_{10} + \frac{1}{2} U_{s,10}^2 = h_{20} + \frac{1}{2} (U_{s,10} - U_5)^2 \tag{30}
\]

where the unknowns are \( p_{10}, \rho_{20}, h_{20}, \) and \( U_{s,10} \). The equation of state represents the required fourth relation. These relations are solved by iteration. An initial guess
of the quantity $U_{s,10}$ is made, this being 1.11 times $U_5$ (corresponding to $\rho_{20}/\rho_{10}$ equal to 10), and $h_{20}$ is obtained from equation (30). The quantity $p_{20}$ (which is equal to $p_5$) and this initial estimate of $h_{20}$ are used as inputs to the source of thermodynamic properties and a value of $\rho_{20}$ is obtained. This value of $\rho_{20}$ is used in equation (29) to obtain a value of $p_{10}$. A new (up-dated) value of $U_{s,10}$ is determined from equation (28), and if not within 0.1 percent of the initial guess of $U_{s,10}$, the procedure is repeated. Iteration on the quantity $U_{s,10}$ is continued until successive values of $U_{s,10}$ are within the desired tolerance.

If helium is to be used as the acceleration gas, as in the experimental study of reference 14, the corresponding value of $p_{10}$ for helium may be estimated from that for air. Combining equations (28) and (29) yields the expression

$$p_5 = p_{10} + \rho_{10}U_{s,10}U_5$$

For a strong incident shock, $p_{10}$ is small compared with the product $\rho_{10}U_{s,10}U_5$; hence, $p_5$ is approximately equal to $\rho_{10}U_{s,10}U_5$. Equating $p_5$ and $U_5$ for both acceleration gases gives

$$(\rho_{10}U_{s,10})_{\text{He}} \approx (\rho_{10}U_{s,10})_{\text{air}}$$

For the same value of $U_5$, the incident shock velocities in air and helium are relatively close; in the limit of maximum separation distance between the shock and interface, these $U_{s,10}$ values are equal. Thus, $\rho_{10,\text{He}}$ is approximately equal to $\rho_{10,\text{air}}$ and $p_{10,\text{He}}$ is equal to 7.24 times $p_{10,\text{air}}$.

An often employed method of measuring the velocity of a moving gas is the microwave interferometer technique (refs. 14 and 15). If helium is used as the acceleration gas, the helium behind the incident shock into region 10 is generally not ionized and thus is transparent to the microwave signal. Hence, the flow being tracked by the signal is the helium-acceleration-gas—air-test-gas interface and the quantity $U_5$ is inferred from measurement. When air is used as the acceleration gas, the microwave signal tracks the incident shock into region 10 and not the interface. For this reason, the laminar theory of reference 6 (discussed previously) is used in the present program to determine the $U_5$ from measured values of $U_{s,10}$, known thermodynamic conditions in region 10, and acceleration-section diameter and length. At the acceleration-section station where $l/l_{\text{max}}$ is nearly unity, the quantity $U_5$ is equal to $U_{s,10}$ and may be inferred directly from measurement.
Calculation Procedure for Expansion Tunnel

Thermochemical-equilibrium steady expansion. - The entrance conditions at the nozzle of the expansion tunnel correspond to the conditions in region \( \text{\textcircled{5}} \). As discussed previously, the expansion tunnel flow is assumed to undergo an isentropic steady expansion from region \( \text{\textcircled{5}} \) to region \( \text{\textcircled{6}} \). The basic differential equation for this expansion is (ref. 1)

\[
dU = -\frac{dh}{U_sW_u/R}
\]

which may be integrated between regions \( \text{\textcircled{5}} \) and \( \text{\textcircled{6}} \) to give

\[
h_5 + \frac{1}{2}U_5^2 = h_6 + \frac{1}{2}U_6^2
\]  

The left-hand side of equation (32) is considered to be known. Inputs considered (individually) for determining expansion tunnel flow conditions are \( p_6 \) and \( U_6 \). For an equilibrium nozzle expansion in which the quantity \( U_6 \) is known, \( h_6 \) is obtained from equation (32) and the corresponding thermodynamic quantities in region \( \text{\textcircled{6}} \) are determined from the source of thermodynamic properties with the quantities \( h_6 \) and \( s_6W_u/R \) (which is equal to \( s_AW_u/R \)) as input. For the case where a value of \( p_6 \) is known, the thermodynamic quantities in region \( \text{\textcircled{6}} \) follow from the source of thermodynamic properties with the quantities \( p_6 \) and \( s_6W_u/R \) as input, and the corresponding value of \( U_6 \) is obtained from equation (32).

Frozen steady expansion. - For a frozen nozzle expansion, it is assumed that the flow in region \( \text{\textcircled{5}} \) is in equilibrium, and the assumption is made that freezing occurs at the nozzle throat. The procedure for calculating frozen flow conditions in region \( \text{\textcircled{6}} \) is similar to that discussed previously for region \( \text{\textcircled{5}} \) of the expansion tube, whereby the equilibrium conditions in region \( \text{\textcircled{5}} \) correspond to those of region \( \text{\textcircled{A}} \) and the frozen conditions of region \( \text{\textcircled{6}} \) correspond to those of region \( \text{\textcircled{5}} \). The difference is that equation (32) for a steady expansion replaces equation (25) which applies to an unsteady expansion.

Nozzle boundary-layer displacement thickness. - A quantity of interest is the nozzle boundary-layer displacement thickness. This quantity, with one-dimensional flow assumed, is given by the relation

\[
\delta^* = r_{\text{geo}} - r_{\text{eff}}
\]
where the radius of the inviscid core is given by

\[ r_{\text{eff}} = r_{\text{eff}} \left( \frac{A}{A^*} \right)^{1/2} \]  \hspace{1cm} (34)

and \( r_{\text{geo}} \) is the nozzle wall radius. The ratio \( (A/A^*)_{\text{eff}} \) is determined from the continuity equation for one-dimensional, steady flow

\[ \left( \frac{A}{A^*} \right)_{\text{eff}} = \frac{\rho_5 U_5}{\rho_6 U_6} \]  \hspace{1cm} (35)

where quantities appearing on the right-hand side have been calculated previously. With the assumption that the displacement thickness at the nozzle entrance (throat) is zero \( (r^*_{\text{geo}} = r^*_{\text{eff}}) \), equation (33) becomes

\[ r^* = r_{\text{geo}} - r^*_{\text{geo}} \left( \frac{\rho_5 U_5}{\rho_6 U_6} \right)^{1/2} \]  \hspace{1cm} (36)

Calculation of Flow Quantities Behind Normal Bow Shock at Test Model

For some tests in the shock tube and most tests in the expansion tube or expansion tunnel, a test model is positioned in the test section. Hence, it is desirable to determine the flow quantities behind the normal part of the bow shock of a blunt test model. The conservation relations for a standing normal shock at a blunt body are given in equations (15) to (17), where the subscripts 2 and 2s are now replaced by 5 and 5s for the expansion tube and 6 and 6s for the expansion tunnel. For an equilibrium expansion, the flow behind the normal bow shock is assumed to be in equilibrium; for a frozen expansion, the flow behind the normal bow shock is assumed to be either in equilibrium or frozen. For the case of equilibrium post-bow-shock flow, the conservation relations are solved, in conjunction with the equation of state, by iteration to obtain the static conditions immediately behind the shock. Stagnation-point properties are determined by using the assumption that the flow region from immediately behind the bow shock to the stagnation point is isentropic \( s_{k s} W_u / R = s_{t,k} W_u / R \), where \( k \) is equal to 2 for shock tube, 5 for expansion tube, and 6 for expansion tunnel and the energy relation for an equilibrium expansion to the test section is \( (k = 2, 5, \text{ or } 6) \)

\[ h_{t,k} = h_k + \frac{1}{2} U_k^2 \]  \hspace{1cm} (37)
and for a frozen expansion is \((k = 5 \text{ or } 6)\)

\[
h_{t,k} = h_{k,f} + h_{A,f} + \frac{1}{2} U_{k,f}^2
\]  

(38)

This procedure, in which \(s_{t,k} W_u/R\) and \(h_{t,k}\) are known, requires usage of the AEDC tape. A second procedure considered, which makes use of the AEDC curve fits, is to estimate \(p_{t,k}\) from the relation (ref. 5)

\[
p_{t,k} = p_{ks} \left(1 + \frac{\gamma E_{k,s} - 1}{2} M_{k,s}^2\right)^{\gamma E_{k,s} - 1}
\]  

(39)

This value of \(p_{t,k}\) is used in conjunction with \(s_{t,k} W_u/R\) as input to the subroutine SAVE. If the value of \(h_{t,k}\) obtained from SAVE is not within 0.1 percent of the value obtained from equation (37) or (38), \(p_{t,k}\) is up-dated by the relation

\[
(p_{t,k})_{\text{new}} = \frac{(p_{t,k})_{\text{previous}} (h_{t,k})_{\text{known}}}{(h_{t,k})_{\text{previous}}}
\]  

(40)

(\text{where } (h_{t,k})_{\text{known}} \text{ was obtained from eq. (37) or (38)}) and the iterative procedure repeated until the desired criteria on \(h_{t,k}\) is obtained. The stagnation-point heat-transfer rate for a spherical body positioned in the shock tube \((k = 2)\), expansion tube \((k = 5)\), or expansion tunnel \((k = 6)\) is determined from the expression (ref. 18)

\[
q_{t,k} = 3.88 \times 10^{-4} \sqrt{\frac{p_{t,k}}{r_n} (h_{t,k} - h_w)}
\]  

(41)

For the case of frozen post-bow-shock flow, normal-shock crossing relations for perfect air (ref. 17) are used to obtain conditions immediately behind the shock and isentropic, perfect air relations are used to obtain stagnation-point conditions.

It should be noted that flow properties behind the normal part of the bow shock wave of an entry body at high velocity are equivalent to the properties behind an incident shock in a shock tube traveling at that velocity. In free flight, the free-stream conditions and flight velocity correspond to the initial conditions in region \(1\) and the incident shock
velocity $U_{s,1}$, respectively, whereas static and stagnation conditions behind the bow shock correspond to conditions in regions 2 and 2, respectively.

RESULTS AND DISCUSSION

Description of the inputs necessary to utilize the present computer program is presented in appendix A along with a flow chart, listing of the program, brief description of basic subroutines, and sample printout. The accuracy and limitations of the program are discussed in appendix B. Results of calculations illustrating the application of the program to shock tube and expansion tube flows are presented in figures 3 to 20, with figures 3, 4, 5, and 18 for the shock tube and figures 6 to 17, 19, and 20 for the expansion tube.

Flow quantities in region 2 may be obtained by using the basic measured inputs in the following combinations:

Case (1): $p_1$, $T_1$, and $U_{s,1}$
Case (2): $p_1$, $T_1$, and $p_2$
Case (3): $p_1$, $T_1$, $p_4$, $T_4$, and $W_4$

Case (3) is useful in ascertaining the theoretical performance prior to a test and in comparison of measured quantities $U_{s,1}$ and $p_2$ with predicted values from simple shock tube theory. The computational method for case (3) is illustrated in figure 3 where velocity-pressure $(U_3, p_3)$ curves for perfect and imperfect, isentropic unsteady expansion of helium and hydrogen driver gases are shown in conjunction with velocity-pressure $(U_2, p_2)$ curves for incident normal shocks in equilibrium, real air. In figure 3, the value of $p_4$ was 68.95 MN/m$^2$ for both driver gases and $T_4$ is varied from 300 K to 10 000 K for helium (figs. 3(a) to 3(c)) and from 300 K to 600 K for hydrogen (figs. 3(d) and 3(e)). The ambient air temperature $T_1$ was 300 K and $p_1$ was varied from 6.9 N/m$^2$ to 6.9 MN/m$^2$. Solutions for case (3) are the intersections of the $U_2, p_2$ air curves (generated by using 20 values of $U_{s,1}$ for each value of $p_1$ and the AEDC curve-fit expressions as a source of thermodynamic properties) and $U_3, p_3$ helium or hydrogen curves. (That is, the solution is obtained when $U_2 = U_3$ and $p_2 = p_3$.)

Shock tube performance for real air with helium and hydrogen driver gases is shown in figure 4, where incident shock velocity $U_{s,1}$ is plotted as a function of pressure...
ratio $p_4/p_1$. These results were generated by two methods. First, two values of $p_1$ (6.9 N/m$^2$ and 6.9 kN/m$^2$) were used in conjunction with various values of $p_4$ to obtain the range of $p_4/p_1$ shown. Compressibility factors for the higher values of $p_4$ for helium and hydrogen driver gases are given in the following table:

<table>
<thead>
<tr>
<th>$p_4$, MN/m$^2$</th>
<th>$T_4$, K</th>
<th>$Z_4$ for -</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Helium</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>0.69</td>
<td>600</td>
<td>1.001</td>
<td>1.002</td>
</tr>
<tr>
<td>3.45</td>
<td>600</td>
<td>1.007</td>
<td>1.012</td>
</tr>
<tr>
<td>6.90</td>
<td>600</td>
<td>1.015</td>
<td>1.024</td>
</tr>
<tr>
<td>13.79</td>
<td>600</td>
<td>1.029</td>
<td>1.051</td>
</tr>
<tr>
<td>34.47</td>
<td>600</td>
<td>1.071</td>
<td>1.135</td>
</tr>
<tr>
<td>68.95</td>
<td>600</td>
<td>1.139</td>
<td>1.282</td>
</tr>
<tr>
<td>137.90</td>
<td>600</td>
<td>1.264</td>
<td>1.566</td>
</tr>
</tbody>
</table>

Second, $p_4$ was held constant at 68.95 MN/m$^2$ and $p_1$ varied from 6.9 N/m$^2$ to 6.9 MN/m$^2$. In both cases, $T_1$ was equal to 300 K and $T_4$ was equal to 600 K. The curves from these two methods were found to be identical for both the helium driver gas and the hydrogen driver gas. Differences between perfect hydrogen ($Z_4 = 1.0$) and imperfect hydrogen driver gas are observed (fig. 4) to be small, and the perfect hydrogen driver gas yields somewhat higher values of $U_{s,1}$ for a given $p_4/p_1$ in agreement with reference 19. The improved performance expected with hydrogen driver gas, in comparison with helium driver gas, is evident in figure 4.

Simple shock tube predictions for real air are shown for helium (figs. 5(a) and 5(b)) and hydrogen (fig. 5(c)) driver gases at $p_4$ equal to 68.95 MN/m$^2$. The $T_4$ for helium is varied in 50 K increments from 300 K to 700 K (fig. 5(a)) and in 1000 K increments from 1000 K to 12 000 K (fig. 5(b)) and for hydrogen (fig. 5(c)) is varied in 50 K increments from 300 K to 600 K. The value $T_4 = 700$ K for helium represents the maximum value obtainable in the Langley expansion tube with resistance heating and the value $T_4 = 600$ K for hydrogen represents the limit of curve fitting as applied to virial coefficients in reference 5. For an arc-driven shock tube or expansion tube using helium driver gas, much higher $T_4$ values than presented in figure 5(a) are realized; hence, figure 5(b) represents an extension in range of $T_4$ to figure 5(a). At the maximum $T_4$ of 12 000 K, ionization of the helium driver gas is essentially negligible. (See ref. 20.) Values of $p_1$, $p_4$, and $T_4$ being known, a theoretical value of $U_{s,1}$ in real air may be obtained from figure 5.
Combinations of measured input for obtaining stagnation-point conditions in the expansion tube test section (region 5), when it is assumed that thermochemical equilibrium flow conditions in region A are known (previously calculated), are summarized in the following table:

<table>
<thead>
<tr>
<th>Case</th>
<th>Measured input</th>
<th>Unsteady expansion</th>
<th>Post normal shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>$U_5$ or $p_5$</td>
<td>Equilibrium</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>(2)</td>
<td>$U_5$ or $p_5$</td>
<td>Frozen</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>(3)</td>
<td>$U_5$ or $p_5$</td>
<td>Frozen</td>
<td>Frozen</td>
</tr>
</tbody>
</table>

Similarly, combinations of measured input for obtaining stagnation-point conditions in the expansion tunnel test section (region 6), when thermochemical equilibrium flow conditions in region 5 are known, are summarized in the following table:

<table>
<thead>
<tr>
<th>Case</th>
<th>Measured input</th>
<th>Steady expansion</th>
<th>Post normal shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>$U_6$ or $p_6$</td>
<td>Equilibrium</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>(2)</td>
<td>$U_6$ or $p_6$</td>
<td>Frozen</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>(3)</td>
<td>$U_6$ or $p_6$</td>
<td>Frozen</td>
<td>Frozen</td>
</tr>
</tbody>
</table>

The first consideration in performing a test in an expansion tube or expansion tunnel is to determine theoretical flow quantities for the chosen mode of operation. Such a procedure is necessary in order to obtain approximate magnitudes of quantities to be measured in the various flow regions. Because of the wide range of flow conditions that may be generated in the expansion tube and the long computer times associated with the program of reference 5, the program of reference 5 was not exercised to generate a family of working plots illustrating expansion tube performance. However, the provision of such plots would be a worthwhile convenience to the experimenter and would also illustrate the versatility of such a facility. Since the present program requires much less computer time than that of reference 5 (present program is approximately 60 to 80 times faster than the program of reference 5 with a 10 species air model), working plots were generated for real-air expansion tube flows and are presented in figures 6 to 17.

Various flow quantities in region 5 ($p_5$, $\rho_5$, $T_5$, $M_5$, and $N_{Re,5}$), region 5s ($p_{5s}/\rho_5$), and region 6 ($p_{t,5}$, $\rho_{t,5}$, $T_{t,5}$, $h_{t,5}$, and $\dot{q}_{t,5}$ for $r_n = 2.54$ cm) are
plotted as a function of input $U_5$ for values of $p_1$ equal to $0.7, 3.45, 6.9, 34.47, 68.95,$ and $344.7 \text{ kN/m}^2$ in figures 6 to 11, respectively. In figures 6 to 11, the flow in region 5 is assumed to be in equilibrium and there is no shock reflection at the secondary diaphragm. These results are shown for a range of $U_{s,1}$ from 2.1 to 4.5 km/sec. The upper limit on $U_{s,1}$ represents the highest value obtained to date in the Langley expansion tube using arc-heated helium as the driver gas. Also shown in figures 6 to 11 are values of $p_{10}$ required to produce the corresponding flow conditions. Figures 12 to 17 correspond to figures 6 to 11, respectively, except that a totally reflected shock at the secondary diaphragm is included. Thus, limiting cases for these shock-wave reflection phenomena are provided. The results of figures 6 to 17 were obtained by using the AEDC real-air curve-fit expressions to determine conditions in regions $2, 2a, 5a,$ and $5b$ and the AEDC real-air tape for determination of the unsteady expansion quantities of region 5. (The reader is referred to appendix B for discussion of the computational procedures incorporated in the present program. For these results, method (2) $(ISAV = 2, IEXP = 1)$ was employed, JAC being 100.) These figures were generated by machine and linear line segments were used to connect adjacent data points.

For purposes of illustration, let it be assumed that a study is to be performed in the expansion tube at $U_5$ equal to 5.4 km/sec and $M_5$ equal to 10. Both the case of no shock reflection at the secondary diaphragm and the existence of a totally reflected shock are considered. The driver gas is unheated helium ($T_4 = 300 \text{ K}$) and a value of $p_1$ equal to 3.45 kN/m$^2$ is selected. From figures 7 and 13, flow conditions and the required $p_{10}$ for this example are as follows:

<table>
<thead>
<tr>
<th>Condition</th>
<th>No shock reflection</th>
<th>Totally reflected shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{s,1}, \text{ km/sec}$</td>
<td>2.48</td>
<td>2.25</td>
</tr>
<tr>
<td>$p_5, \text{ kN/m}^2$</td>
<td>0.78</td>
<td>0.45</td>
</tr>
<tr>
<td>$T_5, \text{ kK}$</td>
<td>0.76</td>
<td>0.75</td>
</tr>
<tr>
<td>$\rho_5, \text{ g/m}^3$</td>
<td>3.6</td>
<td>2.1</td>
</tr>
<tr>
<td>$N_{Re,5}, \text{ m}^{-1}$</td>
<td>$5.6 \times 10^5$</td>
<td>$3.2 \times 10^5$</td>
</tr>
<tr>
<td>$p_{5s}/p_5$</td>
<td>11.85</td>
<td>12.1</td>
</tr>
<tr>
<td>$p_{t,5}, \text{ kN/m}^2$</td>
<td>100.0</td>
<td>57.7</td>
</tr>
<tr>
<td>$T_{t,5}, \text{ kK}$</td>
<td>6.0</td>
<td>5.9</td>
</tr>
<tr>
<td>$\rho_{t,5}, \text{ g/m}^3$</td>
<td>44.5</td>
<td>25.7</td>
</tr>
<tr>
<td>$h_{t,5}, \text{ MJ/kg}$</td>
<td>15.5</td>
<td>15.3</td>
</tr>
<tr>
<td>$q_{t,5}, \text{ MW/m}^2$</td>
<td>11.6</td>
<td>8.8</td>
</tr>
<tr>
<td>$p_{10}, \text{ N/m}^2$</td>
<td>1.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

25
The value of $U_{s,1}$ corresponding to the chosen values of $U_5$ and $M_5$ is obtained from figure 7(d) for no shock reflection and from figure 13(d) for a totally reflected shock. These $U_{s,1}$ values are, in turn, used to obtain the remaining flow quantities presented in figures 7 and 13. At this point the range of $p_{10}$ required to generate the desired values of $U_5$ and $M_5$ for $p_1$ equal to 3.45 kN/m$^2$ is known. The corresponding range of $p_4$ required to produce this range of $U_{s,1}$, for a given $p_1$, is obtained from figure 5. The pressure in region (2) is obtained from figure 18, where the quantities $p_2/p_1$, $\rho_2/\rho_1$, $T_2/T_1$, $h_2/h_1$, and $s_2W_0/R$ (predicted by using the AEDC real-air tape) are plotted as a function of $U_{s,1}$ for the values of $p_1$ considered in figures 6 to 17.

Figure 19 illustrates the effect of frozen expansion, in comparison with a thermochemical equilibrium expansion, for several sample cases. These cases show a large effect of shock reflection at the secondary diaphragm on predicted frozen flow quantities. Such large differences are the result of the increase in dissociation in region (0) from the case of no shock reflection to the case of a standing shock or totally reflected shock, coupled with the assumption that the flow freezes in region (A).

