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

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16. Abstract

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.

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

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SUMMARY

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 μsec 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.

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

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, $pW_u/\rho RT$
Z^*	number of kmol of dissociated air per number of kmol of undissociated air, W_u/W
γ	ratio of specific heats
γ_E	isentropic exponent, $\left(\frac{\partial \log p}{\partial \log \rho}\right)_{sW_u/R}$
α	defined by $Z^* = 1 + \alpha$
δ^*	nozzle boundary-layer displacement thickness, m
μ	coefficient of viscosity, N-sec/m^2

ρ	density, kg/m^3
τ	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 (4) and the quiescent test gas is designated as region (1). Upon rupture of the diaphragm, an incident shock wave propagates into region (1) with velocity $U_{s,1}$. Flow conditions immediately behind this shock are denoted as region (2) (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 (2) is supersonic. (See fig. 1(c).) The flow conditions immediately behind this standing shock are designated as region (2s); the model stagnation conditions, as region (t2). 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 (2). (See fig. 1(d).) Flow conditions behind this reflected shock are designated as region (2r).

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 (2s); if a totally reflected shock at the secondary diaphragm is assumed, flow conditions behind this reflected shock are

denoted as region (2r). (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 (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 (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 (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 (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 $U_{s,1}$, (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 (2).

The conservation relations, in a laboratory coordinate system, for mass, momentum, and energy for a normal shock wave moving through region (1) are

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

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

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

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

$$\rho_2 = \rho_2 \left(p_2, h_2 \right) \tag{4}$$

for the unknown quantities ρ_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 $1 MN/m^2$. 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 $\left(Z_1 = 1, \ \gamma_1 = 7/5 \right)$ 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 $200 \text{ K} \leqq T_4 \leqq 15\,000 \text{ K}$ and hydrogen at $273 \text{ K} \leqq T_4 \leqq 600 \text{ K}$ 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

and 7.) 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 nonuniform. 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)

$$2\ell_{max}\left(\frac{\rho_2}{\rho_1}\right)\left[\log_e\left(1-\sqrt{\frac{U_{s,1}t}{\ell_{max}}}\right)+\sqrt{\frac{U_{s,1}t}{\ell_{max}}}\right]+U_{s,1}t=-X \tag{5}$$

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

$$2\ell_{max}\left(\frac{\rho_2}{\rho_1}\right)\left[\log_e\left(1-\sqrt{\frac{\ell}{\ell_{max}}}\right)+\sqrt{\frac{\ell}{\ell_{max}}}\right]=-X \tag{6}$$

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

$$\ell_{max}=p_1d^2\left(2.060-2.056\times10^{-1}M_{s,1}+8.095\times10^{-3}M_{s,1}^2\right)\qquad\left(4<M_{s,1}\leq14\right)\tag{7a}$$

$$\ell_{max}=p_1d^2\left(8.723\times10^{-1}-7.488\times10^{-3}M_{s,1}\right)\qquad\left(14<M_{s,1}<30\right)\tag{7b}$$

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 ℓ_{max}, the interface velocity approaches the incident shock velocity and is essentially equal to $U_{s,1}$ at ℓ_{max}.

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

$$\frac{5\ell_{max}}{4}\left(\frac{\rho_2}{\rho_1}\right)\left\{\log_e\left[\frac{1+\left(\frac{U_{s,1}t}{\ell_{max}}\right)^{0.2}}{1-\left(\frac{U_{s,1}t}{\ell_{max}}\right)^{0.2}}\right]+2\tan^{-1}\left(\frac{U_{s,1}t}{\ell_{max}}\right)^{0.2}-4\left(\frac{U_{s,1}t}{\ell_{max}}\right)^{0.2}\right\}-U_{s,1}t=X \tag{8}$$

where ℓ is obtained from the relation (ref. 7)

$$\frac{5\ell_{max}}{4}\left(\frac{\rho_2}{\rho_1}\right)\left\{\log_e\left[\frac{1-\left(\frac{\ell}{\ell_{max}}\right)^{0.2}}{1+\left(\frac{\ell}{\ell_{max}}\right)^{0.2}}\right]-2\tan^{-1}\left(\frac{\ell}{\ell_{max}}\right)^{0.2}+4\left(\frac{\ell}{\ell_{max}}\right)^{0.2}\right\}=-X \tag{9}$$

Curve fits to the real-air results of reference 7 yielded the following expressions for ℓ_{max}:

$$\ell_{max}=p_1^{0.25}d^{1.25}\left(5.273-7.514\times10^{-1}M_{s,1}+3.435\times10^{-2}M_{s,1}^2\right)\qquad\left(4<M_{s,1}<10\right) \tag{10a}$$

$$\ell_{max}=p_1^{0.25}d^{1.25}\left(1.546-3.017\times10^{-2}M_{s,1}\right)\qquad\left(10\leq M_{s,1}<30\right) \tag{10b}$$

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

$$t_{i,2}=\frac{\rho_1}{\rho_2}\frac{X}{U_2} \tag{11}$$

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:

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

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

$$\left(\frac{s_2 W_u}{R}\right)_{X_s} = \left(\frac{s_2 W_u}{R}\right)_{X_s=0} \tag{13}$$

and either the energy relation

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

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

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

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 ρ_{2,X_s}, U_{2,X_s}, and p_{2,X_s}, in conjunction with the equation of state, by iteration on ρ_{2,X_s} for a given value of X_s/ℓ_{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 ℓ/ℓ_{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

$$\rho_2 U_2 = \rho_{2s} U_{2s} \tag{15}$$

$$p_2 + \rho_2 U_2^2 = p_{2s} + \rho_{2s} U_{2s}^2 \tag{16}$$

$$h_2 + \frac{1}{2} U_2^2 = h_{2s} + \frac{1}{2} U_{2s}^2 \tag{17}$$

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

$$\rho_2 (U_2 + U_r) = \rho_{2r} U_r \tag{18}$$

$$p_2 + \rho_2\left(U_2 + U_r\right)^2 = p_{2r} + \rho_{2r}U_r^{\,2} \tag{19}$$

$$h_2 + \frac{1}{2}\left(U_2 + U_r\right)^2 = h_{2r} + \frac{1}{2}U_r^{\,2} \tag{20}$$

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

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

$$\Delta U = U_5 - U_A = -\int_{h_A}^{h_5} \left(\frac{dh}{a}\right)_{s_A W_u/R} \tag{21}$$

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 ΔU 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 ΔU is the desired value of h_5. Corresponding thermodynamic quantities in region (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 $s_5 W_u/R$ and p_5 are known. With the limits of integration known, the integral in equation (21) is evaluated numerically to give ΔU, 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 μ_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, μ_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 γ will be constant and the test air behaves as a perfect gas. To obtain an estimate of the ratio of frozen specific heats γ_f for dissociated but unionized air, it is assumed that the dissociated air may be modeled by atoms (O and N) and molecules $(N_2, O_2, \text{and } NO)$. 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, and W_{O_2}, W_{N_2}, and W_{NO} are approximately equal. The molecular weight for this composition is given by the relation

$$W = x_a W_a + x_m W_m \approx W_a(2 - x_a) \tag{22}$$

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

$$Z^* = \frac{2}{2 - x_a} \tag{23}$$

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

$$\gamma_f = \frac{7 + 3\alpha}{5 + \alpha} \tag{24}$$

Since the quantity Z_A^* is assumed to be known, values of α, and hence γ_f, may be obtained.

For a frozen (perfect) gas, equation (21) may be evaluated in closed form to yield

$$U_{5,f} - U_A = \frac{2}{\gamma_f - 1}\left(a_{A,f} - a_{5,f}\right) \tag{25}$$

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)

$$a_{5,f} = a_{A,f}\left(\frac{p_{5,f}}{p_A}\right)^{\frac{\gamma_f - 1}{2\gamma_f}} \tag{26}$$

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

$$t_{i,5} = L_a\left(\frac{1}{U_5 - a_5} - \frac{1}{U_5}\right) \tag{27}$$

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 ΔU_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 (5s) and (t5)) 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

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

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

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

where the unknowns are p_{10}, ρ_{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 ρ_{20}/ρ_{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 ρ_{20} is obtained. This value of ρ_{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

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

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, $\rho_{10,He}$ is approximately equal to $\rho_{10,air}$ and $p_{10,He}$ is equal to 7.24 times $p_{10,air}$.

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_{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 (5). As discussed previously, the expansion tunnel flow is assumed to undergo an isentropic steady expansion from region (5) to region (6). The basic differential equation for this expansion is (ref. 1)

$$dU = -\left(\frac{dh}{U}\right)_{sW_u/R} \tag{31}$$

which may be integrated between regions (5) and (6) to give

$$h_5 + \frac{1}{2} U_5^2 = h_6 + \frac{1}{2} U_6^2 \tag{32}$$

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 (6) are determined from the source of thermodynamic properties with the quantities h_6 and $s_6 W_u/R$ $\left(\text{which is equal to } s_A W_u/R\right)$ as input. For the case where a value of p_6 is known, the thermodynamic quantities in region (6) follow from the source of thermodynamic properties with the quantities p_6 and $s_6 W_u/R$ 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 (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 (6) is similar to that discussed previously for region (5) of the expansion tube, whereby the equilibrium conditions in region (5) correspond to those of region (A) and the frozen conditions of region (6) correspond to those of region (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

$$\delta^* = r_{geo} - r_{eff} \tag{33}$$

where the radius of the inviscid core is given by

$$r_{eff} = r^*_{eff}\left(\frac{A}{A^*}\right)^{1/2}_{eff} \tag{34}$$

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

$$\left(\frac{A}{A^*}\right)_{eff} = \frac{\rho_5 U_5}{\rho_6 U_6} \tag{35}$$

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 $\left(r^*_{geo} = r^*_{eff}\right)$, equation (33) becomes

$$\delta^* = r_{geo} - r^*_{geo}\left(\frac{\rho_5 U_5}{\rho_6 U_6}\right)^{1/2} \tag{36}$$

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 (that is, $s_{ks} W_u/R = s_{t,k} W_u/R$, 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 ($k = 2,5$, or 6)

$$h_{t,k} = h_k + \frac{1}{2} U_k^2 \tag{37}$$

and for a frozen expansion is (k = 5 or 6)

$$h_{t,k} = h_{k,f} + h_{A,f} + \frac{1}{2} U_{k,f}^2 \tag{38}$$

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)

$$p_{t,k} = p_{ks}\left(1 + \frac{\gamma_{E,ks} - 1}{2} M_{ks}^2\right)^{\frac{\gamma_{E,ks}}{\gamma_{E,ks}-1}} \tag{39}$$

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

$$\left(p_{t,k}\right)_{new} = \frac{\left(p_{t,k}\right)_{previous}\left(h_{t,k}\right)_{known}}{\left(h_{t,k}\right)_{previous}} \tag{40}$$

$\left(\text{where } \left(h_{t,k}\right)_{known} \text{ was obtained from eq. (37) or (38)}\right)$ 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)

$$\dot{q}_{t,k} = 3.88 \times 10^{-4} \sqrt{\frac{p_{t,k}}{r_n}}\left(h_{t,k} - h_w\right) \tag{41}$$

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 (t2), 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 $p_2 = p_3$.) For a helium driver gas and the conditions in region (4) of figure 3, no appreciable imperfect helium effects on the predicted isentropic expansion are observed. A small effect of imperfect hydrogen is observed in figures 3(d) and 3(e).

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:

p_4, MN/m^2	T_4, K	Z_4 for –	
		Helium	Hydrogen
0.69	600	1.001	1.002
3.45	600	1.007	1.012
6.90	600	1.015	1.024
13.79	600	1.029	1.051
34.47	600	1.071	1.135
68.95	600	1.139	1.282
137.90	600	1.264	1.566

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 (t5)), when it is assumed that thermochemical equilibrium flow conditions in region (A) are known (previously calculated), are summarized in the following table:

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

Similarly, combinations of measured input for obtaining stagnation-point conditions in the expansion tunnel test section (region (t6)), when thermochemical equilibrium flow conditions in region (5) are known, are summarized in the following table:

Case	Measured input	Steady expansion	Post normal shock
(1)	U_6 or p_6	Equilibrium	Equilibrium
(2)	U_6 or p_6	Frozen	Equilibrium
(3)	U_6 or p_6	Frozen	Frozen

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, ρ_5, T_5, M_5, and $N_{Re,5}$), region (5s) (ρ_{5s}/ρ_5), and region (t5) ($p_{t,5}$, $\rho_{t,5}$, $T_{t,5}$, $h_{t,5}$, 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 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), (2r), (5s), and (t5) 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 $(T_4 = 300\ K)$ 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:

Condition	No shock reflection	Totally reflected shock
$U_{s,1}$, km/sec	2.48	2.25
p_5, kN/m^2	0.78	0.45
T_5, kK	0.76	0.75
ρ_5, g/m^3	3.6	2.1
$N_{Re,5}$, m^{-1}	5.6×10^5	3.2×10^5
ρ_{5s}/ρ_5	11.85	12.1
$p_{t,5}$, kN/m^2	100.0	57.7
$T_{t,5}$, kK	6.0	5.9
$\rho_{t,5}$, g/m^3	44.5	25.7
$h_{t,5}$, MJ/kg	15.5	15.3
$\dot{q}_{t,5}$, MW/m^2	11.6	8.8
p_{10}, N/m^2	1.9	1.2

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, ρ_2/ρ_1, T_2/T_1, h_2/h_1, and s_2W_u/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 (A) 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 τ_i, τ, ℓ/ℓ_{max}, and $U_{s,10}/U_I$ as a function of nondimensionalized 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 ℓ_{max} more rapidly with increasing U_5 (fig. 20(c)). When the value of ℓ is essentially equal to ℓ_{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 $\left(p_6,\ T_6,\ U_6,\ M_6,\ N_{Re,6},\ \rho_{6s}/\rho_6,\right.$ and $\left.p_{t,6}\right)$ are shown in figure 21 as a function of effective area ratio $(A/A^*)_{eff}$. Nozzle entrance conditions $\left(\text{conditions at } (A/A^*)_{eff} \text{ of unity}\right)$ 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 $(A/A^*)_{geo}$ is 70 and the nozzle half angle if 10^o. Now, let $(A/A^*)_{eff}$ be equal to $(A/A^*)_{geo}$, corresponding to zero tunnel wall boundary-layer displacement thickness. The quantities M_6 and $N_{Re,6}$ corresponding to this first estimate of $(A/A^*)_{eff}$ 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 δ^* for this example, where $\gamma_{E,6}$ was equal to 1.4.) Having determined an initial estimate of δ^* at the nozzle exit, a new value of $(A/A^*)_{eff}$ 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 $(A/A^*)_{eff}$ are obtained and a second value of δ^* is calculated. This iterative procedure is continued until successive values of $(A/A^*)_{eff}$ are within a desired tolerance. For this particular example, iteration to within 2 percent on $(A/A^*)_{eff}$ (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 7.4×10^4 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,
Hampton, Va., September 4, 1974.

APPENDIX A

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

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:

Program symbol	Description
P1	Pressure of quiescent test air in region (1)
T1	Temperature of quiescent test air in region (1)
US1	Incident-shock velocity into region (1)
P2	Static pressure in region (2)
P4	Driver-gas pressure in region (4)
T4	Driver-gas temperature in region (4)
U5	Velocity in region (5)
P5	Static pressure in region (5)
U6	Velocity in region (6)
P6	Static pressure in region (6)
DIA	Shock tube or expansion tube diameter
DIAT	Nozzle entrance diameter
DIAN	Nozzle test-section diameter

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)

INU	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)
IEXP	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
JAC	Number of enthalpy increments used in unsteady expansion from region (A) for IEXP = 1 (300 maximum)
IAC	Number of pressure increments used in unsteady expansion from region (A) for IEXP = 2 (100 maximum)
IREP	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
U5I	Velocity increment for IREP = 2
NVEL	Total number of U_5 of interest for IREP = 2 (10 maximum)
DELU5	Difference between maximum and minimum interface velocity along acceleration section
LREP	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
NUMU6	Total number of U_6 of interest for LREP = 2 (10 maximum)
U6I	Velocity increment for LREP = 2

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), (2s), (t2), and (2r) 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:

Program symbol	Assigned value
T1	300.
DIA	0.1524
DIAT	0.0762
DIAN	0.6452
XIS	4.65
XAS	16.98
TW	300.
RUN	1.0
BNR	0.0254
NDRIV	0
LB	0
ISTET	1
LF	1
LG	1
ISAV	2
IEXP	1
JAC	50
IAC	50

APPENDIX A

Program symbol	Assigned value
IREP	2
NVEL	8
U5I	400.
LD	4
INU	2
DELU5	0.
LREP	2
NUMU6	5
U6I	50.

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 $U_{s,1}$ (LB = 0), p_2 (LB = 1), or p_4 and T_4 (LB = 2) need be included in INP. Similarly, for a given LF, only U_5 (LF = 1) or p_5 (LF = 2) need be included in INP; 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

Option	ISAV	IEXP
(1)	1	1
(2)	2	1
(3)	2	2

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 a^{-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 (t5)). 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.

APPENDIX A

The basic subroutines of this program are as follows:

(1) SLOW – determines imperfect, real-air thermodynamic quantities p, ρ, h, T, a, Z, γ_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 ρ, sW_u/R, T, a, Z, γ_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 ρ

   (3) p and h

   (4) ρ and h

   (5) p and T

(4) VISC – computes real-air μ for given p and T

(5) BDT – computes virial coefficients for helium or hydrogen for given T

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

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

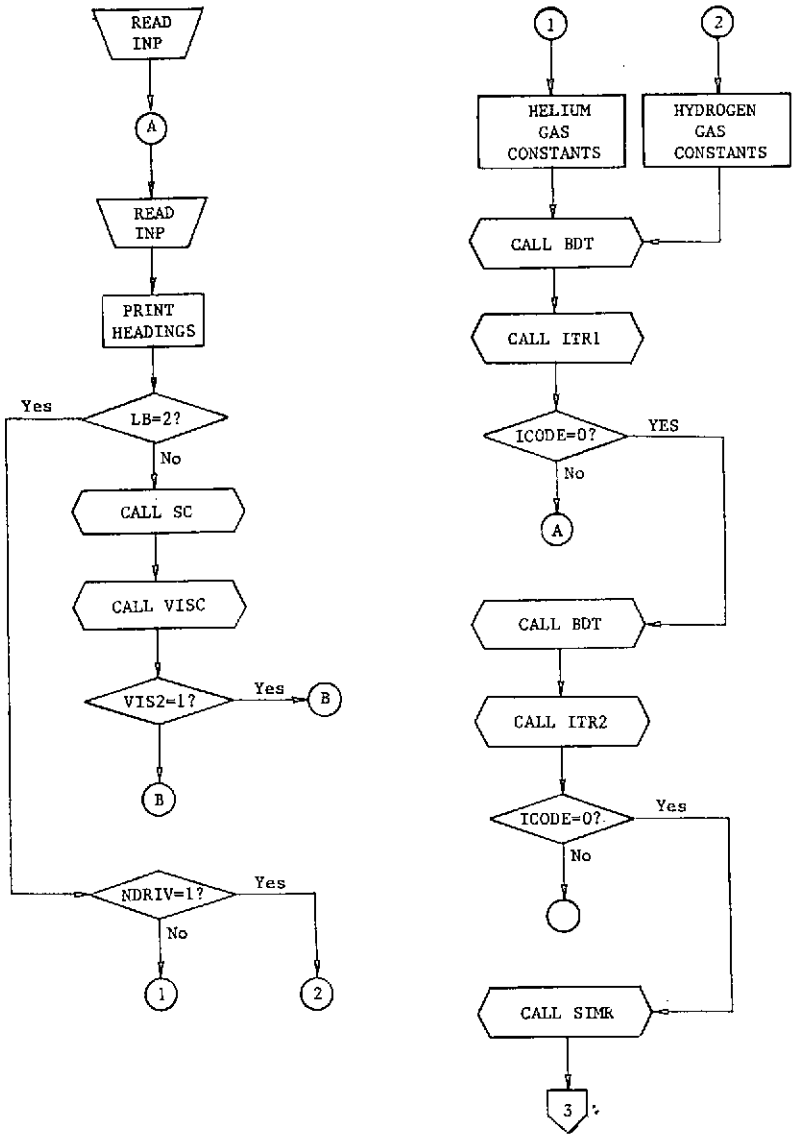
(8) SNS – iterative procedure for solving conservation relations for a standing shock at secondary diaphragm or a normal bow shock at a model, including stagnation-point conditions

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

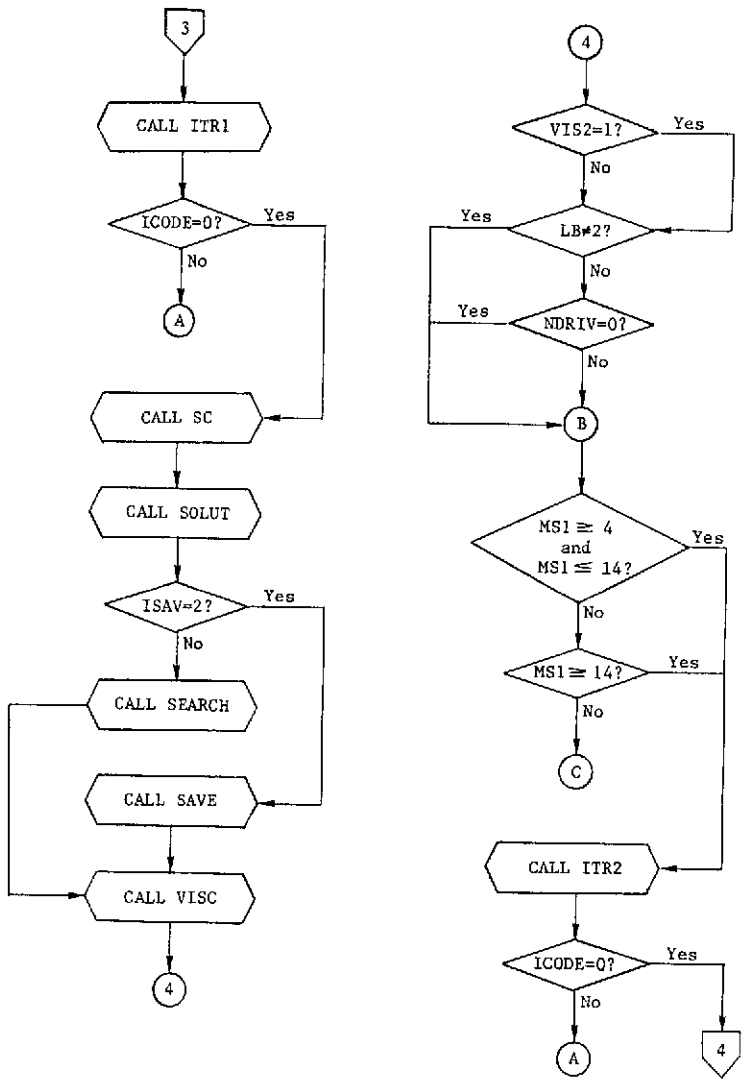
Langley Library Subroutines ITR1, ITR2, FTLUP, and DISCOT are used with this program and are presented as appendixes C, D, E, and F.

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

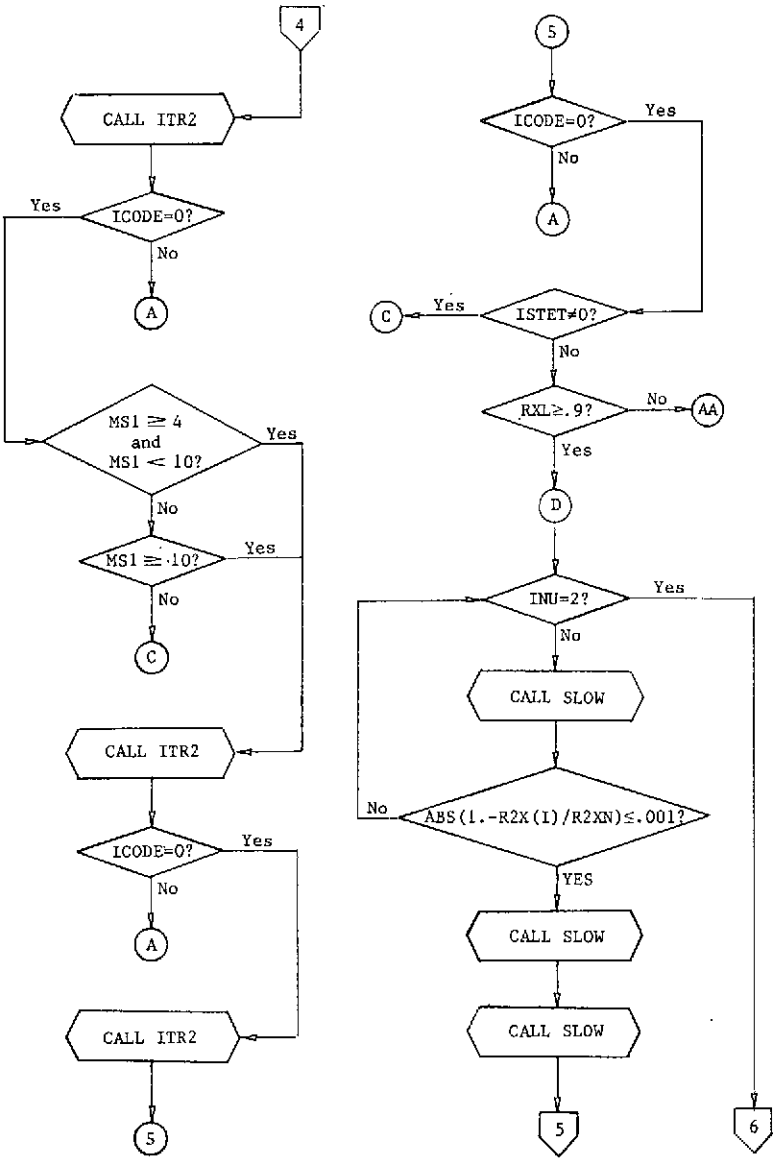
APPENDIX A


READ INP
A
READ INP
PRINT HEADINGS
LB=2?
Yes
No
CALL SC
CALL VISC
VIS2=1?
Yes
B
B
NDRIV=1?
Yes
No
1
2
1
2
HELIUM GAS CONSTANTS
HYDROGEN GAS CONSTANTS
CALL BDT
CALL ITR1
ICODE=0?
YES
No
A
CALL BDT
CALL ITR2
ICODE=0?
Yes
No
CALL SIMR
3

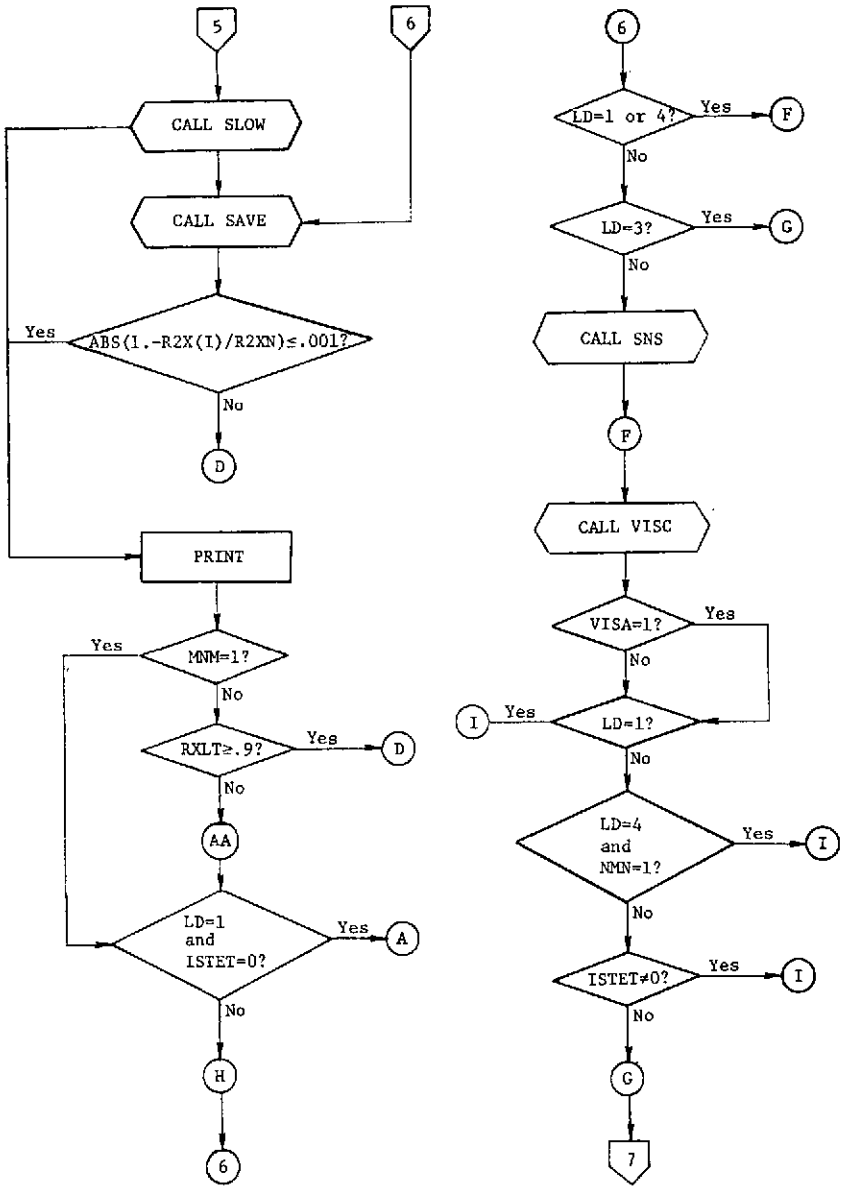
APPENDIX A


3
CALL ITR1
ICODE=0?
Yes
No
A
CALL SC
CALL SOLUT
ISAV=2?
Yes
No
CALL SEARCH
CALL SAVE
CALL VISC
4
4
VIS2=1?
Yes
No
Yes
LB≠2?
No
Yes
NDRIV=0?
No
B
MS1 ≧ 4
and
MS1 ≦ 14?
Yes
No
MS1 ≧ 14?
Yes
No
C
CALL ITR2
ICODE=0?
Yes
No
A
4

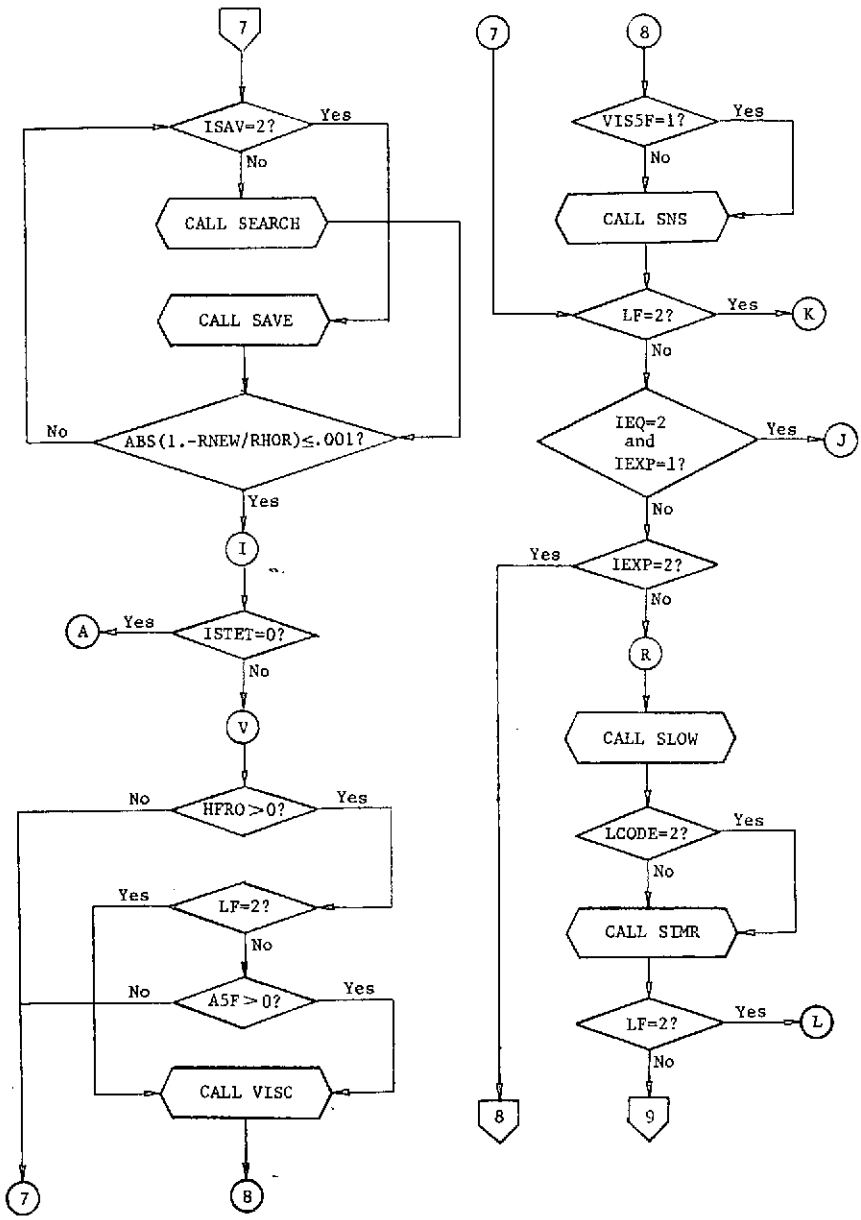
APPENDIX A


4
CALL ITR2
Yes
ICODE=0?
No
A
MS1 ≧ 4
and
MS1 < 10?
Yes
No
MS1 ≧ 10?
Yes
No
C
CALL ITR2
ICODE=0?
Yes
No
A
CALL ITR2
5
5
ICODE=0?
Yes
No
A
C
Yes
ISTET≠0?
No
RXL≥.9?
No
AA
Yes
D
INU=2?
Yes
No
CALL SLOW
No
ABS(1.-R2X(I)/R2XN)≤.001?
YES
CALL SLOW
CALL SLOW
5
6

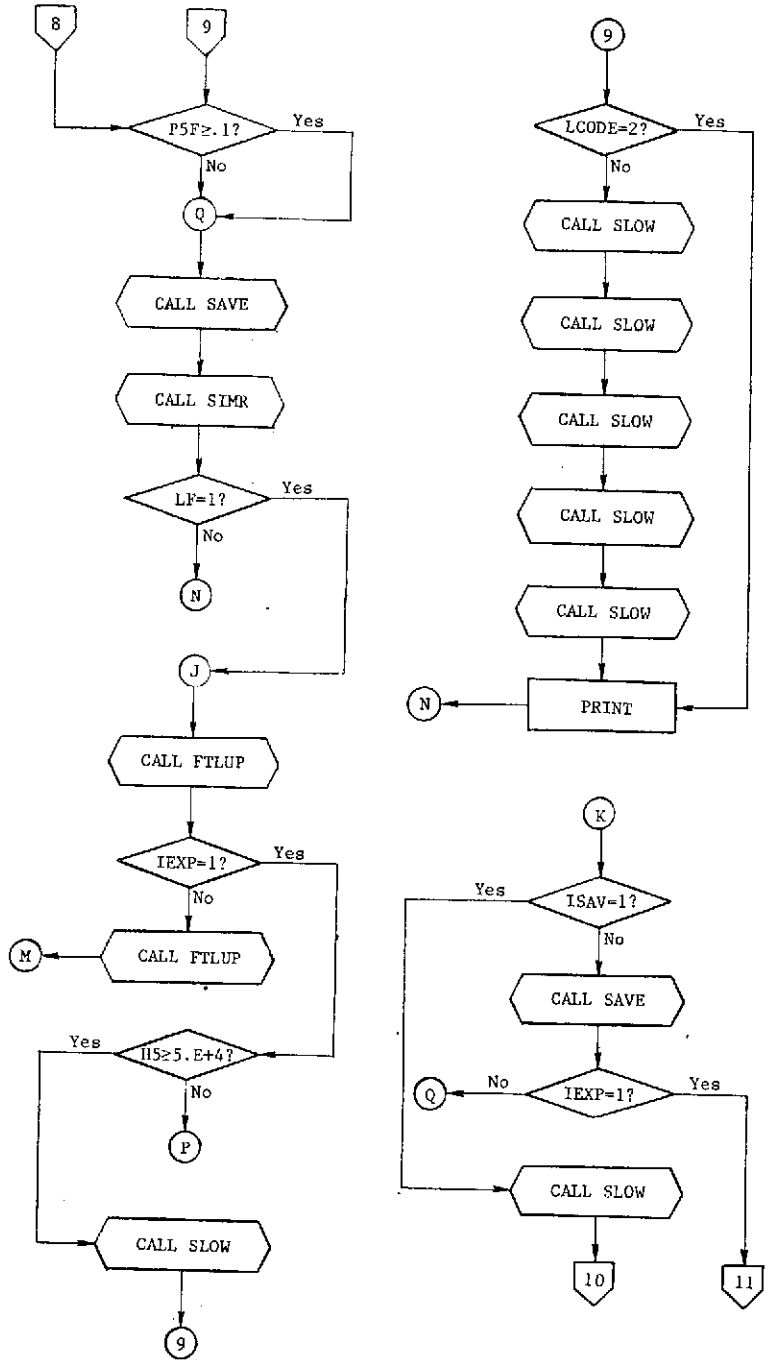
APPENDIX A


5
6
CALL SLOW
CALL SAVE
Yes
ABS(1.-R2X(I)/R2XN)≤.001?
No
D
PRINT
Yes
MNM=1?
No
RXLT≥.9?
Yes
D
No
AA
LD=1
and
ISTET=0?
Yes
A
No
H
6
6
LD=1 or 4?
Yes
F
No
LD=3?
Yes
G
No
CALL SNS
F
CALL VISC
VISA=1?
Yes
No
I
Yes
LD=1?
No
LD=4
and
NMN=1?
Yes
I
No
ISTET≠0?
Yes
I
No
G
7

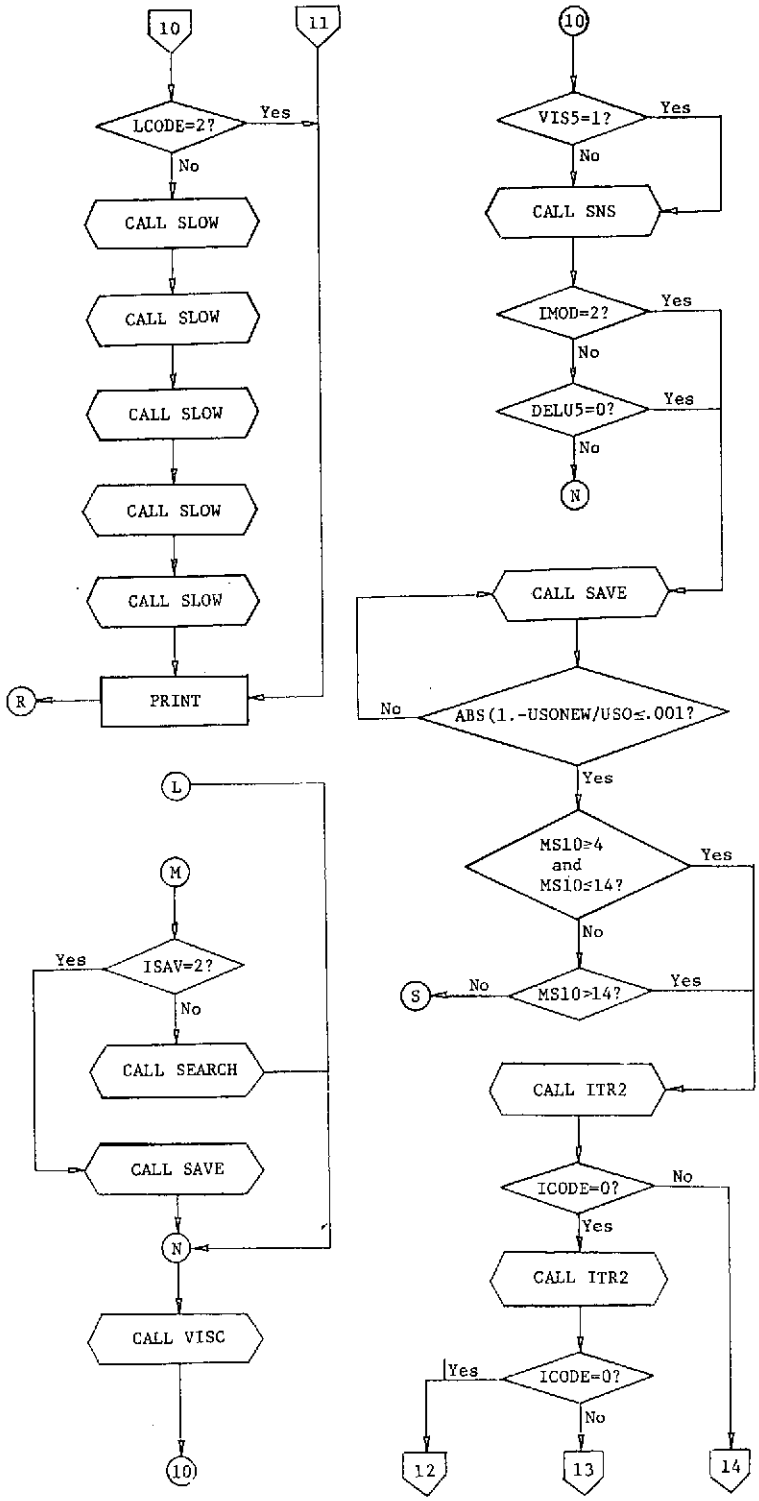
APPENDIX A


7
ISAV=2?
Yes
No
CALL SEARCH
CALL SAVE
No
ABS(1.-RNEW/RHOR)≤.001?
Yes
I
A
Yes
ISTET=0?
No
V
No
HFRO>0?
Yes
Yes
LF=2?
No
No
A5F>0?
Yes
CALL VISC
7
8
7
8
VIS5F=1?
Yes
No
CALL SNS
LF=2?
Yes
K
No
IEQ=2
and
IEXP=1?
Yes
J
No
Yes
IEXP=2?
No
R
CALL SLOW
LCODE=2?
Yes
No
CALL SIMR
LF=2?
Yes
L
No
8
9