As discussed previously, it is often necessary to infer the test-air—acceleration-air interface velocity $U_I$ from measured $U_{s,10}$ by using the theory of reference 6. Figure 20 shows flow quantities $\tau_1$, $\tau$, $\ell/\ell_{\text{max}}$, and $U_{s,10}/U_I$ as a function of non-dimensionalized distance downstream of the secondary diaphragm for a representative expansion tube test. For the results of figure 20, $p_1$ is equal to 3.45 kN/m$^2$, $U_{s,1}$ is equal to 2.85 km/sec, and $L_a$ is equal to 17 m. From figure 20(b), the time a model positioned at the test section (tube exit) is subjected to acceleration-air flow diminishes with increasing $U_5$. The separation distance between the incident shock in region (10) and the test-air—acceleration-air interface approaches the maximum separation distance $\ell_{\text{max}}$ more rapidly with increasing $U_5$ (fig. 20(c)). When the value of $\ell$ is essentially equal to $\ell_{\text{max}}$, the interface velocity $U_I$ is essentially equal to the incident shock velocity $U_{s,10}$, as illustrated in figure 20(d). For this sample case, the interface velocity is equal to the incident shock velocity (measured) at the tube exit for values of $U_5$ in excess of 5.0 km/sec.

Several expansion tunnel flow quantities ($p_6$, $T_6$, $U_6$, $M_6$, $N_{\text{Re},6}$, $\rho_6S/\rho_6$, and $p_{t,6}$) are shown in figure 21 as a function of effective area ratio ($A/A^*$)$_{\text{eff}}$. Nozzle entrance conditions (conditions at ($A/A^*$)$_{\text{eff}}$ of unity) correspond to a representative expansion tube test (ref. 15) with unheated helium driver gas and air test gas having a value of $p_1$ of 3.45 kN/m$^2$. These entrance conditions were determined by assuming no shock reflection at the secondary diaphragm, no flow attenuation in the acceleration section, and a thermochemical equilibrium expansion to region (5). The tunnel results were generated, assuming quasi one-dimensional flow, by increasing input $U_6$ from
5.3 to 5.5 km/sec in increments of 50 m/sec and from 5.50 to 5.57 km/sec in increments of 10 m/sec. These tunnel predictions also assume a thermochemical equilibrium expansion.

The results of figure 21 may be used to obtain a rough estimate of inviscid test core diameter and corresponding nozzle exit flow quantities for given entrance conditions. For example, use the dimensions of the Langley expansion tunnel configuration and assume that the conical nozzle has an entrance diameter of 7.62 cm, an exit diameter of 63.75 cm, and a length of 1.59 m. Hence, the geometric area ratio \( \left( \frac{A}{A^*} \right)_{geo} \) is 70 and the nozzle half angle is 10°. Now, let \( \left( \frac{A}{A^*} \right)_{eff} \) be equal to \( \left( \frac{A}{A^*} \right)_{geo} \) corresponding to zero tunnel wall boundary-layer displacement thickness. The quantities \( M_6 \) and \( N_{Re,6} \) corresponding to this first estimate of \( \left( \frac{A}{A^*} \right)_{eff} \) may be obtained from figure 21. From these quantities, the displacement thickness at the nozzle exit may be estimated by using simple expressions in terms of \( M_6 \) and \( N_{Re,6} \) based on nozzle axial distance from the nozzle apex. (See ref. 21.) (Eq. (7) of ref. 21 was used to predict \( \delta^* \) for this example, where \( \gamma_{E,6} \) was equal to 1.4.) Having determined an initial estimate of \( \delta^* \) at the nozzle exit, a new value of \( \left( \frac{A}{A^*} \right)_{eff} \) is calculated where the effective exit diameter is the nozzle (geometric) exit diameter minus \( 2\delta^* \). At the nozzle entrance, the effective entrance diameter is assumed equal to the geometric entrance diameter and hence a constant. From figure 21, \( M_6 \) and \( N_{Re,6} \) corresponding to this new value of \( \left( \frac{A}{A^*} \right)_{eff} \) are obtained and a second value of \( \delta^* \) is calculated. This iterative procedure is continued until successive values of \( \left( \frac{A}{A^*} \right)_{eff} \) are within a desired tolerance. For this particular example, iteration to within 2 percent on \( \left( \frac{A}{A^*} \right)_{eff} \) (three iterations required) showed that the inviscid test core diameter is approximately 48.5 cm. The corresponding values of \( M_6 \) and \( N_{Re,6} \) are 13.2 and \( 7.4 \times 10^4 \) per meter, respectively.

CONCLUDING REMARKS

A computer program written in FORTRAN IV language which determines shock tube, expansion tube, and expansion tunnel flow quantities for real-air test gas is presented. This program permits, as input data, a number of possible combinations of flow quantities generally measured during a test. The versatility of the program is enhanced by the inclusion of such effects as a standing or totally reflected shock at the secondary diaphragm, thermochemical-equilibrium flow expansion and frozen flow expansion for the expansion tube and expansion tunnel, flow attenuation in traversing the acceleration section of the expansion tube, real air as the acceleration gas, and the effect of wall boundary layer on the acceleration section air flow. The effects of several of these phenomena are demonstrated by sample calculations.
The usage of the program in preparing the shock tube and expansion tube for testing is illustrated from working charts. These charts, which were generated with the present program, cover a wide range of flow conditions and should prove to be a convenience for the experimenter in such facilities. The expansion tunnel phase of the program is demonstrated by a sample calculation. This program is similar to, but more comprehensive than, the real-gas mixture program previously available for air test gas. The present program requires approximately $1/70$ the computer time of the gas-mixture program with no appreciable sacrifice in accuracy.

Langley Research Center,
National Aeronautics and Space Administration,
The present program is written in FORTRAN IV language for Control Data series 6000 computer systems. Minimum machine requirements are 110000 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:

<table>
<thead>
<tr>
<th>Program symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Pressure of quiescent test air in region 1</td>
</tr>
<tr>
<td>T1</td>
<td>Temperature of quiescent test air in region 1</td>
</tr>
<tr>
<td>US1</td>
<td>Incident-shock velocity into region 1</td>
</tr>
<tr>
<td>P2</td>
<td>Static pressure in region 2</td>
</tr>
<tr>
<td>P4</td>
<td>Driver-gas pressure in region 4</td>
</tr>
<tr>
<td>T4</td>
<td>Driver-gas temperature in region 4</td>
</tr>
<tr>
<td>U5</td>
<td>Velocity in region 5</td>
</tr>
<tr>
<td>P5</td>
<td>Static pressure in region 5</td>
</tr>
<tr>
<td>U6</td>
<td>Velocity in region 6</td>
</tr>
<tr>
<td>P6</td>
<td>Static pressure in region 6</td>
</tr>
<tr>
<td>DIA</td>
<td>Shock tube or expansion tube diameter</td>
</tr>
<tr>
<td>DIAT</td>
<td>Nozzle entrance diameter</td>
</tr>
<tr>
<td>DIAN</td>
<td>Nozzle test-section diameter</td>
</tr>
</tbody>
</table>
APPENDIX A

XIS  Distance downstream of primary diaphragm

XAS  Distance downstream of secondary diaphragm

TW   Model surface temperature

BNR  Model nose radius

RUN  Facility test number

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

ISTET ISTET = 0 denotes only quantities in regions 2, 2s, and 2r determined

ISTET = 1 denotes shock tube and expansion tube flow quantities determined

ISTET = 2 denotes shock tube, expansion tube, and expansion tunnel 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

LG   LG = 1 denotes $U_6$ is basic input in region 6

LG = 2 denotes $p_6$ is basic input in region 6

ISAV ISAV = 1 denotes use of AEDC real-air tape (subroutines SLOW and SEARCH)

ISAV = 2 denotes use of AEDC real-air curve fits (subroutine SAVE)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>INU</td>
<td>INU = 1 denotes use of AEDC real-air tape in determining flow nonuniformities in region 2. INU = 2 denotes use of AEDC real-air curve fits in determining flow nonuniformities in region 2.</td>
</tr>
<tr>
<td>IEXP</td>
<td>IEXP = 1 denotes use of AEDC real-air tape in determining unsteady expansion process for expansion tube. IEXP = 2 denotes use of AEDC real-air curve fits in determining unsteady expansion process for expansion tube.</td>
</tr>
<tr>
<td>JAC</td>
<td>Number of enthalpy increments used in unsteady expansion from region A for IEXP = 1 (300 maximum).</td>
</tr>
<tr>
<td>IAC</td>
<td>Number of pressure increments used in unsteady expansion from region A for IEXP = 2 (100 maximum).</td>
</tr>
<tr>
<td>IREP</td>
<td>IREP = 1 denotes only a single value of $U_5$ is of interest for given region A quantities. IREP = 2 denotes several $U_5$ of interest for given region A quantities.</td>
</tr>
<tr>
<td>U5I</td>
<td>Velocity increment for IREP = 2.</td>
</tr>
<tr>
<td>NVEL</td>
<td>Total number of $U_5$ of interest for IREP = 2 (10 maximum).</td>
</tr>
<tr>
<td>DELU5</td>
<td>Difference between maximum and minimum interface velocity along acceleration section.</td>
</tr>
<tr>
<td>LREP</td>
<td>LREP = 1 denotes only a single value of $U_6$ is of interest for given region 5 quantities. LREP = 2 denotes several $U_6$ values of interest for given region 5 quantities.</td>
</tr>
<tr>
<td>NUMU6</td>
<td>Total number of $U_6$ of interest for LREP = 2 (10 maximum).</td>
</tr>
<tr>
<td>U6I</td>
<td>Velocity increment for LREP = 2.</td>
</tr>
</tbody>
</table>
APPENDIX A

LD

LD = 1 denotes no shock reflection at secondary diaphragm
LD = 2 denotes existence of standing shock at secondary diaphragm
for ISTET = 1; for ISTET = 0, LD = 2 denotes conditions in
regions \(2, 2_s, 12,\) and \(2_r\) determined
LD = 3 denotes existence of totally reflected shock from secondary
diaphragm
LD = 4 denotes all three cases (LD = 1, LD = 2, and LD = 3) are
performed

To minimize the number of inputs required for running cases on the computer, inputs
are assigned values within the program. These assigned values, which represent values
most commonly used for data reduction in the Langley 6-inch expansion tube, are as
follows:

<table>
<thead>
<tr>
<th>Program symbol</th>
<th>Assigned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>300.</td>
</tr>
<tr>
<td>DIA</td>
<td>0.1524</td>
</tr>
<tr>
<td>DIAT</td>
<td>0.0762</td>
</tr>
<tr>
<td>DIAN</td>
<td>0.6452</td>
</tr>
<tr>
<td>XIS</td>
<td>4.65</td>
</tr>
<tr>
<td>XAS</td>
<td>16.98</td>
</tr>
<tr>
<td>TW</td>
<td>300.</td>
</tr>
<tr>
<td>RUN</td>
<td>1.0</td>
</tr>
<tr>
<td>BNR</td>
<td>0.0254</td>
</tr>
<tr>
<td>NDRIV</td>
<td>0</td>
</tr>
<tr>
<td>LB</td>
<td>0</td>
</tr>
<tr>
<td>ISTET</td>
<td>1</td>
</tr>
<tr>
<td>LF</td>
<td>1</td>
</tr>
<tr>
<td>LG</td>
<td>1</td>
</tr>
<tr>
<td>ISAV</td>
<td>2</td>
</tr>
<tr>
<td>IEXP</td>
<td>1</td>
</tr>
<tr>
<td>JAC</td>
<td>50</td>
</tr>
<tr>
<td>IAC</td>
<td>50</td>
</tr>
<tr>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX A

<table>
<thead>
<tr>
<th>Program symbol</th>
<th>Assigned value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IREP</td>
<td>2</td>
</tr>
<tr>
<td>NVEL</td>
<td>8</td>
</tr>
<tr>
<td>U5I</td>
<td>400.</td>
</tr>
<tr>
<td>LD</td>
<td>4</td>
</tr>
<tr>
<td>INU</td>
<td>2</td>
</tr>
<tr>
<td>DELU5</td>
<td>0.</td>
</tr>
<tr>
<td>LREP</td>
<td>2</td>
</tr>
<tr>
<td>NUMU6</td>
<td>5</td>
</tr>
<tr>
<td>U6I</td>
<td>50.</td>
</tr>
</tbody>
</table>

Each of these values may be changed from its assigned value by a card change or inclusion in the NAMELIST INP. For a given LB, only the basic parameters $p_1$, $T_1$, and $U_{5,1}$ (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; for a given LG, only $U_6$ (LG = 1) or $p_6$ (LG = 2) need be included in INP.

Three options exist for determining flow conditions in region 5 for LF equal to 1 or LF equal to 2. These options, in terms of inputs ISAV and IEXP, are

<table>
<thead>
<tr>
<th>Option</th>
<th>ISAV</th>
<th>IEXP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(2)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(3)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Thus, for option (1), the AEDC real-air tape is used as the source of real-air thermodynamic properties necessary to generate tables of $h$ as a function of $\alpha^{-1}$ required for numerical integration. Corresponding flow properties in region 5 are also obtained from the tape. For option (2), the tape is used for the numerical integration and for obtaining conditions in region 5, whereas real-air curve-fit expressions are used to obtain corresponding flow properties for the other flow regions (that is, regions 2, 2s, 2r, 5s, and 5t). Curve-fit expressions are used in option (3) for the integration and determination of corresponding properties. Option (1) will provide the highest accuracy (appendix B) in calculated flow parameters and demand the most computer time, whereas option (3) will have the lowest accuracy but fastest computational time.
The basic subroutines of this program are as follows:

1. **SLOW** – determines imperfect, real-air thermodynamic quantities $p$, $\rho$, $h$, $T$, $a$, $Z$, $\gamma_E$, and $Z^*$ from AEDC real-air tape for given $sW_u/R$ and any one of the thermodynamic quantities.

2. **SEARCH** – determines imperfect, real-air thermodynamic quantities $p$, $sW_u/R$, $T$, $a$, $Z$, $\gamma_E$, and $Z^*$ from AEDC real-air tape for given $p$ and $h$.

3. **SAVE** – determines real-air thermodynamic quantities from AEDC real-air curve-fit expressions with combinations:
   - (1) $p$ and $sW_u/R$
   - (2) $p$ and $\rho$
   - (3) $p$ and $h$
   - (4) $\rho$ and $h$
   - (5) $p$ and $T$

4. **VISC** – computes real-air $\mu$ for given $p$ and $T$.

5. **BDT** – computes virial coefficients for helium or hydrogen for given $T$.

6. **SOLUT** – given $\left(p_2, U_2\right)$ array and $\left(p_3, U_3\right)$ array, finds solution to curves.

7. **SC** – iterative procedure for solving conservation relations for a moving normal shock.

8. **SNS** – iterative procedure for solving conservation relations for a standing shock at secondary diaphragm or a normal bow shock at a model, including stagnation-point conditions.

9. **SIMR** – computes $\int \frac{dh}{a} sW_u/R$ by Simpson's rule.

Langley Library Subroutines ITR1, ITR2, FTLUP, and DISCOT are used with this program and are presented as appendixes C, D, E, and F.

A flow chart of this program is given on the following pages.
CALL ITR1

ICODE=0?
Yes

CALL SC

CALL SOLUT

ISAV=2?
Yes

CALL SEARCH

CALL SAVE

CALL VISC

CALL ITR2

ICODE=0?
Yes

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10 11

10

LCODE=2?

Yes VIS5=1?

Yes

No No

CALL SNS

CALL SLOW

CALL SNS

Yes

CALL SLOW IMOD=2?

No

CALL SLOW DELU5=0?

Yes

No

CALL SLOW

CALL SAVE

R PRINT

PRINT

No ABS(1-USONEW/USO-.001?

Yes

MS10=4

and

MS10=14?

Yes

M

ISAV=2?

No

Yes

CALL SEARCH

CALL SAVE

CALL VISC

CALL VISC

CALL ITR2

CALL ITR2

ICODE=0?

No

Yes

ICODE=0?

No

Yes

ICODE=0?

No
APPENDIX A

A listing of this program, including subroutines and comments, is reproduced on the following pages.
APPENDIX A

INU1 denotes use of tape for flow nonuniformity calc in region 2
INU2 denotes use of curve fits for flow nonuniformity in region 2

LD=1 denotes incident shock only
LD=2 denotes standing shock only
LD=3 denotes reflected shock only
LD=4 denotes incident+standing+ and reflected shocks

For ISET=0 and LD=2, conditions in regions 2, 29, 21, 20 determined

IFXP=1 denotes use of tape for unsteady expansion
IFXP=2 denotes use of curve fits for unsteady expansion

JAC is number of increments used in unsteady expansion for IFXP=1
JAC has maximum value of 200

JAC is number of increments used in unsteady expansion for IFXP=2
JAC has maximum value of 100

DELUE is attenuation in interface velocity Ue, m/sec

IREP=1 denotes single value of Us of interest
IREP=2 denotes several Us of interest

UI is Us increment for IREP=2
NVFL is total number of Us of interest for IREP=2

LRREP=1 denotes single value of Us of interest
LRREP=2 denotes several Us of interest

US is Us increment for LRREP=2
NUMUS is total number of Us of interest for LRREP=2

IT=3
NV=9
RU=A*14384*1
W=92*0.67
MM=0
READ (5,234) N

1

US=2*PA*TA=UA=PA*UA=96*DELUE=O
NM=NN=LB=SN=NP=0
NM=RUN=IST=LF=1 IFXP=LG=1 ISD=1
ISAV=1 REP=LRREP=INUS?
LD=4
NVFL=8
NUMUS=6
JAC=1 JAC=90
TI=TW=300.
DIA=1524
DIAT=0.762
DIAN=6442
X1=4.65
X6=16,00
BNO=0.254
US=200.
US=90.
READ (5,INP)
IF (FNDFILE 5) 144,
CONTINUE
PRINT 235, RESULT(1)
PRINT 234, IN
PRINT 148
PRINT 149
PRINT 150
PRINT 151
APPENDIX A

PRINT 152
PRINT 153, RUN, P1, TI, US1, P2, P4, T4, V15, DIA, ISA, IN1, LO
IM1ET(1)=IM1ET(2)=0
LCONF=1
SSUM=0
LI=0
I=0
H1=1.046E+37
RHO1=(P1/W1)/(D1*W1)
H1=9.498*(R1/W1)*T1
A1=SQRT((1.48*(P1/W1)+T1)
IF (LR3*FO2) GO TO 4
C
INPUTS P1, TI, AND US1 (LP=0)
C
INPUTS P1, TI, AND P2 (LP=1)
C
CALL SC (RHO2, U2, P2, H2, RHO1, US1, P1, H1, ISA)
SPR=SR
T2=TI1
A2=A1
Z2=TI1
GAM2=G1
W2=W1/A2
=1=W1/A1
P2=0.00
CALL VISC (T2, P2, V15)
IF (VIS2*FO2) GO TO 2
P2=RHO2*U2/V15
3
CONTINUE
GO TO 31
C
INPUTS P4, T4, P1, AND T1 (LB=2)
C
C
LU=PO
R2=114.34E+3
IF (NDRIV*FO1) GO TO 5
C
HELUM DRIVER GAS (NDRIV=0)
C
HRT=27.5
CUR1=1.65
SRF=4.8024
GAM4=1.6667
W4=4.003
RHO4=(P4*W4)/(R4*T4)
A0=0.70*RHOG
GO TO 6
C
HYDROGEN DRIVER GAS (NDRIV=1)
C
HRT=35
CUR4=2.5
SRF=-1.356
GAM4=1.6
W4=2.016
RHO4=(P4*W4)/(R4*T4)
A0=0.50*RHOG
AUP=1.059*RHOG
DFLTX=(AUP-ALOW)/100
E1=1.1E-6
CALL BDT (RTA, CT4, DRTA, DCT4, D2RTA, D2CT4, T4)
RHO4=1.2*RHOG
CALL ITRI (RHO4, DFLTX, F0F1, E1, E2PO, ICONF)
IF (ICONE) 7=10.7
7
GO TO (B, 9, 9.9, ICONF
8
PRINT 154
GO TO 1

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APPENDIX A

9 PRINT 155, 1, CODE
GO TO 1

10 Z4=1+RH04*RT4+RH04**2*CT4
H4=(R*RT4/W4)*(HWRT+RH04*(RT4-T4*RT4)+(RH04**2/3)*(P*CT4-T4*CT4)

11 S4=CVR1*AL0G(T4)-AL0G(RH04)-RH04*(RT4-T4*RT4)+RHO4**2/3*(CT4+T4*CT4)+SRE
CVR=CVR1-T4+(RH04*(2.5*DT4+T4)/2DT4)+(RH04**2/3)*(P*CT4+T4*CT4)

12 PPR=(RH04*RT/W4)+(1+RH04*(RT4-T4*RT4)+(RH04**2/3)*(CT4+T4*CT4)
PPRT=(T4*RT/W4)+(1+2+RH04*RT4+3+RH04**2*CT4)
AA=S0RT(PPRT+(T4*W4)/(CVR*RHO4))/PRTD**2

13 TART(1)=T4
TARR(1)=PH4
TAR(1)=1
TAR(1)=T4*W4
14 TARR(1)=RH04
TARR(1)=74
TARR(1)=W4
TARR(1)=1/A4
TSC=ALOG(T4)
NUT=TS/CIR

15 CONTINUE
AUP=1+RH04
ALOW=1.1E-6
DELR=(AUP-ALOW)/2.0
RIR=RH04
DO 17 I=2,50
17 T4=TABT(1)

18 IF (T4*LT.3) GO TO 18
CALL BDT (RT1, CT1, DBT1, DCT1, 3DBT1, DCT1, T1)
CALL TR2 (RI, ALOW, AUP, DELR, 50R, F1, F1, 400, 1, CODE)
IF (ICODE) 12, 16, 12
GO TO (13, 14, 15, 1, CODE)

19 PRINT 154
GO TO 1

20 PRINT 155, 1, CODE
GO TO 1

21 PRINT 156, 1, CODE, RI, DFR
GO TO 1

22 TARR(I)=RI
TARR(I)=1+RI**2*CT1
TARR(I)=T4/R(W4)+RI**2*T4
CVR=CVR1-T4*(RI**2/3)*(RT4+T4*RT4)+(PT4/3)*(CT4+T4*CT4)
CVR=(1+RI/T4)**2
PPRT=(T4**2/3)*RI**2*(RT4+T4*RT4)+(PT4/3)*(CT4+T4*CT4)
PPRT=(T4**2/3)*RI**2*(RT4+T4*RT4)+(PT4/3)*(CT4+T4*CT4)