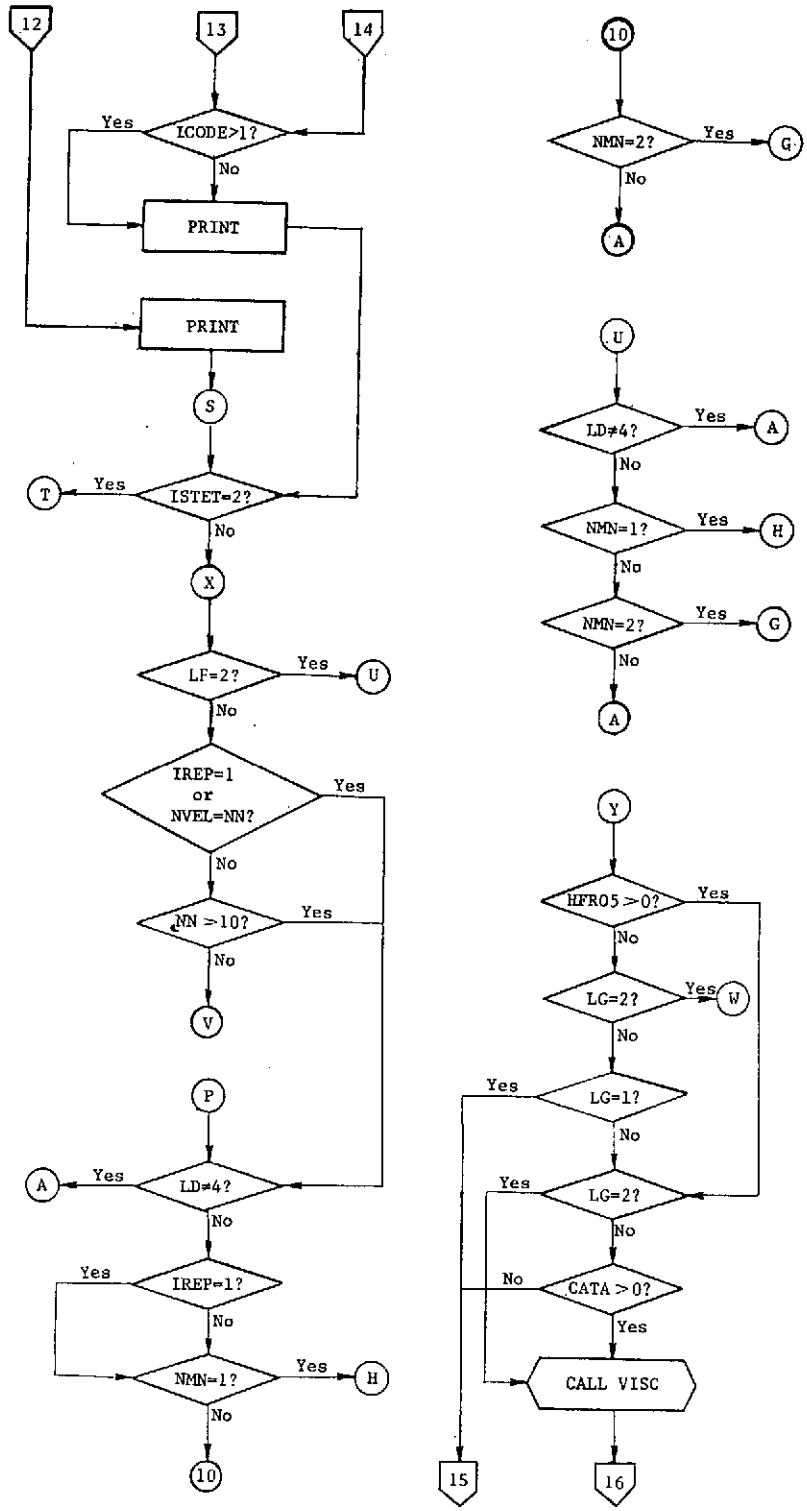
APPENDIX A


8
9
P5F≥.1?
Yes
No
Q
CALL SAVE
CALL SIMR
LF=1?
Yes
No
N
J
CALL FTLUP
IEXP=1?
Yes
No
M
CALL FTLUP
Yes
II5≥5.E+4?
No
P
CALL SLOW
9
9
LCODE=2?
Yes
No
CALL SLOW
CALL SLOW
CALL SLOW
CALL SLOW
CALL SLOW
N
PRINT
K
Yes
ISAV=1?
No
CALL SAVE
Q
No
IEXP=1?
Yes
CALL SLOW
10
11

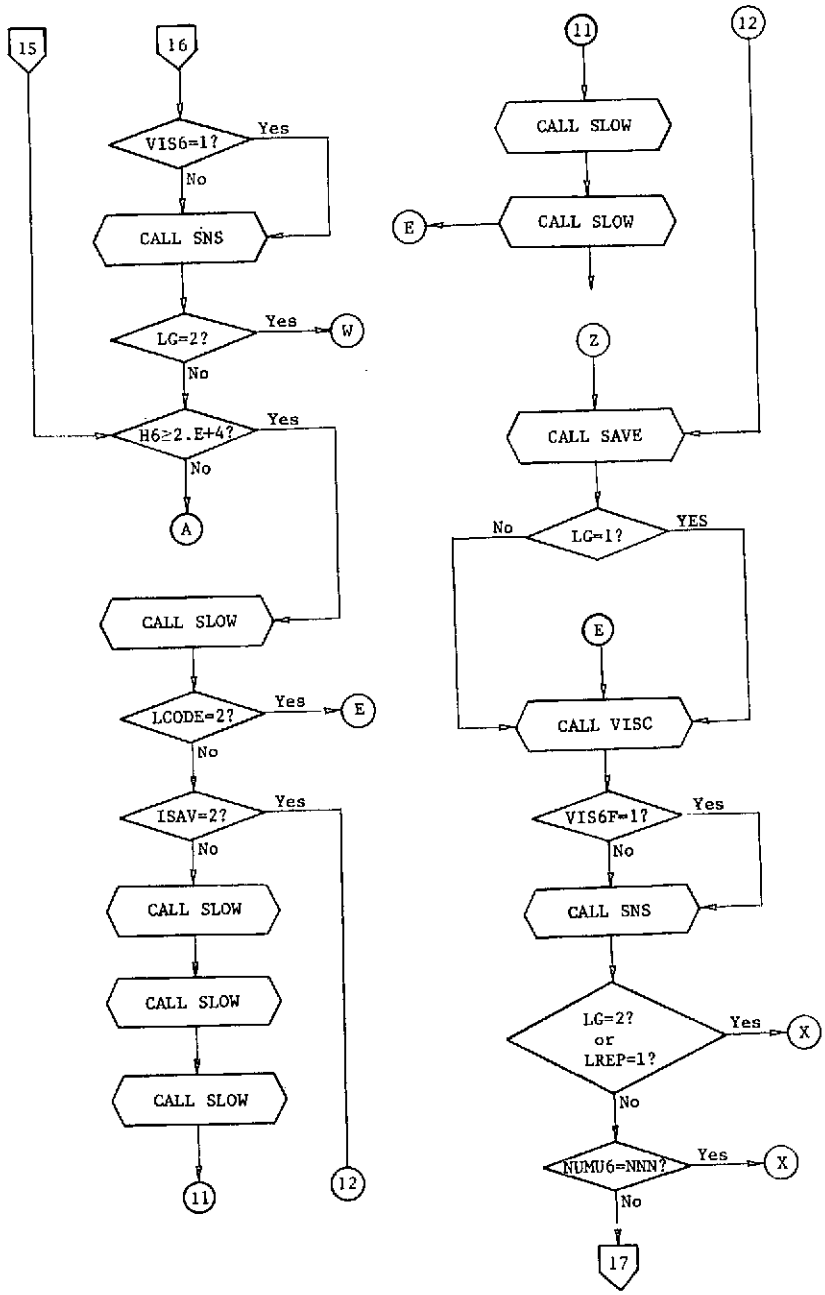
APPENDIX A


10
11
LCODE=2?
Yes
No
CALL SLOW
CALL SLOW
CALL SLOW
CALL SLOW
CALL SLOW
R
PRINT
10
VIS5=1?
Yes
No
CALL SNS
IMOD=2?
Yes
No
DELU5=0?
Yes
No
N
CALL SAVE
No
ABS(1.-USONEW/USO≤.001?
Yes
MS10≥4
and
MS10≤14?
Yes
No
S
No
MS10≥14?
Yes
CALL ITR2
ICODE=0?
No
Yes
CALL ITR2
Yes
ICODE=0?
No
12
13
14
L
M
Yes
ISAV=2?
No
CALL SEARCH
CALL SAVE
N
CALL VISC
10

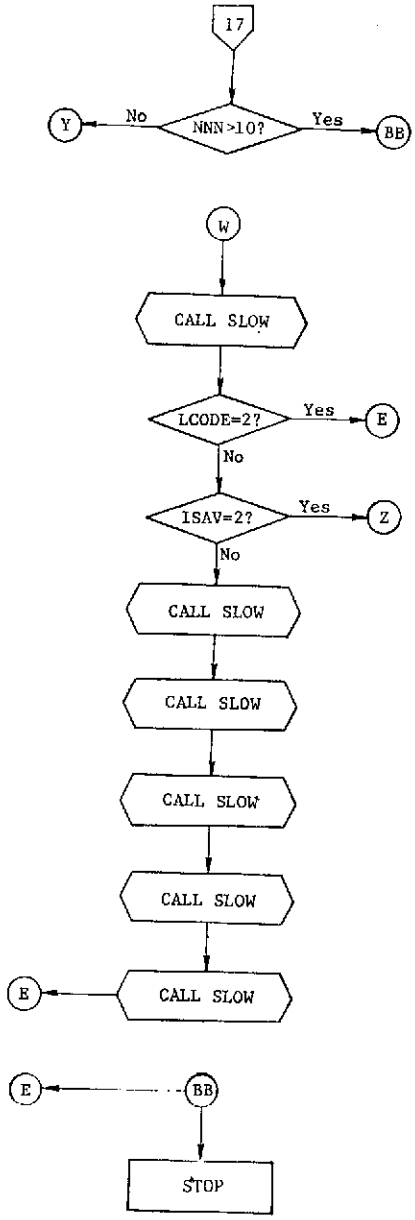
APPENDIX A


12
13
14
Yes
ICODE>1?
No
PRINT
PRINT
S
T
Yes
ISTET=2?
No
X
LF=2?
Yes
U
No
IREP=1
or
NVEL=NN?
Yes
No
NN >10?
Yes
No
V
P
A
Yes
LD≠4?
No
Yes
IREP=1?
No
NMN=1?
Yes
H
No
10
10
NMN=2?
Yes
G
No
A
U
LD≠4?
Yes
A
No
NMN=1?
Yes
H
No
NMN=2?
Yes
G
No
A
Y
HFR05 >0?
Yes
No
LG=2?
Yes
W
No
Yes
LG=1?
No
Yes
LG=2?
No
No
CATA >0?
Yes
CALL VISC
15
16

APPENDIX A


15
16
VIS6=1?
Yes
No
CALL SNS
LG=2?
Yes
W
No
H6≥2.E+4?
Yes
No
A
CALL SLOW
LCODE=2?
Yes
E
No
ISAV=2?
Yes
No
CALL SLOW
CALL SLOW
CALL SLOW
11
12
11
12
CALL SLOW
E
CALL SLOW
Z
CALL SAVE
No
LG=1?
YES
E
CALL VISC
VIS6F=1?
Yes
No
CALL SNS
LG=2?
or
LREP=1?
Yes
X
No
NUMU6=NNN?
Yes
X
No
17

APPENDIX A


17
NNN>10?
No
Yes
Y
BB
W
CALL SLOW
LCODE=2?
Yes
E
No
ISAV=2?
Yes
Z
No
CALL SLOW
CALL SLOW
CALL SLOW
CALL SLOW
E
CALL SLOW
E
BB
STOP

APPENDIX A

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

```
JOB,1,0700,115000,20000.          A3187   P3348       100690          1250          CENT
USER,MILLER, CHARLES G  III              000605575N 64720
LINECNT(20000),
RUN(S),
REQUEST,TAPE8,HY,X.       716011,ROL
REWIND(TAPE8),
SETINDF.  ,
LGO.      ,
SPPRINT(OUTPUT,3),
UNLOAD(TAPE8),
EXIT..
SPPRINT(OUTPUT,3),
UNLOAD(TAPE8),
- ,
      PROGRAM LET(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8)                    A    1
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NB(4)                   A    2
      DIMENSION TABHR(300), TABA(300), TABANS(300), TABR(100), R5G(100)           A    3
      DIMENSION RESULT(2), IN(4), R5K(100)                                        A    4
      DIMENSION TABTI(50), TABRI(50), TABZI(50), TABHI(50)                        A    5
      DIMENSION TABAI(50), TABUI(50), XA(10)                                      A    6
      DIMENSION US1I(20), U2I(20), P2I(20), H2I(20), RH2I(20)                     A    7
      DIMENSION XSLM(5), RNON(5), P2X(5), U2X(5), H2X(5), T2X(5), R2Y(5)          A    8
     1, A2X(5), RXR(5), RXH(5), RXU(5), RXR(5), RXT(5), RXA(5)                    A    9
      REAL MS1,M2,M5,M55,MX,MN,MNS,MS,MA,M5F,M55F,M55FF,MR,M20                    A   10
      REAL M6,M65,M6F,M65F,M6FF,M510                                              A   11
      EXTERNAL FOFX,FOFR,FOFMS,FOFAX,FOFRX,FOFAXT,FOFRXT                          A   12
      COMMON ICOUNT,IMET(2),ND,ARAR,MF,MF,SAR,LCODE,DELU,ISAV                     A   13
      COMMON /BLK1/ RT4,CT4,RHOG                                                  A   14
      COMMON /BLK2/ RTI,CTI,TI,CVRI,S4R,SRFF,DRTI,DCTI                            A   15
      COMMON /BLK3/ T1,GAM4,W4,T4,P4,R1                                           A   16
      COMMON /BLK4/ LF,NON,LU,NDRIV,LB,LD,LG                                      A   17
      COMMON /BLK5/ SR,TII,AI,ZI,CI,K,P2,ISP                                      A   18
      COMMON /BLK6/ BETA1,BETA2                                                   A   19
      NAMELIST /INP/ T1,P1,US1,P2,LB,LD,LF,LG,U5,R5,R6,U6,R4,T4,IAC,RUN,          A   20
     1ISTET,DIA,NDRIV,XIS,XAS,TW,RNR,ISAV,IEXP,US1,IREP,NVEL,INU,DIAT,DI          A   21
     2AN,LREP,NUMU6,U61,JAC,DELUS                                                 A   22
      CALL DAYTIM (RESULT)                                                        A   23
C                                                                                 A   24
C     SHOCK TUBE PHASE                                                            A   25
C                                                                                 A   26
C     NDRIV=0 DENOTES IMPERFECT HELIUM DRIVER GAS                                 A   27
C     NDRIV=1 DENOTES IMPERFECT HYDROGEN GAS                                      A   28
C                                                                                 A   29
C     LB=0 DENOTES SHOCK TUBE INPUTS P1,T1,US1                                    A   30
C     LB=1 DENOTES SHOCK TUBE INPUTS P1,T1,P2                                     A   31
C     LB=2 DENOTES SHOCK TUBE INPUTS P1,T1,P4,T4                                  A   32
C                                                                                 A   33
C     XIS IS DISTANCE DOWNSTREAM FROM PRIMARY DIAPHRAGM                           A   34
C     XAS IS DISTANCE DOWNSTREAM FROM SECONDARY DIAPHRAGM                         A   35
C                                                                                 A   36
C     DIA IS SHOCK TUBE OR EXPANSION TUBE DIAMETER                                A   37
C     DIAT IS NOZZLE THROAT DIAMETER                                              A   38
C     DIAN IS NOZZLE TEST SECTION DIAMETER                                        A   39
C                                                                                 A   40
C     ISTET DENOTES PHASE(S) CALCULATED                                           A   41
C     ISTET=0 DENOTES SHOCK TUBE PHASE ONLY                                       A   42
C     ISTET=1 DENOTES EXPANSION TUBE PHASE                                        A   43
C     ISTET=2 DENOTES EXPANSION TUNNEL PHASE                                      A   44
C                                                                                 A   45
C     ISAV=1 DENOTES USE OF REAL AIR TAPE (SLOW,SEARCH)                           A   46
C     ISAV=2 DENOTES USE OF AEDC CURVE FITS (SAVE)                                A   47
```

```
C
C     INU=1 DENOTES USE OF TAPE FOR FLOW NONUNIFORMITY CALC IN REGION 2
C     INU=2 DENOTES USE OF CURVE FITS FOR FLOW NONUNIFORMITY IN REGION 2
C
C     LD=1 DENOTES INCIDENT SHOCK ONLY
C     LD=2 DENOTES STANDING SHOCK ONLY
C     LD=3 DENOTES REFLECTED SHOCK ONLY
C     LD=4 DENOTES INCIDENT,STANDING, AND REFLECTED SHOCKS
C
C     FOR ISTET=0 AND LD=2, CONDITIONS IN REGIONS 2,2S,2T,2R DETERMINED
C
C     IEXP=1 DENOTES USE OF TAPE FOR UNSTEADY EXPANSION
C     IEXP=2 DENOTES USE OF CURVE FITS FOR UNSTEADY EXPANSION
C
C     JAC IS NUMBER OF INCREMENTS USED IN UNSTEADY EXPANSION FOR IEXP=1
C     JAC HAS MAXIMUN VALUE OF 300
C
C     IAC IS NUMBER OF INCREMENTS USED IN UNSTEADY EXPANSION FOR IEXP=2
C     IAC HAS MAXIMUN VALUE OF 100
C
C     DELUS IS ATTENUATION IN INTERFACE VELOCITY US, M/SEC
C
C     IREP=1 DENOTES SINGLE VALUE OF US OF INTEREST
C     IREP=2 DENOTES SEVERAL US OF INTEREST
C
C     US1 IS US INCREMENT FOR IREP=2
C     NVEL IS TOTAL NUMBER OF US OF INTEREST FOR IREP=2
C
C     LREP=1 DENOTES SINGLE VALUE OF U6 OF INTEREST
C     LREP=2 DENOTES SEVERAL U6 OF INTEREST
C
C     U61 IS U6 INCREMENT FOR LREP=2
C     NUMU6 IS TOTAL NUMBER OF U6 OF INTEREST FOR LREP=2
C
      IT=8
      NV=0
      RU=8.31434E+3
      W=28.967
      MM=0
      READ (5,234) IN
1     US1=P2=P4=T4=US=P5=U6=P6=DELUS=0.0
      NN=NNN=LB=NDRIV=0
      NMN=RUN=ISTET=LE=IEXP=LG=ISP=1
      ISAV=IREP=LREP=INU=2
      LD=4
      NVEL=8
      NUMU6=5
      JAC=IAC=50
      T1=TW=300.
      DIA=.1524
      DIAT=.0762
      DIAN=.6452
      XIS=4.65
      XAS=16.98
      BNR=.0254
      US1=400.
      U61=50.
      READ (5,INP)
      IF (ENDFILE 5) 144,2
2     CONTINUE
      PRINT 235, RESULT(1)
      PRINT 234, IN
      PRINT 148
      PRINT 149
      PRINT 150
      PRINT 151
```