23 CONTINUE
MS=1,4
DELS=2
CALL TR1 (MC, DELF, 50R, E4, E1, 200, 1, CODE)
IF (ICODE) 20, 20, 12
GO TO (21, 22, 2, 1, CODE)

24 PRINT 154
GO TO 1
APPENDIX A

22 PRINT 155, I CODE
GO TO 1
23 A1=SORT(401,839PT1)
USMAX=1.18456
USMIN=6.9*USMAX
US1(I)=USMAX
DFL=USMAX-USMIN/20.
PRINT 159
DO P4=1, P20
US1(I)=USMAX-FLOAT(I-1)*DFL
CALL SC(RH2(I),U2(I),P2(I),H2(I),RH1,US1(I),PL,H1,ISAV)
PRINT 160, P2(I),P2(I),H2(I),U2(I),US1(I)
24 CONTINUE
CALL SOLUT(TABAN,TABDT,UPID,PH,RP1,UP,US,USII)
PI=USII(I)
DFLIB=(USMAX-USMIN)/20.
PRINT 159
25 CONTINUE
26 CALL SAVE (PP,P1,H2,RP1,USII,ISAV)
27 CONTINUE
28 IF (LB=NE.2) GO TO 31
IF (NDRIV=FO.0) GO TO 29
PRINT 161
GO TO 30
29 PRINT 162
30 PRINT 163
31 PRINT 164
32 PRINT 165, P4,RH04,T4,H4,S4,Z4,A4,W4
33 PRINT 147
34 PRINT 147
35 PRINT 167
36 PRINT 167
37 PRINT 168, P2,RH02,T2,H2,S2,Z2,GAM2,A2,UP2,MP2,REF2
RAP=P2/PP
RAPHO=RHO2/RH01
RAT=T2/T1
RH=H2/H1
PA=A2/A1
PRINT 169
PRINT 170
PRINT 171, RAP, RAPHO, RAT, PA, H1
C
C SHOCK TUBE TEST TIME-REFERENCE MIREL (PHYS OF FLUIDS, SEPT 1963)
C
C PRINT 172
PRINT 173
IF (MS1<10.63AND.MS1<14.1) GO TO 33
IF (MS1<16.71) GO TO 33
PRINT 174
GO TO 95
C
C XLMAX IS MAXIMUM SEPARATION DISTANCE-SHOCK TO INTERFACE
C XL IS SEPARATION DISTANCE-SHOCK TO INTERFACE
C
C LAMINAR CASE
APPENDIX A

32 XLMAX=P1*Dia**2*(2.06-20*MS1*RHSF-3*MS1**2)
GO TO 34
33 XLMAX=P1*Dia**2*(872-7.48PE-3*MS1)
34 BETA1=15*RHO1/(2*XLMAX*RHO2)
BETA2=2*RHO2/RHO1
AXUP=9999999
AXLOW=00001
DELTAX=(AXUP-AXLOW)/100
E1=1E-6
AX=.
CALL ITR2 (AX,AXLOW,AXUP,DELTAX,FOFX,T1,F1,200,ICODE)
IF (ICODE) 7, 35, 7
35
36 XL IS RATIO OF XL TO XLMAX
XL=XL*XLMAX
37
38 XLMAX=(P1**25)*(Dia1**125)*(5,272-75138*MS1+3475*MS1**2)
GO TO 39
39 XLMAX=(P1**25)*(Dia1**125)*(1,5464-.30174*MS1)
34 DELTAX=DELTAX
AXT=2.
BETA1=X15*RHO1/(P*XLMAX*RHO2)
CALL ITR2 (AXT,AXLOW,AXUP,DELTAX,FOFX,T1,F1,200,ICODE)
IF (ICODE) 7, 40, 7
35 TAU=AX**2*XLMAX/US1
UI=XL/TAU
36
37 TURBULENT CASE
IF (MS1.GE.4.5 AND MS1.LT.10) GO TO 37
IF (MS1.GE.10.1) GO TO 38
PRINT 174
GO TO 55
38 XLMAX=(P1**25)*(Dia1**125)*(1,5464-.30174*MS1)
39 DELTAX=DELTAX
AXT=5.
BETA1=XIS*RHO1/(P*XLMAX*RHO2)
CALL ITR2 (AXT,AXLOW,AXUP,DELTAX,FOFX,T1,F1,200,ICODE)
IF (ICODE) 7, 40, 7
35 TAU=AX**2*XLMAX/US1
UI=XL/TAU
PRINT 174
XL=XLMAX+XLX+UI*XLMAX+YLT+XLT+TAU+UI+TAU+UI
IF (ISTF+1) GO TO 55
36 SHOCK TUBE FLOW NONUNIFORMITY-LAMINAR CASE
37
38
39
40 XLX=AX**2*
XLX=XLX*XLMAX
BXUP=9999999
BXLOW=00001
DELTAX=(BXUP-BXLOW)/100
BX=.
CALL ITR2 (BX,BXLOW,BXUP,DELTAX,FOFX,T1,F1,200,ICODE)
IF (ICODE) 7, 41, 7
41 TAU=BX**2*XLMAX/US1
UI=XLX/TAU
PRINT 175
XLX=XLX+ULX+UI*XLMAX+YLT+XLT+TAU+ULX+UI+TAU+UI
IF (ISTF+1) GO TO 55
42
43
APPENDIX A

IF (RXLTGE0.9) GO TO 41
PRINT 176
GO TO 50
42 PRINT 177
PRINT 178
PRINT 179
C
C FUD IS RATIO OF XS TO XL
C
MNM=0
FUD=2
XSLM(1)=FUD*RXL
DO 49 I=1,N
BNON(I)=RH02*(US1-U2)*(1-SORT(XSLM(I)))
CNON=H2+2*(US1-U2)*(US1-U2)
R2X(I)=1.00*RH02
U2X(I)=US1-BNON(I)/R2X(I)
GO TO 49
45 H2X(I)=CNON+1.0*(US1-U2X(I))*R2X(I)
Z(4)=ALOG10(H2X(I)/287.0295)
IMFT(1)=IMFT(2)=0
CALL SLOW (S2R,Z,P1,T+NV*NERR,Y,X)
R2XN(I)=10.00*Z(2)/2914889
IF (ABS(1.0-R2X(I)/R2XN(I))<0.001) GO TO 46
R2X(I)=R2XN(I)
GO TO 44
46 Z(2)=ALOG10(R2X(I)/1.002914889)
CALL SLOW (S2R,Z,P1,T+NV*NERR,Y,X)
T2X(I)=Z(1)
CALL SLOW (S2R,Z,P1,T+NV*NERR,Y,X)
P2X(I)=10.00*Z(3)/2.01214889
CALL SLOW (S2R,Z,P1,T+NV*NERR,Y,X)
A2X(I)=Z(6)*331.00
GO TO 48
47 P2X(I)=DNON-R2X(I)*(US1-U2X(I))*R2X(I)
CALL SAVF (P2X(I),R2XN,H2X(I),S2R,T2X(I),P2X(I),Z2X,GAM2X(I))
IF (ABS(1.0-R2X(I)/R2XN(I))<0.001) GO TO 48
R2X(I)=R2XN(I)
GO TO 44
48 RXR(I)=R2X(I)/RH02
RXH(I)=H2X(I)/H2
RXU(I)=U2X(I)/U2
RXP(I)=P2X(I)/P2
RXT(I)=T2X(I)/T2
RXA(I)=A2X(I)/A2
PRINT 180, XSLM(1), RXP(I), RXR(I), RXT(I), RXH(I), RXU(I), RXA(I)
IF (MNM=FC1) GO TO 42
FUN=FUN+2
XSLM(I+1)=FUD*RXL
CONTINUE
C
C SHOCK TUBE FLOW NONUNIFORMITIES-TURBULENT CASE
C
IF (RXLTGE0.9) GO TO 51
PRINT 181
GO TO 54
51 PRINT 182
PRINT 179
FUN=2
XSLM(I)=FUD*RXL
DO 53 I=1,N
APPENDIX A

\[ \text{ANNON(1)} = \text{RHO2} \times (\text{US1} - \text{U2}) \times (1 - \text{XSLM(1)}) \times \text{R} \]

\[ \text{MN} = 1 \]

\[ \text{GO TO 43} \]

52 \[ \text{FUD} = \text{FUD} + \frac{\text{UR}}{\text{R1D} \times \text{RXL}} \]

53 \[ \text{CONTINUE} \]

C C STANDING OR REFLECTED SHOCK AT SECOND DIAPHRAGM

C

54 \[ \text{IF (LD.EQ.1 AND ISTT.EQ.0)} \text{GO TO 1} \]

55 \[ \text{GO TO (57, 56, 60, 57, LD)} \]

C C STANDING SHOCK PHASE

C

56 \[ \text{CALL SNS (RHOA, TA, HA, SAR, TA, AA, ZA, GAMMA, ZSTAR, MA, RHO2, U2, P2, W2,} \]

1HT2, PT2, RT2, ST2R, TT2, AT2, ZT2, GT2, ZSTART2)

HUP = HA

NMN = P

GO TO 58

C C CONDITIONS IN REGION A FOR NO STANDING SHOCK

C

57 \[ \text{PA = P2} \]

RHOA = RHO2

TA = T2

SAR = S2R

HA = H2

HUP = HA

AA = AP

UA = UP

ZA = Z2

GAMMA = GAM2

ZSA = ZSP2

58 \[ \text{MA = MA/AA} \]

IFQ = 1

RFA = 0.0

CALL VISC (TA, PA, VISA)

IF (VISA.EQ.1.0) GO TO 59

RFA = RHOA * IA / VISA

59 \[ \text{CONTINUE} \]

IF (LD.EQ.1) GO TO 66

IF (LD.EQ.4 AND MNM.EQ.0) GO TO 66

PRINT 147

PRINT 183

PRINT 147

PRINT 167

PRINT 168, PA, PHOA, TA, HA, SAR, TA, GAMMA, AA, IA, MA, RFA

IF (ISTT.EQ.0) GO TO 66

C C STAGNATION CONDITIONS BEHIND STANDING SHOCK IN SHOCK TUBE

C

60 \[ \text{HT2} = 3.8798 \times (\text{SORTPT2/RNR}) \times (\text{HT2}-\text{HW}) \]

PRINT 184

PRINT 185

PRINT 212, PT2, RT2, ST2, TT2, AT2, ZT2, GT2, ZSTART2

C C REFLECTED SHOCK PHASE

C

61 \[ \text{UR} = \frac{\text{U2}}{\text{R2} / (\text{RHO2/RHO2-1.0})} \]

PRES = P2 + RHO2 * (U2 + UR) * (U2 + UR) * (U2 + UR) * (U2 + UR)

HR = H2 + S2 * (U2 + UR) * (U2 + UR) * (U2 + UR)

GO TO (62, 63), IEAV
APPENDIX A

62 CALL SEARCH (PR, RNEW, HR, SADD, TR, AR, 7R, GAMR, ZSR, ISP)
GO TO 64

63 CALL SAVE (PR, RNEW, HR, SADD, TR, AR, 7R, GAMR, 31)

64 IF (ABS(1.0 - RNEW/RHOR) ≤ 0.001) GO TO 65
RHOR = RNEW
GO TO 61

65 RHOR = RNEW
MR = READ = U = 0.0
PRINT 147
PRINT 146
PRINT 147
PRINT 167
PRINT 168, PR, RHOR, TR, HR, SADD, 7R, GAMR, AR, 10, MR, READ
PA = PR
RHOR = RHOR
TA = TR
HA = HR
HIP = HR
SADD = SADD
Z = ZR
GAMR = GAMR
AA = AR
UA = 0.0
ZSR = ZSR
MA = 0.0
IFQ = 1

66 IF (ISTET = 5000) GO TO 1
C
C EXPANSION TUBE PHASE
C
CFE = 1 DENOTES U5 IS BASIC INPUT
CFE = 2 DENOTES P5 IS BASIC INPUT
C
C FROZEN FLOW- EXPANSION TUBE
C
PRINT 147
PRINT 187
PRINT 146
PRINT 188
PRINT 189
IF (LFE = 0.0) PR = 0.0
IF (LFE = 0.0) UR = 0.0
PRINT 190, U5, P5, XA5, DELU5, ISOV5, IFP5, IREP5, NFE5, IAC5, JAC5

67 ALPHA = 7R - 1.0
GAMACT = (7.0 + 2.0 * ALPHA) / (8.0 + ALPHA)
AACT = AACT + (GAMACT - 2.0) * U5 / GAMACT
HFR = HACT - AACT
IF (HFR = 0.0) GO TO 68
PRINT 191
P5F = 0.1
GO TO 68

68 GO TO (69, 71) + LF

69 USF = 0.066
AACT = AACT + ((GAMACT - 1.0) / 2.0) * (UA - USF)
IF (AACT = 0.0) GO TO 70
PRINT 192
P5F = 0.1
GO TO 74

70 P5F = P5F * (AACT / AACT) * (2.0 * GAMACT / (GAMACT - 1.0))
GO TO 72

71 P5F = P5F * (AACT / AACT) * (2.0 * GAMACT / (GAMACT - 1.0))
APPENDIX A

79

\[ M_S = 15F/AF \]
\[ T_S = T_A + (A_S / A_{ACT}) \] **2 \]
\[ RHO_S = P_S F / (R_U Z_A T_S) \]
\[ S_S = S_A \]
\[ H_S = A_{ACT} / (T_S / T_A) \]
\[ Z_S = Z_A \]
\[ G_A S_F = G_A M_{ACT} \]
\[ R_E S_F = 0.0 \]
\[ \text{CALL VISC \quad T_S, P_S F, V_{IS S_F}} \]
\[ \text{IF (V_{IS S_F, EQ. 10}) \quad \text{GO TO 77}} \]
\[ \text{RE_S_R = R_HO_S \# U_S F / V_{IS S_F}} \]
\[ \text{CONTINUE} \]
\[ T_S = T_A S \times (1.0 / (U_S F - A_S F)) - (1.0 / U_S F) \]
\[ \text{PRINT 193} \]
\[ \text{PRINT 167} \]
\[ \text{PRINT 168, D_S F, R_HO_S, T_S F, H_S F, S_S R_F, Z_S F, G_A S_F, A_S F, U_S F, N_S F, D_E S_F} \]

C

C

SHOCK CROSSING - FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

\[ H_S F_S C = H_S F + H_F R O \]
\[ \text{CALL SNS \quad (R_S S_F, U_S S_F, P_S S_F, H_S S_F, S_S S_F, T_S F, A_K S_F, Z_S S_F, G_S S_F, Z_S S_F, N_S S_F, M_S S_F, R_E S_F)} \]
\[ \text{IF (R_H O_S F \# (G_A M_{ACT} \#)) \# M_S F \# 2)} \]
\[ \text{R_A T_F F = R_S S_F / R_H O_S F} \]
\[ \text{PRINT 203} \]
\[ \text{PRINT 194} \]
\[ \text{PRINT 206} \]
\[ \text{PRINT 207} \]
\[ \text{PRINT 208} \]
\[ \text{O_T Z_O F = 3.8798E+4 \# S_Q R T (P_T S_F, A_N R) \# (H_T S_F - H_W)} \]
\[ \text{PRINT 203} \]
\[ \text{PRINT 195} \]
\[ \text{PRINT 206, P_S S_F, R_S S_F, T_S S_F, H_S S_F, S_S S_F, Z_S S_F, G_S S_F, A_S S_F, U_S S_F, N_S S_F, R_E S_F, R_A T_F F} \]
\[ \text{PRINT 207} \]
\[ \text{PRINT 104} \]
\[ \text{PRINT 208} \]
\[ \text{H_T S_F = H_S F + 5.0 \# U_S S_F} \]
\[ \text{T_T S_F = T_S S_F \# H_S S_F} \]
\[ \text{P_T S_F = P_S S_F \# (H_T S_F / H_S S_F) \# (G_A M_{ACT} / (G_A M_{ACT} - 1)) \# S_S S_F} \]
\[ \text{R_A T_F F = R_S S_F / R_H O_S F} \]
\[ \text{PRINT 206, P_S S_F, R_S S_F, T_S S_F, H_S S_F, S_S S_F, Z_S S_F, G_S S_F, A_S S_F, U_S S_F, N_S S_F, R_E S_F, R_A T_F F} \]
\[ \text{PRINT 207} \]
\[ \text{PRINT 104} \]
\[ \text{PRINT 208} \]
\[ \text{H_T S_F = H_S F \# 5.0 \# U_S S_F} \]
\[ \text{T_T S_F = T_S S_F \# H_S S_F} \]
\[ \text{P_T S_F = P_S S_F \# (H_T S_F / H_S S_F) \# (G_A M_{ACT} / (G_A M_{ACT} - 1)) \# S_S S_F} \]
\[ \text{R_A T_F F = R_S S_F / (T_S S_F \# Z_A \# M)} \]
\[ \text{Z_T S_F = Z_A} \]
\[ \text{G_T S_F = G_A M_{ACT}} \]
\[ \text{A_T S_F = A_S F \# S_Q R T (T_T S_F / T_S S_F)} \]
\[ \text{O_T Z_O F = 3.8798E+4 \# S_Q R T (P_T S_F, A_N R) \# (H_T S_F - H_W)} \]

C

C

EQUILIBRIUM EXPANSION-EXPANSION TUBE
APPENDIX A

C
74 IF (LF=EQ.0) GO TO 93
C
C
75 LFE=1 CASE
C
76 IF (IEO=EQ.2) GO TO 87
C
77 DFLU=US-UJ
GO TO 198
76 HMIN=1.0E45
C
76 DFLH=(HUP-HMIN)/(FLOAT(JAC)-1.0)
PRINT 196
IMET(1)=IMET(2)=0
LCONF=1
GO 80 J=1+JAC
Z(4)=(HUP-FLOAT(J-1)*DFLH)/287.0045
Z(4)=ALOG10(Z(4))
GO TO (90, 77), LCONF
78 L=J
DO 79 K=1+JAC
TAPHR(K)=HUP-FLOAT(K-1)*DFLH
TARA(K)=1.0/57666/SORT(TAPHR(K))
CONTINUE
PRINT 197
GO TO 91
79 TAPHR(J)=(1.0+Z(4))**287.0045
TARA(J)=1.0/(Z(4)**287.0045)
CONTINUE
80 CALL SIMR (TAPHR, TARA, JAC, JAC, TARANS)
C
81 IF (LF=EQ.2) GO TO 90
C
82 IF (PSF=EQ.0+1) GO TO 83
PSF=0+1
83 DFLPG=ALOG10(PA/PSF)/(FLOAT(JAC)-1.0)
84 PFS(1)=ALOG10(PA)
PRINT 198
PSK(1)=PA
TAPHR(1)=PA
TARA(1)=1.0/AA
TAPP(1)=PA
GO 85 J=2+JAC
PSC(J)=PSC(J-1)-DFLPG
PSC(J)=1.0**8*PSC(J)
CALL SAVE (PSK(J), RK, HK, EAR, TK, AK, TK, AK, 1)
TAPHR(J)=HK
TARA(J)=1.0/AK
TAPP(J)=PSK(J)
CONTINUE
CALL SIMR (TAPHR, TARA, JAC, JAC, TARANS)
C
85 IF (LF=EQ.1) GO TO 87
C
86 CALL FTLUP (DFLU, HS+2, NON, TARANS, TAPHR)
IMODE=1
GO TO (89, 88), IFXP
87 CALL FTLUP (DFLU, HS+2, NON, TARANS, TAPP)
GO TO 100
88 IF (HS+EQ.5+4) GO TO 90
PRINT 199
GO TO 100
89 XX=SAP
Z(4)=ALOG10(HS/287.0045)
IMET(1)=IMET(2)=0
LCONF=1
GO TO (91, 92), LCODE
C
C
APPENDIX A

CALL SLOW (XX, 7, 4, 2, IT, NV, NFRR, Y, X)  
CALL SLOW (XX, 7, 4, 3, IT, NV, NFRR, Y, X)  
CALL SLOW (XX, 7, 4, 5, IT, NV, NFRR, Y, X)  
CALL SLOW (XX, 7, 4, 6, IT, NV, NFRR, Y, X)  
CALL SLOW (XX, 7, 4, 7, IT, NV, NFRR, Y, X)  
T5 = 7(1)  
P5 = (10, 2*7(2))*1, 201, PRO  
PS = (10, 2*7(3))*1, 013, 246, F+5  
GAMS = Z(5)  
A5 = 7(6)*331, 4193  
Z5 = 7(7)  
GO TO 103  

PRINT 200  
PRINT 201  
PS = 1*032, F+5*/(PS/2, 996, 57)+5)***1.*EXP(27, 019, 5, SAR)  
T5 = HS/998, 847  
PS = 4, 3, 2, 3, 2, 5, 1, 3, 246, F+5  
IMP(1) = IMP(2) = 0  
LCOR = 1  
CALL SLOW (SAR, Z, 3, 1, IT, NV, NFRR, Y, X)  
GO TO (96, 97), LCORF  

CALL SLOW (SAR, Z, 3, 2, IT, NV, NFRR, Y, X)  
CALL SLOW (SAR, Z, 3, 3, IT, NV, NFRR, Y, X)  
CALL SLOW (SAR, Z, 3, 4, IT, NV, NFRR, Y, X)  
CALL SLOW (SAR, Z, 3, 5, IT, NV, NFRR, Y, X)  
CALL SLOW (SAR, Z, 3, 6, IT, NV, NFRR, Y, X)  
CALL SLOW (SAR, Z, 3, 7, IT, NV, NFRR, Y, X)  
T5 = 7(1)  
RS = (10, 3*7(2))*1, 291, 4889  
HS = (10, 2*7(4))*287, 0245  
GAMS = Z(5)  
A5 = 7(6)*331, 4193  
Z5 = 7(7)  
GO TO 98  

PRINT 200  
PRINT 201  
HS = 2, 996, 57+5*(PS/1, 017, 246, F+5)/EXP(27, 019, 5, SAR)***0, 2867  
T5 = HS/998, 847  
RS = 4, 8398, F+3*PS/TE  
A5 = 20, 046, F+5*SOR(T5)  
Z5 = ZST5 = 1, 0  
GAMS = 1, 4  