APPENDIX A

```
      PRINT 152                                                          A 114
      PRINT 153, RUN,P1,T1,US1,P2,P4,T4,XIS,DIA,ISAV,INU,LD              A 115
      IMET(1)=IMET(2)=0                                                  A 116
      LCODE=1                                                            A 117
      SSUM=0.                                                            A 118
      LU=0                                                               A 119
      K=3                                                                A 120
      HW=1.0046E+3*TW                                                    A 121
      RHO1=(P1*W)/(RU*T1)                                                A 122
      H1=3.49*(RU/W)*T1                                                  A 123
      A1=SQRT(1.4*(RU/W)*T1)                                             A 124
      IF (LB.EQ.2) GO TO 4                                               A 125
C                                                                        A 126
C     INPUTS P1, T1, AND US1(LB=0)                                       A 127
C     INPUTS P1, T1, AND P2(LB=1)                                        A 128
C                                                                        A 129
      CALL SC (RHO2,U2,P2,H2,RHO1,US1,P1,H1,ISAV)                        A 130
      S2R=SR                                                             A 131
      T2=T11                                                             A 132
      A2=A1                                                              A 133
      Z2=Z1                                                              A 134
      GAM2=G1                                                            A 135
      M2=U2/A2                                                           A 136
      MS1=US1/A1                                                         A 137
      RE2=0.0                                                            A 138
      CALL VISC (T2,P2,VIS2)                                             A 139
      IF (VIS2.EQ.1.0) GO TO 3                                           A 140
      RE2=RHO2*U2/VIS2                                                   A 141
3     CONTINUE                                                           A 142
      GO TO 31                                                           A 143
C                                                                        A 144
C     INPUTS P4, T4, P1, AND T1(LB=2)                                    A 145
C                                                                        A 146
4     LU=20                                                              A 147
      R=8.31434E+3                                                       A 148
      IF (NDRIV.EQ.1) GO TO 5                                            A 149
C                                                                        A 150
C     HELIUM DRIVER GAS(NDRIV=0)                                         A 151
C                                                                        A 152
      HWRT=2.5                                                           A 153
      CVR1=1.5                                                           A 154
      SREF=4.8024                                                        A 155
      GAM4=1.66667                                                       A 156
      W4=4.003                                                           A 157
      RHOG=(P4*W4)/(R*T4)                                                A 158
      ALOW=.70*RHOG                                                      A 159
      GO TO 6                                                            A 160
C                                                                        A 161
C     HYDROGEN DRIVER GAS(NDRIV=1)                                       A 162
C                                                                        A 163
5     HWRT=3.5                                                           A 164
      CVR1=2.5                                                           A 165
      SREF=-1.0363                                                       A 166
      GAM4=1.4                                                           A 167
      W4=2.016                                                           A 168
      RHOG=(P4*W4)/(R*T4)                                                A 169
      ALOW=.50*RHOG                                                      A 170
6     AUP=1.05*RHOG                                                      A 171
      DELTX=(AUP-ALOW)/100.                                              A 172
      E1=.1E-6                                                           A 173
      CALL BDT (BT4,CT4,DBT4,DCT4,D2BT4,D2CT4,T4)                        A 174
      RHO4=1.2*RHOG                                                      A 175
      CALL ITR1 (RHO4,DELTX,FOFX,E1,E1,200,ICODE)                        A 176
      IF (ICODE) 7,10,7                                                  A 177
7     GO TO (8,9,9,9), ICODE                                             A 178
8     PRINT 154                                                          A 179
      GO TO 1                                                            A 180
```

```
9       PRINT 155, ICODE                                                    A 181
        GO TO 1                                                             A 182
10      Z4=1.+RH04*BT4+RH04**2*CT4                                          A 183
        H4=(R*T4/W4)*(HWRT+RH04*(BT4-T4*DBT4)+(RH04**2/2.)*(2.*CT4-T4*DCT4  A 184
       1))                                                                  A 185
        S4R=CVRI*ALOG(T4)-ALOG(RH04)-RH04*(BT4+T4*DBT4)-(RH04**2/2.)*(CT4+  A 186
       1T4*DCT4)+SREF                                                       A 187
        CVR=CVRI-T4*(RH04*(2.*DBT4+T4*D2BT4)+(RH04**2/2.)*(2.*DCT4+T4*D2CT  A 188
       14))                                                                 A 189
        PPTR=(RH04*R/W4)*(1.+RH04*(BT4+T4*DBT4)+(RH04**2)*(CT4+T4*DCT4))    A 190
        PPRT=(T4*R/W4)*(1.+2.*RH04*BT4+3.*RH04**2*CT4)                      A 191
        A4=SQRT(PPRT+((T4*W4)/(CVR*R*RH04**2))*PPTR**2)                     A 192
        TABTI(1)=T4                                                         A 193
        TABPI(1)=P4                                                         A 194
        TABRI(1)=RH04                                                       A 195
        TABZI(1)=Z4                                                         A 196
        TABHI(1)=H4                                                         A 197
        TABAI(1)=1./A4                                                      A 198
        TSC=ALOG10(T4)                                                      A 199
        DELT=TSC/50.                                                        A 200
        NU=1                                                                A 201
        DO 11 I=2,50                                                        A 202
        TABTI(I)=TSC-FLOAT(I-1)*DELT                                        A 203
        TABTI(I)=10.**TABTI(I)                                              A 204
11      CONTINUE                                                            A 205
        AUP=1.1*RH04                                                        A 206
        ALOW=1.E-6                                                          A 207
        DELR=(AUP-ALOW)/200.                                                A 208
        RI=RH04                                                             A 209
        DO 17 I=2,50                                                        A 210
        TI=TABTI(I)                                                         A 211
        IF (TI.LT.3.) GO TO 18                                              A 212
        CALL BDT (BTI,CTI,DBTI,DCTI,D2BTI,D2CTI,TI)                         A 213
        CALL ITR2 (RI,ALOW,AUP,DELR,FOFR,F1,F1,400,ICODE)                   A 214
        IF (ICODE) 12,16,12                                                 A 215
12      GO TO (13,14,14,15), ICODE                                          A 216
13      PRINT 154                                                           A 217
        GO TO 1                                                             A 218
14      PRINT 155, ICODE                                                    A 219
        GO TO 1                                                             A 220
15      PRINT 156, ICODE,RI,DELR                                            A 221
        GO TO 1                                                             A 222
16      TABRI(I)=RI                                                         A 223
        TABZI(I)=1.+RI*BTI+RI**2*CTI                                        A 224
        TABPI(I)=TI*(R/W4)*RI*TABZI(I)                                      A 225
        TABHI(I)=(R*TI/W4)*(HWRT+RI*(BTI-TI*DBTI)+(RI**2/2.)*(2.*CTI-TI*DC  A 226
       1TI))                                                                A 227
        CVIR=CVRI-TI*(RI*(2.*DBTI+TI*D2BTI)+(RI**2/2.)*(2.*DCTI+TI*D2CTI))  A 228
        PPTRI=(RI*R/W4)*(1.+RI*(BTI+TI*DBTI)+(RI**2)*(CTI+TI*DCTI))         A 229
        PPRTI=(TI*R/W4)*(1.+2.*RI*BTI+3.*RI**2*CTI)                         A 230
        TABAI(I)=1./(SQRT(PPRTI+((TI*W4)/(CVIR*R*RI**2))*PPTRI**2))         A 231
        NU=NU+1                                                             A 232
17      CONTINUE                                                            A 233
18      CALL SIMR (TABHI,TABAI,NU,NU,TABANS)                                A 234
        PRINT 157                                                           A 235
        DO 19 I=1,NU                                                        A 236
        PRINT 158, TABPI(I),TABTI(I),TABRI(I),TABZI(I),TABHI(I),TABAI(I),T  A 237
       1ABANS(I)                                                            A 238
19      CONTINUE                                                            A 239
        MS=1.4                                                              A 240
        DELS=.2                                                             A 241
        CALL ITR1 (MS,DELS,FOFMS,F1,E1,200,ICODE)                           A 242
        IF (ICODE) 20,23,20                                                 A 243
20      GO TO (21,22,22), ICODE                                             A 244
21      PRINT 154                                                           A 245
        GO TO 1                                                             A 246
```

```
22    PRINT 155, ICODE                                                    A 247
      GO TO 1                                                             A 248
23    A1=SQRT(401.839*T1)                                                 A 249
      USMAX=1.1*A1*MS                                                     A 250
      USMIN=.65*USMAX                                                     A 251
      US1I(1)=USMAX                                                       A 252
      DEL1=(USMAX-USMIN)/20.                                              A 253
      PRINT 159                                                           A 254
      DO 24 I=1,20                                                        A 255
      US1I(I)=USMAX-FLOAT(I-1)*DEL1                                       A 256
      CALL SC (RH2I(I),U2I(I),P2I(I),H2I(I),RH01,US1I(I),P1,H1,ISAV)      A 257
      PRINT 160, P2I(I),RH2I(I),H2I(I),U2I(I),US1I(I)                     A 258
24    CONTINUE                                                            A 259
      CALL SOLUT (TABANS,TABPI,U2I,P2I,NU,20,UR,P)                        A 260
      P2=P                                                                A 261
      U2=UP                                                               A 262
      US1=(P2-P1)/(RH01*U2)                                               A 263
      MS1=US1/A1                                                          A 264
      H2=H1+.5*US1**2-.5*(US1-U2)**2                                      A 265
      GO TO (25,26), ISAV                                                 A 266
25    CALL SEARCH (P2,RH02,H2,S2R,T2,A2,Z2,GAM2,ZS2,ISP)                  A 267
      GO TO 27                                                            A 268
26    CALL SAVE (P2,RH02,H2,S2R,T2,A2,Z2,GAM2,3)                          A 269
      ZS2=Z2                                                              A 270
27    M2=U2/A2                                                            A 271
      RE2=0.0                                                             A 272
      CALL VISC (T2,P2,VIS2)                                              A 273
      IF (VIS2.EQ.1.0) GO TO 28                                           A 274
      RE2=RH02*U2/VIS2                                                    A 275
28    CONTINUE                                                            A 276
      IF (LB.NE.2) GO TO 31                                               A 277
      IF (NDRIV.EQ.0) GO TO 29                                            A 278
      PRINT 161                                                           A 279
      GO TO 30                                                            A 280
29    PRINT 162                                                           A 281
30    PRINT 163                                                           A 282
      PRINT 164                                                           A 283
      PRINT 165, P4,RH04,T4,H4,S4R,Z4,A4,W4                               A 284
31    PRINT 147                                                           A 285
      PRINT 166                                                           A 286
      PRINT 147                                                           A 287
      PRINT 167                                                           A 288
      PRINT 168, P2,RH02,T2,H2,S2R,Z2,GAM2,A2,U2,M2,RE2                   A 289
      RAP=P2/P1                                                           A 290
      RARHO=RH02/RH01                                                     A 291
      RAT=T2/T1                                                           A 292
      RAH=H2/H1                                                           A 293
      RAA=A2/A1                                                           A 294
      PRINT 169                                                           A 295
      PRINT 170                                                           A 296
      PRINT 171, RAP,RARHO,RAT,RAH,RAA,MS1,US1                            A 297
C                                                                         A 298
C     SHOCK TUBE TEST TIME-REFERENCE MIRELS(PHYS OF FLUIDS,SEPT 1963)     A 299
C                                                                         A 300
      PRINT 172                                                           A 301
      PRINT 173                                                           A 302
      IF (MS1.GE.4..AND.MS1.LE.14.) GO TO 32                              A 303
      IF (MS1.GT.14.) GO TO 33                                            A 304
      PRINT 174                                                           A 305
      GO TO 55                                                            A 306
C                                                                         A 307
C     XLMAX IS MAXIMUM SEPARATION DISTANCE-SHOCK TO INTERFACE             A 308
C     XL IS SEPARATION DISTANCE-SHOCK TO INTERFACE                        A 309
C                                                                         A 310
C     LAMINAR CASE                                                        A 311
C                                                                         A 312
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32    XLMAX=P1*DIA**2*(2.06-.2056*MS1+8.095E-3*MS1**2)                    A 313
      GO TO 34                                                            A 314
33    XLMAX=P1*DIA**2*(.8723-7.488E-3*MS1)                                A 315
34    BETA1=XIS*RHO1/(2.*XLMAX*RHO2)                                      A 316
      BETA2=2.*RHO2/RHO1                                                  A 317
      AXUP=.999999999                                                     A 318
      AXLOW=.00001                                                        A 319
      DELTAX=(AXUP-AXLOW)/100.                                            A 320
      E1=.1E-6                                                            A 321
      AX=.5                                                               A 322
      CALL ITR2 (AX,AXLOW,AXUP,DELTAX,FOFAX,E1,E1,200,ICODE)              A 323
      IF (ICODE) 7,35,7                                                   A 324
C                                                                         A 325
C     RXL IS RATIO OF XL TO XLMAX                                         A 326
C                                                                         A 327
35    RXL=AX**2                                                           A 328
      XL=RXL*XLMAX                                                        A 329
C                                                                         A 330
C     TAUI IS IDEAL TEST TIME                                             A 331
C                                                                         A 332
      TAUI=RHO1*XIS/(RHO2*U2)                                             A 333
C                                                                         A 334
C     BX IS SQRT OF US1*TAU/XLMAX                                         A 335
C                                                                         A 336
      BXUP=.999999999                                                     A 337
      BXLOW=.00001                                                        A 338
      DELTBX=(BXUP-BXLOW)/100.                                            A 339
      BX=.5                                                               A 340
      CALL ITR2 (BX,BXLOW,BXUP,DELTBX,FOFBX,E1,E1,200,ICODE)              A 341
      IF (ICODE) 7,36,7                                                   A 342
36    TAU=BX**2*XLMAX/US1                                                 A 343
      UI=XL/TAU                                                           A 344
C                                                                         A 345
C     TURBULENT CASE                                                      A 346
C                                                                         A 347
      IF (MS1.GE.4..AND.MS1.LT.10.) GO TO 37                              A 348
      IF (MS1.GE.10.) GO TO 38                                            A 349
      PRINT 174                                                           A 350
      GO TO 55                                                            A 351
37    XLMAXT=(P1**.25)*(DIA**1.25)*(5.2729-.751385*MS1+.03435*MS1**2)     A 352
      GO TO 39                                                            A 353
38    XLMAXT=(P1**.25)*(DIA**1.25)*(1.5464-.030174*MS1)                   A 354
39    DELAXT=DELTAX                                                       A 355
      AXT=.5                                                              A 356
      BETA1=XIS*RHO1/(2.*XLMAXT*RHO2)                                     A 357
      CALL ITR2 (AXT,AXLOW,AXUP,DELAXT,FOFAXT,E1,E1,200,ICODE)            A 358
      IF (ICODE) 7,40,7                                                   A 359
C                                                                         A 360
C     RXLT IS RATIO OF XLT TO LTMAXT(TURBULENT CASE)                      A 361
C                                                                         A 362
40    RXLT=AXT**5                                                         A 363
      XLT=RXLT*XLMAXT                                                     A 364
      BXTUP=.999999999                                                    A 365
      BXTLOW=.00001                                                       A 366
      DELBXT=(BXTUP-BXTLOW)/100.                                          A 367
      BXT=.5                                                              A 368
      CALL ITR2 (BXT,BXTLOW,BXTUP,DELBXT,FOFBXT,E1,E1,200,ICODE)          A 369
      IF (ICODE) 7,41,7                                                   A 370
41    TAUT=BXT**5*XLMAXT/US1                                              A 371
      UIT=XLT/TAUT                                                        A 372
      PRINT 175, XLMAX,XL,RXL,TAU,UI,XLMAXT,XLT,RXLT,TAUT,UIT,TAUI       A 373
      IF (ISTET.NE.0) GO TO 55                                            A 374
C                                                                         A 375
C     SHOCK TUBE FLOW NONUNIFORMITY-LAMINAR CASE                          A 376
C                                                                         A 377
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      IF (RXL.GE.0.9) GO TO 42                                          A 378
      PRINT 176                                                         A 379
      GO TO 50                                                          A 380
42    PRINT 177                                                         A 381
      PRINT 178                                                         A 382
      PRINT 179                                                         A 383
C                                                                       A 384
C     FUD IS RATIO OF XS TO XL                                          A 385
C                                                                       A 386
      MNM=0                                                             A 387
      FUD=.2                                                            A 388
      XSLM(1)=FUD*RXL                                                   A 389
      DO 49 I=1,5                                                       A 390
      BNON(I)=RH02*(US1-U2)*(1.-SQRT(XSLM(I)))                          A 391
43    CNON=H2+.5*(US1-U2)**2                                            A 392
      DNON=P2+RH02*(US1-U2)**2                                          A 393
      R2X(I)=1.01*RH02                                                  A 394
44    U2X(I)=US1-BNON(I)/R2X(I)                                         A 395
      GO TO (45,47), INU                                                A 396
45    H2X(I)=CNON-.5*(US1-U2X(I))**2                                    A 397
      Z(4)=ALOG10(H2X(I)/287.0245)                                      A 398
      IMFT(1)=IMFT(2)=0                                                 A 399
      CALL SLOW (S2R,Z,4,2,IT,NV,NERR,Y,X)                              A 400
      R2XN=(10.**Z(2))*1.2914889                                        A 401
      IF (ABS(1.-R2X(I)/R2XN).LE..001) GO TO 46                         A 402
      R2X(I)=R2XN                                                       A 403
      GO TO 44                                                          A 404
46    Z(2)=ALOG10(R2X(I)/1.2914889)                                     A 405
      CALL SLOW (S2R,Z,2,1,IT,NV,NERR,Y,X)                              A 406
      T2X(I)=Z(1)                                                       A 407
      CALL SLOW (S2R,Z,2,3,IT,NV,NERR,Y,X)                              A 408
      P2X(I)=(10.**Z(3))*1.013245E+5                                    A 409
      CALL SLOW (S2R,Z,2,6,IT,NV,NERR,Y,X)                              A 410
      A2X(I)=Z(6)*331.4193                                              A 411
      GO TO 48                                                          A 412
C                                                                       A 413
C     INU=1 BASED ON ENERGY EQ. AND INU=2 BASED ON MOMENTUM EQ.         A 414
C                                                                       A 415
47    P2X(I)=DNON-R2X(I)*(US1-U2X(I))**2                                A 416
      CALL SAVE (P2X(I),R2XN,H2X(I),S2R,T2X(I),A2X(I),Z2X,GAM2X,I)      A 417
      IF (ABS(1.-R2X(I)/R2XN).LE..001) GO TO 48                         A 418
      R2X(I)=R2XN                                                       A 419
      GO TO 44                                                          A 420
48    RXR(I)=R2X(I)/RH02                                                A 421
      RXH(I)=H2X(I)/H2                                                  A 422
      RXU(I)=U2X(I)/U2                                                  A 423
      RXP(I)=P2X(I)/P2                                                  A 424
      RXT(I)=T2X(I)/T2                                                  A 425
      RXA(I)=A2X(I)/A2                                                  A 426
      PRINT 180, XSLM(I),RXP(I),RXR(I),RXT(I),RXH(I),RXA(I),RXU(I)     A 427
      IF (MNM.EQ.1) GO TO 52                                            A 428
      FUD=FUD+.2                                                        A 429
      XSLM(I+1)=FUD*RXL                                                 A 430
49    CONTINUE                                                          A 431
C                                                                       A 432
C     SHOCK TUBE FLOW NONUNIFORMITIES-TURBULENT CASE                    A 433
C                                                                       A 434
50    IF (RXLT.GE.0.9) GO TO 51                                         A 435
      PRINT 181                                                         A 436
      GO TO 54                                                          A 437
51    PRINT 182                                                         A 438
      PRINT 178                                                         A 439
      PRINT 179                                                         A 440
      FUD=.2                                                            A 441
      XSLM(1)=FUD*RXLT                                                  A 442
      DO 53 I=1,5                                                       A 443
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```
      RNON(I)=RHO2*(US1-U2)*(1.-(XSLM(I))**.8)                          A 444
      MNM=1                                                             A 445
      GO TO 43                                                          A 446
52    FUD=FUD+.2                                                        A 447
      XSLM(I+1)=FUD*RXLT                                                A 448
53    CONTINUE                                                          A 449
C                                                                       A 450
C     STANDING OR REFLECTED SHOCK AT SECOND DIAPHRAGM                   A 451
C                                                                       A 452
54    IF (LD.EQ.1.AND.ISTET.EQ.0) GO TO 1                               A 453
55    GO TO (57,56,60,57), LD                                           A 454
C                                                                       A 455
C     STANDING SHOCK PHASE                                              A 456
C                                                                       A 457
56    CALL SNS (RHOA,UA,PA,HA,SAR,TA,AA,ZA,GAMA,ZSTARA,MA,RHO2,U2,P2,H2,  A 458
     1HT2,PT2,RT2,ST2R,TT2,AT2,ZT2,GT2,ZSTART2)                         A 459
      HUP=HA                                                            A 460
      NMN=2                                                             A 461
      GO TO 58                                                          A 462
C                                                                       A 463
C     CONDITIONS IN REGION A FOR NO STANDING SHOCK                      A 464
C                                                                       A 465
57    PA=P2                                                             A 466
      RHOA=RHO2                                                         A 467
      TA=T2                                                             A 468
      SAR=S2R                                                           A 469
      HA=H2                                                             A 470
      HUP=HA                                                            A 471
      AA=A2                                                             A 472
      UA=U2                                                             A 473
      ZA=Z2                                                             A 474
      GAMA=GAM2                                                         A 475
      ZSA=ZS2                                                           A 476
58    MA=UA/AA                                                          A 477
      IFO=1                                                             A 478
      REA=0.0                                                           A 479
      CALL VISC (TA,PA,VISA)                                            A 480
      IF (VISA.EQ.1.0) GO TO 59                                         A 481
      REA=RHOA*UA/VISA                                                  A 482
59    CONTINUE                                                          A 483
      IF (LD.EQ.1) GO TO 66                                             A 484
      IF (LD.EQ.4.AND.NMN.EQ.1) GO TO 66                                A 485
      PRINT 147                                                         A 486
      PRINT 183                                                         A 487
      PRINT 147                                                         A 488
      PRINT 167                                                         A 489
      PRINT 168, PA,RHOA,TA,HA,SAR,ZA,GAMA,AA,UA,MA,REA                 A 490
      IF (ISTET.NE.0) GO TO 66                                          A 491
C                                                                       A 492
C     STAGNATION CONDITIONS BEHIND STANDING SHOCK IN SHOCK TUBE         A 493
C                                                                       A 494
      QT2=3.8798E-4*SQRT(PT2/BNR)*(HT2-HW)                              A 495
      PRINT 184                                                         A 496
      PRINT 185                                                         A 497
      PRINT 212, PT2,RT2,TT2,HT2,SAR,ZT2,GT2,AT2,QT2,BNR                A 498
C                                                                       A 499
C     REFLECTED SHOCK PHASE                                             A 500
C                                                                       A 501
60    RHOR=10.*RHO2                                                     A 502
      NMN=3                                                             A 503
61    UR=U2/(RHOR/RHO2-1.)                                              A 504
      PR=P2+RHO2*((U2+UR)**2)-RHOR*UR**2                                A 505
      HR=H2+.5*((U2+UR)**2)-.5*UR**2                                    A 506
      GO TO (62,63), ISAV                                               A 507
```

APPENDIX A

```
62    CALL SEARCH (PR,RNEW,HR,SARR,TR,AR,ZR,GAMR,ZSR,ISP)                A 508
      GO TO 64                                                           A 509
63    CALL SAVE (PR,RNEW,HR,SARR,TR,AR,ZR,GAMR,3)                        A 510
      ZSR=ZR                                                             A 511
64    IF (ABS(1.-RNEW/RHOR).LE..001) GO TO 65                            A 512
      RHOR=RNEW                                                          A 513
      GO TO 61                                                           A 514
65    RHOR=RNEW                                                          A 515
      MR=REAR=UR=0.0                                                     A 516
      PRINT 147                                                          A 517
      PRINT 186                                                          A 518
      PRINT 147                                                          A 519
      PRINT 167                                                          A 520
      PRINT 168, PR,RHOR,TR,HR,SARR,ZR,GAMR,AR,UR,MR,REAR               A 521
      PA=PR                                                              A 522
      RHOA=RHOR                                                          A 523
      TA=TR                                                              A 524
      HA=HR                                                              A 525
      HUR=HR                                                             A 526
      SAR=SARR                                                           A 527
      ZA=ZR                                                              A 528
      GAMA=GAMR                                                          A 529
      AA=AR                                                              A 530
      UA=0.0                                                             A 531
      ZSA=ZSR                                                            A 532
      MA=0.0                                                             A 533
      IFQ=1                                                              A 534
66    IF (ISTET.EQ.0) GO TO 1                                            A 535
C                                                                        A 536
C     EXPANSION TUBE PHASE                                               A 537
C                                                                        A 538
C     LF=1 DENOTES U5 IS BASIC INPUT                                     A 539
C     LF=2 DENOTES P5 IS BASIC INPUT                                     A 540
C                                                                        A 541
C                                                                        A 542
C     FROZEN FLOW- EXPANSION TUBE                                        A 543
C                                                                        A 544
      PRINT 147                                                          A 545
      PRINT 187                                                          A 546
      PRINT 146                                                          A 547
      PRINT 188                                                          A 548
      PRINT 189                                                          A 549
      IF(LF.EQ.1) P5=0.0
      IF(LF.EQ.2) U5=0.0
      PRINT 190, U5,P5,XAS,DELU5,ISAV,IEXP,IREF,NVEL,IAC,JAC             A 550
67    ALPHA=ZA-1.                                                        A 551
      GAMACT=(7.+3.*ALPHA)/(5.+ALPHA)                                    A 552
      AACT=SQRT(GAMACT*ZA*RU*TA/W)                                       A 553
      HACT=AACT**2/(GAMACT-1.)                                           A 554
      HERO=HA-HACT                                                       A 555
      IF (HERO.GT.0.) GO TO 68                                           A 556
      PRINT 191                                                          A 557
      P5F=0.1                                                            A 558
      GO TO 74                                                           A 559
68    GO TO (69,71), LF                                                  A 560
69    U5F=U5                                                             A 561
      A5F=AACT+((GAMACT-1.)/2.)*(UA-U5F)                                 A 562
      IF (A5F.GT.0.) GO TO 70                                            A 563
      PRINT 192                                                          A 564
      P5F=0.1                                                            A 565
      GO TO 74                                                           A 566
70    P5F=PA*((A5F/AACT)**(2.*GAMACT/(GAMACT-1.)))                       A 567
      GO TO 72                                                           A 568
71    P5F=P5                                                             A 569
      A5F=AACT*(P5F/PA)**((GAMACT-1.)/(2.*GAMACT))                       A 570
      U5F=2.*(AACT-A5F)/(GAMACT-1.)+UA                                   A 571
```

```
72      M5F=U5F/A5F                                                     A 572
        T5F=TA*(A5F/AACT)**2                                            A 573
        RHO5F=P5F*W/(RU*ZA*T5F)                                         A 574
        S5RF=SAR                                                        A 575
        H5F=HACT*(T5F/TA)                                               A 576
        ZS5F=ZSA                                                        A 577
        Z5F=ZA                                                          A 578
        GAM5F=GAMACT                                                    A 579
        RE5F=0.0                                                        A 580
        CALL VISC (T5F,P5F,VIS5F)                                       A 581
        IF (VIS5F.EQ.1.0) GO TO 73                                      A 582
        RE5F=RHO5F*U5F/VIS5F                                            A 583
73      CONTINUE                                                        A 584
        TI5F=XAS*((1.0/(U5F-A5F))-(1.0/U5F))                            A 585
        PRINT 193                                                       A 586
        PRINT 167                                                       A 587
        PRINT 168, P5F,RHO5F,T5F,H5F,S5RF,Z5F,GAM5F,A5F,U5F,M5F,RE5F    A 588
C                                                                       A 589
C       SHOCK CROSSING - FROZEN EXPANSION - EQUILIBRIUM POST SHOCK      A 590
C                                                                       A 591
        H5FSC=H5F+HFRO                                                  A 592
        CALL SNS (R5SF,U5SF,P5SF,H5SF,S5SRF,T5SF,A5SF,Z5SF,G5SF,ZS5SF,M5SF  A 593
       1,RHO5F,U5F,P5F,H5FSC,HT5F,PT5F,RT5F,ST5RF,TT5F,AT5F,ZT5F,GT5F,ZST5  A 594
       2F)                                                              A 595
        RATF=R5SF/RHO5F                                                 A 596
        PRINT 203                                                       A 597
        PRINT 194                                                       A 598
        PRINT 205                                                       A 599
        PRINT 206, P5SF,R5SF,T5SF,H5SF,S5SRF,Z5SF,G5SF,A5SF,U5SF,M5SF,RATF  A 600
       1E                                                               A 601
        PRINT 207                                                       A 602
        PRINT 194                                                       A 603
        PRINT 208                                                       A 604
        QTZ0F=3.8798E-4*SQRT(PT5F/RNR)*(HT5F-HW)                        A 605
        PRINT 212, PT5F,RT5F,TT5F,HT5F,ZT5F,GT5F,AT5F,QTZ0F,RNR,TI5F    A 606
        PRINT 203                                                       A 607
        PRINT 195                                                       A 608
        PRINT 205                                                       A 609
        P5SFF=P5F*(2.*GAMACT*M5F**2-GAMACT+1.)/(GAMACT+1.)              A 610
        R5SFF=(RHO5F*(GAMACT+1.)*M5F**2)/((GAMACT-1.)*M5F**2+2.)        A 611
        T5SFF=P5SFF*W/(R5SFF*RU*ZA)                                     A 612
        H5SFF=H5F*T5SFF/T5F                                             A 613
        Z5SFF=ZA                                                        A 614
        G5SFF=GAMACT                                                    A 615
        A5SFF=A5F*SQRT(T5SFF/T5F)                                       A 616
        U5SFF=RHO5F*U5F/R5SFF                                           A 617
        M5SFF=U5SFF/A5SFF                                               A 618
        S5SRFF=(ALOG(P5SFF/P5F)-GAMACT*ALOG(R5SFF/RHO5F))/(GAMACT-1.)+S5RF  A 619
        RATFF=R5SFF/RHO5F                                               A 620
        PRINT 206, P5SFF,R5SFF,T5SFF,H5SFF,S5SRFF,Z5SFF,G5SFF,A5SFF,U5SFF,  A 621
       1M5SFF,RATFF                                                     A 622
        PRINT 207                                                       A 623
        PRINT 195                                                       A 624
        PRINT 208                                                       A 625
        HT5FF=H5F+.5*U5F**2                                             A 626
        TT5FF=T5SFF*HT5FF/H5SFF                                         A 627
        PT5FF=P5SFF*(HT5FF/H5SFF)**(GAMACT/(GAMACT-1.))                 A 628
        RT5FF=PT5FF*W/(TT5FF*ZA*RU)                                     A 629
        ZT5FF=ZA                                                        A 630
        GT5FF=GAMACT                                                    A 631
        AT5FF=A5SFF*SQRT(TT5FF/T5SFF)                                   A 632
        QTZ0FF=3.8798E-4*SQRT(PT5FF/RNR)*(HT5FF-HW)                     A 633
        PRINT 212, PT5FF,RT5FF,TT5FF,HT5FF,ZT5FF,GT5FF,AT5FF,QTZ0FF,RNR,TI  A 634
       1F                                                               A 635
C                                                                       A 636
C       EQUILIBRIUM EXPANSION-EXPANSION TUBE                            A 637
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C                                                                       A 638
74      IF (LF.EQ.2) GO TO 93                                           A 639
C                                                                       A 640
C       LF=1 CASE                                                       A 641
C                                                                       A 642
        IF (IEQ.EQ.2.AND.IEXP.EQ.1) GO TO 87                            A 643
        DELU=U5-UA                                                      A 644
        GO TO (75,82), IEXP                                             A 645
75      HMIN=1.0E+5                                                     A 646
76      DELH=(HUP-HMIN)/(FLOAT(JAC)-1.0)                                A 647
        PRINT 196                                                       A 648
        IMET(1)=IMET(2)=0                                               A 649
        LCODE=1                                                         A 650
        DO 80 J=1,JAC                                                   A 651
        Z(4)=(HUP-FLOAT(J-1)*DELH)/287.0245                             A 652
        Z(4)=ALOG10(Z(4))                                               A 653
        CALL SLOW (SAR,Z,4,6,IT,NV,NERR,Y,X)                            A 654
        GO TO (79,77), LCODE                                            A 655
77      L=J                                                             A 656
        DO 78 K=L,JAC                                                   A 657
        TABHR(K)=HUP-FLOAT(K-1)*DELH                                    A 658
        TABA(K)=1.5766/SQRT(TABHR(K))                                   A 659
78      CONTINUE                                                        A 660
        PRINT 197                                                       A 661
        GO TO 81                                                        A 662
79      TABHR(J)=(10.**Z(4))*287.0245                                   A 663
        TABA(J)=1./(Z(6)*3.314193E+2)                                   A 664
80      CONTINUE                                                        A 665
81      CALL SIMR (TABHR,TABA,JAC,JAC,TABANS)                           A 666
        IF (LF.EQ.2) GO TO 99                                           A 667
        GO TO 86                                                        A 668
82      IF (P5F.GE.0.1) GO TO 83                                        A 669
        P5F=0.1                                                         A 670
83      DELPG=ALOG10(PA/P5F)/(FLOAT(IAC)-1.0)                           A 671
84      P5G(1)=ALOG10(PA)                                               A 672
        PRINT 198                                                       A 673
        P5K(1)=PA                                                       A 674
        TABHR(1)=HA                                                     A 675
        TABA(1)=1./AA                                                   A 676
        TABP(1)=PA                                                      A 677
        DO 85 J=2,IAC                                                   A 678
        P5G(J)=P5G(J-1)-DELPG                                           A 679
        P5K(J)=10.**P5G(J)                                              A 680
        CALL SAVE (P5K(J),RK,HK,SAR,TK,AK,ZK,GK,1)                      A 681
        TABHR(J)=HK                                                     A 682
        TABA(J)=1./AK                                                   A 683
        TABP(J)=P5K(J)                                                  A 684
85      CONTINUE                                                        A 685
        CALL SIMR (TABHR,TABA,IAC,IAC,TABANS)                           A 686
86      IF (LF.EQ.1) GO TO 87                                           A 687
        U5=UA+TABANS(IAC)                                               A 688
        GO TO 103                                                       A 689
87      CALL FTLUP (DELU,H5,2,NON,TABANS,TABHR)                         A 690
        IMOD=1                                                          A 691
        GO TO (89,88), IEXP                                             A 692
88      CALL FTLUP (DELU,P5,2,NON,TABANS,TABP)                          A 693
        GO TO 100                                                       A 694
89      IF (H5.GE.5.E+4) GO TO 90                                       A 695
        PRINT 199                                                       A 696
        GO TO 120                                                       A 697
90      XX=SAR                                                          A 698
        Z(4)=ALOG10(H5/287.0245)                                        A 699
        IMET(1)=IMET(2)=0                                               A 700
        LCODE=1                                                         A 701
        CALL SLOW (XX,Z,4,1,IT,NV,NERR,Y,X)                             A 702
        GO TO (91,92), LCODE                                            A 703
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```
91    CALL SLOW (XX,Z,4,2,IT,NV,NERR,Y,X)                                   A 704
      CALL SLOW (XX,Z,4,3,IT,NV,NERR,Y,X)                                   A 705
      CALL SLOW (XX,Z,4,5,IT,NV,NERR,Y,X)                                   A 706
      CALL SLOW (XX,Z,4,6,IT,NV,NERR,Y,X)                                   A 707
      CALL SLOW (XX,Z,4,7,IT,NV,NERR,Y,X)                                   A 708
      T5=Z(1)                                                               A 709
      R5=(10.**Z(2))*1.2914889                                              A 710
      P5=(10.**Z(3))*1.013246E+5                                            A 711
      GAM5=Z(5)                                                             A 712
      A5=Z(6)*331.4193                                                      A 713
      ZZ5=Z(7)                                                              A 714
      GO TO 103                                                             A 715
92    PRINT 200                                                             A 716
      PRINT 201                                                             A 717
      P5=1.01325E+5*(H5/2.99657E+5)**3.5*EXP(23.919-SAR)                    A 718
      T5=H5/998.857                                                         A 719
      R5=3.48398E-3*P5/T5                                                   A 720
      A5=20.046*SQRT(T5)                                                    A 721
      ZZ5=ZST5=1.0                                                          A 722
      GAM5=1.4                                                              A 723
      GO TO 103                                                             A 724
C                                                                           A 725
C     LF=2 CASE                                                             A 726
C                                                                           A 727
93    GO TO (95,94), ISAV                                                   A 728
94    CALL SAVE (P5,R5,H5,SAR,T5,A5,ZZ5,GAM5,1)                             A 729
      IF (IEXP.EQ.1) GO TO 98                                               A 730
      DELPG=ALOG10(PA/P5)/(FLOAT(IAC)-1.)                                   A 731
      GO TO 84                                                              A 732
95    Z(3)=ALOG10(P5/1.013246E+5)                                           A 733
      IMET(1)=IMET(2)=0                                                     A 734
      LCODE=1                                                               A 735
      CALL SLOW (SAR,Z,3,1,IT,NV,NERR,Y,X)                                  A 736
      GO TO (96,97), LCODE                                                  A 737
96    CALL SLOW (SAR,Z,3,2,IT,NV,NERR,Y,X)                                  A 738
      CALL SLOW (SAR,Z,3,4,IT,NV,NERR,Y,X)                                  A 739
      CALL SLOW (SAR,Z,3,5,IT,NV,NERR,Y,X)                                  A 740
      CALL SLOW (SAR,Z,3,6,IT,NV,NERR,Y,X)                                  A 741
      CALL SLOW (SAR,Z,3,7,IT,NV,NERR,Y,X)                                  A 742
      T5=Z(1)                                                               A 743
      R5=(10.0**Z(2))*1.2914889                                             A 744
      H5=(10.0**Z(4))*287.0245                                              A 745
      GAM5=Z(5)                                                             A 746
      A5=Z(6)*331.4193                                                      A 747
      ZZ5=Z(7)                                                              A 748
      GO TO 98                                                              A 749
97    PRINT 200                                                             A 750
      PRINT 201                                                             A 751
      H5=2.99657E+5*((P5/1.01325E+5)/(EXP(23.919-SAR)))**0.2857             A 752
      T5=H5/998.857                                                         A 753
      R5=3.48398E-3*P5/T5                                                   A 754
      A5=20.046*SQRT(T5)                                                    A 755
      ZZ5=ZST5=1.0                                                          A 756
      GAM5=1.4                                                              A 757
98    HMIN=H5                                                               A 758
      GO TO 76                                                              A 759
99    U5=UA+TABANS(JAC)                                                     A 760
      GO TO 103                                                             A 761
100   GO TO (101,102), ISAV                                                 A 762
101   CALL SEARCH (P5,R5,H5,SAR,T5,A5,ZZ5,GAM5,ZST5,ISP)                    A 763
      GO TO 103                                                             A 764
102   CALL SAVE (P5,R5,H5,SAR,T5,A5,ZZ5,GAM5,1)                             A 765
      ZST5=ZZ5                                                              A 766
103   M5=U5/A5                                                              A 767
      RE5=0.0                                                               A 768
      CALL VISC (T5,P5,VIS5)                                                A 769
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      IF (VIS5.EQ.1.0) GO TO 104                                        A 770
      RE5=R5*U5/VIS5                                                    A 771
104   CONTINUE                                                          A 772
      TI5=XAS*((1.0/(U5-A5))-(1.0/U5))                                  A 773
      PRINT 202                                                         A 774
      PRINT 167                                                         A 775
      PRINT 168, P5,R5,T5,H5,SAR,Z5,GAM5,A5,U5,M5,RE5                   A 776
      CALL SNS (RHO5S,U5S,P5S,H5S,S5SR,T5S,A5S,Z5S,GAME5S,ZSTAR5S,M5S,R5 A 777
     1,U5,P5,H5,HT5,PT5,RT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5)            A 778
      RATEF=RHO5S/R5                                                    A 779
      PRINT 203                                                         A 780
      PRINT 204                                                         A 781
      PRINT 205                                                         A 782
      PRINT 206, P5S,RHO5S,T5S,H5S,S5SR,Z5S,GAME5S,A5S,U5S,M5S,RATEF    A 783
      PRINT 207                                                         A 784
      PRINT 204                                                         A 785
      PRINT 208                                                         A 786
C                                                                       A 787
C     HEAT TRANSFER RELATION OF NASA TN D-4799                          A 788
C                                                                       A 789
      QTZ0=3.8798E-4*SQRT(PT5/BNR)*(HT5-HW)                             A 790
      PRINT 209, PT5,RT5,TT5,HT5,ZT5,GAMET5,AT5,QTZ0,BNR,TI5            A 791
      IF (IMOD.EQ.2) GO TO 105                                          A 792
      IF (DELU5.EQ.0.0) GO TO 106                                       A 793
      IMOD=2                                                            A 794
      PRINT 147                                                         A 795
      PRINT 145                                                         A 796
      PRINT 146                                                         A 797
      U5=U5-2.0*DELU5                                                   A 798
      GO TO 103                                                         A 799
105   U5=U5+2.0*DELU5                                                   A 800
C                                                                       A 801
C     COMPUTING ACCELERATION GAS (AIR) CONDITIONS                       A 802
C                                                                       A 803
106   US0=1.1*U5                                                        A 804
107   H20=1004.598*T1+0.5*US0**2-0.5*(US0-U5)**2                        A 805
      CALL SAVE (P5,RHO20,H20,SR20,T20,A20,Z20,GAM20,3)                 A 806
      P10=(P5+RHO20*(US0-U5)**2)/(1.+(.003484*US0**2)/T1)               A 807
      USONEW=U5/(1.-(.003484*P10)/(T1*RHO20))                           A 808
      IF (ABS(1.-USONEW/US0).LE..0010) GO TO 108                        A 809
      US0=USONEW                                                        A 810
      GO TO 107                                                         A 811
108   M20=U5/A20                                                        A 812
      MS10=US0/A1                                                       A 813
      RHO10=(P10*W)/(RU*T1)                                             A 814
      R20R=RHO20/RHO10                                                  A 815
      PRINT 210                                                         A 816
      PRINT 211                                                         A 817
      PRINT 212, P5,RHO20,T20,H20,Z20,M20,P10,US0,MS10,R20R             A 818
      PRINT 213                                                         A 819
      PRINT 214                                                         A 820
C                                                                       A 821
C     ACCELERATION TEST TIME- MIRELS THEORY (LAMINAR)                   A 822
C                                                                       A 823
      XA(1)=.1*XAS                                                      A 824
      IF (MS10.GE.4.0.AND.MS10.LE.14.) GO TO 109                        A 825
      IF (MS10.GT.14.) GO TO 110                                        A 826
      PRINT 215                                                         A 827
      GO TO 118                                                         A 828
109   XXMAX=P10*DIA**2*(2.06-.2056*MS10+8.095E-3*MS10**2)               A 829
      GO TO 111                                                         A 830
110   XXMAX=P10*DIA**2*(.8723-7.488E-3*MS10)                            A 831
C                                                                       A 832
C     XAS IS DIVIDED INTO 10 INTERVALS XA                               A 833
C                                                                       A 834
111   DO 117 I=1,10                                                     A 835
      BETAI=XA(I)*RHO10/(2.*XXMAX*RHO20)                                A 836
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```
      BETA2=2.*RH020/RH010                                              A 837
      AXUP=.99999                                                       A 838
      AXLOW=.00001                                                      A 839
      DELTAX=(AXUP-AXLOW)/100.                                          A 840
      E1=.1E-6                                                          A 841
      AX=.5                                                             A 842
      CALL ITR2 (AX,AXLOW,AXUP,DELTAX,FOFAX,E1,E1,200,ICODE)            A 843
      IF (ICODE) 113,112,113                                            A 844
112   RXL=AX**2                                                         A 845
      XL=RXL*XXMAX                                                      A 846
      TAUI=RH010*XA(I)/(RH020*U5)                                       A 847
      BXUP=.99999                                                       A 848
      BXLOW=.00001                                                      A 849
      DELTBX=(BXUP-BXLOW)/100.                                          A 850
      BX=.5                                                             A 851
      CALL ITR2 (BX,BXLOW,BXUP,DELTBX,FOFBX,E1,E1,200,ICODE)            A 852
      IF (ICODE) 113,116,113                                            A 853
113   GO TO (114,115,115,115), ICODE                                    A 854
114   PRINT 154                                                         A 855
      GO TO 118                                                         A 856
115   PRINT 155, ICODE                                                  A 857
      GO TO 118                                                         A 858
116   TAU=BX**2*XXMAX/US0                                               A 859
      UI=XL/TAU                                                         A 860
      URAT=UI/U5                                                        A 861
      URA=US0/UI                                                        A 862
      PRINT 216, XAS,XA(I),XXMAX,XL,RXL,TAU,UI,URAT,URA,TAUI            A 863
      XA(I+1)=XA(I)+.1*XAS                                              A 864
117   CONTINUE                                                          A 865
118   IF (ISTET.EQ.2) GO TO 122                                         A 866
119   IF (LF.EQ.2) GO TO 121                                            A 867
      NN=NN+1                                                           A 868
      IF (IREP.EQ.1.OR.NVEL.EQ.NN) GO TO 120                            A 869
      IF (NN.GT.10) GO TO 120                                           A 870
      U5=U5+US1                                                         A 871
      DELU=U5-UA                                                        A 872
      IFO=2                                                             A 873
      GO TO 67                                                          A 874
120   IF (LD.NE.4) GO TO 1                                              A 875
      IF(IREP.EQ.1) GO TO 250
      U5=U5-(FLOAT(NVEL)-1.)*US1                                        A 876
250   NN=0                                                              A 877
      IMET(1)=IMET(2)=0                                                 A 878
      LCODE=1                                                           A 879
      IF (NMN.EQ.1) GO TO 56                                            A 880
      IF (NMN.EQ.2) GO TO 60                                            A 881
      GO TO 1                                                           A 882
121   IF (LD.NE.4) GO TO 1                                              A 883
      IFO=2                                                             A 884
      IMET(1)=IMET(2)=0                                                 A 885
      LCODE=1                                                           A 886
      IF (NMN.EQ.1) GO TO 56                                            A 887
      IF (NMN.EQ.2) GO TO 60                                            A 888
      GO TO 1                                                           A 889
C                                                                       A 890
C     EXPANSION TUNNEL - EQUILIBRIUM EXPANSION                          A 891
C                                                                       A 892
122   PRINT 147                                                         A 893
      PRINT 217                                                         A 894
      PRINT 146                                                         A 895
      PRINT 218                                                         A 896
      PRINT 219                                                         A 897
      IF(LG.EQ.1) P6=0.0
      IF(LG.EQ.2) U6=0.0
      PRINT 220, U6,P6,DIAT,DIAN,ISAV                                   A 898
C                                                                       A 899
```