HMTN = HS  
GO TO 76  

USE = 1, 4, TABANS (JAC)  
GO TO 103  

GO TO (101, 102), ISAV  

CALL SEARCH (PS, RS, HS, SAR, T5, A5, Z5, GAMS, ZST5, ISP)  
GO TO 103  

CALL SAVE (PS, RS, HS, SAR, T5, A5, Z5, GAMS, 1)  
ZST5 = Z5  

CALL VISC (T5, PS, V155)
IF (VIS < FO & 1.0) GO TO 104
RES = RES / VIS
CONTINUE

104 PRINT 202
PRINT 167
PRINT 168, PS, RS, TS, HS, SAR, 75, Gam, 85, U, M, RF
CALL SNS (PHOSS, US, PS, HES, 65, TS, ES, 75, Gam, 85, 2STARS, 85, M, RS, RS, TIF = XAS * ((1.0 / (U - A)) - (I On / U)), 87, 11)
PRINT 207
PRINT 208

HEAT TRANSFER RELATION OF NASA TN D-4799
OTZ0 = 3.8796 * 40 * SQRT (PT5 / RN) # (HT5 - HW)
PRINT 209, PT5, RT5, TS5, HS5, 75, GamT5, AT5, OTZ0, RN, T16
IF (I MOD = 0) GO TO 108
IF (OS + FO = 0) GO TO 106
IMOD = 2
PRINT 147
PRINT 145
PRINT 146
PRINT 147
PRINT 148
PRINT 149
PRINT 210
PRINT 211
PRINT 212
PRINT 213
PRINT 214

ACCELERATION TEST TIME- MIRFLS THEORY (LAMINAR)

C XAS = XAX
IF (MS10 * GF < 1.0 AND 4.99 < Lam <= 14.0) GO TO 109
IF (MS10 * GF > 14.0) GO TO 110
PRINT 215
GO TO 118

109 XXMAX = P10 * 1 + 29 * (PA - 2056 * MS10 + 1408) / 100 * 1000 * 1000
GO TO 111

110 XXMAX = P10 * 1 + 29 * (1231 - 74 * RF - 3 * MS10)

C XAS IS DIVIDED INTO 10 INTERVALS XA

C

111 DO 117 J = 1, 10
BETA1 = XAS (11) / RH010 / (2.0 * XXMAX * RH020)

C
APPENDIX A

BETA2=2*RHO20/RHO10
AXUP=.99999
AXLOW=.00001
DFLTAX=(AXUP-AXLOW)/100.
F1=1.0F-6
AX=.5
CALL ITR2 (AX,AXLOW,AXUP,DFLTAX,F0,AX,F1,200,ICODE)
IF (ICODE) 113,112,111

112
RXL=AX**2
XL=RXL*XXMAX
TAU=RHO10*XA(1)/(RHO20*UP)
BXUP=.99999
BXLOW=.00001
DFLTAX=(BXUP-BXLOW)/100.
BX=.5
CALL ITR2 (RX,RXLOW,RXUP,DFLTAX,F0,RX,F1,200,ICODE)
IF (ICODE) 113,114,115,116,117

113
GO TO (114,115,116,117,118,119,120,121

114
PRINT 146
GO TO 118

115
PRINT 147,ICODE
GO TO 118

116
TAU=RX**2+XXMAX/USO
UI=XL/TAU
URAT=UI/US
URAT=URAT/TAU
PRINT 216, XAS, XA(1), XXMAX, XL, RXL, TAU, UI, URAT, TAU
XA(1+1)=XA(1)+1*XA

117
CONTINUE

118 IF (ISTET.FOE.2) GO TO 122

119 IF (LF.EQ.2) GO TO 121

NN=NN+1
IF (NN.EQ.1) GO TO 120
IF (NN.GT.10) GO TO 120
US=US+US
DFLU=US-UA
IMET(1)=IMET(2)

120 IF (LD.NE.4) GO TO 1
IF (LF.EQ.3) GO TO 250
US=US-(FLOAT(NVEL)-1.)*US

250
NN=0
IMET(1)=IMET(2)
CONF=1
IF (NN.EQ.1) GO TO 56
IF (NN.EQ.2) GO TO 60
GO TO 1

121 IF (LD.NE.4) GO TO 1
IF=2
IMET(1)=IMET(2)
CONF=1
IF (NN.EQ.1) GO TO 56
IF (NN.EQ.2) GO TO 60
GO TO 1

C

C EXPANSION TUNNEL - EQUILIBRIUM EXPANSION
C

122 PRINT 147
PRINT 217
PRINT 146
PRINT 218
PRINT 219
IF (LG.EQ.1) P6=0.0
IF (LG.EQ.2) U6=0.0
PRINT 220, U6,P6,DIAT,DIAV,ISAV

C

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APPENDIX A

PROZEN FLOW - EXPANSION TUNNEL

ALP$=Z75-10
GACT5=(7.3+3.9*ALP$)/(E$+ALP$)
AACT5=SORT(GACT5*Z75*RUI8TE/W)
HACT5=AACT5**2/(GACT5-1.0)
HFR05=H5-HACT5
IF (HFR05<GT0.0) GO TO 124
PRINT 221
GO TO (119+140, LG)

GO TO (125+127, LG)

U6F=H6
CATA=(GACT5-1.0)/(UR88P-WUH2)+AACT5**2
IF (CATA<GT0.0) GO TO 126
PRINT 222
GO TO 130

126 A6F=SORT(CATA)
P6F=P50+((A6F/AACT5)**(2.0*GACT5/(GACT5-1.0)))
GO TO 128

127 P6F=PF
A6F=AACT5*(P6F/PF)*((GACT5-1.0)/(GACT5-1.0))
U6F=SORT(U6F*2+AACT5**2-A6F**2)/(GACT5-1.0))

128 M6F=H6F/A6F
T6F=T58*(A6F/AACT5)**2
RH06F=P6F/U6F//RUSWZ*T6F)
H6F=HACT5*(T6F/T9)
Z6F=Z5
GAMAF=GACT5
S6F=SFAR
P6F=0.0
CALL VISC (T6F,P6F,VIS6F)
IF (VIS6F<FO.0) GO TO 129
PRINT 223

129 PRINT 167
PRINT 16B16F,RH06F,T6F,H6F*SFAR,Z6F*GAMAF,A6F,UI6F,M6F,P6F
H6F=H6F-HFR05
1+RH06F*U6F*PF6F*H6SF*TT6F*PT6F*RT6F*ST6F*TT6F*AT6F*7T6F*CT6F*Z6SF

2F)
RAT6F=R6SF/RH06F
PRINT 224
PRINT 194
PRINT 201
PRINT 206
P6SF,P6SF,T6SF,HA6SF,S6SF,Z6SF,GAMSF,AA6SF,UI6SF,M6SF,PA6F

16
PRINT 225
PRINT 194
PRINT 208
QT6F=3.8798-*4*SORT(P1T6F/RH05)*H16F-HW)
T16F=0.0
PRINT 212
P1T6F+RT6F+TT6F+HT6F+ZT6F+GT6F+AT6F+QT6F+P06F+T6F
PRINT 219
PRINT 205
PRINT 206
P6SF=P6F*(P6F*GACT5*M6F**2-GACT5**1.0)/(GACT5**1.0)
R6SF=F06F+M6F**2)/(GACT5-1.0)**M6F**2)/(GACT5-1.0)**M6F**2)/(GACT5-1.0)**M6F**2)
T6SF=P6SF**W/(R6SF*PRU75.0)
H6SF=H6F*76SF/T6F
Z6SF=Z55
G6SF=GACT5
A6SF=AA6F*SORT(T6SF/T6F)
U6SF=R6SF*U6F/R6SF
M6SF=U6SF/AA6SF
S6SF=ALOG(R6SF/P6F)-GACT5*ALOG(R6SF/RH06F)/(GACT5-1.0)+S6F
RAT6F=R6SF/RH06F
PRINT 206
P6SF,P6SF,T6SF,H6SF,S6SF,Z6SF,GAMSF,AA6SF,U6SF,16SF.
APPENDIX A

IM4SF,PATFF
PRINT 225
PRINT 195
PRINT 20A
HTAFF=H6F+5*U6F**2
TTAFF=TTAFF*HTAFF/HTAFF
PTAFF=PTAFF*(HTAFF/HASFF)**(GACT5/(GACT5-1.))
RTAFF=PTAFF**W/(TTAFF**Z5+R1)
ZTAFF=Z25
GTAFF=GACT5
ATAFF=A5E+S**5/SORT(TTAFF/TAFF)
OTTFF=3*(PTAFF**4/SORT(PAFF**BNR))*(HTAFF**W)
PRINT 212,PTAFF,PTAFF,TTAFF,HTAFF,TTAFF,GTAFF,GTAFF,GTAFF,PAFF,BNR,TAFF
IF
GO TO (130,140), LG
C
LG=1 DENOTES U6 IS INPUT
C
130 H6=H*5+(1*5-2-U6**2)
IF (H6+G**2-E*4) GO TO 131
PRINT 225
GO TO 1...
131 Z(4)=ALOG10((HA/287.045)
IMEF(1)=IMET(2)=0
LCDEF=1
CALL SLOW (SAR,Z4,1,T,INV,NFRR,Y,X)
GO TO (132,135), LCDEF
132 P=10**1*Z(3)*1.0135FE++
GO TO (133,134), P
133 CALL SLOW (SAR,Z4,1,T,INV,NFRR,Y,X)
CALL SLOW (SAR,Z4,2,T,INV,NFRR,Y,X)
CALL SLOW (SAR,Z4,3,T,INV,NFRR,Y,X)
CALL SLOW (SAR,Z4,4,T,INV,NFRR,Y,X)
CALL SLOW (SAR,Z4,6,T,INV,NFRR,Y,X)
T6=Z(1)
R6=10.*(Z(2)+1.014869)
GAM6=7(5)
Z6=Z(7)
PRINT 227
GO TO 137
134 CALL SAVF (P6,R6,H6,SAR,TA,A6,Z76,GAM6,1)
PRINT 228
IF (LG=E0.1) GO TO 137
U6=SORT(T2,H6-H6**2)
GO TO 137
135 P=1.0135F1*E1*HA**2+R6**2)**1*EXP(P1,10-9)4
176 T6=1/H6**R3
R6=3.4A83FE-3*P6/T6
A6=20.046K*SORT(T6)
GAM6=1.4
Z6=7ST6+1.0
PRINT 229
177 M6=1/A6
RFA=0.0
CALL VISC (T6,P6,V156)
IF (V156>EQ.1.0) GO TO 138
R6=P6/U6/V156
178 PRINT 230
PRINT 167
PRINT 168, P6,R6,T6,H6,SAR,Z76,GAM6,A6,UA,WA,RFA
1*U6,P6,H6,HT6,P6T6,STAR,T6,T6A,T6Z1,T6Z2,GAM6T6,ST6T6)
RATFF=R065/R6
Q6=3.479B6-E*SORT(P6/BNR)*(HT6-H6)
A6=(R6**U6)/(R6**U6)
APPENDIX A

DELTA=2.9101AN-DIA#SORT(AA6))
PRINT 231
PRINT 204
PRINT 205
PRINT 206, PA5, PMA5, T5A, H5A, S55, P55, GM5, PMA5, AA5, U5A, MAC, DAT5F
PRINT 232
PRINT 204
PRINT 233
PRINT 206, PA5, RTA5, T5A, H5A, GAM5F, AT5, QT6, RT6, RNP, AA6, DEL5T6
IF (LG.EQ.2.0RT.LREP.FD.0) GO TO 119
NNN=NNN+1
IF (NUMU.EQ.NNN) GO TO 129
IF (NNN.GT.10) GO TO 119
U6=U6+U61
GO TO 123
179 U6=I-(FLOAT (NUMU)-1)8161
NNN=1
GO TO 119

C LG=2 DENOTES PA 15 INPUT

140 IMFT(1)=IMFT(2)=0
LCONF=1
Z(1)=ALOG10 (PA/1.0177646F5)
CALL SLOW (SARZ, 3, 1, IT, NV, NERR, +Y, X)
GO TO (141, 147), LCONF
141 GO TO (142, 134), 154
142 CALL SLOW (SARZ, 3, 2, IT, NV, NERR, +Y, X)
CALL SLOW (SARZ, 3, 4, IT, NV, NERR, +Y, X)
CALL SLOW (SARZ, 3, 5, IT, NV, NERR, +Y, X)
CALL SLOW (SARZ, 3, 6, IT, NV, NERR, +Y, X)
CALL SLOW (SARZ, 3, 7, IT, NV, NERR, +Y, X)
T6=Z(1)
PA=10.89Z(2)+1.9(104890
H6=10.89Z(4)+1.9(287+245
GAM6=Z(5)
A6=Z(6)+331+413
ZZA=Z(7)
PRINT 227
143 H6=99657F5+58((PA/1.0177646F5)/EXP(2.910-5AR11))8C+287
U6=SORT (2*(H6-H6)+1R882)
GO TO 137
144 STOP

146 FORMAT (/51H FOLLOWING EQUILIBRUM CONDITIONS INCLUDE FLOW ATTN)
146 FORMAT (/55H XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX
147 FORMAT (/55H XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX XXXXXXXXXX
148 FORMAT (/46H EXPANSION TURB PROGRAM OF MILLER FOR DEAL AIR)
149 FORMAT (/51H ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012)
150 FORMAT (/52H SHOCK TURF PHASE OF PROGRAM)
151 FORMAT (/47H MEASURED INPUTS FOR SHOCK TURF PHASE)
152 FORMAT (/105H RUN RUM TURF T1 US1 P2
153 FORMAT (8E10.3, 315)
154 FORMAT (20H MAX COUNT EXCEEDED )
155 FORMAT (17H DERIVATIVE = 0.0, 415)
156 FORMAT (7H ICODF=15, 8H 6155, 7H DEL5T=17155)
157 FORMAT (/65H P3 T3 PMA3 257 271 751 155 71 251
158 FORMAT (7F10.3)
APPENDIX A

159 FORMAT (/46H P2 RH0 T H HP US1) A100
160 FORMAT (5E10.3) A100
161 FORMAT (/30H IMPERFECT HYDROGEN DRIVER GAS) A101
162 FORMAT (/28H IMPERFECT HELIUM DRIVER GAS) A102
163 FORMAT (/13H 4 CONDITIONS) A103
164 FORMAT (/75H P RH0 T H CS/P) 7 A104
17 FORMAT (/A1) A105
165 FORMAT (RF10.3) A106
166 FORMAT (/44H CONDITIONS BEHIND INCIDENT SHOCK - REGION 2) A107
167 FORMAT (/106H P RH0 T H CS/P) A108
17 FORMAT (44H FORMULA MEANS- SHOCK CONDITIONS) A109
170 FORMAT (/66H P RH0 T H A M) A110
171 FORMAT (/7F10.3) A111
172 FORMAT (/47H SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY) A112
173 FORMAT (/107H LT MAX L/LMAX TIM TIM) A113
174 FORMAT (/45H SHOCK TUBE TEST TIME NOT COMPUTED - MS1 LT 4) A114
175 FORMAT (/17F10.3) A115
176 FORMAT (/71H SHOCK TUBE LAMINAR FLOW NONUNIFORMITY NOT COMPUTED) A116
177 FORMAT (/45H SHOCK TUBE FLOW NONUNIFORMITIES-LAMINAR CASE) A117
178 FORMAT (/44H RATIOS-PARAMETER AT XS TO PARAMETER AT X50) A118
179 FORMAT (/65H X/L P RH0 T H A M) A119
180 FORMAT (/7F10.3) A120
181 FORMAT (/53H SHOCK TUBE TURBULENT FLOW NONUNIFORMITY NOT COMPUTED) A121
182 FORMAT (/47H SHOCK TUBE FLOW NONUNIFORMITIES-TURBULENT CASE) A122
183 FORMAT (/52H CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPHRAGM) A123
184 FORMAT (/46H STAGNATION CONDITIONS BEHIND STANDING SHOCK-REGION T) A124
185 FORMAT (/98H P RH0 T H CS/P) 7 A125
186 FORMAT (/53H CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPHRAGM) A126
187 FORMAT (/52H EXPANSION TUBE PHASE OF PROGRAM) A127
188 FORMAT (/47H INPUTS FOR EXPANSION TUBE PHASE) A128
189 FORMAT (/72H US 5 PS XAS DELUS 16AV 1EXP 1) A129
190 FORMAT (7F10.3 615) A130
191 FORMAT (/40H FROZEN ENTHALPY IN REGION A IS NEGATIVE) A131
192 FORMAT (/15H ASF IS NEGATIVE) A132
193 FORMAT (/34H 4 CONDITIONS FOR FROZEN EXPANSION) A133
194 FORMAT (/41H FROZEN EXPANSION-EQUILIBRIUM POST SHOCK) A134
195 FORMAT (/37H FROZEN EXPANSION-- FROZEN POST SHOCK) A135
196 FORMAT (/54H AFDC REAL-AIR TATE USED FOR INSTANT EXPANSION-EXP1) A136
197 FORMAT (/53H PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION) A137
198 FORMAT (/55H AFDC CURVE FIT EXPRESSIONS USED FOR INSTANT EXPANSION\N) A138
199 FORMAT (/50H HS LT 5E4- EQUILIBRIUM 5 CONDITIONS NOT COMPUTED) A139
200 FORMAT (/37H QUANTITIES IN REGION 5 OFF AFDC TARE) A140
201 FORMAT (/53H THESE QUANTITIES DETERMINED FROM IDEAL AIR RELATIONS) A141
202 FORMAT (/19H 5 CONDITIONS FOR EQUILIBRIUM EXPANSION) A142
203 FORMAT (/47H STATIC CONDITIONS BEHIND RAW SHOCK - REGION 55) A143
204 FORMAT (/46H EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK) A144
205 FORMAT (/108H P RH0 T H CS/R) A145
206 FORMAT (/A1) A146
207 FORMAT (/1E10.3) A147
208 FORMAT (/49H STAGNATION CONDITIONS BEHIND RAW SHOCK-REGION TR) A148
209 FORMAT (/97H P RH0 T H Z) A149
210 FORMAT (/48H ACCELERATION AIR CONDITIONS (REGION 20) AND R10) A150

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APPENDIX A

211 FORMAT (10I4) P20 RHO20 T20 H20 Z20
100 P10 RHO50 MS10 RAT10 1
212 FORMAT (10E10.3)
213 FORMAT (//53H ACCELERATION AIR FLOW PARAMETERS USING WILES THEORY
1)
214 FORMAT (//53H XAS XA LMAX L L/LMAX
1
TIM UI U1/U5 U520/UI TIM1)
215 FORMAT (//53H ACCELERATION AIR LEAKY PISTON EFFECT NOT COMPUTED)
216 FORMAT (10E10.3)
217 FORMAT (//53H EXPANSION TUNNEL PHASE OF PROGRAM)
218 FORMAT (//53H INPUTS FOR EXPANSION TUNNEL PHASE)
219 FORMAT (//53H US PC D-THROAT D-NOZZLE ISAV)
220 FORMAT (4F10.3,11E)
221 FORMAT (40H FROZEN ENTHALPY IN REGION F IS NEGATIVE)
222 FORMAT (40H AEROF NEGATIVE - FROZEN CONDITIONS NOT COMPUTED)
223 FORMAT (40H STATIC CONDITIONS BEHIND RAW SHOCK - REGION AS)
224 FORMAT (40H DEATH CONDITIONS BEHIND RAW SHOCK - REGION TA)
225 FORMAT (40H STAGNATION CONDITIONS BEHIND RAW SHOCK - REGION TA)
226 FORMAT (40H H6 LESS THAN 2.0F+14 - 7.6 LESS THAN 2.0F+14)
227 FORMAT (40H AERODYNAMIC TAUPE USED FOR STEADY NOZZLE EXPANSION)
228 FORMAT (40H AERODYNAMIC TAUPE EXPANSION FOR NOZZLE EXPANSION)
229 FORMAT (40H REGION 6 QUANTITIES OFF TAPE - PERFECT RELATIONS USED
1)
230 FORMAT (//40H 6 CONDITIONS FOR EQUILIBRIUM NOZZLE EXPANSION)
231 FORMAT (40H STATIC CONDITIONS BEHIND RAW SHOCK-REGION AS)
232 FORMAT (40H DEATH CONDITIONS BEHIND RAW SHOCK-REGION TA)
233 FORMAT (40H STAGNATION CONDITIONS BEHIND RAW SHOCK-REGION TA)
234 FORMAT (4A10)
235 FORMAT (1H1+1A10/)
END
SUBROUTINE VISC (T,P,VIS)
DIMENSION TAPY(4), TABY(13), TBNYU(52)
C
C TABLE OF VISCOSITY FROM VOS(AVCO RAD-TM-63-7)
C
IF (T>T=1600), GO TO 1
CALL DISCOT (T,P,TAPY,TBNYU,TAPY,11,52,4,VI5)
GO TO 3
1 VIS=10.0
GO TO 3
2 VIS=1462F+4*SORT(T)/11+120/T
RETURN
END
SUBROUTINE SHOCK (RN,CN,DN,RN,DP,CN,CP,DN,CP)
RETURN
END
FUNCTION FOFAXT (AX)
RETURN
END
FUNCTION FOFAXT (AX)
RETURN
END
APPENDIX A

FUNCTION FOFX (XT)
COMMON /BLK4/ META1,BETA2
FOFXT=-4*RTA1+2*ALOG((1+XT)/(1-XT))+(4*ATAN(2*XT)*(4*XT)**2
RETURN
END

FUNCTION FOFAX (AX)
COMMON /BLK6/ BETA1,BETA2
FOFAX=-BETA1-ALOG(1-AX)-AX
RETURN
END

FUNCTION FOFPX (PX)
COMMON /BLK6/ BETA1,BETA2
FOFPX=-BETA1-ALOG(1-PX)-AX**2/BETA2-PX
RETURN
END

FUNCTION FOFX (RN)
COMMON /BLK1/ RTA1,RTA2,RHOC
FOFX=RHOC-(RTA*RNX**2+RTA*RN**2)
RETURN
END

FUNCTION FOFD (RN)
COMMON /BLK2/ ATI,CTI,RLK6,RFRT,ARTI,CTI
ASCVR=ALOG(TI)
RFRT+TI*RTA
CCTI+TI*RTA
FOFD=AVLOG(RN)-(RN**2)-(RN**22)*CCRF+CTI
RETURN
END

FUNCTION FORMS (MN)
COMMON /BLK7/ Ti,GAU4,MD,TA4,P4,PI
REAL MN
A=GAU4/PI
B=(GAU4-1.)/2.*A
C=SORT((GAU4**3*(1+GAU4)/GAU4**4))
D=P2*GAU4/(GAU4-1.)
Q=1-(C*B)***(C**M-1)/MN1**2
RETURN
END

SUBROUTINE SNS (RX,UX,DX,XX,SY,TX,AX,ZV,GX,7SY,WY,RY,XY,3V,XY,7X)
CALL FTLUP (X,Y,2,N,TARX,TARY)
SUM=(TAXX(J-1)+AX**2+TAXY(J-1))*ABS(DFLX)*2.
TARANS(J)=TARANS(J-1)+SUM
CONTINUE
RETURN
END

SUBROUTINE SNS (RX,UX,DX,XX,SY,TX,AX,ZV,GX,7SY,WY,RY,XY,3V,XY,7X)
CALL FTLUP (X,Y,2,N,TARX,TARY)
SUM=(TAXX(J-1)+AX**2+TAXY(J-1))*ABS(DFLX)*2.
TARANS(J)=TARANS(J-1)+SUM
CONTINUE
RETURN
END
APPENDIX A

```
IT=8
NV=9
ISP=1
RX=IP,=NPX
HTX=NSN
UX=SN/RX
PX=SN-NSN
UX=SN
GO TO (2.3) 15A
2 CALL SEARCH (PX, RNEW, HX, SX, TX, VX, CY, ZV, 150)
3 CALL SAVE (PX, RNEW, HX, SX, TX, VX, CY, ZV, X)
4 IF (ABS(1.0-RX/RNEW)+0.0) GO TO 5
   RX=RNEW
5 RX=RNEW
STX=SN
GO TO (6,7) 15A
6 HTX=HX+SN
Z(4)=ALOG(7(14))
CALL SLOW (SX+7+7, IT, NV, NEFP, YY)
PTX=(1.0-7(7.11)) 1.07246E
CALL SEARCH (PTX, HTX, STX, TX, VX, CY, ZV, X)
STX=SN
GO TO 7
7 PTX=(PX*(1+1(X-1)))*Q*2)**(CY+C(1))
CALL SAVE (PTX, RX, HTX, STX, TX, VX, CY, ZV, X)
ZTX=STX
IF (ABS(1.0-HTX/(HX+SN))>0.01) GO TO 8
PTX=(PTX*(HX+SN))/HTX
GO TO 9
8 RETURN
END
SUBROUTINE ANT (RTM, CTM, DPM, DCM, DPM, DCM, TM)
COMMON \(a, b, c, m, n, o, p, q, r\) GO TO 1

C

HFLAIR used as driver gas

AMT=15492-AlOG(TM)
AMT2=-7.4715(TM)
ATM=1.3566666666666666
CTM=6.373E-12/AMT1
DPM=1.0/AT+0.6666666666666666
DCM=-3.779E-11/ATM1
DPM=2.0/AT+0.6666666666666666
DCM=3.779E-11/ATM1
LX=AMT
LX=(1.0 ALOG-10/TM)**2+AMT1+4+(7.779E-11/TM)**2
AMT1
GO TO 9
2 RETURN
END
SUBROUTINE SEARCH (P, PHO, H1, CPA, T1, A1, 71, 7C, 7C, 1C)
DIMENSION COUNT(25), JPLAC(25), Y(4), T(25), PHO(25)
DIMENSION SAVEX(25), SAYS(25), SAVAY(25), SAVEX(25), SAVAY(25)
DIMENSION HIX(25), T1(25), A1(25), 71(25), 7C(25), 7C(25), 7C(25)
```

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APPENDIX A

DIMENSION TART(150), TARR(150), TARP(150), TAPH(150)
DIMENSION TAPC(150), TAP7(150), TAPG(150), TAPZ(150)

DO 1 =1,150
1 CONTINUE
JUMP=0
1 T=R

2 IF (JFLAG(J).EQ.0) GO TO A
GO TO 5

3 CONTINUE
RH0(J)=0.
TI(J)=0.
A1(J)=0.
Z1(J)=0.
SOR(J)=0.
GAM(J)=0.
ZS(J)=0.

4 CONTINUE
GO TO 15

5 CONTINUE
DO 14 J=1,ISP
IF (JFLAG(J)=0.0) GO TO 14

A=1/COUNT(J)
PP=ALOG10(P(J)/1.01326E+8)
HH=ALOG10(H(J)/1.0287024E+1)
IF (PP-Y(3,J))*(PP-Y(3,NV)) LT 0.) GO TO 7

SAVFH(J,J)=0.
SAVFR(J,J)=0.
SAVFT(J,J)=0.
SAVFJ(J,J)=0.
SAVFF(J,J)=0.
SAVFS(J,J)=0.
SAVFH(J,J)=0.
SAVFR(J,J)=0.
SAVFT(J,J)=0.
SAVFF(J,J)=0.
SAVFS(J,J)=0.

PNP=1
GO TO 10

7 DO 8 J=1,NV
TART(J)=Y(1,J)
TARR(J)=Y(2,J)
TARP(J)=Y(3,J)
TAPC(J)=Y(4,J)
TAPG(J)=Y(5,J)
TAPH(J)=Y(6,J)
TAP7(J)=Y(7,J)
TAPZ(J)=Y(9,J)

8 CONTINUE
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)
CALL DISCOT (PP,PPTA,APDTAP,AP7,A7H,A7H-130,NV,0,ANS)

SAVEF(J,NV)=X
SAVFH(J,NV)=ANS
SAVFR(J,NV)=ANS
SAVFT(J,NV)=ANS
SAVFS(J,NV)=ANS
SAVFZ(J,NV)=ANS

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APPENDIX A

SAVEG(J, NN)=ANS6
SAVEF7S(J, NN)=ANS7
IF (SAVEH(J, NN)=AN, GT=HH) GO TO 11
IF (NN=ENG, 1) GO TO 9
NN=NN+1
GO TO 10
9 SAVE(R(J,1)=SAVEF(J,1)
SAVEHJ, J, 1)=SAVEH(J, 2)
SAVEF(J, J, 1)=SAVEF(J, 2)
SAVFA(J, J, 1)=SAVFA(J, 2)
SAVEZ(J, J, 1)=SAVEZ(J, 2)
SAVES(J, J, 1)=SAVES(J, 2)
SAVEG(J, J, 1)=SAVEG(J, 2)
SAVEZS(J, J, 1)=SAVEZS(J, 2)
SAVEF(J, J, 2)=SAVEF(J, 3)
SAVEH(J, J, 2)=SAVEH(J, 3)
SAVEF(J, J, 2)=SAVEF(J, 3)
SAVFA(J, J, 2)=SAVFA(J, 3)
SAVEZ(J, J, 2)=SAVEZ(J, 3)
SAVES(J, J, 2)=SAVES(J, 3)
SAVEG(J, J, 2)=SAVEG(J, 3)
SAVEZS(J, J, 2)=SAVEZS(J, 3)
ICOUNT(J)=NN
GO TO 14
10 IF (NN=ENG, 4) GO TO 12
NN=NN+1
ICOUNT(J)=NN
GO TO 14
11 JPLAG(J)=1
GO 17 HJ=10
G(M)=SAVEH(J, M)
Y1(M)=SAVEF(J, M)
Y2(M)=SAVEF(J, M)
Y3(M)=SAVEF(J, M)
Y4(M)=SAVEF(J, M)
Y5(M)=SAVEF(J, M)
Y6(M)=SAVEF(J, M)
Y7(M)=SAVEF(J, M)
CONTINUE
CALL INTRP(4, G, Y, M, HH, R)
CALL INTRP(4, G, Y, M, HH, T)
CALL INTRP(4, G, Y, M, HH, 4)
CALL INTRP(4, G, Y, M, HH, 2)
CALL INTRP(4, G, Y, M, HH, 2)
CALL INTRP(4, G, Y, M, HH, 2)
RHC(J)=(1.0)*801*2.91489
T1(J)=T
A1(J)=A, 331.0414
Z1(J)=Z
S0(J)=SR1
GAM(J)=GAM1
Z5(J)=Z5J
JUMP=JUMP+1
IF (JUMP=ENG, 1) GO TO 15
CONTINUE
GO TO 2
CONTINUE
RETURN
C
C
16 FORMAT (1H1, 60X, 7HWARNING/\///)
END
SUBROUTINE SLOW (XX, 7, 1, J, 1, T, NV, NFR, Y, X)
C TAPE IS WRITTEN WITH LINES OF CONSTANT XX

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APPENDIX A

Z(11) AND XX ARE INDEPENDENT VARIABLES
Z(11) IS THE DEPENDENT VARIABLE
AK = +1, IF XX INCREASES MONOTONICALLY ON TAPE
AK = -1, IF XX DECREASES MONOTONICALLY ON TAPE
IT = TAPE UNIT
NV = NO. OF VARIABLES ON TAPE FOR EACH XX (NOT GREATER THAN 9)
NO. OF POINTS FOR EACH XX NOT GREATER THAN 150
BEGIN EXECUTION
DIMENSION X(4), Y(4,150), Z(9), U(4), V(4), N0(4)
COMMON ICOUNT, IMET(2), NV, APAR, MP, MF, SAR, LSEQ, OPL, IT
REAL MP, MF
ICOUNT=ICOUNT+1
IF (IMET(1)) 3,1,7
1 BACKSPACE IT
READ (IT) NUM
REWIND IT
DO 2 K=1,3
READ (IT) X(K),Y(K),L=(1,NV),L=1,J
2 NP(K)=J
XW=X(2)-X(1)
AK=ABS(XW)/XW
DIR=1,
IMET(1)=1
XXX=XX
NFPR=0
IM=3
GO TO 18
3 NFPR=0
C EXCEPT FOR FIRST TIME THROUGH
IF ((XX-X(M1))*(XX-X(M2))) 26,29,4
4 TEMP=(XX-XXX)*AK
DIR2=ABS(TEMP)/TEMP
GO=GO*DIR2
XX=XX
DIR=DIR2
IF (GO) 5,36,16
C NEGATIVE DIRECTION
5 IF (GO) 6,35,7
6 BACKSPACE IT
BACKSPACE IT
BACKSPACE IT
GO TO 9
7 IM=IM-1
IF (IM) 8,8,9
8 IM=4
9 M1=IM+1
BACKSPACE IT
BACKSPACE IT
IF (M1-4) 11,11,10
10 M1=1
11 M2=M1+1
IF (M2-4) 13,13,12
12 M2=1
13 READ (IT) X(IM),Y(IM),L=(1,NV),L=1,J
NP(IM)=J
IF ((XX-X(M1))*(XX-X(M2))) 26,29,14
14 IF (X(M1)-X(M2)) 7,15,7
C ERROR, VARIABLE OFF FRONT END OF TAPE
15 CONTINUE
NFPR=1
GO TO 36
C POSITIVE DIRECTION
16 IF (GO) 17,35,18
APPENDIX A

17  READ (IT) DUM
19  READ (IT) DUM
21  READ (IT) DUM
23  GO TO 20
25  [M]=1+1
27  IF (M-4) 20,20,20
29  [M]=1
31  IF (M) 21,21,22
33  [M]=4
35  [M]=M-1
37  IF (M2) 23,23,24
39  [M]=4
41  READ (IT) X(JM1+I,J,*((Y(I1+1,L)+1,NV)+L=1+J)
43  NP(I)=J
45  IF ((XX-X(I1))=(XX-X(Y2))) 25,26,1A
47  TAP SEARCH COMPLETE, NO CROSS FOUR POINT
49  DO 34 K=1,4
51  NPK=NPK(K)-1
53  DO 26 L=1,NPK
55  IF (((Y(K)I1)+Z(I1)+Y(K)I1+1)-Z(I1))) 27,27,26
57  CONTINUE
59  NERR=1
61  GO TO 36
63  IF (I-1) 29,28,29
65  J=0
67  GO TO 32
69  IF (I-NPK) 31,30,31
71  J=NPK-1
73  GO TO 32
75  J=I-2
77  DO 33 L=1,4
79  MX=L+J
81  U(L)=Y(K)I1+MX)
83  V(L)=Y(K)I1+J(+MX)
85  CALL INTPR (4+X+Y+Z(IK))
87  CALL INTPR (4+X+Y+Z(IK))
89  RETURN
91  CONTINUE
93  NERR=1
95  IF (IMFT(2)) 38,37,38
97  IMFT(2)=1
99  LCODE=2
101  WRITE (6,39) XX1117(I1),11
103  RETURN
105  FORMAT (///39H NO SOLUTION ON TAP FOR THE CONDITIONS//5X,6H <R=1
107  IF12,6+7X,9H EVALUATE//6X,9H/I1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+/11
109  END
111  SAVE ROUTINE, TABULAR THERMODYNAMIC PROPERTIES FOR REAL AIR
113  IS BASED ON CURVE FIT EXPRESSIONS OF AFDC-TOR-63-13B
115  EXPRESSIONS OF AFDC-TOR-63-13B APPLICABLE FOR T=90 TO 15000
117  MAXIMUM PERCENT ERRORS= T=20,000 TO 15000, AND P=1F+8 TO 1F+6
119  INPUTS ARE PRESSURE IN (MN/SQ METER) AND-
121  (1) ENTROPY, S/R (K=1)
123  (2) DENSITY, KG/CMIC METER (K=3)
125  (3) ENTHALPY, SQ METER/50 SEC (K=3)
APPENDIX A

ALSO, INPUTS DENSITY AND ENTHALPY ARE INCLUDED (K=4)

MODIFIED 9/7/71 FOR INPUTS P AND T (K=5)

DIMENSION TARR(6), TARM(6), TABM(6)
DIMENSION TARM(13), TARM(13), TARM(13), PM(17)
DIMENSION TARR(17), TARR(17), TARR(17), TARR(17), TARR(17)
DIMENSION TARR(17), TARR(17), TARR(17), TARR(17)
DIMENSION TARR(17), TARR(17), TARR(17)

W0=28*967
RUNIV=8314.34
NN=0
MM=0

IF (K.NE.4) GO TO 3

ZK=1.2
DO J=1,17
RHO=P*WO/(RUNIV**77*T)
GO TO 6

TAR&R(J)=SR
TAR&R(J)=HA
TAR&R(J)=Z
TAR&R(J)=T
ZK=ZK+2
MM=0
NN=0

CONTINUE
CALL FTLUP (T,SR,2,17,TAR&R,TARRP)
CALL FTLUP (T,HA,2,17,TAR&R,TARP)
CALL FTLUP (T,Z,2,17,TAR&R,TARR)
CALL FTLUP (T,RH,2,17,TARRR,TARRP)

GO TO A

IF (K.NE.4) GO TO 6

CON&=0.03
DO J=1,13
PM(J)=RHO*H*CON&
TAR&M(J)=PM(J)
P=PM(J)
GO TO 6

TAR&MM(J)=HA
TAR&RM(J)=SR
CON&=CON&+0.03
MM=0
NN=0

CONTINUE
CALL FTLUP (T,PM,2,13,TAR&MM,TAR&RM)
CALL FTLUP (T,TM,2,13,TAR&MM,TAR&RM)
MM=3

GO TO A

IF (K.NE.4) GO TO 6

A=ALOG10(P/1.013**7)
C=A*ALOG
IF (K.EQ.1) GO TO 6

IF (K.EQ.4.AND.MM.EQ.3) GO TO 6
SRUP=148.
SR=SRUP-SRLOW/2+14.
SR=SRUP-DFLRS
IF (NN.EQ.0) GO TO A
SR=SRUP-DFLRS
SR=SRLOG-ALOG10(SR)
C=SRLOG+SRLOG
IF (X151.EQ.0) 10,9,9
APPENDIX A

1. \( T1 = 0.0 \)
   GO TO 13

10. IF \((X15 + 400) \geq 11, 12, 13\)
   \( T1 = 1.0 \)
   GO TO 13

12. \( T1 = 1.0 \times \exp(X15) \)

13. IF \((KoF0 + 3 \times \text{AND}2 \times M0 + \text{F0} 2) \geq 10\)
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 39
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 39
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 61
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 39
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 39
   \( T1 = 1.0 \times \exp(X15) \)
   GO TO 81

C

COMPUTING RHO AS A FUNCTION OF \( \rho \) AND \( \kappa / \rho \)

14. \( X12 = 1.6 + 85 + 7.4 + 5 \times \text{SLOG} + 7.0 + 803 \times \text{A} \)
   \( X23 = 4.4 + 4.6 + 4.4 + 4.4 \times \text{SLOG} + 7.0 + 803 \times \text{A} \)
   \( X34 = 3.0 + 4.0 + 4.0 \times \text{SLOG} + 7.0 + 803 \times \text{A} \)
   \( X45 = 4.0 + 4.0 \times \text{SLOG} + 7.0 + 803 \times \text{A} \)
   \( X12 = 1.0 \times \exp(X12) \)
   \( X23 = 1.0 \times \exp(X23) \)
   \( X34 = 1.0 \times \exp(X34) \)
   \( X45 = 1.0 \times \exp(X45) \)

15. \( T1 = 1.0 \)
   GO TO 19

16. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   GO TO 19

17. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   GO TO 19

18. \( T1 = 0.0 \)

19. IF \((X45 + 40) - 20 \geq 2, 23 \)
   \( T1 = 0.0 \)
   \( T1 = 2.0 \)

20. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

21. \( T1 = 0.0 \)
   GO TO 24

22. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

23. \( T1 = 0.0 \)

24. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

25. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)

26. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

27. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

28. \( T1 = 0.0 \)

29. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

30. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)

31. \( T1 = 0.0 \)

32. \( T1 = 1.0 \times \exp(X12 + X23 + X34 + X45) \)
   \( T1 = 0.0 \)

33. \( T1 = 0.0 \)

34. \( T1 = 0.0 \)

35. \( T1 = 0.0 \)

36. \( T1 = 0.0 \)

37. \( T1 = 0.0 \)

38. \( T1 = 0.0 \)

39. \( T1 = 0.0 \)
APPENDIX A

122*PLOG*SRLOG-123.95E62R+0010077477+C+00418=11*SRLOG+12=09
266*PLOG*R+30.203R62=0

RHCAL=RH15+(RHCAL-RH1)\*T
RHOA=(10*RHCAL)*1.2222
IF (K*EQ.1) GO TO 39
IF (K*EQ.3) GO TO 61
IF (K*EQ.2*ANDMM*EQ.0) GO TO 69
IF (K*EQ.4*ANDMM*EQ.0) GO TO 69
IF (K*EQ.5*ANDMM*EQ.0) GO TO 69

CONVERGENCE TFST FOR K=2

IF (APS(I.-RHO/PHOA).LT..nl) GO TO 39
NN=NN+1

IF (RHO.GT.PHOA) GO TO 7

SPLOG=SR
Sr P=SP+FLSR
IF (FLSR.GT.1.) GO TO 7

XH=-61.2053+114.103*04LOG-47.9932*R
XHI=-10.*(PLOG-XHI)
IF (XH1-40.) 43.46*
IF (XHI+40.) 44.49*

TH=1.*
GO TO 47

TH=1.*(1.+EXP(XH))
GO TO 47

HRCAL=HR21+(HR22-HR21)*TH
GO TO 51

IF (SRLOG-1.92) 49.40*
IF (SRLOG-1.76) 42.42*

HR21=156.37196+6.6989228*PLOG+269.91077*SRLOG-19710006=6.7670
HR22=156.37196+6.6989228*PLOG+269.91077*SRLOG-19710006=6.7670

1194*PLOG*SRLOG-32.1645*SR
XH=-61.2053+114.103*04LOG-47.9932*R
XHI=-10.*(PLOG-XH)

TH=(1.*EXP(XH1))
GO TO 47

TH=1.*
GO TO 47

CONVERGENCE TFST FOR K=2

IF (APS(I.-RHO/RHOA).LT..nl) GO TO 39
NN=NN+1

IF (RHO.GT.RHOA) GO TO 7

SPLOG=SR
Sr P=SP+FLSR
IF (FLSR.GT.1.) GO TO 7

XH=-61.2053+114.103*04LOG-47.9932*R
XHI=-10.*(PLOG-XH)
IF (XH1-40.) 43.46*
IF (XHI+40.) 44.49*

TH=1.*
GO TO 47

TH=1.*(1.+EXP(XH))
GO TO 47

TH=1.*
GO TO 47
APPENDIX A

50  HRCAL=114.94396+6.00458*PLOG+18.04278*SRLGC-4.1327787*A-4.0766
1539*PLOG*ELOG=90.7666688+9.000792694*C+0.9245628*A*ELOG+1.0462
22999*PLOG8+15.46780480
61  HRCAL=HR15*(HRCAL-HPI)+(CHRCAL-HPI)*TI
205*SRLGC=3.2*3.264280
HRCAL=HR15*(HRCAL-HPI)+TI
HA=(10.6*HRCAL)*PAP
IF (K*EQ1*OR*K*EQ2) GO TO 61
IF (K*EQ0*OR*K*EQ4) GO TO 61
IF (K*EQ3*AND*K*EQ0) GO TO 61
IF (K*EQ4) GO TO 4

C
CONVERGENCE TEST FOR K=3
C
IF (ABS(H-HA)*LE.*001) GO TO 14
NN=NN+1
IF (HA*GT.0*H) GO TO 27
GO TO 36
C
INTERPOLATION FOR DELSP LESS THAN 1
C
62  TAPH(I)=HA
63  DELSP=|TABS9(I)-TABS9(1)|/5
DO 56  I=2,5
TAPS9(I)=TABS9(I-1)+DELSP
CONTINUE
IF (K*EQ0*OR*K*EQ4) GO TO 58
IF (K*EQ2*OR*K*EQ4) GO TO 58
DO 56  I=2,6
MM=1
SR=TABS9(I)
GO TO 14
65  TAPR(I)=HA
66  CONTINUE
CALL FTLPUP (H,SR,N,6,TAPR,TAPS9)
MM=2
GO TO 14
67  TAPR(I)=HOA
68  DO 60  I=2,6
MM=1
SR=TAPS9(I)
GO TO 14
69  TAPR(I)=HOA
70  CONTINUE
CALL FTLPUP (RH0,SR,N,6,TABR,TAPS9)
MM=2
GO TO 18
C
COMPUTING 7
C
71  XZ12=62.91-41.5*SRLOG
XZ22=79.92-41.579*SRLOG
XZ74=65.979-79.5*SRLOG
XZ26=29.92-79.5*SRLOG
XZ21=-10.7*(PLGC-Y712)
XZ23=10.7*(PLGC-Y723)
XZ31=-10.7*(PLGC-X731)
XZ41=10.7*(PLGC-X741)
ZCAL=2619.80374-27.8*691*PLOG-98.8*7928*ELOG+39.5*83+39.8*83
179*PLGC*ELOG=620.96416*8*0.016448*68-2.7710*70*8*ELOG-9.69*83
2*PLGC=8.29*79281
ZCAL=366.04674-15.51784*PLOG-64.0284*ELOG+19.71*88*18+8.8
183*PLOG*ELOG+370.997268*8*0.098792*79*ELOG+1.68*98*83*SRLOG=1.9982
APPENDIX A