APPENDIX A

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C       FROZEN FLOW- EXPANSION TUNNEL                                   A 900
C                                                                       A 901
123     ALP5=ZZ5-1.                                                     A 902
        GACT5=(7.+3.*ALP5)/(5.+ALP5)                                    A 903
        AACT5=SQRT(GACT5*ZZ5*RU*T5/W)                                   A 904
        HACT5=AACT5**2/(GACT5-1.)                                       A 905
        HFR05=H5-HACT5                                                  A 906
        IF (HFR05.GT.0.0) GO TO 124                                     A 907
        PRINT 221                                                       A 908
        GO TO (130,140), LG                                             A 909
124     GO TO (125,127), LG                                             A 910
125     U6F=U6                                                          A 911
        CATA=(GACT5-1.0)*(U5**2-U6**2)+AACT5**2                         A 912
        IF (CATA.GT.0.0) GO TO 126                                      A 913
        PRINT 222                                                       A 914
        GO TO 130                                                       A 915
126     A6F=SQRT(CATA)                                                  A 916
        P6F=P5*((A6F/AACT5)**(2.*GACT5/(GACT5-1.0)))                    A 917
        GO TO 128                                                       A 918
127     P6F=P6                                                          A 919
        A6F=AACT5*(P6F/P5)**((GACT5-1.)/(2.*GACT5))                     A 920
        U6F=SQRT(U5**2+(AACT5**2-A6F**2)/(GACT5-1.0))                   A 921
128     M6F=U6F/A6F                                                     A 922
        T6F=T5*(A6F/AACT5)**2                                           A 923
        RH06F=P6F*W/(RU*ZZ5*T6F)                                        A 924
        H6F=HACT5*(T6F/T5)                                              A 925
        Z6F=ZZ5                                                         A 926
        GAM6F=GACT5                                                     A 927
        S6RF=SAR                                                        A 928
        RE6F=0.0                                                        A 929
        CALL VISC (T6F,P6F,VIS6F)                                       A 930
        IF (VIS6F.E0.1.0) GO TO 129                                     A 931
        RE6F=RH06F*U6F/VIS6F                                            A 932
129     PRINT 223                                                       A 933
        PRINT 167                                                       A 934
        PRINT 168, P6F,RH06F,T6F,H6F,SAR,Z6F,GAM6F,A6F,U6F,M6F,RE6F     A 935
        H6FSC=H6F+HFR05                                                 A 936
        CALL SNS (R6SF,U6SF,P6SF,H6SF,S6SRF,T6SF,A6SF,Z6SF,G6SF,ZS6SF,M6SF  A 937
       1,RH06F,U6F,P6F,H6FSC,HT6F,PT6F,RT6F,ST6RF,TT6F,AT6F,ZT6F,GT6F,ZST6  A 938
       2F)                                                              A 939
        RATE6=R6SF/RH06F                                                A 940
        PRINT 224                                                       A 941
        PRINT 194                                                       A 942
        PRINT 205                                                       A 943
        PRINT 206, P6SF,R6SF,T6SF,H6SF,S6SRF,Z6SF,G6SF,A6SF,U6SF,M6SF,RATE  A 944
       16                                                               A 945
        PRINT 225                                                       A 946
        PRINT 194                                                       A 947
        PRINT 208                                                       A 948
        QTF6=3.8798E-4*SQRT(PT6F/RNR)*(HT6F-HW)                         A 949
        TI6F=0.0                                                        A 950
        PRINT 212, PT6F,RT6F,TT6F,HT6F,ZT6F,GT6F,AT6F,QTF6,RNR,TI6F     A 951
        PRINT 224                                                       A 952
        PRINT 195                                                       A 953
        PRINT 205                                                       A 954
        P6SFF=P6F*(2.*GACT5*M6F**2-GACT5+1.)/(GACT5+1.)                 A 955
        R6SFF=(RH06F*(GACT5+1.)*M6F**2)/((GACT5-1.)*M6F**2+2.)          A 956
        T6SFF=P6SFF*W/(R6SFF*RU*ZZ5)                                    A 957
        H6SFF=H6F*T6SFF/T6F                                             A 958
        Z6SFF=ZZ5                                                       A 959
        G6SFF=GACT5                                                     A 960
        A6SFF=A6F*SQRT(T6SFF/T6F)                                       A 961
        U6SFF=RH06F*U6F/R6SFF                                           A 962
        M6SFF=U6SFF/A6SFF                                               A 963
        S6SRFF=(ALOG(P6SFF/P6F)-GACT5*ALOG(R6SFF/RH06F))/(GACT5-1.)+S6RF  A 964
        RATFF6=R6SFF/RH06F                                              A 965
        PRINT 206, P6SFF,R6SFF,T6SFF,H6SFF,S6SRFF,Z6SFF,G6SFF,A6SFF,U6SFF,  A 966
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     1M6SFF,RATFF6                                                                  A 967
      PRINT 225                                                                     A 968
      PRINT 195                                                                     A 969
      PRINT 208                                                                     A 970
      HT6FF=H6F+.5*U6F**2                                                           A 971
      TT6FF=T6SFF*HT6FF/H6SFF                                                       A 972
      PT6FF=P6SFF*(HT6FF/H6SFF)**(GACT5/(GACT5-1.))                                 A 973
      RT6FF=PT6FF*W/(TT6FF*ZZ5*RU)                                                  A 974
      ZT6FF=ZZ5                                                                     A 975
      GT6FF=GACT5                                                                   A 976
      AT6FF=A6SFF*SQRT(TT6FF/T6SFF)                                                 A 977
      QTFF6=3.8798E-4*SQRT(PT6FF/BNR)*(HT6FF-HW)                                    A 978
      PRINT 212, PT6FF,RT6FF,TT6FF,HT6FF,ZT6FF,GT6FF,AT6FF,QTFF6,BNR,TI6           A 979
     1F                                                                             A 980
      GO TO (130,140), LG                                                           A 981
C                                                                                   A 982
C     LG=1 DENOTES U6 IS INPUT                                                      A 983
C                                                                                   A 984
130   H6=H5+.5*(U5**2-U6**2)                                                        A 985
      IF (H6.GE.2.E+4) GO TO 131                                                    A 986
      PRINT 226                                                                     A 987
      GO TO 1                                                                       A 988
131   Z(4)=ALOG10(H6/287.0245)                                                      A 989
      IMET(1)=IMET(2)=0                                                             A 990
      LCODE=1                                                                       A 991
      CALL SLOW (SAR,Z,4,3,IT,NV,NERR,Y,X)                                          A 992
      GO TO (132,135), LCODE                                                        A 993
132   P6=(10.0**Z(3))*1.01325E+5                                                    A 994
      GO TO (133,134), ISAV                                                         A 995
133   CALL SLOW (SAR,Z,4,1,IT,NV,NERR,Y,X)                                          A 996
      CALL SLOW (SAR,Z,4,2,IT,NV,NERR,Y,X)                                          A 997
      CALL SLOW (SAR,Z,4,5,IT,NV,NERR,Y,X)                                          A 998
      CALL SLOW (SAR,Z,4,6,IT,NV,NERR,Y,X)                                          A 999
      CALL SLOW (SAR,Z,4,7,IT,NV,NERR,Y,X)                                          A1000
      T6=Z(1)                                                                       A1001
      R6=(10.**Z(2))*1.2914889                                                      A1002
      GAM6=Z(5)                                                                     A1003
      A6=Z(6)*331.4193                                                              A1004
      ZZ6=Z(7)                                                                      A1005
      PRINT 227                                                                     A1006
      GO TO 137                                                                     A1007
134   CALL SAVE (P6,R6,H6,SAR,T6,A6,ZZ6,GAM6,1)                                     A1008
      PRINT 228                                                                     A1009
      IF (LG.EQ.1) GO TO 137                                                        A1010
      U6=SQRT(2.*(H5-H6)+U5**2)                                                     A1011
      GO TO 137                                                                     A1012
135   P6=1.01325E+5*(H6/2.99657E+5)**3.5*EXP(23.019-SAR)                            A1013
136   T6=H6/998.857                                                                 A1014
      R6=3.48398E-3*P6/T6                                                           A1015
      A6=20.046*SQRT(T6)                                                            A1016
      GAM6=1.4                                                                      A1017
      ZZ6=ZST6=1.0                                                                  A1018
      PRINT 229                                                                     A1019
137   M6=U6/A6                                                                      A1020
      RE6=0.0                                                                       A1021
      CALL VISC (T6,P6,VIS6)                                                        A1022
      IF (VIS6.EQ.1.0) GO TO 138                                                    A1023
      RE6=P6*U6/VIS6                                                                A1024
138   PRINT 230                                                                     A1025
      PRINT 167                                                                     A1026
      PRINT 168, P6,R6,T6,H6,SAR,ZZ6,GAM6,A6,U6,M6,RE6                              A1027
      CALL SNS (RH06S,U6S,P6S,H6S,S6SR,T6S,A6S,Z6S,GAMF6S,ZSTAR6S,M6S,R6            A1028
     1,U6,P6,H6,HT6,PT6,RT6,ST6R,TT6,AT6,ZT6,GAMET6,ZSTART6)                        A1029
      RAT6F=RH06S/R6                                                                A1030
      QT6=3.8798E-4*SQRT(PT6/BNR)*(HT6-HW)                                          A1031
      AA6=(R5*U5)/(R6*U6)                                                           A1032
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      DELT6=0.5*(DIAN-DIAT*SQRT(AA6))                                          A1033
      PRINT 231                                                                A1034
      PRINT 204                                                                A1035
      PRINT 205                                                                A1036
      PRINT 206, P6S,RH06S,T6S,H6S,S6SR,Z6S,GAME6S,A6S,U6S,M6S,PAT6F           A1037
      PRINT 232                                                                A1038
      PRINT 204                                                                A1039
      PRINT 233                                                                A1040
      PRINT 206, PT6,RT6,TT6,HT6,ZT6,GAMET6,AT6,QT6,BNP,AA6,DELT6              A1041
      IF (LG.EQ.2.OR.LREP.EQ.1) GO TO 119                                      A1042
      NNN=NNN+1                                                                A1043
      IF (NUMU6.EQ.NNN) GO TO 139                                              A1044
      IF (NNN.GT.10) GO TO 119                                                 A1045
      U6=U6+U61                                                                A1046
      GO TO 123                                                                A1047
139   U6=U6-(FLOAT(NUMU6)-1.)*U61                                              A1048
      NNN=0                                                                    A1049
      GO TO 119                                                                A1050
C                                                                              A1051
C     LG=2 DENOTES P6 IS INPUT                                                 A1052
C                                                                              A1053
140   IMET(1)=IMET(2)=0                                                        A1054
      LCODE=1                                                                  A1055
      Z(3)=ALOG10(P6/1.013246E+5)                                              A1056
      CALL SLOW (SAR,Z,3,1,IT,NV,NERR,Y,X)                                     A1057
      GO TO (141,143), LCODE                                                   A1058
141   GO TO (142,134), ISAV                                                    A1059
142   CALL SLOW (SAR,Z,3,2,IT,NV,NERR,Y,X)                                     A1060
      CALL SLOW (SAR,Z,3,4,IT,NV,NERR,Y,X)                                     A1061
      CALL SLOW (SAR,Z,3,5,IT,NV,NERR,Y,X)                                     A1062
      CALL SLOW (SAR,Z,3,6,IT,NV,NERR,Y,X)                                     A1063
      CALL SLOW (SAR,Z,3,7,IT,NV,NERR,Y,X)                                     A1064
      T6=Z(1)                                                                  A1065
      R6=(10.**Z(2))*1.2914889                                                 A1066
      H6=(10.**Z(4))*287.0245                                                  A1067
      GAM6=Z(5)                                                                A1068
      A6=Z(6)*331.4193                                                         A1069
      ZZ6=Z(7)                                                                 A1070
      PRINT 227                                                                A1071
      U6=SQRT(2.*(H5-H6)+U5**2)                                                A1072
      GO TO 137                                                                A1073
143   H6=2.99657E+5*((P6/1.01325E+5)/(EXP(23.919-SAR)))**0.2857                A1074
      U6=SQRT(2.*(H5-H6)+U5**2)                                                A1075
      GO TO 136                                                                A1076
144   STOP                                                                     A1077
C                                                                              A1078
C                                                                              A1079
C                                                                              A1080
145   FORMAT (/51H FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN)         A1081
146   FORMAT (/55H XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  A1082
     1X)                                                                       A1083
147   FORMAT (//55H XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  A1084
     1XX)                                                                      A1085
148   FORMAT (//46H EXPANSION TUBE PROGRAM OF MILLER FOR REAL AIR)             A1086
149   FORMAT (51H ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012)          A1087
150   FORMAT (//28H SHOCK TUBE PHASE OF PROGRAM)                               A1088
151   FORMAT (//37H MEASURED INPUTS FOR SHOCK TUBE PHASE)                      A1089
152   FORMAT (/105H   RUN        P1          T1          US1          P2       A1090
     1P4          T4        XIS        DIA     ISAV  INU  LD)                A1091
153   FORMAT (9E10.3,315)                                                      A1092
154   FORMAT (20H MAX COUNT EXCEEDED )                                         A1093
155   FORMAT (17H DERIVATIVE = 0. ,I5)                                         A1094
156   FORMAT (7H ICODE=,I5,5H  RI=,E12.3,7H  DELR=,E12.3)                      A1095
157   FORMAT (/65H     P3          T3        RH03          Z3          H3     1/ A1096
     1A3        U3)                                                           A1097
158   FORMAT (7E10.3)                                                          A1098
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159   FORMAT (/46H     P2          RHO2          H2          U2          US1)          A1099
160   FORMAT (5E10.3)                                                                  A1100
161   FORMAT (//30H IMPERFECT HYDROGEN DRIVER GAS)                                     A1101
162   FORMAT (//28H IMPERFECT HELIUM DRIVER GAS)                                       A1102
163   FORMAT (//13H 4 CONDITIONS)                                                      A1103
164   FORMAT (/75H    P           RHO         T           H           S/R         Z    A1104
     1            A           W)                                                      A1105
165   FORMAT (8E10.3)                                                                  A1106
166   FORMAT (//44H CONDITIONS BEHIND INCIDENT SHOCK - REGION 2)                       A1107
167   FORMAT (/106H    P           RHO         T           H           S/R            A1108
     1Z          GAME        A           U           M           NRE)                A1109
168   FORMAT (11E10.3)                                                                 A1110
169   FORMAT (//44H RATIO- 2 TO 1 CONDITIONS AND SHOCK VELOCITY)                       A1111
170   FORMAT (/66H    P           RHO         T           H           A           M    A1112
     1S1         US1)                                                                A1113
171   FORMAT (7E10.3)                                                                  A1114
172   FORMAT (//47H SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY)                    A1115
173   FORMAT (/107H     LMAX          L         L/LMAX       TIM         UT           A1116
     1LMAXT        LT        LT/LMAXT    TIMT        UIT         TIMI)               A1117
174   FORMAT (/45H SHOCK TUBE TEST TIME NOT COMPUTED - MS1 LT 4)                       A1118
175   FORMAT (11E10.3)                                                                 A1119
176   FORMAT (//51H SHOCK TUBE LAMINAR FLOW NONUNIFORMITY NOT COMPUTED)                A1120
177   FORMAT (//45H SHOCK TUBE FLOW NONUNIFORMITIES-LAMINAR CASE)                      A1121
178   FORMAT (/44H RATIOS-PARAMETER AT XS TO PARAMETER AT XS=0)                        A1122
179   FORMAT (/65H  XS/L          P           RHO         T           H           A    A1123
     1            U)                                                                  A1124
180   FORMAT (7E10.3)                                                                  A1125
181   FORMAT (//53H SHOCK TUBE TURBULENT FLOW NONUNIFORMITY NOT COMPUTED               A1126
     1)                                                                              A1127
182   FORMAT (//47H SHOCK TUBE FLOW NONUNIFORMITIES-TURBULENT CASE)                    A1128
183   FORMAT (//52H CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPH)               A1129
184   FORMAT (//54H STAGNATION CONDITIONS BEHIND STANDING SHOCK-REGION T               A1130
     12)                                                                             A1131
185   FORMAT (/98H    P           RHO         T           H           S/R         Z    A1132
     1            GAME        A           QT          RN)                           A1133
186   FORMAT (//53H CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPH               A1134
     1)                                                                              A1135
187   FORMAT (/32H EXPANSION TUBE PHASE OF PROGRAM)                                    A1136
188   FORMAT (//32H INPUTS FOR EXPANSION TUBE PHASE)                                   A1137
189   FORMAT (/72H     U5          P5          XAS         DELU5     ISAV IEXP I     A1138
     1REP NVEL IAC JAC  )                                                            A1139
190   FORMAT (4F10.3,6I5)                                                              A1140
191   FORMAT (40H FROZEN ENTHALPY IN REGION 4 IS NEGATIVE)                             A1141
192   FORMAT (/16H A5F IS NEGATIVE)                                                    A1142
193   FORMAT (//34H 5 CONDITIONS FOR FROZEN EXPANSION)                                 A1143
194   FORMAT (41H FROZEN EXPANSION--EQUILIBRIUM POST SHOCK)                            A1144
195   FORMAT (37H FROZEN EXPANSION-- FROZEN POST SHOCK)                                A1145
196   FORMAT (/54H AEDC REAL-AIR TAPE USED FOR UNSTEADY EXPANSION-IEXP=1               A1146
     1)                                                                              A1147
197   FORMAT (/53H PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION)               A1148
198   FORMAT (/55H AEDC CURVE FIT EXPRESSIONS USED FOR UNSTEADY EXPANSIO               A1149
     1N)                                                                             A1150
199   FORMAT (/50H H5 LT 5E+4- EQUILIBRIUM 5 CONDITIONS NOT COMPUTED)                  A1151
200   FORMAT (//37H QUANTITIES IN REGION 5 OFF AEDC TAPE)                              A1152
201   FORMAT (53H THESE QUANTITIES DETERMINED FROM IDEAL AIR RELATIONS)                A1153
202   FORMAT (//39H 5 CONDITIONS FOR EQUILIBRIUM EXPANSION)                            A1154
203   FORMAT (//47H STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S)                    A1155
204   FORMAT (46H EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK)                       A1156
205   FORMAT (/108H    P           RHO         T           H           S/R            A1157
     1Z          GAME        A           U           M           RATIO)              A1158
206   FORMAT (11E10.3)                                                                 A1159
207   FORMAT (//49H STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5)                  A1160
208   FORMAT (/97H    P           RHO         T           H           Z           G    A1161
     1AME        A           QT          RN          TIMI)                           A1162
209   FORMAT (10E10.3)                                                                 A1163
210   FORMAT (//48H ACCELERATION AIR CONDITIONS (REGION 20) AND P10)                   A1164
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211   FORMAT (101H     P20        RHO20        T20         H20         Z20          A1165
     1M20         P10        US10        MS10        RATIO    )                  A1166
                                                                                   A1167
212   FORMAT (10E10.3)                                                            A1168
213   FORMAT (//53H ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY          A1169
     1)                                                                           A1170
214   FORMAT (/97H    XAS         XA          LMAX         L           L/LMAX     A1171
     1TIM       UI          UI/U5     US20/UI     TIM1)                          A1172
215   FORMAT (//50H ACCELERATION AIR LEAKY PISTON EFFECT NOT COMPUTED)            A1173
216   FORMAT (10E10.3)                                                            A1174
217   FORMAT (/34H EXPANSION TUNNEL PHASE OF PROGRAM)                             A1175
218   FORMAT (//34H INPUTS FOR EXPANSION TUNNEL PHASE)                            A1176
219   FORMAT (/47H     U6          P6          D-THROAT  D-NOZZLE    ISAV)        A1177
220   FORMAT (4E10.3,I15)                                                         A1178
221   FORMAT (/40H FROZEN ENTHALPY IN REGION 6 IS NEGATIVE)                       A1179
222   FORMAT (/46H A6F NEGATIVE - FROZEN CONDITIONS NOT COMPUTED)                 A1180
223   FORMAT (//41H 6 CONDITIONS FOR FROZEN NOZZLE EXPANSION)                     A1181
224   FORMAT (//47H STATIC CONDITIONS BEHIND BOW SHOCK - REGION 6S)               A1182
225   FORMAT (//51H STAGNATION CONDITIONS BEHIND BOW SHOCK - REGION T6)           A1183
226   FORMAT (//44H H6 LESS THAN 2.0E+4-  T6 LESS THAN 20 DEG K)                  A1184
227   FORMAT (/43H AEDC TAPE USED FOR STEADY NOZZLE EXPANSION)                    A1185
228   FORMAT (/53H AEDC CURVE FIT EXPRESSIONS USED FOR NOZZLE EXPANSION)          A1186
229   FORMAT (/54H REGION 6 QUANTITIES OFF TAPE - PERFECT RELATIONS USED          A1187
     1)                                                                           A1188
230   FORMAT (//46H 6 CONDITIONS FOR EQUILIBRIUM NOZZLE EXPANSION)                A1189
231   FORMAT (//45H STATIC CONDITIONS BEHIND BOW SHOCK-REGION 6S)                  A1190
232   FORMAT (//49H STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T6)              A1191
233   FORMAT (/109H     P          RHO          T           H           Z          A1192
     1GAME        A           QT          RN       A/ASTAR    DELSTAR)          A1193
234   FORMAT (4A10)                                                               A1194
235   FORMAT (1H1,A10/)                                                           A1195-
      END
      SUBROUTINE VISC (T,P,VIS)                                                 B    1
      DIMENSION TAPY(4), TABTY(13), TABNUY(52)                                  B    2
                                                                                B    3
C                                                                               B    4
C     TABLE OF VISCOSITY FROM YOS(AVCO RAD-TM-63-7)                             B    5
C                                                                               B    6
      DATA TAPY/1.01325E+5,3.03975E+5,1.01325E+6,3.03975E+6/                    B    7
      DATA TABTY/1000.,2000.,3000.,4000.,5000.,6000.,7000.,8000.,9000.,1       B    8
     10000.,12000.,14000.,16000./                                               B    9
      DATA TABNUY/.418E-4,.648E-4,.858E-4,1.08E-4,1.30E-4,1.54E-4,1.86E-       B   10
     14,2.21E-4,2.45E-4,2.63E-4,2.63E-4,1.77E-4,.96E-4,.418E-4,.648E-4,.       B   11
     2857E-4,1.07E-4,1.30E-4,1.52E-4,1.80E-4,2.14E-4,2.45E-4,2.66E-4,2.8       B   12
     35E-4,2.34E-4,1.53E-4,.418E-4,.648E-4,.857E-4,1.07E-4,1.30E-4,1.51E       B   13
     4-4,1.76E-4,2.06E-4,2.4E-4,2.67E-4,3.00E-4,2.82E-4,2.24E-4,.418E-4,       B   14
     5.648E-4,.856E-4,1.06E-4,1.27E-4,1.50E-4,1.73E-4,2.00E-4,2.32E-4,2.       B   15
     663E-4,3.06E-4,3.10E-4,2.66E-4/                                            B   16
      IF (T.LE.1500.) GO TO 2                                                   B   17
      IF (T.GT.16000..OR.P.GT.3.04E+06) GO TO 1                                 B   18
      CALL DISCOT (T,P,TABTY,TABNUY,TAPY,11,52,4,VIS)                           B   19
      GO TO 3                                                                   B   20
1     VIS=1.0                                                                   B   21
      GO TO 3                                                                   B   22
2     VIS=1.462E-6*SQRT(T)/(1.+112./T)                                          B   23
3     RETURN                                                                    B   24-
      END
      SUBROUTINE SHOCK (BN,CN,DN,RN,UN,PN,HN)                                   C    1
      BN=RN*UN                                                                  C    2
      CN=PN+RN*UN**2                                                            C    3
      DN=HN+.5*UN**2                                                            C    4
      RETURN                                                                    C    5
      END                                                                       C    6-
      FUNCTION FOFAXT (AXT)                                                     D    1
      COMMON /BLK6/ BETA1,BETA2                                                 D    2
      FOFAXT=-.4*BETA1-.25*ALOG((1.-AXT)/(1.+AXT))+.5*ATAN(AXT)-AXT             D    3
      RETURN                                                                    D    4
      END                                                                       D    5-
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APPENDIX A