254*PLOG*P - 73,504269*0
ZCAL = 516.07371-16029230*PLOG-0.825205*ZCAL0.75623684+1.62968
206*PLOG*P - 71,79342*P
IF (XZ121-401) 62,65,65
62 IF (XZ121+401) 61,64,64
63 T2Z1=1
GO TO 66
64 T2Z1=1/(1*EXP(XZ121))
GO TO 66
65 T2Z1=0
GO TO 71
66 IF (XZ231-401) 67,64,60
67 IF (XZ231+401) 68,69,69
68 T2Z2=1
GO TO 71
69 T2Z2=1/(1*EXP(XZ231))
GO TO 71
70 T2Z2=0
GO TO 76
71 IF (XZ341-401) 72,75,75
72 IF (XZ341+401) 73,74,74
73 T2Z3=1
GO TO 76
74 T2Z3=1/(1*EXP(XZ341))
GO TO 76
75 T2Z3=0
GO TO 81
76 IF (XZ451-401) 77,80,80
77 IF (XZ451+401) 78,79,79
78 T2Z4=1
GO TO 81
79 T2Z4=1/(1*EXP(XZ451))
GO TO 81
80 T2Z4=0
GO TO 86
81 ZCAL = 1.0*(ZCAL-1.0)*T2Z1+(ZCAL+1.0)*T2Z1+ZCAL1.0*Z2CAL
ZCAL = 1.0*(ZCAL-1.0)*T2Z1
...
APPENDIX A

20C8R+1777.6718D
A21=-1814.511756.996078PLUG+3735.460096SRLOG-1.75920748A-107.4574
1PLUG&SRLOG-2023.2018R+0129767598C+137813424SRLOG+72.694769DL
20G9R+41341949D
A23=26512944-A1+4005696SRLOG-3098.4664855C4.40726686858A63656
1PLUG&SRLOG+9077778488
IF (XA221-40.) 80,RA,88
88 TA22=0.0
GO TO 92
89 IF (XA221+40.) 90,90,91
90 TA22=1.0
GO TO 92
91 TA22=1.1/(1+EXP(XA221))
92 A2=A21+A22-A21+TA22
A3=-2117.8037195340648SRLOG+348.2173855-4.62867684-221.1279
1PLUG&SRLOG-2970.86408C+646413588C+2.70701778SRLOG+65.0428036D
2LOG&=553.120074D
A4=16975.939-476.10242&PLUG-17441.98855786SRLOG+3.6534078124.41128
1PLUG&SRLOG+4486.911898
IF (Xa121-40.) 94,93,93
93 TA12=0.0
GO TO 97
94 IF (Xa121+40.) 95,95,96
95 TA12=1.0
GO TO 97
96 TA12=1.1/(1+EXP(XA121))
97 IF (XA231-40.) 99,98,98
98 TA23=0.0
GO TO 102
99 IF (XA231+40.) 100,100,101
100 TA23=1.0
GO TO 102
101 TA23=1.1/(1+EXP(XA231))
102 IF (XA341-40.) 104,103,103
103 TA34=0.0
GO TO 107
104 IF (XA341+40.) 106,105,106
105 TA34=1.0
GO TO 107
106 TA34=1.1/(1+EXP(XA341))
107 A040=A1+A2-A1)*TA12+(A3-A2)*TA23+(A4-A3)*TA34
AM=1.31154A040
C
C COMPUTING GAME
C
C 108 GAME=W0*AM**2/(RUNIV*7*T)
108 IF (K0EQ=2) GO TO 109
109 IF (K0EQ=3ORK0EQ=4) GO TO 110
109 IF (K0EQ=5) GO TO 110
H=HA
GO TO 110
H=HA
110 RETURN
C
C END
SUBROUTINE INTRP (N,X,Y,XINT,YINT)
DIMENSION X(N), Y(N)
YINT=0
DO 1 J=1,N
SUMN=1
SUMD=1
DO 2 J=1,N
IF (J=1) 1,2
1 SUMN=SUMN*(XINT-X(J))
SUMD=SUMD*(X(J)-X(J))
2 CONTINUE

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APPENDIX A

3

YINT = YINT + Y

I) * S(mN', Mr =~ PrTi IRN

END

SURPnUTINr

SC

CPIU.IH.10tSPHIAI

COMMON /BLK4/

FNON.LUqNDrIPVLrI.rLn.

P

COMMON /BLK9/ SRP,TTI I .47! .nI.KiP. P

GO TO (2.:1). ISAV

1

CALL SEARCH CP,~?HqRTIA.IGCC)P

GO TO 4

1

CALL SAVE (PI.RNFW,41HI.SR;.TII.AI,71.G.,")

1

IF (ABSCI.-NW/2).LF.0.

P2! = RNFW

GO TO 1

GO TO 1

1

CALL SPARCH P

GO TO 

CALL SAVF


1

END

SURPOUTINF

SOLUT C1.3,~p,.*

DIMENSION U7(?O).

01(P201.

lip(10.. p21)

C

USP

ND POINTS

FOR FIRST INTERSECTRnN

C

P'

I=P3l(1

I

I

P32=0, CM) I

P21=P2CI I

PP?=02

U?P=t2 (N)

U31 =()3

! I I

U32=tl 1(M)

In)

A=PlNA0PP';.0P1I,,.,l CI

PRFIENA9(P3.p3.t)7.t~jjl

C C

= FUN

C

D(P21

uq

AA=PlNA0PP';.0P1I,,.,l CI

OOD=F(NCD(P3I

U13I

RR)

2

tJR=(CC-DD))/CPA-AA

PP=CC+OR*AA

CALL FTLUP (PR,UCI

CALL

FTLUP

P4.

IF (ABS(S1.-DNFW/21)!LF.0)

IF (U3(0,F,2) GO TO 3

CALL SEARCH (PR1.PFWRI.E.o

IF (U3(0,F,2) GO TO 3

CALL SEARCH (P1.PFWRI.E.o

IF (U3(0,F,2) GO TO 3

CALL SEARCH (P1.PFWRI.E.o

IF (U3(0,F,2) GO TO 3

CALL SEARCH (P1.PFWRI.E.o

GO TO A

GO TO A

GO TO A

GO TO A

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GO TO A

GO TO A
Sample data printouts for representative tests in the Langley 6-inch expansion tube with unheated and arc-heated helium driver gases are presented on the following pages. In most instances, the headings for various flow regions correspond to those in the section entitled "Symbols." Exceptions are UI, which denotes either the test-air—driver-gas interface velocity or acceleration-air—test-air interface velocity, RATIO, which denotes the ratio of density immediately behind an incident or standing shock to freestream density, and labels ending in T (under heading "Shock Tube Flow Parameters Using Mirels Theory") which denote turbulent flow quantities. The sample printouts are as follows:

Unheated Helium Driver Gas

06/19/74
L.E.T. PROGRAM FOR EQUILIBRIUM REAL AIR
EXPANSION TUBE PROGRAM OF MILLER FOR REAL AIR
ALL PHYSICAL QUANTITIES IN MKS UNITS - NASA SP-7012
SHOCK TUBE PHASE OF PROGRAM
MEASURED INPUTS FOR SHOCK TUBE PHASE

<table>
<thead>
<tr>
<th>RUN</th>
<th>T1</th>
<th>US1</th>
<th>P2</th>
<th>T4</th>
<th>XIS</th>
<th>DIA</th>
<th>ISAV</th>
<th>INU</th>
<th>LD</th>
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</thead>
<tbody>
<tr>
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<td>0.</td>
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CONDITIONS BEHIND INCIDENT SHOCK - REGION 2

P  RHO  T  M  S/R  Z  GAME  A  U  K  NAC
2.895E+05  3.08E-01  3.175E+03  4.336E+06  3.302E+01  1.029E+00  1.151E+00  1.039E+03  2.499E+03  2.400E+00  8.495E+06
RATIO- 2 TO 1 CONDITIONS AND SHOCK VELOCITY
APPENDIX A

SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY

LMAX  L  L/LMAX  TIM  Ultr  LMAXT  LT  LT/LMAXT  TIMT  UlT  TIMI
7.324E+01  5.675E-01  7.748E-03  2.245E-04  2.572E+03  1.030E+00  4.235E-01  2.992E+00  8.252E+00  2.865E+03

EXPANSION TUBE PHASE OF PROGRAM

INPUTS FOR EXPANSION TUBE PHASE

US  PS  XAS  DELUS  ISAV  IEXP  IPREP  NVEL  IAC  JAC
5.500E+03  0.  1.698E+01  3.300E+02  2  1  1  8  50  50

5 CONDITIONS FOR FROZEN EXPANSION

P  RHO  T  H  S/R  I  GAME  A  U  M  NRE
1.481E+03  7.307E-03  1.698E-03  6.850E+00  6.979F+05  3.302F+01  1.029E+00  1.409E+00  5.345E+02  2.681E+03

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S

FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
2.027E+05  8.157E-02  6.398E+03  1.625E+00  1.029E+00  1.409E+00  5.345E+00  4.243E+01  2.921E+00  5.500E+03

STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION TS

FROZEN EXPANSION - FROZEN POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
1.832E+05  4.111E-02  1.509E+04  1.535E+00  1.029E+00  1.409E+00  2.506E+00  9.775E+02  3.900E+00  5.500E+03

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S

FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
1.832E+05  4.111E-02  1.509E+04  1.535E+00  1.029E+00  1.409E+00  2.506E+00  9.775E+02  3.900E+00  5.500E+03

STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION TS

FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
2.036E+05  4.431E-02  1.555E+04  1.582E+00  1.029E+00  1.409E+00  2.545E+03  1.705E+00  2.540E-02  3.323E-04

AEAC REAL-AIR TAPE USED FOR UNSTEADY EXPANSION - IEXP=1

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
4.847E+03  1.059E-02  1.693E+00  1.029E+00  1.409E+00  2.506E+00  9.775E+02  3.900E+00  5.500E+03

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S

EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
2.964E+05  1.186E-01  6.484E+03  1.660E+00  4.180E+01  1.029E+00  1.409E+00  2.540E+03  2.540E-02  3.323E-04

STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION TS

EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

P  RHO  T  H  S/R  I  GAME  A  QT  RN  TIMI
3.110E+05  1.237E-01  6.514E+03  1.672E+00  1.345E+00  1.029E+00  1.409E+00  2.229E+00  2.540E-02  4.807E-04

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
APPENDIX A

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

<table>
<thead>
<tr>
<th>P</th>
<th>RHO</th>
<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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<td>1.306E+00</td>
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STATIC CONDITIONS BEHIND BOW SHOCK - REGION SS
EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

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<th>S/R</th>
<th>Z</th>
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<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION TS
EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

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<th>S/R</th>
<th>Z</th>
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<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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ACCELERATION AIR CONDITIONS (REGION 201 AND P1O)

ACCCELERATION AIR FLOW PARAMETERS USING MIERELS THEORY

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<th>L</th>
<th>L/LMAX</th>
<th>TIM</th>
<th>UI</th>
<th>Ui/US</th>
<th>US20/UI</th>
<th>TIMI</th>
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<td>3.395E-01</td>
<td>1.193E-03</td>
<td>5.738E+03</td>
<td>1.043E+00</td>
<td>1.030E+00</td>
<td>2.127E+05</td>
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<tr>
<td>1.698E+01</td>
<td>1.698E+03</td>
<td>2.038E-01</td>
<td>6.847E-02</td>
<td>3.395E-01</td>
<td>1.193E-03</td>
<td>5.738E+03</td>
<td>1.043E+00</td>
<td>1.030E+00</td>
<td>2.127E+05</td>
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<tr>
<td>1.698E+01</td>
<td>1.698E+03</td>
<td>2.038E-01</td>
<td>6.847E-02</td>
<td>3.395E-01</td>
<td>1.193E-03</td>
<td>5.738E+03</td>
<td>1.043E+00</td>
<td>1.030E+00</td>
<td>2.127E+05</td>
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CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPH

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<tr>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.751E+06</td>
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EXPANSION TUBE PHASE OF PROGRAM

<table>
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<th>US</th>
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<th>LSAV</th>
<th>TEXP</th>
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<th>NYEL</th>
<th>FAC</th>
<th>JAC</th>
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<tr>
<td>5.500E+03</td>
<td>O.</td>
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5 CONDITIONS FOR FROZEN EXPANSION

<table>
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<tr>
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<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.400E+02</td>
<td>1.762E-03</td>
<td>2.529E+02</td>
<td>2.643E+03</td>
<td>3.380E+01</td>
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<td>3.370E+02</td>
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<td>1.632E+01</td>
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STATIC CONDITIONS BEHIND BOW SHOCK - REGION SS
FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

<table>
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<th>P</th>
<th>RHO</th>
<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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<tbody>
<tr>
<td>4.860E+04</td>
<td>1.972E-02</td>
<td>6.122E+03</td>
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STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION TS
FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

<table>
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<th>RHO</th>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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<tbody>
<tr>
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</table>
APPENDIX A

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
EQUILIBRIUM EXPANSION -- FROZEN POST SHOCK

<table>
<thead>
<tr>
<th>P</th>
<th>RHO</th>
<th>T</th>
<th>S/R</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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<tbody>
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STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION 55
EQUILIBRIUM EXPANSION -- FROZEN POST SHOCK

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<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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<tr>
<td>4.836E+04</td>
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ACCELERATION

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</thead>
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ACCELERATION AIR CONDITIONS (REGION 20) AND P10

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<th>P20</th>
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<th>H2O</th>
<th>Z20</th>
<th>P10</th>
<th>U510</th>
<th>M510</th>
<th>RATIO</th>
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<tbody>
<tr>
<td>5.052E+03</td>
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ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

<table>
<thead>
<tr>
<th>KAS</th>
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<th>LMAX</th>
<th>L</th>
<th>L/LMAX</th>
<th>TIM</th>
<th>UI</th>
<th>UI/US</th>
<th>US20/UI</th>
<th>TIMI</th>
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<td>1.072E+00</td>
<td>1.003E+00</td>
<td>2.149E-04</td>
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APPENDIX A

CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPH

EXPANSION TUBE PHASE OF PROGRAM

INPUTS FOR EXPANSION TUBE PHASE

US PS XAS DELUS IAW IEKP IREP NVEL IAC JAC
5.500E+03 1.698E01 3.300E+02 2 1 1 8 50 50

5 CONDITIONS FOR FROZEN EXPANSION

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
FROZEN EXPANSION-- FROZEN POST SHOCK

AEDC REAL-AIR TAPE USED FOR UNSTEADY EXPANSION- IIXP=1

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN
### APPENDIX A

**5 CONDITIONS FOR EQUILIBRIUM EXPANSION**

<table>
<thead>
<tr>
<th>P</th>
<th>RHO</th>
<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.729E+03</td>
<td>1.188E-02</td>
<td>2.256E+03</td>
<td>2.676E+06</td>
<td>3.451E+01</td>
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<td>8.925E+02</td>
<td>4.840E+03</td>
<td>5.423E+00</td>
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**STATIC CONDITIONS BEHIND DOW SHOCK - REGION 5**

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<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATI</th>
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</thead>
<tbody>
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<td>2.571E+05</td>
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<td>6.085E+03</td>
<td>1.426E+07</td>
<td>4.067E+01</td>
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<td>1.156E+00</td>
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<td>5.029E+02</td>
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**STAGNATION CONDITIONS BEHIND DOW SHOCK - REGION 5**

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<th>Z</th>
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<th>A</th>
<th>U</th>
<th>M</th>
<th>RATI</th>
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**ACCELERATION AIR FLOW PARAMETERS**

**ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY**

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<th>XAS</th>
<th>XA</th>
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<th>UI/US</th>
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<td>2.310E-05</td>
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Arc-Heated Helium Driver Gas

06/19/74

L.E.T. PROGRAM FOR EQUILIBRIUM REAL AIR

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

SHOCK TUBE PHASE OF PROGRAM

MEASURED INPUTS FOR SHOCK TUBE PHASE

<table>
<thead>
<tr>
<th>RUN</th>
<th>P1</th>
<th>T1</th>
<th>US1</th>
<th>P2</th>
<th>P4</th>
<th>T4</th>
<th>XIS</th>
<th>DIA</th>
<th>ISAV</th>
<th>IMU</th>
<th>LD</th>
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<tr>
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XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

CONDITIONS BEHIND INCIDENT SHOCK - REGION 2

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

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<th>U</th>
<th>M</th>
<th>NRE</th>
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<tbody>
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RATIO TO 1 CONDITIONS AND SHOCK VELOCITY

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<th>Z</th>
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SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY

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<th>TIM</th>
<th>UI</th>
<th>LM/MAX</th>
<th>LT</th>
<th>LT/LMAX</th>
<th>TIMT</th>
<th>UI</th>
<th>TIMT</th>
</tr>
</thead>
</table>
APPENDIX A

EXPANSION TUBE PHASE OF PROGRAM

INPUTS FOR EXPANSION TUBE PHASE

US  PS  XAS  DELUS  ISAV  IEXP  IREP  NVEL  IAC  JAC
7.500E+03 0.  1.698E+01 5.000E+02 2 1 1 8 50 50

5 CONDITIONS FOR FROZEN EXPANSION

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55
FROZEN EXPANSION - EQUILIBRIUM POST SHOCK

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
FROZEN EXPANSION - FROZEN POST SHOCK

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55
FROZEN EXPANSION - FROZEN POST SHOCK

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55
EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55
EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

REAL-AIR TAPE USED FOR UNSTEADY EXPANSION - IEXP=1

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## APPENDIX A

### STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55

**EQUILIBRIUM EXPANSION---EQUILIBRIUM POST SHOCK**

<table>
<thead>
<tr>
<th>P</th>
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<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.699E+06</td>
<td>4.768E-01</td>
<td>8.107E+03</td>
<td>2.590E+07</td>
<td>4.315E+04</td>
<td>1.535E+00</td>
<td>1.179E+00</td>
<td>2.044E+03</td>
<td>5.503E+02</td>
<td>2.888E-01</td>
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### ACCELERATION AIR CONDITIONS (REGION 20) AND P10

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<th>US10</th>
<th>M10</th>
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<td>3.668E+00</td>
<td>6.000E+01</td>
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### ACCELERATION AIR FLOW PARAMETERS USING MIMREL'S THEORY

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<th>TIM</th>
<th>UI</th>
<th>UI/US</th>
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<th>TIMI</th>
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</thead>
<tbody>
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<td>1.699E+00</td>
<td>9.755E-01</td>
<td>8.203E-02</td>
<td>8.408E-02</td>
<td>1.073E-03</td>
<td>7.644E-03</td>
<td>1.014E+00</td>
<td>1.045E+00</td>
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### CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPH

<table>
<thead>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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### EXPANSION TUBE PHASE OF PROGRAM

<table>
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<th>L</th>
<th>L/LMAX</th>
<th>TIM</th>
<th>UI</th>
<th>UI/US</th>
<th>US20/US</th>
<th>TIMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.699E+01</td>
<td>1.699E+00</td>
<td>9.755E-01</td>
<td>8.203E-02</td>
<td>8.408E-02</td>
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### INPUTS FOR EXPANSION TUBE PHASE

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<th>IEXP</th>
<th>TREP</th>
<th>NVEL</th>
<th>TAC</th>
<th>JAC</th>
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<td>1</td>
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### 5 CONDITIONS FOR FROZEN EXPANSION

<table>
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<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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<tbody>
<tr>
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<td>3.368E+02</td>
<td>3.784E+05</td>
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<td>1.276E+00</td>
<td>1.484E+00</td>
<td>4.278E+02</td>
<td>7.500E+03</td>
<td>1.753E+01</td>
<td>2.168E+06</td>
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### STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55

**FROZEN EXPANSION---EQUILIBRIUM POST SHOCK**

<table>
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<tr>
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<th>RHOD</th>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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</thead>
<tbody>
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<td>1.175E+00</td>
<td>2.261E+03</td>
<td>6.310E+02</td>
<td>2.791E-01</td>
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### STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55

**FROZEN EXPANSION---EQUILIBRIUM POST SHOCK**

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<tr>
<th>P</th>
<th>RHOD</th>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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<tbody>
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<td>8.373E+03</td>
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<td>4.933E+07</td>
<td>2.540E-02</td>
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### STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55

**FROZEN EXPANSION--- FROZEN POST SHOCK**

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<th>H</th>
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<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>RATIO</th>
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<tbody>
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<td>2.741E+07</td>
<td>4.432E+01</td>
<td>1.276E+00</td>
<td>1.484E+00</td>
<td>3.641E+03</td>
<td>1.400E+03</td>
<td>4.066E-01</td>
<td>5.066E+00</td>
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### STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION 55

**FROZEN EXPANSION--- FROZEN POST SHOCK**
APPENDIX A

4EDC REAL-AIR TAPE USED FOR UNSTEADY EXPANSION - IEXP=1

NO SOLUTION ON TAPE FOR THE CONDITIONS

\[
S/R = 37,000, 000,000 \\
\text{Evaluate } \mathcal{T}(t) = 2.5420, 0, 03E+00
\]

PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

P RHO T H Z GAME A Q R TIMI
2.972E+05 3.198E-02 2.537E+04 1.726E+00 1.464E+00 3.713E+03 3.743E+07 2.540E-02 1.570E-04

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 55

EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

P RHO T H S/R Z GAME A U M NRE
2.540E+04 4.166E-02 3.599E+03 6.461E+06 3.709E+01 1.115E+00 1.155E+00 6.492E+00 3.162E+06

STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION 55

EQUILIBRIUM EXPANSION - EQUILIBRIUM POST SHOCK

P RHO T H S/R Z GAME A U M \text{ RATIO}
2.282E+06 4.386E-01 9.044E+03 3.438E+07 1.730E+00 1.189E+00 2.309E+03 6.390E+02 2.768E-01

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

P RHO T H S/R Z GAME A U M \text{ RATIO}
1.634E+06 4.396E-01 8.222E+03 2.740E+07 4.445E+01 1.575E+00 1.710E+00 1.060E+01

ACCELERATION AIR CONDITIONS (REGION 20) AND PO1

P RHO T H S/R Z GAME A U M \text{ RATIO}
1.698E+01 6.792E+00 1.104E+00 5.152E-02 4.666E+00 6.576E+03 7.835E+03 1.098E+04 1.372E-04

ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

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### APPENDIX A

**CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPHRAGM**

<table>
<thead>
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<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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**EXPANSION TUBE PHASE OF PROGRAM**

**INPUTS FOR EXPANSION TUBE PHASE**

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<th>XAS</th>
<th>DELUS</th>
<th>ISAV</th>
<th>IEXP</th>
<th>IREP</th>
<th>NYEL</th>
<th>IAC</th>
<th>JAC</th>
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**5 CONDITIONS FOR FROZEN EXPANSION**

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<th>H</th>
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<th>U</th>
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<tr>
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**STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S**

**FROZEN EXPANSION--EQUILIBRIUM POST SHOCK**

<table>
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<tr>
<th>P</th>
<th>RHO</th>
<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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<td>1.258E+05</td>
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**STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5**

**FROZEN EXPANSION--EQUILIBRIUM POST SHOCK**

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<thead>
<tr>
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<th>RHO</th>
<th>T</th>
<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>OT</th>
<th>RN</th>
<th>TIMI</th>
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**STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S**

**FROZEN EXPANSION-- FROZEN POST SHOCK**

<table>
<thead>
<tr>
<th>P</th>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
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<th>A</th>
<th>U</th>
<th>M</th>
<th>NRE</th>
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**STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5**

**FROZEN EXPANSION-- FROZEN POST SHOCK**

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<th>H</th>
<th>S/R</th>
<th>Z</th>
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<th>A</th>
<th>OT</th>
<th>RN</th>
<th>TIMI</th>
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**6EDC REAL-AIR TAPE USED FOR UNSTEADY EXPANSION-IEXP=1**

**NO SOLUTION ON TAPE FOR THE CONDITIONS**

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<th>S/R</th>
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**PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION**

**5 CONDITIONS FOR EQUILIBRIUM EXPANSION**

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<th>S/R</th>
<th>Z</th>
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<th>M</th>
<th>NRE</th>
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**STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S**

**EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK**

<table>
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<th>P</th>
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**STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5**

**EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK**
APPENDIX A

<table>
<thead>
<tr>
<th>P</th>
<th>RHO</th>
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<th>H</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>QT</th>
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<th>TIMI</th>
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<tbody>
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Following equilibrium conditions include flow attn

Static conditions for equilibrium expansion

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<tr>
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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>H</th>
<th>NIE</th>
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<tbody>
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Static conditions behind bow shock - region 55

Equilibrium expansion—equilibrium post shock

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<th>H</th>
<th>S/R</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>U</th>
<th>H</th>
<th>RATIO</th>
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<tbody>
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<td>6.329E+03</td>
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Stagnation conditions behind bow shock—region 55

Equilibrium expansion—equilibrium post shock

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<th>H</th>
<th>Z</th>
<th>GAME</th>
<th>A</th>
<th>QT</th>
<th>RN</th>
<th>TIMI</th>
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</thead>
<tbody>
<tr>
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<td>2.883E+07</td>
<td>4.491E+01</td>
<td>1.603E+00</td>
<td>1.174E+00</td>
<td>2.124E+03</td>
<td>6.329E+03</td>
<td>2.980E-01</td>
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Acceleration air conditions (region 20) and Pl0

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<th>H20</th>
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<th>QT20</th>
<th>RN20</th>
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<td>2.883E+07</td>
<td>4.491E+01</td>
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<td>1.174E+00</td>
<td>2.124E+03</td>
<td>6.329E+03</td>
<td>2.980E-01</td>
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</table>

Acceleration air flow parameters using Mirels theory

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<th>XA</th>
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<th>L</th>
<th>L/LMAX</th>
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<th>UI</th>
<th>UI/US</th>
<th>US20/US</th>
<th>TIMI</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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APPENDIX B

PROGRAM LIMITATIONS AND UNCERTAINTIES

Limitations on the present program are those restrictions on the source of equilibrium, real-air, thermodynamic properties. The temperature range of both the AEDC real-air tape (ref. 9) and AEDC real-air curve-fit expressions (ref. 11) is 100 K to 15 000 K; however, the pressure range of the tape is greater than that of the curve-fit expressions for given values of entropy. Imperfect air (intermolecular force) effects are neglected in the curve-fit expressions; thus, discretion should be exercised in using these expressions at pressures greater than 10 MN/m$^2$ or so. If the lower temperature limit of the AEDC real-air tape is exceeded during the unsteady or steady flow expansion computation, perfect air relations are used to determine thermodynamic properties at these low temperatures. For this case, a statement is printed in the printout acknowledging that perfect air relations were used; thereby, the user is cautioned that the temperature-pressure range may be such that air condensation effects (see, for example, ref. 22) are significant and should be considered.

Primary sources of uncertainties are iteration convergence criteria, source of real-air thermodynamic properties, and computational procedure. To reduce uncertainties arising from usage of various iteration convergence tolerances, tolerances were constant for all iterations in the present study, being 0.1 percent. Real-air thermodynamic properties as obtained from the AEDC tape are believed to be representative of the state of the art in calculation of air properties. However, some differences exist between the AEDC tape and the AEDC curve-fit expressions. For a pressure range of 10 to 1000 kN/m$^2$ and a temperature range of 2000 K to 15 000 K, the maximum percentage errors in thermodynamic properties obtained from the curve-fit expressions, as compared with those from the AEDC tape, are (ref. 11):

<table>
<thead>
<tr>
<th>Property</th>
<th>Error, percent</th>
</tr>
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<tbody>
<tr>
<td>$a$</td>
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<td>$h$</td>
<td>1.96</td>
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<tr>
<td>$T$</td>
<td>2.24</td>
</tr>
<tr>
<td>$Z^*$</td>
<td>0.75</td>
</tr>
<tr>
<td>$\gamma_E$</td>
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</tr>
<tr>
<td>$\rho$</td>
<td>2.52</td>
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</table>

Because of the wide range of possible shock tube and expansion tube flow conditions and the large number of methods (combinations of inputs) contained within the present program for computing these flow conditions, a comprehensive study of program uncertainties is not feasible. Instead, computations for specific cases, representative of tests performed in the Langley expansion tube, are considered. Values of flow quantities in
APPENDIX B

regions \( \pm \) and \( \pm \), obtained for various values of input \( U_{s,1} \) (LB = 0; see appendix A) and using the AEDC real-air tape, were compared with those values calculated by using the program of reference 5. This comparison showed excellent agreement, as expected. For the case where \( p_2 \) is an input, the values of \( p_2 \) were obtained from the case where \( U_{s,1} \) is an input. This cross-check showed exact agreement between the results.

Flow quantities in region \( \pm \) where \( p_4 \) and \( T_4 \) are inputs were also compared with results from reference 5. For these comparisons, \( p_4 \) was equal to 34.5 MN/m\(^2\), \( T_4 \) was equal to 300 K and to 600 K, and \( p_1 \) was varied from 0.07 to 689.5 kN/m\(^2\). Both helium and hydrogen driver gases are considered. For the present program, the AEDC real-air curve-fit expressions (\( ISAV = 2; \) see appendix A) are used and 20 values of \( U_{s,1} \) are used in generating the \( (p_2, U_2) \) curves. A 10-species \( (e^-, \text{Ar}, \text{N}, \text{N}^+, \text{N}_2, \text{O}, \text{O}^+, \text{O}_2, \text{NO}, \text{and NO}^+) \) air model is employed in reference 5, the air composition by volume being 78.08 percent \( \text{N}_2 \), 20.95 percent \( \text{O}_2 \), and 0.97 percent \( \text{Ar} \). This composition yields an undissociated molecular weight \( \text{W}_u \) of 28.97 in agreement with references 9 and 11. As expected, thermodynamic properties in region \( \pm \) were in perfect agreement between the two programs for both driver gases. The maximum uncertainties observed between flow quantities in region \( \pm \) and \( U_{s,1} \), as determined from the present program and reference 5, are

\[
\begin{align*}
p_2, \text{ percent} & \quad \ldots \quad 0.3 \\
p_2, \text{ percent} & \quad \ldots \quad 2.3 \\
T_2, \text{ percent} & \quad \ldots \quad 2.6 \\
h_2, \text{ percent} & \quad \ldots \quad 0.5 \\
s_2 \text{W}_u/R, \text{ percent} & \quad \ldots \quad 0.2 \\
a_2, \text{ percent} & \quad \ldots \quad 1.6 \\
U_2, \text{ percent} & \quad \ldots \quad 0.2 \\
U_{s,1}, \text{ percent} & \quad \ldots \quad 0.5
\end{align*}
\]

The ratios of flow conditions in region \( \pm \) to conditions in region \( \pm \) presented in figure 18 are shown in figure 22 as a function of \( U_{s,1} \). The results of figure 18 were calculated by use of the AEDC tape, whereas the results of figure 22 were calculated by use of the AEDC curve-fit expressions. Comparison of figures 18 and 22 shows \( p_2/p_1 \), \( h_2/h_1 \) (which are relatively insensitive to variation in \( p_1 \)), and \( s_2 \text{W}_u/R \) are in good agreement for the two sources of real-air thermodynamic properties. However, agreement for \( p_2/p_1 \) and \( T_2/T_1 \) is poorer, differences up to approximately 10 percent occurring for the range of \( U_{s,1} \) examined. This comparison implies that some shock tube parameters in regions \( \pm \) and \( \pm \) calculated by using the curve-fit expressions
APPENDIX B

may also contain relatively large uncertainties. Thus, the user of the present program should exercise discretion in using these expressions to calculate shock tube flow quantities.

Expansion tube flow quantities in regions (5), (5s), and (5f) are compared for the three methods of the present program and with the results of reference 5. The three methods of the present program, in terms of inputs ISAV and IEXP (see appendix A), are

<table>
<thead>
<tr>
<th>Method</th>
<th>ISAV</th>
<th>IEXP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(2)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(3)</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

where ISAV = 1 denotes that the AEDC real-air tape is used to determine flow quantities in the expansion tube cycle and ISAV = 2 denotes that the AEDC real-air curve-fit expressions are used. For IEXP = 1, the required table of \( h \) as a function of \( a^{-1} \) for the unsteady expansion calculation is generated from the AEDC tape. This table is generated by using subroutine SLOW with inputs \( s_A W_u / R \) and \( h \), where \( h \) is varied from a maximum value of \( h_A \) to a minimum value chosen to be 0.1 MJ/kg. This range of \( h \) is divided into increments (number of increments is input JAC with maximum of 300) and the numerical integration performed beginning with the upper limit \( h_A \). The integration by Simpson's Rule is terminated when a value of \( h \) is obtained that equates to \( \Delta U \) of equation (21). For IEXP = 2, this table is generated by using the curve-fit expressions. The pressure is varied from a maximum value of \( p_A \) to a minimum value of either \( p_{5f} \) or 0.1 N/m\(^2\), whichever is largest. These values of \( p \) are inputs to subroutine SAVE, in conjunction with \( s_A W_u / R \), and the corresponding values of \( h \) and \( a^{-1} \) are tabulated. The number of pressure increments used in generating this table is an input (maximum of 100). Method (1) (ISAV = IEXP = 1) is expected to be the most accurate method but requires more computer time primarily because of the time required for tape manipulation. Method (3) (ISAV = IEXP = 2) should contain the greatest uncertainty but has the smallest computer time. Method (2) represents a compromise between methods (1) and (3) and uses the AEDC tape only for the unsteady expansion calculations.

Flow quantities in regions (5), (5s), and (5f) were calculated with these three methods for the following basic inputs:

\[
\begin{align*}
p_1 &= 1.724 \text{ kN/m}^2 \\
T_1 &= 300 \text{ K}
\end{align*}
\]
APPENDIX B

$$U_{s,1} = 2.865 \text{ km/sec}$$

$$U_5 = 4, 5, 6, \text{ and } 7 \text{ km/sec}$$

No shock reflection at the secondary diaphragm is considered. All quantities are based on the assumption of thermochemical-equilibrium flow throughout the expansion tube flow cycle. The results of methods (2) and (3) are compared with the results of method (1) in the following table. Also illustrated in this table is a comparison of method (1) with results from the program of reference 5 for a 10-species air model and with the same inputs as method (1). For methods (1) and (2), input JAC is equal to 300, and for method (3), input IAC is equal to 50. Fifty pressure increments are also used in the program of reference 5. Agreement between method (1) and the results from the program of reference 5 for all flow quantities of table I is good (generally within 0.5 percent). The results of

<table>
<thead>
<tr>
<th>Flow quantity</th>
<th>Percent difference between methods (1) and (2) for $U_5$, km/sec, of -</th>
<th>Percent difference between methods (1) and (3) for $U_5$, km/sec, of -</th>
<th>Percent difference between method (1) and reference 5 for $U_5$, km/sec, of -</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_5$</td>
<td>5.47, 5.48, 5.50, 5.54</td>
<td>1.67, 7.85, 7.47, 8.70</td>
<td>0.09, 0.15, 0.14, 0.50</td>
</tr>
<tr>
<td>$\rho_5$</td>
<td>5.43, 5.43, 5.48, 5.49</td>
<td>3.98, 7.28, 6.45, 7.24</td>
<td>0.18, 0.28, 0.22, 0.51</td>
</tr>
<tr>
<td>$T_5$</td>
<td>.04, .00, .08, .03</td>
<td>2.77, .45, 1.01, 1.51</td>
<td>0.04, 0.06, 0.00, 0.05</td>
</tr>
<tr>
<td>$h_5$</td>
<td>.03, .05, .00, .02</td>
<td>.49, .30, .71, 1.11</td>
<td>0.00, 0.08, 0.06, 0.06</td>
</tr>
<tr>
<td>$Z_5$</td>
<td>.00, .00, .00, .00</td>
<td>.30, .00, .00, .00</td>
<td>0.00, 0.00, 0.00, 0.00</td>
</tr>
<tr>
<td>$\gamma E_5$</td>
<td>.00, .00, .00, .00</td>
<td>3.67, 6.88, .68, .65</td>
<td>0.00, 0.00, 0.07, 0.00</td>
</tr>
<tr>
<td>$a_5$</td>
<td>.05, .01, .01, .00</td>
<td>.60, 3.26, .19, .45</td>
<td>0.01, 0.01, 0.04, 0.02</td>
</tr>
<tr>
<td>$M_6$</td>
<td>.05, .02, .01, .00</td>
<td>.59, 3.26, .19, .43</td>
<td>0.02, 0.02, 0.04, 0.00</td>
</tr>
<tr>
<td>$N_{Re,5}$</td>
<td>5.44, 5.46, 5.47, 5.44</td>
<td>5.87, 7.02, 5.88, 6.26</td>
<td>.75, .38, .72, .00</td>
</tr>
<tr>
<td>$p_{5s}$</td>
<td>5.32, 5.40, 5.46, 5.47</td>
<td>3.79, 7.22, 4.28, 7.19</td>
<td>.14, .20, .21, .51</td>
</tr>
<tr>
<td>$\rho_{5s}$</td>
<td>4.63, 4.61, 5.25, 5.18</td>
<td>1.96, 6.46, .62, .83</td>
<td>.11, .18, .25, .57</td>
</tr>
<tr>
<td>$T_{5s}$</td>
<td>.87, .88, .53, .93</td>
<td>.74, .93, .59, 1.03</td>
<td>.13, .07, .05, .05</td>
</tr>
<tr>
<td>$h_{5s}$</td>
<td>.00, .00, .00, .00</td>
<td>.19, .07, .05, .04</td>
<td>0.00, 0.00, 0.00, 0.00</td>
</tr>
<tr>
<td>$s_{5sw_d/R}$</td>
<td>.05, .12, .29, .48</td>
<td>.79, .17, .31, .46</td>
<td>0.00, 0.05, 0.04, 0.02</td>
</tr>
<tr>
<td>$Z_{5s}$</td>
<td>.25, .15, .42, .75</td>
<td>.25, .15, .42, .75</td>
<td>0.00, 0.00, 0.00, 0.00</td>
</tr>
<tr>
<td>$\gamma E_{5s}$</td>
<td>.91, .17, .26, .00</td>
<td>.99, .17, .26, .00</td>
<td>0.08, 0.09, 0.09, 0.09</td>
</tr>
<tr>
<td>$a_{5s}$</td>
<td>.86, .31, .23, .16</td>
<td>.80, .37, .29, .22</td>
<td>0.00, 0.00, 0.00, 0.05</td>
</tr>
<tr>
<td>$p_{t,5}$</td>
<td>5.37, 5.42, 5.65, 5.49</td>
<td>3.85, 7.31, 6.54, 7.24</td>
<td>.15, .23, .21, .50</td>
</tr>
<tr>
<td>$\rho_{t,5}$</td>
<td>4.55, 4.58, 5.27, 5.18</td>
<td>3.13, 6.43, 6.20, 6.85</td>
<td>.14, .26, .27, .56</td>
</tr>
<tr>
<td>$T_{t,5}$</td>
<td>.99, .86, .54, .93</td>
<td>.84, .92, .60, 1.02</td>
<td>.13, .06, .03, .05</td>
</tr>
<tr>
<td>$h_{t,5}$</td>
<td>.00, .00, .00, .00</td>
<td>.09, .07, .05, .04</td>
<td>0.00, 0.00, 0.00, 0.00</td>
</tr>
</tbody>
</table>
method (3) are within 8 percent or so of those of method (1) for the range of $U_5$ examined. (It should be noted that for a value of $U_5$ of 7 km/sec, the corresponding value of $p_5$ exceeded the range curve fitted in ref. 11.) Differences between method (1) and method (2) or (3) in table I are believed to be representative of the present program as applied to a wide range of practical expansion tube flow conditions.

Uncertainty in flow quantities is expected to be a function of the number of increments used for the numerical integration required for the unsteady expansion. Hence, inputs JAC and IAC for methods (2) and (3), respectively, were varied to examine uncertainties resulting from these inputs. Percentage differences for flow quantities in region 5 are shown for method (3) with various IAC in the following table. These differences were obtained by comparing results for given values of IAC to results obtained with the maximum value of 100. The inputs $p_1$, $T_1$, and $U_{s1}$ are those considered in the previous comparison and the input $U_5$ is 7 km/sec; thereby, the maximum difference between $h_A$ and $h_5$ or $p_A$ and $p_5$ for this case is provided. To minimize computer time without sacrificing accuracy in calculated flow quantities, a value of IAC equal to 50 for method (3) is recommended for most cases.

<table>
<thead>
<tr>
<th>Flow quantity</th>
<th>IAC of -</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>$p_5$</td>
<td>5.74</td>
</tr>
<tr>
<td>$p_5$</td>
<td>4.23</td>
</tr>
<tr>
<td>$T_5$</td>
<td>1.58</td>
</tr>
<tr>
<td>$h_5$</td>
<td>1.65</td>
</tr>
<tr>
<td>$Z_5$</td>
<td>.00</td>
</tr>
<tr>
<td>$\gamma_{E,5}$</td>
<td>.07</td>
</tr>
<tr>
<td>$a_5$</td>
<td>.77</td>
</tr>
<tr>
<td>$M_5$</td>
<td>.07</td>
</tr>
<tr>
<td>$N_{Re,5}$</td>
<td>3.29</td>
</tr>
</tbody>
</table>

A similar comparison for method (2) was performed, where the maximum value of input JAC was 300. This comparison showed the maximum difference between flow quantities in region 5 for JAC equal to 25 and the maximum of 300 was less than 0.25 percent for $U_5$ equal to 7 km/sec. However, extending the velocity to 8 km/sec yielded differences up to 5.5 percent. Increasing input JAC from 25 to 50 diminished this difference to
APPENDIX B

less than 0.2 percent. (It should be noted that for \( U_5 \) equal to 8 km/sec, the temperature \( T_5 \) was 250 K; hence, these conditions did not exceed the limits of the AEDC real-air tape.) Therefore, for methods (1) and (2), a value of JAC equal to 50 is recommended for most cases. More severe expansions from region (A) to region (5) than for this sample case may require larger values of JAC and IAC than recommended herein.

For the case where \( p_5 \) is an input (\( \text{LF} = 2; \) see appendix A), the values of \( p_5 \) calculated for methods (1) and (3) are, in turn, used as inputs. (The values from method (1) were used for \( \text{LF} = 2 \) and ISAV = IEXP = 1, and the values from method (3) were used for \( \text{LF} = 2 \) and ISAV = IEXP = 2.) This cross-check shows excellent agreement between the results.

The present program was run at conditions for which air behaves, approximately, as an ideal gas in all phases of the expansion tube cycle. Inputs for this case are

\[
\begin{align*}
p_1 &= 6.895 \text{kN/m}^2 \\
T_1 &= 300 \text{ K} \\
U_{S,1} &= 500 \text{ m/sec} \\
U_5 &= 700, 900, \text{ and } 1100 \text{ m/sec}
\end{align*}
\]

and the AEDC tape was used for the unsteady expansion. The purpose of this case was to compare flow quantities for a frozen expansion with those for a thermochemical equilibrium expansion. Flow quantities in region (5), (6), and (15) were observed to be within 2 percent between the frozen and equilibrium cases. Comparison of frozen flow quantities between the present program and the program of reference 5 showed agreement to worsen with increasing level of dissociation in region (A). Since the composition of the air in region (A) is calculated in reference 5, the corresponding frozen flow calculations of reference 5 are believed to be more accurate than those of the present program.

Flow quantities calculated in region (6) of the expansion tunnel were verified by manual calculations and usage of reference 9. The same subroutine (SNS; see appendix A) was used to obtain conditions in regions (6@) and (16) as was used to obtain conditions in regions (5@) and (15).
APPENDIX C

LANGLEY LIBRARY SUBROUTINE ITRI

Language: FORTRAN

Purpose: To solve the single equation of the form \( x = f(x) \) for one real root by the Newton-Raphson iteration method.

Use: CALL ITRI (X, DELTX, FOFX, E1, E2, MAXI, ICODE)

- **X** An initial guess supplied by the user. On a normal return to the calling program from ITRI, X contains the root.
- **DELTX** An increment supplied by the user so that \( f(x + \text{DELTX}) - f(x) \) is a reasonable approximation to the derivative of \( f(x) \).
- **FOFX** A function subprogram to evaluate \( f(x) \).
- **E1** Relative error criterion.
- **E2** Absolute error criterion.
- **MAXI** A maximum iteration count supplied by the user.
- **ICODE** An integer supplied by ITRI as an error code. This code should be tested by the user on return to the calling program.
  - ICODE = 0: Normal return.
  - ICODE = 1: Maximum iteration exceeded.
  - ICODE = 2: Derivative = 0.

Restrictions: A function subprogram with a single argument \( x \) must be written by the user to evaluate \( f(x) \). The name given to the FOFX subprogram must appear in an EXTERNAL statement in the calling program.

Method: The Newton-Raphson iteration technique (ref. (a) of this subroutine) is used where

\[
x_{n+1} = q_n + (1 - q) f(x_n)
\]

\[
q = \frac{a}{a - 1}
\]

\[
a = \frac{f(x_n) - f(x_{n-1})}{x_n - x_{n-1}}
\]
APPENDIX C

Accuracy: The iteration process is continued until either of two convergence criteria is satisfied. These criteria are given as follows:

If

\[ |f(x_n)| \geq \epsilon_1 \]

then

\[ \left| \frac{f(x_n) - x_n}{f(x_n)} \right| \leq \epsilon_1 \] \hspace{1cm} (C1)

and if

\[ |f(x_n)| < \epsilon_1 \]

then

\[ |f(x_n) - x_n| \leq \epsilon_2 \] \hspace{1cm} (C2)


Storage: 1378 locations.

Subroutine date: August 1, 1968.
APPENDIX D

LANGLEY LIBRARY SUBROUTINE ITR2

Language: FORTRAN

Purpose: Given \( F(X) = 0 \), to find a value for \( X \) within a given epsilon of relative error in a given interval \((a,b)\).

Use: CALL ITR2 (X, A, B, DELTX, FOFX, E1, E2, MAXI, ICODE)

- \( X \): The root.
- \( A \): The lower bound on \( X \). This value is used by ITR2 as an initial guess.
- \( B \): The upper bound on \( X \). This value is used by ITR2 as a final guess if the entire interval is scanned.
- \( \text{DELTX} \): \( \Delta X \), the size of the scanning interval.
- \( \text{FOFX} \): The name of a function subprogram to evaluate \( F(X) \).
- \( \text{E1} \): Relative error criterion.
- \( \text{E2} \): Absolute error criterion.
- \( \text{MAXI} \): A maximum iteration count supplied by the user.
- \( \text{ICODE} \): An integer supplied by ITR2 as an error code. This code should be tested by the user on return to the calling program.
  - \( \text{ICODE} = 0 \): Normal return
  - \( \text{ICODE} = 1 \): Maximum iterations are exceeded
  - \( \text{ICODE} = 2 \): \( \text{DELTX} = 0 \), or negative
  - \( \text{ICODE} = 3 \): a root cannot be found within the given bounds
  - \( \text{ICODE} = 4 \): \( A > B \)

Restrictions: Make \( A < B \), \( \Delta X \) positive. A function subprogram with a single argument \( X \) must be written by the user to evaluate \( F(X) \). The name of this subprogram, \( \text{FOFX} \), must appear in an EXTERNAL statement of the calling program.
APPENDIX D

Method: The given function $F(X)$ is evaluated at a given starting point $a$ and at intervals of a specified $\Delta X$ thereafter, up to and including a specified end point $b$. A change of sign of the function across a $\Delta X$ interval indicates a possible root in that interval. The interval is then halved successively toward $F(X) = 0$ until the prescribed accuracy is satisfied. The given function $F(X)$ is evaluated once for each halving step.

If the given function is expected to have more than one root between the prescribed starting and end points, it is suggested that a sufficiently small $\Delta X$ be given such that no more than one root be present within a $\Delta X$ interval. A normal return is given upon the location of the first root from the starting point $a$. Additional roots must be located by new entries into the subroutine using a new starting point $a$ which is just beyond the previous root.

Accuracy: The iteration process is continued until either of two convergence criteria is satisfied. These criteria are

If

$$|X_i| > \epsilon_1$$

then

$$\left| \frac{X_i - X_{i-1}}{X_i} \right| \leq \epsilon_1$$

and if

$$|X_i| \leq \epsilon_1$$

then

$$|X_i - X_{i-1}| \leq \epsilon_2$$


Storage: 260 locations.
APPENDIX E

LANGLEY LIBRARY SUBROUTINE FTLUP

Language: FORTRAN

Purpose: Computes $y = F(x)$ from a table of values using first- or second-order interpolation. An option to give $y$ a constant value for any $x$ is also provided.

Use: CALL FTLUP (X, Y, M, N, VARI, VARD)

- **X** The name of the independent variable $x$.
- **Y** The name of the dependent variable $y = f(x)$.
- **M** The order of interpolation (an integer)
  - $M = 0$ for $y$ a constant as explained in the note below.
  - $M = 1$ or $2$. First or second order if VARI is strictly increasing (not equal).
  - $M = -1$ or $-2$. First or second order if VARI is strictly decreasing (not equal).
- **N** The number of points in the table (an integer).
- **VARI** The name of a one-dimensional array which contains the $N$ values of the independent variable.
- **VARD** The name of a one-dimensional array which contains the $N$ values of the dependent variable.

Note that VARD(I) corresponds to VARI(I) for $I = 1, 2, \ldots, N$. For $M = 0$ or $N \leq 1$, $y = F(VARI(I))$ for any value of $x$. The program extrapolates.

Restrictions: All the numbers must be floating point. The values of the independent variable $x$ in the table must be strictly increasing or strictly decreasing. The following arrays must be dimensioned by the calling program as indicated: VARI(N), VARD(N).

Accuracy: A function of the order of interpolation used.
APPENDIX E


Storage:  4308 locations.

Error condition: If the VARI values are not in order, the subroutine will print "TABLE BELOW OUT OF ORDER FOR FTLUP AT POSITION xxx TABLE IS STORED IN LOCATION xxxxxx" (absolute). It then prints the contents of VARI and VARD and stops the program.

Subroutine date: September 12, 1969.
APPENDIX F

LANGLEY LIBRARY SUBROUTINE DISCOT

Language: FORTRAN

Purpose: DISCOT performs single or double interpolation for continuous or discontinuous functions. Given a table of some function $y$ with two independent variables, $x$ and $z$, this subroutine performs $K_x$th- and $K_z$th-order interpolation to calculate the dependent variable. In this subroutine all single-line functions are read in as two separate arrays and all multiline functions are read in as three separate arrays; that is,

\[
\begin{align*}
  x_i & \quad (i = 1, 2, \ldots, L) \\
  y_j & \quad (i = 1, 2, \ldots, M) \\
  z_k & \quad (k = 1, 2, \ldots, N)
\end{align*}
\]

Use: CALL DISCOT (XA, ZA, TABX, TABY, TABZ, NC, NY, NZ, ANS)

- XA The $x$ argument
- ZA The $z$ argument (may be the same name as $x$ on single lines)
- TABX A one-dimensional array of $x$ values
- TABY A one-dimensional array of $y$ values
- TABZ A one-dimensional array of $z$ values
- NC A control word that consists of a sign (+ or -) and three digits. The control word is formed as follows:
  
  (1) If $NX = NY$, the sign is negative. If $NX \neq NY$, then $NX$ is computed by DISCOT as $NX = NY/NZ$ and the sign is positive and may be omitted if desired.
  
  (2) A one in the hundreds position of the word indicates that no extrapolation occurs above $z_{\text{max}}$. With a zero in this position, extrapolation occurs when $z > z_{\text{max}}$. The zero may be omitted if desired.
  
  (3) A digit (1 to 7) in the tens position of the word indicates the order of interpolation in the $x$-direction.
APPENDIX F

(4) A digit (1 to 7) in the units position of the word indicates the order of interpolation in the z-direction

NY  The number of points in y array
NZ  The number of points in z array
ANS The dependent variable y

Restrictions: See rule (5c) of section "Method" for restrictions on tabulating arrays and discontinuous functions. The order of interpolation in the x- and z-directions may be from 1 to 7. The following subprograms are used by DISCOT: UNS, DISSER, LAGRAN.

Method: Lagrange's interpolation formula is used in both the x- and z-directions for interpolation. This method is explained in detail in reference (a) of this subroutine. For a search in either the x- or z-direction, the following rules are observed:

(1) If x < x₁, the routine chooses the following points for extrapolation:
   \[ x_1, x_2, \ldots, x_{k+1} \text{ and } y_1, y_2, \ldots, y_{k+1} \]

(2) If x > xₙ, the routine chooses the following points for extrapolation:
   \[ x_{n-k}, x_{n-k+1}, \ldots, x_n \text{ and } y_{n-k}, y_{n-k+1}, \ldots, y_n \]

(3) If x ≤ xₙ, the routine chooses the following points for interpolation:
   When k is odd,
   \[ \frac{x_{i-k+1}}{2}, \frac{x_{i-k+1}}{2} + 1, \ldots, \frac{x_{i-k+1}}{2} + k \text{ and } \frac{y_{i-k+1}}{2}, \frac{y_{i-k+1}}{2} + 1, \ldots, \frac{y_{i-k+1}}{2} + k \]
   When k is even,
   \[ \frac{x_{i-k+1}}{2}, \frac{x_{i-k+1}}{2} + 1, \ldots, \frac{x_{i-k+1}}{2} + k \text{ and } \frac{y_{i-k+1}}{2}, \frac{y_{i-k+1}}{2} + 1, \ldots, \frac{y_{i-k+1}}{2} + k \]

(4) If any of the subscripts in rule (3) become negative or greater than n (number of points), rules (1) and (2) apply. When discontinuous functions are tabulated, the independent variable at the point of discontinuity is repeated.

(5) The subroutine will automatically examine the points selected before interpolation and if there is a discontinuity, the following rules apply. Let x_d and x_{d+1} be the point of discontinuity.
APPENDIX F

(a) If \( x \leq x_d \), points previously chosen are modified for interpolation as shown:

\[ x_{d-k}, x_{d-k+1}, \ldots, x_d \quad \text{and} \quad y_{d-k}, y_{d-k+1}, \ldots, y_d \]

(b) If \( x > x_d \), points previously chosen are modified for interpolation as shown:

\[ x_{d+1}, x_{d+2}, \ldots, x_{d+k} \quad \text{and} \quad y_{d+1}, y_{d+2}, \ldots, y_{d+k} \]

(c) When tabulating discontinuous functions, there must always be \( k + 1 \) points above and below the discontinuity in order to get proper interpolation.

(6) When tabulating arrays for this subroutine, both independent variables must be in ascending order.

(7) In some engineering programs with many tables, it is quite desirable to read in one array of \( x \) values that could be used for all lines of a multilne function or different functions. Even though this situation is not always applicable, the subroutine has been written to handle it. This procedure not only saves much time in preparing tabular data, but also can save many locations previously used when every \( y \) coordinate had to have a corresponding \( x \) coordinate. Another additional feature that may be useful is the possibility of a multilne function with no extrapolation above the top line.

Accuracy: A function of the order of interpolation used.


Storage: 5558 locations.

Subprograms used: UNS 408 locations.

DISSER 1108 locations.

LAGRAN 558 locations.

Subroutine date: August 1, 1968.
REFERENCES


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(a) Helium driver gas with $300 \text{ K} \leq T_4 \leq 700 \text{ K}$. 

$T_4, K$

- 700
- 650
- 600
- 550
- 500
- 450
- 400
- 350
- 300

$u_s, \text{ cm/sec}$

- 2.75
- 2.70
- 2.65
- 2.60
- 2.55
- 2.50
- 2.45
- 2.40
- 2.35
- 2.30
- 2.25
- 2.20
- 2.15
- 2.10
- 2.05
- 2.00
- 1.95
- 1.90
- 1.85
- 1.80
- 1.75
- 1.70
- 1.65
- 1.60
- 1.55
- 1.50
- 1.45
- 1.40
- 1.35
- 1.30
- 1.25
- 1.20
- 1.15
- 1.10
- 1.05
- 1.00
- 0.95
- 0.90
- 0.85
- 0.80
- 0.75
(b) Helium driver gas with $1000 \, K \leq T_4 \leq 12000 \, K$.

Figure 5. - Continued.
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Figure 5.- Concluded.
(a) Static pressure in region 5.

Figure 6.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming no shock reflection at secondary diaphragm. $p_1 = 0.6895 \text{kN/m}^2$. 
(b) Static density in region 5.

Figure 6.- Continued.
(c) Static temperature in region (5).

Figure 6.- Continued.
(d) Mach number in region 5.

Figure 6.- Continued.
(e) Unit Reynolds number in region \( 5 \).

Figure 6.- Continued.
(f) Normal-shock density ratio.

Figure 6.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 6.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 6.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 6.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 6. - Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 6.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 6.- Concluded.
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(a) Static pressure in region (5).
(b) Static density in region 5.

Figure 7. - Continued.
(c) Static temperature in region 5.

Figure 7.- Continued.
(d) Mach number in region 5.

Figure 7. - Continued.
(e) Unit Reynolds number in region (5).

Figure 7.—Continued.
(f) Normal shock density ratio.

Figure 7.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 7.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 7. - Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 7. - Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 7. - Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 7.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 7.- Concluded.
Figure 8. - Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming no shock reflection at secondary diaphragm. $p_1 = 6.90 \, \text{kN}/\text{m}^2$. 

(a) Static pressure in region (5).
Figure 8. - Continued.

(b) Static density in region \((5)\).
(c) Static temperature in region (5).

Figure 8. - Continued.
(d) Mach number in region 5.

Figure 8.- Continued.
(e) Unit Reynolds number in region 5.

Figure 8.- Continued.
(f) Normal shock density ratio.

Figure 8. - Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 8. - Continued.
(h) Stagnation density behind normal bow shock.

Figure 8.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 8 - Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 8. - Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 8.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 8.- Concluded.
Figure 9.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming no shock reflection at secondary diaphragm. $p_1 = 34.47 \text{ kN/m}^2$. 

(a) Static pressure in region (5).
(b) Static density in region ⑤.

Figure 9. - Continued.
(c) Static temperature in region 5.

Figure 9.- Continued.
(d) Mach number in region 5.

Figure 9. - Continued.
(e) Unit Reynolds number in region 5.

Figure 9.- Continued.
(f) Normal shock density ratio.

Figure 9.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 9.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 9.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 9. - Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 9.—Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 9.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 9.- Concluded.
(a) Static pressure in region (5).

Figure 10.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming no shock reflection at secondary diaphragm. \( p_1 = 68.95 \text{kN/m}^2 \).
(b) Static density in region $\mathbb{V}$.

Figure 10.- Continued.
(c) Static temperature in region (5).

Figure 10.- Continued.
(d) Mach number in region 5.

Figure 10. - Continued.
(e) Unit Reynolds number in region 5.

Figure 10.—Continued.
(f) Normal shock density ratio.

Figure 10.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 10.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 10.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 10.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 10. - Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 10. - Continued.
1) Quiescent acceleration air pressure in region 10.

Figure 10.- Concluded.
Figure 11.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming no shock reflection at secondary diaphragm. $p_1 = 344.74$ kN/m$^2$. 

(a) Static pressure in region 5.
(b) Static density in region 5.

Figure 11. - Continued.
(c) Static temperature in region \(\mathcal{S}\).

Figure 11. - Continued.
(d) Mach number in region 5.

Figure 11.- Continued.
(e) Unit Reynolds number in region 5.

Figure 11.- Continued.
(f) Normal shock density ratio.

Figure 11.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 11. - Continued.
(h) Stagnation density behind normal bow shock.

Figure 11.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 11.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 11.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 11.- Continued.
Figure 11.- Concluded.
Figure 12.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. $p_1 = 689.5 \text{ N/m}^2$. 

(a) Static pressure in region 5.
(b) Static density in region (5).

Figure 12.- Continued.
Figure 12. - Continued.

(c) Static temperature in region 5.
(d) Mach number in region \( \mathbf{5} \).

Figure 12.- Continued.
(e) Unit Reynolds number in region 5.

Figure 12.- Continued.
(f) Normal shock density ratio.

Figure 12.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 12. - Continued.
(h) Stagnation density behind normal bow shock.

Figure 12. - Continued.
(1) Stagnation temperature behind normal bow shock.

Figure 12. - Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 12. - Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 12.—Continued.
Quiescent acceleration air pressure in region (10).

Figure 12.- Concluded.
(a) Static pressure in region 5.

Figure 13.-- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. \( p_1 = 3.45 \text{ kN/m}^2 \).
Figure 13. - Continued.

(b) Static density in region (5).
Figure 13.- Continued.

(c) Static temperature in region (5).
(d) Mach number in region (5).

Figure 13. - Continued.
(e) Unit Reynolds number in region 5.

Figure 13.- Continued.
(f) Normal shock density ratio.

Figure 13.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 13.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 13. - Continued.
Figure 13.- Continued.

(i) Stagnation temperature behind normal bow shock.

Stagnation temperature behind normal bow shock.
(j) Stagnation enthalpy behind normal bow shock.

Figure 13.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 13.- Continued.
(1) Quiescent acceleration air pressure in region (10).

Figure 13.- Concluded.
Figure 14.— Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. $p_1 = 6.90 \text{ kN/m}^2$. 

(a) Static pressure in region 5.
(b) Static density in region ⑤.

Figure 14.- Continued.
(c) Static temperature in region (5).

Figure 14.- Continued.
(d) Mach number in region 5.

Figure 14.- Continued.
(e) Unit Reynolds number in region 5.

Figure 14.- Continued.
(f) Normal shock density ratio.

Figure 14.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 14.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 14.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 14. - Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 14.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 14.- Continued.
(1) Quiescent acceleration air pressure in region \(10\).

Figure 14. – Concluded.
Figure 15.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. \( p_1 = 34.47 \text{ kN/m}^2 \).
(b) Static density in region 5.

Figure 15. - Continued.
(c) Static temperature in region ⑤.

Figure 15.- Continued.
(d) Mach number in region 5.

Figure 15.- Continued.
(e) Unit Reynolds number in region 5.

Figure 15.- Continued.
(f) Normal shock density ratio.

Figure 15.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 15.- Continued.
Figure 15.- Continued.

(h) Stagnation density behind normal bow shock.
(i) Stagnation temperature behind normal bow shock.

Figure 15.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 15.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 15.- Continued.
(1) Qui\-scent acceleration air pressure in region (10).

Figure 15.- Concluded.
Figure 16. - Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. \( p_1 = 68.95 \text{ kN/m}^2 \).
(b) Static density in region (5).

Figure 16.- Continued.
(c) Static temperature in region 5.

Figure 16. - Continued.
(d) Mach number in region 5.

Figure 16.- Continued.
(e) Unit Reynolds number in region $\mathbb{5}$. 

Figure 16.—Continued.
(f) Normal shock density ratio.

Figure 16. - Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 16. - Continued.
(h) Stagnation density behind normal bow shock.

Figure 16.—Continued.
(1) Stagnation temperature behind normal bow shock.

Figure 16.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 16.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 16.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 16.- Concluded.
(a) Static pressure in region 5.

Figure 17.- Various expansion tube flow parameters for real air in thermochemical equilibrium as a function of flow velocity and assuming a totally reflected shock at the secondary diaphragm. \( p_1 = 344.74 \text{kN/m}^2 \).
(b) Static density in region (5).

Figure 17.- Continued.
(c) Static temperature in region (5).

Figure 17.- Continued.
Figure 17. - Continued.

(d) Mach number in region 5.
(e) Unit Reynolds number in region ⑤.

Figure 17.- Continued.
(f) Normal shock density ratio.

Figure 17.- Continued.
(g) Stagnation pressure behind normal bow shock.

Figure 17.- Continued.
(h) Stagnation density behind normal bow shock.

Figure 17.- Continued.
(i) Stagnation temperature behind normal bow shock.

Figure 17.- Continued.
(j) Stagnation enthalpy behind normal bow shock.

Figure 17.- Continued.
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 17.- Continued.
(1) Quiescent acceleration air pressure in region 10.

Figure 17. - Concluded.
(a) Static pressure, \( p_2/p_1 \).

Figure 18.- Various nondimensionalized flow parameters in region \( \text{2} \) as a function of incident normal shock velocity.
Figure 18. - Continued.

(b) Static density, $\rho_2/\rho_1$. 
(c) Static temperature, $T_2/T_1$.  

Figure 18.- Continued.
Figure 18.—Continued.

(d) Static enthalpy, \( \frac{h_2}{h_1} \).

\begin{align*}
U_{5,1}, \text{ km/ sec} & \\
\frac{h_2}{h_1} &
\end{align*}
(e) Entropy, $s_2 W_u / R$.

Figure 18. - Concluded.
Figure 19.- Static pressure in region (5) as a function of air flow velocity for $p_1 = 3.45 \text{kN/m}^2$ and various incident normal-shock velocities.
Thermochemical state of expansion

Shock reflection at secondary diaphragm

<table>
<thead>
<tr>
<th>Equilibrium</th>
<th>Frozen</th>
<th>None</th>
<th>Totally reflected</th>
</tr>
</thead>
</table>

$U_5$, km/sec

$P_5$, N/m$^2$

(b) $U_{s,1} = 2.85$ km/sec.

Figure 19.- Continued.
Thermochemical state of expansion

Shock reflection at secondary diaphragm

- Equilibrium
- Frozen
- Equilibrium
- Frozen

(c) $U_{s,1} = 3.6 \text{ km/sec}$.

Figure 19.- Continued.
Thermochemical state of expansion

- Equilibrium
- Frozen
- Equilibrium
- Frozen

Shock reflection at secondary diaphragm
- None
- None
- Totally reflected
- Totally reflected

Figure 19.- Concluded.

(d) $U_{s,1} = 4.5 \text{ km/sec}$. 

Figure 19.- Concluded.
(a) Ideal time interval between arrival of incident normal shock into region (10) and acceleration-air—test-air interface.

Figure 20.- Acceleration air flow quantities as a function of distance downstream from secondary diaphragm for $p_1 = 3.45 \text{kN/m}^2$ and $U_{s,1} = 2.85 \text{km/sec}$.
(b) Time interval between arrival of incident normal shock into region 10 and acceleration-air—test-air interface.

Figure 20.—Continued.
(c) Nondimensionalized distance between incident normal shock into region \(10\) and acceleration-air—test-air interface.

Figure 20.—Continued.
(d) Ratio of incident normal shock into region (10) to acceleration-air—test-air interface velocity.

Figure 20.- Concluded.
Figure 21.- Various expansion tunnel flow quantities as a function of effective area ratio.
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Figure 22. - Continued.

(b) Static density, $\rho_2/\rho_1$. 

Graph showing the relationship between $\rho_2/\rho_1$ and $U_{s,1}$, km/sec with $\rho_1$ kN/m$^2$.
(c) Static temperature, $T_2/T_1$.

Figure 22.- Continued.
(d) Static enthalpy, $h_2/h_1$.

Figure 22. - Continued.
Figure 22. - Concluded.

(e) Entropy, $s_2 W_u / R$. 