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      FUNCTION FOFBXT (BXT)                                                    E   1
      COMMON /BLK6/ BETA1,BETA2                                                E   2
      FOFBXT=-.4*BETA1+.25*ALOG((1.+BXT)/(1.-BXT))+.5*ATAN(BXT)-.4*BXT**       E   3
     15/BETA2-BXT                                                              E   4
      RETURN                                                                   E   5
      END                                                                      E   6-
      FUNCTION FOFAX (AX)                                                      F   1
      COMMON /BLK6/ BETA1,BETA2                                                F   2
      FOFAX=-BETA1-ALOG(1.-AX)-AX                                              F   3
      RETURN                                                                   F   4
      END                                                                      F   5-
      FUNCTION FOFBX (BX)                                                      G   1
      COMMON /BLK6/ BETA1,BETA2                                                G   2
      FOFBX=-BETA1-ALOG(1.-BX)-BX**2/BETA2-BX                                  G   3
      RETURN                                                                   G   4
      END                                                                      G   5-
      FUNCTION FOFX (RN)                                                       H   1
      COMMON /BLK1/ BT4,CT4,RHOG                                               H   2
      FOFX=RHOG-(BT4*RN**2+CT4*RN**3)                                          H   3
      RETURN                                                                   H   4
      END                                                                      H   5-
      FUNCTION FOFR (RNI)                                                      I   1
      COMMON /BLK2/ BTI,CTI,TI,CVRI,S4R,SREF,DBTI,DCTI                         I   2
      A=CVRI*ALOG(TI)                                                          I   3
      B=BTI+TI*DBTI                                                            I   4
      C=CTI+TI*DCTI                                                            I   5
      FOFR=A-ALOG(RNI)-(RNI*B)-(RNI**2/2.)*C+SREF-S4R                          I   6
1     RETURN                                                                   I   7
      END                                                                      I   8-
      FUNCTION FOFMS (MSN)                                                     J   1
      COMMON /BLK3/ TI,GAM4,W4,T4,P4,P1                                        J   2
      REAL MSN                                                                 J   3
      A=P4/P1                                                                  J   4
      B=(GAM4-1.)/2.4                                                          J   5
      C=SQRT(.04833*((TI*W4)/(GAM4*T4)))                                       J   6
      D=2.*GAM4/(GAM4-1.)                                                      J   7
      DEN=(1.-B*C*(MSN-1./MSN))**D                                             J   8
      FOFMS=SQRT(((A*DEN)+.1667)/1.1667)                                       J   9
      RETURN                                                                   J  10
      END                                                                      J  11-
      SUBROUTINE SIMP (TABX,TABY,N,NMAX,TABANS)                                K   1
      DIMENSION TABX(NMAX), TABY(NMAX), TABANS(NMAX)                           K   2
      DIMENSION NP(4)                                                          K   3
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,MF,SAR,LCODE,DELU                       K   4
      COMMON /BLK4/ LF,NON,LU,NDRIV,LR,LD,LG                                   K   5
      TABANS(1)=0                                                              K   6
      DEN=2.                                                                   K   7
      K=2                                                                      K   8
C     TABX(THAT IS TABHR) IN DECREASING ORDER - DELX THUS NEGATIVE             K   9
      DO 1 J=K,N                                                               K  10
      NON=J                                                                    K  11
      DELX=(TABX(J)-TABX(J-1))/DEN                                             K  12
      X=TABX(J-1)+DELX                                                         K  13
      CALL FTLUP (X,Y,-2,N,TABX,TABY)                                          K  14
      SUM=(TABY(J-1)+4.*Y+TABY(J))*(ABS(DELX))/3.                              K  15
      TABANS(J)=TABANS(J-1)+SUM                                                K  16
1     CONTINUE                                                                 K  17
      RETURN                                                                   K  18
      END                                                                      K  19-
      SUBROUTINE SNS (RX,UX,PX,HX,SX,TX,AX,ZX,GX,ZSX,MX,RSX,USX,PSX,HSX,       L   1
     1HTX,PTX,RTX,STX,TTX,ATX,ZTX,GTX,ZTSX)                                    L   2
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), ND(4)                L   3
      REAL MS1,M2,MS,MSS,MX,MN,MNS                                             L   4
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,MF,SAR,LCODE,DELU,ISAV                  L   5
      CALL SHOCK (BSN,CSN,DSN,PSX,USX,PSX,HSX)                                 L   6
      IMET(1)=IMET(2)=0                                                        L   7
```

```
      IT=8                                                                  L    8
      NV=9                                                                  L    9
      ISP=1                                                                 L   10
      RX=12.*RSX                                                            L   11
      HTX=DSN                                                               L   12
1     UX=BSN/RX                                                             L   13
      PX=CSN-BSN*UX                                                         L   14
      HX=DSN-.5*UX**2                                                       L   15
      GO TO (2,3), ISAV                                                     L   16
2     CALL SEARCH (PX,RNEW,HX,SX,TX,AX,ZX,GX,ZSX,ISP)                       L   17
      GO TO 4                                                               L   18
3     CALL SAVE (PX,RNEW,HX,SX,TX,AX,ZX,GX,3)                               L   19
      ZSX=ZX                                                                L   20
4     IF (ABS(1.-RX/RNEW).LE..001) GO TO 5                                  L   21
      RX=RNEW                                                               L   22
      GO TO 1                                                               L   23
5     RX=RNEW                                                               L   24
      MX=UX/AX                                                              L   25
      STX=SX                                                                L   26
      GO TO (6,7), ISAV                                                     L   27
6     HTX=HX+.5*UX**2                                                       L   28
      Z(4)=HTX/287.024E                                                     L   29
      Z(4)=ALOG10(Z(4))                                                     L   30
      CALL SLOW (SX,Z,4,3,IT,NV,NEPR,Y,X)                                   L   31
      PTX=(10.0**Z(3))*1.013246E+5                                          L   32
      CALL SEARCH (PTX,RTX,HTX,STX,TTX,ATX,ZTX,GTX,ZTSX,ISP)                L   33
      STX=SX                                                                L   34
      GO TO 9                                                               L   35
7     PTX=PX*(1.+((GX-1.)/2.)*MX**2)**(GX/(GX-1.))                          L   36
8     CALL SAVE (PTX,RTX,HTX,STX,TTX,ATX,ZTX,GTX,1)                         L   37
      ZTSX=ZTX                                                              L   38
      IF (ABS(1.-HTX/(HX+.5*UX**2)).LE..001) GO TO 9                        L   39
      PTX=(PTX*(HX+.5*UX**2))/HTX                                           L   40
      GO TO 8                                                               L   41
9     RETURN                                                                L   42
      END                                                                   L   43
      SUBROUTINE BDT (BTM,CTM,DBM,DCM,D2BM,D2CM,TM)                         M    1
      COMMON /BLK4/ LF,NON,LU,NDRIV,LR,LD,LG                                M    2
      IF (NDRIV.EQ.1) GO TO 1                                               M    3
C                                                                           M    4
C     HELIUM  USED AS DRIVER GAS                                            M    5
C                                                                           M    6
      AMT1=15.8922-ALOG(TM)                                                 M    7
      AMT2=-3.7156E-3*TM                                                    M    8
      BTM=3.3565E-6*AMT1**3-2.0085E-3*EXP(AMT2)                             M    9
      CTM=5.633E-12*AMT1**6                                                 M   10
      DBM=(-1.00695E-5/TM)*AMT1**2+7.4628E-6*EXP(AMT2)                      M   11
      DCM=(-3.3798E-11/TM)*AMT1**5                                          M   12
      D2BM=(2.0139E-5/TM**2)*AMT1+(1.00695E-5/TM**2)*AMT1**2-2.7729E-8*E    M   13
     1XP(AMT2)                                                              M   14
      D2CM=(1.6899E-10/TM**2)*AMT1**4+(3.3798E-11/TM**2)*AMT1**5            M   15
      GO TO 2                                                               M   16
C     HYDROGEN USED AS DRIVER GAS                                           M   17
1     BTM=1.6994E-3*TM**.25                                                 M   18
      CTM=2.1E-4                                                            M   19
      DBM=4.2485E-4*TM**(-.75)                                              M   20
      DCM=D2CM=0.                                                           M   21
      D2BM=-3.1864E-4*TM**(-1.75)                                           M   22
2     RETURN                                                                M   23
      END                                                                   M   24
      SUBROUTINE SEARCH (P,PHO,H1,SOR,T1,A1,Z1,GAM,ZS,ISP)                  N    1
      DIMENSION G(4), Y1(4), Y2(4), Y3(4), Y4(4), Y5(4), Y6(4), Y7(4)       N    2
      DIMENSION ICOUNT(25), JFLAG(25), Y(9,150), P(25), PHO(25)             N    3
      DIMENSION SAVEH(25,4), SAVEP(25,4), SAVET(25,4), SAVEA(25,4)          N    4
      DIMENSION SAVEZ(25,4), SAVES(25,4), SAVEG(25,4), SAVEZS(25,4)         N    5
      DIMENSION H1(25), T1(25), A1(25), Z1(25), SOR(25), GAM(25), ZS(25)    N    6
```

APPENDIX A

```
      DIMENSION TABT(150), TABR(150), TABP(150), TABH(150)                    N    7
      DIMENSION TABA(150), TABZ(150), TABG(150), TABZS(150)                   N    8
      DO 1 I=1,ISP                                                           N    9
      ICOUNT(I)=1                                                            N   10
      JFLAG(I)=0                                                             N   11
1     CONTINUE                                                               N   12
      JUMP=0                                                                 N   13
      IT=8                                                                   N   14
      REWIND IT                                                              N   15
2     READ (IT) X,NV,((Y(I,L),I=1,9),L=1,NV)                                 N   16
      IF (ENDFILE IT) 3,6                                                    N   17
3     CONTINUE                                                               N   18
      WRITE (6,16)                                                           N   19
      DO 5 I=1,ISP                                                           N   20
      IF (JFLAG(I).EQ.0) GO TO 4                                             N   21
      GO TO 5                                                                N   22
4     CONTINUE                                                               N   23
      RHO(I)=0.                                                              N   24
      TI(I)=0.                                                               N   25
      AI(I)=0.                                                               N   26
      ZI(I)=0.                                                               N   27
      SOR(I)=0.                                                              N   28
      GAM(I)=0.                                                              N   29
      ZS(I)=0.                                                               N   30
5     CONTINUE                                                               N   31
      GO TO 15                                                               N   32
6     CONTINUE                                                               N   33
      DO 14 J=1,ISP                                                          N   34
      IF (JFLAG(J).EQ.1) GO TO 14                                            N   35
      NN=ICOUNT(J)                                                           N   36
      PP=ALOG10(P(J)/1.0132E+5)                                              N   37
      HH=ALOG10(H1(J)/287.0345)                                              N   38
      IF ((PP-Y(3,1))*(PP-Y(3,NV)).LT.0.) GO TO 7                            N   39
      SAVEH(J,1)=0.                                                          N   40
      SAVER(J,1)=0.                                                          N   41
      SAVET(J,1)=0.                                                          N   42
      SAVEA(J,1)=0.                                                          N   43
      SAVEZ(J,1)=0.                                                          N   44
      SAVES(J,1)=0.                                                          N   45
      SAVEG(J,1)=0.                                                          N   46
      SAVEZS(J,1)=0.                                                         N   47
      NN=2                                                                   N   48
      GO TO 10                                                               N   49
7     DO 8 I=1,NV                                                            N   50
      TABT(I)=Y(1,I)                                                         N   51
      TABR(I)=Y(2,I)                                                         N   52
      TABP(I)=Y(3,I)                                                         N   53
      TABH(I)=Y(4,I)                                                         N   54
      TABG(I)=Y(5,I)                                                         N   55
      TABA(I)=Y(6,I)                                                         N   56
      TABZ(I)=Y(7,I)                                                         N   57
      TABZS(I)=Y(9,I)                                                        N   58
8     CONTINUE                                                               N   59
      CALL DISCOT (PP,PP,TABP,TABH,TABH,-130,NV,0,ANS1)                      N   60
      CALL DISCOT (PP,PP,TABP,TABR,TABR,-130,NV,0,ANS2)                      N   61
      CALL DISCOT (PP,PP,TABP,TABT,TABT,-130,NV,0,ANS3)                      N   62
      CALL DISCOT (PP,PP,TABP,TABA,TABA,-130,NV,0,ANS4)                      N   63
      CALL DISCOT (PP,PP,TABP,TABZ,TABZ,-130,NV,0,ANS5)                      N   64
      CALL DISCOT (PP,PP,TABP,TABG,TABG,-130,NV,0,ANS6)                      N   65
      CALL DISCOT (PP,PP,TABP,TABZS,TABZS,-130,NV,0,ANS7)                    N   66
      SAVES(J,NN)=X                                                          N   67
      SAVEH(J,NN)=ANS1                                                       N   68
      SAVER(J,NN)=ANS2                                                       N   69
      SAVET(J,NN)=ANS3                                                       N   70
      SAVEA(J,NN)=ANS4                                                       N   71
      SAVEZ(J,NN)=ANS5                                                       N   72
```

```
      SAVEG(J,NN)=ANS6                                                  N  73
      SAVEZS(J,NN)=ANS7                                                 N  74
      IF (SAVEH(J,NN).GT.HH) GO TO 11                                   N  75
      IF (NN.EQ.3) GO TO 9                                              N  76
      NN=NN+1                                                           N  77
      GO TO 10                                                          N  78
9     SAVER(J,1)=SAVER(J,2)                                             N  79
      SAVEH(J,1)=SAVEH(J,2)                                             N  80
      SAVET(J,1)=SAVET(J,2)                                             N  81
      SAVEA(J,1)=SAVEA(J,2)                                             N  82
      SAVEZ(J,1)=SAVEZ(J,2)                                             N  83
      SAVES(J,1)=SAVES(J,2)                                             N  84
      SAVEG(J,1)=SAVEG(J,2)                                             N  85
      SAVEZS(J,1)=SAVEZS(J,2)                                           N  86
      SAVER(J,2)=SAVER(J,3)                                             N  87
      SAVEH(J,2)=SAVEH(J,3)                                             N  88
      SAVET(J,2)=SAVET(J,3)                                             N  89
      SAVEA(J,2)=SAVEA(J,3)                                             N  90
      SAVEZ(J,2)=SAVEZ(J,3)                                             N  91
      SAVES(J,2)=SAVES(J,3)                                             N  92
      SAVEG(J,2)=SAVEG(J,3)                                             N  93
      SAVEZS(J,2)=SAVEZS(J,3)                                           N  94
10    ICOUNT(J)=NN                                                      N  95
      GO TO 14                                                          N  96
11    IF (NN.EQ.4) GO TO 12                                             N  97
      NN=NN+1                                                           N  98
      ICOUNT(J)=NN                                                      N  99
      GO TO 14                                                          N 100
12    JFLAG(J)=1                                                        N 101
      DO 13 M=1,4                                                       N 102
      G(M)=SAVEH(J,M)                                                   N 103
      Y1(M)=SAVER(J,M)                                                  N 104
      Y2(M)=SAVET(J,M)                                                  N 105
      Y3(M)=SAVEA(J,M)                                                  N 106
      Y4(M)=SAVEZ(J,M)                                                  N 107
      Y5(M)=SAVES(J,M)                                                  N 108
      Y6(M)=SAVEG(J,M)                                                  N 109
      Y7(M)=SAVEZS(J,M)                                                 N 110
13    CONTINUE                                                          N 111
      CALL INTRP (4,G,Y1,HH,R)                                          N 112
      CALL INTRP (4,G,Y2,HH,T)                                          N 113
      CALL INTRP (4,G,Y3,HH,A)                                          N 114
      CALL INTRP (4,G,Y4,HH,Z)                                          N 115
      CALL INTRP (4,G,Y5,HH,SR1)                                        N 116
      CALL INTRP (4,G,Y6,HH,GAM1)                                       N 117
      CALL INTRP (4,G,Y7,HH,ZS1)                                        N 118
      RHO(J)=(10.**R)*1.291489                                          N 119
      T1(J)=T                                                           N 120
      A1(J)=A*331.4184                                                  N 121
      Z1(J)=Z                                                           N 122
      SOR(J)=SR1                                                        N 123
      GAM(J)=GAM1                                                       N 124
      ZS(J)=ZS1                                                         N 125
      JUMP=JUMP+1                                                       N 126
      IF (JUMP.EQ.ISP) GO TO 15                                         N 127
14    CONTINUE                                                          N 128
      GO TO 2                                                           N 129
15    CONTINUE                                                          N 130
      RETURN                                                            N 131
C                                                                       N 132
C                                                                       N 133
C                                                                       N 134
16    FORMAT (1H1,60X,7HWARNING////)                                    N 135
      END                                                               N 136-
      SUBROUTINE SLOW (XX,Z,I1,J1,IT,NV,NERR,Y,X)                       O   1
C     TAPE IS WRITTEN WITH LINES OF CONSTANT XX                         O   2
```

```
C     Z(I) AND XX ARE INDEPENDENT VARIABLES                                    3
C     Z(J) IS THE DEPENDENT VARIABLE                                           4
C     AK= +1. IF XX INCREASES MONOTONICALLY ON TAPE                            5
C     AK= -1. IF XX DECREASES MONOTONICALLY ON TAPE                            6
C     IT= TAPE UNIT                                                            7
C     NV= NO. OF VARIABLES ON TAPE FOR EACH XX .(NOT GREATER THAN 9)           8
C     NO. OF POINTS FOR EACH XX NOT GREATER THAN 150                           9
C     BEGIN EXECUTION                                                          10
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NP(4)                11
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,ME,SAR,LCODE,DELU                       12
      REAL ME,ME                                                               13
      ICOUNT=ICOUNT+1                                                          14
      IF (IMET(1)) 3,1,3                                                       15
1     BACKSPACE IT                                                             16
      READ (IT) DUM                                                            17
      REWIND IT                                                                18
      DO 2 K=1,3                                                               19
      READ (IT) X(K),J,((Y(K,I,L),I=1,NV),L=1,J)                               20
2     NP(K)=J                                                                  21
      XW=X(2)-X(1)                                                             22
      AK=ABS(XW)/XW                                                            23
      DIR1=1.                                                                  24
      IMET(1)=1                                                                25
      XXX=YX                                                                   26
      NERR=0                                                                   27
      IM=3                                                                     28
      GO TO 18                                                                 29
3     NERR=0                                                                   30
C     EXCEPT FOR FIRST TIME THROUGH                                            31
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,4                                       32
4     TEMP=(XX-XXX)*AK                                                         33
      DIR2=ABS(TEMP)/TEMP                                                      34
      GO=DIR1*DIR2                                                             35
      XXX=YX                                                                   36
      DIR1=DIR2                                                                37
      IF (DIR2) 5,35,16                                                        38
C                                                                              39
C     NEGATIVE DIRECTION                                                       40
5     IF (GO) 6,35,7                                                           41
6     BACKSPACE IT                                                             42
      BACKSPACE IT                                                             43
      BACKSPACE IT                                                             44
      GO TO 9                                                                  45
7     IM=IM-1                                                                  46
      IF (IM) 8,8,9                                                            47
8     IM=4                                                                     48
9     M1=IM+1                                                                  49
      BACKSPACE IT                                                             50
      BACKSPACE IT                                                             51
      IF (M1-4) 11,11,10                                                       52
10    M1=1                                                                     53
11    M2=M1+1                                                                  54
      IF (M2-4) 13,13,12                                                       55
12    M2=1                                                                     56
13    READ (IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J)                             57
      NP(IM)=J                                                                 58
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,14                                      59
14    IF (X(M1)-X(M2)) 7,15,7                                                  60
C     ERROR, VARIABLE OFF FRONT END OF TAPE                                    61
15    CONTINUE                                                                 62
      NERR=1                                                                   63
      GO TO 36                                                                 64
C                                                                              65
C     POSITIVE DIRECTION                                                       66
16    IF (GO) 17,35,18                                                         67
```

```
17    READ (IT) DUM
      READ (IT) DUM
      READ (IT) DUM
      GO TO 20
18    IM=IM+1
      IF (IM-4) 20,20,19
19    IM=1
20    M1=IM-1
      IF (M1) 21,21,22
21    M1=4
22    M2=M1-1
      IF (M2) 23,23,24
23    M2=4
24    READ (IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J)
      NP(IM)=J
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,18
C
C     TAPE SEARCH COMPLETE , DO CROSS FOUR POINT
25    DO 34 K=1,4
      NPK=NP(K)-1
      DO 26 I=1,NPK
      IF ((Y(K,I1,I)-Z(I1))*(Y(K,J1,I+1)-Z(I1))) 27,27,26
26    CONTINUE
      NERR=1
      GO TO 36
27    IF (I-1) 29,28,29
28    J=0
      GO TO 32
29    IF (I-NPK) 31,30,31
30    J=NPK-3
      GO TO 32
31    J=I-2
32    DO 33 L=1,4
      MX=L+J
      U(L)=Y(K,I1,MX)
33    V(L)=Y(K,J1,MX)
34    CALL INTRP (4,U,V,Z(I1),W(K))
      CALL INTRP (4,X,W,XX,Z(J1))
      RETURN
35    CONTINUE
36    NERR=1
      IF (IMFT(2)) 38,37,38
37    IMFT(2)=1
      LCODE=2
      WRITE (6,39) XX,I1,Z(I1),J1
38    RETURN
C
C
C
39    FORMAT (///39H NO SOLUTION ON TAPE FOR THE CONDITIONS//5X,6H  S/R=
     1F12.6,37X,9H EVALUATE/6X,2H7(I1,2H)=E16.8,38X,3H Z(I1,1H)///)
      END
      SUBROUTINE SAVE (P,RHO,H,SP,T,AM,Z,GAME,K)
C
C        SAVE OBTAINS THERMODYNAMIC PROPERTIES FOR REAL AIR
C        IS BASED ON CURVE FIT EXPRESSIONS OF AEDC-TDR-63-138
C        EXPRESSIONS OF AEDC-TDR-63-138 APPLICABLE FOR T=90 TO 15000
C
C        MAXIMUM PERCENT ERRORS- T=2000 TO 15000, AND P=1E+4 TO 1E+6
C
C              RHO        H          T          A          Z          GAME
C              2.42       1.96       2.24       2.78       0.75       5.68
C
C        INPUTS ARE PRESSURE(N/SQ METER) AND-
C              (1) ENTROPY,S/R  (K=1)
C              (2) DENSITY, KG/CUBIC METER  (K=2)
C              (3) ENTHALPY, SQ METER/SQ SEC  (K=3)
```

```
C                                                                       P  16
C       ALSO, INPUTS DENSITY AND ENTHALPY ARE INCLUDED  (K=4)           P  17
C                                                                       P  18
C                                                                       P  19
C       MODIFIED 9/7/71 FOR INPUTS P AND T (K=5)                        P  20
C                                                                       P  21
      DIMENSION TABSR(6), TABR(6), TABH(6)                              P  22
      DIMENSION TABPM(13), TABHM(13), TABSRM(13), PM(13)                P  23
      DIMENSION TABTR(17), TABRR(17), TABSRR(17), TABHR(17), TABZR(17)  P  24
      WO=28.967                                                         P  25
      RUNIV=8314.34                                                     P  26
      NN=0                                                              P  27
      MM=0                                                              P  28
      IF (K.NE.5) GO TO 3                                               P  29
      ZZ=.8                                                             P  30
      DO 2 II=1,17                                                      P  31
      RHO=P*WO/(RUNIV*ZZ*T)                                             P  32
      TABRR(II)=RHO                                                     P  33
      GO TO 6                                                           P  34
1     TABSRR(II)=SR                                                     P  35
      TABHR(II)=HA                                                      P  36
      TABZR(II)=Z                                                       P  37
      TABTR(II)=TA                                                      P  38
      ZZ=ZZ+.2                                                          P  39
      MM=0                                                              P  40
      NN=0                                                              P  41
2     CONTINUE                                                          P  42
      CALL FTLUP (T,SR,2,17,TABTR,TABSRR)                               P  43
      CALL FTLUP (T,H,2,17,TABTR,TABHR)                                 P  44
      CALL FTLUP (T,Z,2,17,TABTR,TABZR)                                 P  45
      CALL FTLUP (T,RHO,2,17,TABTR,TABRR)                               P  46
      MM=3                                                              P  47
      GO TO 8                                                           P  48
3     IF (K.NE.4) GO TO 4                                               P  49
      CON5=.03                                                          P  50
      DO 5 J=1,13                                                       P  51
      PM(J)=RHO*H*CON5                                                  P  52
      TABPM(J)=PM(J)                                                    P  53
      P=PM(J)                                                           P  54
      GO TO 6                                                           P  55
4     TABHM(J)=HA                                                       P  56
      TABSRM(J)=SR                                                      P  57
      CON5=CON5+.03                                                     P  58
      MM=0                                                              P  59
      NN=0                                                              P  60
5     CONTINUE                                                          P  61
      CALL FTLUP (H,P,2,13,TABHM,TABPM)                                 P  62
      CALL FTLUP (H,SR,2,13,TABHM,TABSRM)                               P  63
      MM=3                                                              P  64
6     PLOG=ALOG10(P/1.0132E+5)                                          P  65
      A=PLOG*PLOG                                                       P  66
      C=A*PLOG                                                          P  67
      IF (K.EQ.1) GO TO 8                                               P  68
      IF (K.EQ.4.AND.MM.EQ.3) GO TO 8                                   P  69
      SRUP=142.                                                         P  70
      SRLOW=14.                                                         P  71
      SR=(SRUP-SRLOW)/2.+14.                                            P  72
7     DELSR=(SRUP-SRLOW)/2.                                             P  73
      IF (NN.EQ.0) GO TO 8                                              P  74
      SR=SRUP-DELSR                                                     P  75
8     SRLOG=ALOG10(SR)                                                  P  76
      B=SRLOG*SRLOG                                                     P  77
      D=B*SRLOG                                                         P  78
      X15=-39.1442+83.0558*SRLOG-38.2842*SRLOG*SRLOG                    P  79
      X151=-10.*(PLOG-X15)                                              P  80
      IF (X151-40.) 10,9,9                                              P  81
```

```
9       T15=0.0                                                                 D  82
        GO TO 13                                                                D  83
10      IF (X151+40.) 11,12,12                                                  D  84
11      T15=1.0                                                                 D  85
        GO TO 13                                                                D  86
12      T15=1./(1.+EXP(X151))                                                   D  87
13      IF (K.EQ.3.AND.MM.NE.2) GO TO 39                                        D  88
        IF (K.EQ.2.AND.MM.EQ.2) GO TO 39                                        D  89
        IF (K.EQ.4.AND.MM.EQ.3) GO TO 61                                        D  90
        IF (K.EQ.4.AND.MM.EQ.2) GO TO 39                                        D  91
        IF (K.EQ.5.AND.MM.EQ.2) GO TO 39                                        D  92
        IF (K.EQ.5.AND.MM.EQ.3) GO TO 83                                        D  93
C                                                                               D  94
C          COMPUTING RHO AS A FUNCTION OF P AND S/P                             D  95
C                                                                               D  96
14      XR12=-16.5527+57.45*SRLOG-30.8036*P                                     D  97
        XR23=499.544-938.91*SRLOG+609.028*P-135.995*D                           D  98
        XR34=360.507-634.538*SRLOG+389.174*P-82.4653*D                          D  99
        XR45=489.628-458.5*SRLOG+106.25*P                                       D 100
        XR121=-10.*(PLOG-XR12)                                                  D 101
        XR231=-10.*(PLOG-XR23)                                                  D 102
        XR341=-10.*(PLOG-XR34)                                                  D 103
        XR451=-10.*(PLOG-XR45)                                                  D 104
        IF (XR121-40.) 15,18,18                                                 D 105
15      IF (XR121+40.) 16,17,17                                                 D 106
16      TR12=1.0                                                                D 107
        GO TO 19                                                                D 108
17      TR12=1./(1.+EXP(XR121))                                                 D 109
        GO TO 19                                                                D 110
18      TR12=0.0                                                                D 111
19      IF (XR231-40.) 20,23,23                                                 D 112
20      IF (XR231+40.) 21,22,22                                                 D 113
21      TR23=1.0                                                                D 114
        GO TO 24                                                                D 115
22      TR23=1./(1.+EXP(XR231))                                                 D 116
        GO TO 24                                                                D 117
23      TR23=0.0                                                                D 118
24      IF (XR341-40.) 25,28,28                                                 D 119
25      IF (XR341+40.) 26,27,27                                                 D 120
26      TR34=1.                                                                 D 121
        GO TO 29                                                                D 122
27      TR34=1./(1.+EXP(XR341))                                                 D 123
        GO TO 29                                                                D 124
28      TR34=0.0                                                                D 125
29      IF (XR451-40.) 30,33,33                                                 D 126
30      IF (XR451+40.) 31,32,32                                                 D 127
31      TR45=1.0                                                                D 128
        GO TO 34                                                                D 129
32      TR45=1./(1.+EXP(XR451))                                                 D 130
        GO TO 34                                                                D 131
33      TR45=0.0                                                                D 132
34      RHCL1=15.951867-0.0022829S*PLOG-15.994242*SRLOG+.006518726?*A+.530      D 133
     179685*PLOG*SRLOG+3.175974*P                                               D 134
        RHCL2=1541.1666-63.93035*PLOG-2993.1662*SRLOG+.935437*A+84.30375*S      D 135
     1RLOG*PLOG+1938.7061*P-.0047460?6*C-.612840?*A*SRLOG-27.422666*P*PL         D 136
     2OG-419.0881*D                                                             D 137
        RHCL3=427.4745-18.126622*PLOG-765.47626*SRLOG+.2934369*A+22.92687       D 138
     17*PLOG*SRLOG+456.717*P-.0017033404*C-.1806830?*A*SRLOG-6.9143617*P        D 139
     2*PLOG-91.131851*D                                                         D 140
        RHCL4=206.23144-8.227027?*PLOG-329.5465*SRLOG+.1324191*A+9.8884165      D 141
     1*PLOG*SRLOG+175.03931*P-.0011017845?*C-.0765437?*A*SRLOG-2.6920144*       D 142
     2P*PLOG-31.237834*D                                                        D 143
        RHCL5=-399.52358+12.899477*PLOG+411.64144*SRLOG-.0976949?9*A-5.220      D 144
     14477*PLOG*SRLOG-106.6733*P                                                D 145
        RHCAL=RHCL1+(RHCL2-RHCL1)*TR12+(RHCL3-RHCL2)*TR23+(RHCL4-RHCL3)*TR      D 146
     134+(RHCL5-RHCL4)*TR45                                                     D 147
        RH15=-79.282533+6.3537078*PLOG+179.22721*SRLOG-.1260709?*A-8.40131      D 148
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```
      122*PLOG*SRLOG-129.95269*B+.0010037437*C+.00418551 1*A*SRLOG+3.12569   P 149
      266*PLOG*B+30.203862*D                                                 P 150
       RHCAL=RH15+(RHCAL-RH15)*T15                                           P 151
       RHOA=(10.**RHCAL)*1.29233                                             P 152
       IF (K.EQ.1) GO TO 39                                                  P 153
       IF (K.EQ.3) GO TO 61                                                  P 154
       IF (K.EQ.2.AND.MM.EQ.1) GO TO 59                                      P 155
       IF (K.EQ.4.AND.MM.EQ.1) GO TO 59                                      P 156
       IF (K.EQ.5.AND.MM.EQ.1) GO TO 59                                      P 157
C                                                                            P 158
C         CONVERGENCE TEST FOR K=2                                           P 159
C                                                                            P 160
       IF (ABS(1.-RHO/RHOA).LE..001) GO TO 39                                P 161
       NN=NN+1                                                               P 162
       IF (RHO.GT.RHOA) GO TO 37                                             P 163
35     SRLOW=SR                                                              P 164
       SRUP=SR+DELSR                                                         P 165
       IF (DELSR.GT.1.) GO TO 7                                              P 166
       TABSR(1)=SRLOW                                                        P 167
       TABSR(6)=SRUP                                                         P 168
       IF (K.EQ.2.OR.K.EQ.4) GO TO 36                                        P 169
       IF (K.EQ.5) GO TO 36                                                  P 170
       N=2                                                                   P 171
       GO TO 52                                                              P 172
36     N=-2                                                                  P 173
       GO TO 57                                                              P 174
37     SRUP=SR                                                               P 175
       SRLOW=SR-DELSR                                                        P 176
       IF (DELSR.GT.1.) GO TO 7                                              P 177
       TABSR(1)=SRUP                                                         P 178
       TABSR(6)=SRLOW                                                        P 179
       IF (K.EQ.2.OR.K.EQ.4) GO TO 38                                        P 180
       IF (K.EQ.5) GO TO 38                                                  P 181
       N=-2                                                                  P 182
       GO TO 52                                                              P 183
38     N=2                                                                   P 184
       GO TO 57                                                              P 185
C                                                                            P 186
C         COMPUTING ENTHALPY AS A FUNCTION OF P AND S/R                      P 187
C                                                                            P 188
39     IF (SRLOG-1.6) 40,40,41                                               P 189
40     HRCAL=12.693869+5.3975312*PLOG-48.729217*SRLOG-.1496152 1*A-5.87887   P 190
      174*PLOG*SRLOG+48.19278*B+.000901441 32*C+.00115147 3*A*SRLOG+1.62828  P 191
      229*PLOG*B-13.065267*D                                                 P 192
       GO TO 51                                                              P 193
41     IF (SRLOG-1.76) 42,42,48                                              P 194
42     HR22=-156.37194+6.6959228*PLOG+269.93097*SRLOG-.09717996 5*A-7.5379   P 195
      1714*PLOG*SRLOG-152.13866*B+.000570299 37*C+.05836479 5*A*SRLOG+2.159  P 196
      22755*PLOG*B+28.940926*D                                               P 197
       HR21=-84.008522+2.5761318*PLOG+107.06198*SRLOG-.01435290 4*A-1.5313   P 198
      1194*PLOG*SRLOG-32.316439*B                                            P 199
       XH=-61.2053+114.103*SRLOG-47.5532*B                                   P 200
       XH1=-10.*(PLOG-XH)                                                    P 201
       IF (XH1-40.) 43,45,46                                                 P 202
43     IF (XH1+40.) 44,45,45                                                 P 203
44     TH=1.                                                                 P 204
       GO TO 47                                                              P 205
45     TH=1./(1.+EXP(XH1))                                                   P 206
       GO TO 47                                                              P 207
46     TH=0.0                                                                P 208
47     HRCAL=HR21+(HR22-HR21)*TH                                             P 209
       GO TO 51                                                              P 210
48     IF (SRLOG-1.92) 49,49,50                                              P 211
49     HRCAL=-35.160671+.5366924*PLOG+56.99585*SRLOG-.02266136 8*A-.484703   P 212
      105*SRLOG*PLOG-27.641087*B+.000585688 39*C+.01629996 2*A*SRLOG+.14073  P 213
      2606*B*PLOG+4.712261*D                                                 P 214
       GO TO 51                                                              P 215
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50     HRCAL=-114.94796+4.00458*PLOG+180.08427*SRLOG-.041327787*A-4.0366
      1535*PLOG*SRLOG-90.76006*B+.00040320694*C+.02436024B*A*SRLOG+1.0462
      2299*PLOG*B+15.467804*D
51     HR15=28.160464-2.2339873*PLOG-59.053694*SRLOG+.054973544*A+3.71832
      157*PLOG*SRLOG+40.986503*B-.00042992698*C-.04072633Z*A*SRLOG-1.37045
      205*PLOG*B-8.253645*D
       HRCAL=HR15+(HRCAL-HR15)*T15
       HA=(10.**HRCAL)*287.0388
       IF (K.EQ.1.OR.K.EQ.2) GO TO 61
       IF (K.EQ.5) GO TO 61
       IF (K.EQ.3.AND.MM.EQ.1) GO TO 55
       IF (K.EQ.4) GO TO 4
C
C         CONVERGENCE TEST FOR K=3
C
       IF (ABS(1.-H/HA).LE..001) GO TO 14
       NN=NN+1
       IF (HA.GT.H) GO TO 37
       GO TO 35
C
C         INTERPOLATION FOR DELSR LESS THAN 1
C
52     TABH(1)=HA
53     DELSR=(TABSR(6)-TABSR(1))/5.
       DO 54 I=2,5
       TABSR(I)=TABSR(I-1)+DELSR
54     CONTINUE
       IF (K.EQ.2.OR.K.EQ.4) GO TO 58
       IF (K.EQ.5) GO TO 58
       DO 56 I=2,6
       MM=1
       SR=TABSR(I)
       GO TO 8
55     TABH(I)=HA
56     CONTINUE
       CALL FTLUP (H,SR,N,6,TAPH,TABSR)
       MM=2
       GO TO 8
57     TABR(I)=RHOA
       GO TO 53
58     DO 60 I=2,6
       MM=1
       SR=TABSR(I)
       GO TO 8
59     TABR(I)=RHOA
60     CONTINUE
       CALL FTLUP (RHO,SR,N,6,TABR,TABSR)
       MM=2
       GO TO 8
C
C         COMPUTING Z
C
61     XZ12=62.91-41.5*SRLOG
       XZ23=72.945-45.75*SRLOG
       XZ34=65.75-37.5*SRLOG
       XZ45=62.92-32.0*SRLOG
       XZ121=-10.*(PLOG-XZ12)
       XZ231=-10.*(PLOG-XZ23)
       XZ341=-10.*(PLOG-XZ34)
       XZ451=-10.*(PLOG-XZ45)
       ZCAL2=519.80374-23.752514*PLOG-983.90729*SRLOG+.2729657*A+30.0843
      179*PLOG*SRLOG+620.04168*B-.0021648826*C-.23710079*A*SRLOG-9.496903
      2*PLOG*B-129.78921*D
       ZCAL3=366.40674-15.517444*PLOG-647.42436*SRLOG+.1870175B*A+18.0403
      183*PLOG*SRLOG+379.59834*B-.0008795843B*C-.105B0139*A*SRLOG-5.18882
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      254*PLOG*B-73.504269*D                                                    D 281
       ZCAL4=516.07331-16.59277*PLOG-808.49823*SRLOG+.071256235*A+16.5268       D 282
      113*PLOG*SRLOG+418.45341*B+.000941837*C-.019727817*A*SRLOG-3.994B         D 283
      2906*PLOG*B-71.038921*D                                                   D 284
       IF (XZ121-40.) 62,65,65                                                  D 285
62     IF (XZ121+40.) 63,64,64                                                  D 286
63     TZ12=1.                                                                  D 287
       GO TO 66                                                                 D 288
64     TZ12=1./(1.+EXP(XZ121))                                                  D 289
       GO TO 66                                                                 D 290
65     TZ12=0.0                                                                 D 291
66     IF (XZ231-40.) 67,70,70                                                  D 292
67     IF (XZ231+40.) 68,69,69                                                  D 293
68     TZ23=1.                                                                  D 294
       GO TO 71                                                                 D 295
69     TZ23=1./(1.+EXP(XZ231))                                                  D 296
       GO TO 71                                                                 D 297
70     TZ23=0.0                                                                 D 298
71     IF (XZ341-40.) 72,75,75                                                  D 299
72     IF (XZ341+40.) 73,74,74                                                  D 300
73     TZ34=1.                                                                  D 301
       GO TO 76                                                                 D 302
74     TZ34=1./(1.+EXP(XZ341))                                                  D 303
       GO TO 76                                                                 D 304
75     TZ34=0.0                                                                 D 305
76     IF (XZ451-40.) 77,80,80                                                  D 306
77     IF (XZ451+40.) 78,79,79                                                  D 307
78     TZ45=1.                                                                  D 308
       GO TO 81                                                                 D 309
79     TZ45=1./(1.+EXP(XZ451))                                                  D 310
       GO TO 81                                                                 D 311
80     TZ45=0.0                                                                 D 312
81     ZCAL=1.0+(ZCAL2-1.)*TZ12+(ZCAL3-ZCAL2)*TZ23+(ZCAL4-ZCAL3)*TZ34+(4.       D 313
      10-ZCAL4)*TZ45                                                            D 314
       ZCAL=1.+(ZCAL-1.)*T15                                                    D 315
       Z=ZCAL                                                                   D 316
C                                                                               D 317
C         COMPUTING T(DEG K)                                                    D 318
C                                                                               D 319
       IF (K.EQ.2.OR.K.EQ.4) GO TO 82                                           D 320
       IF (K.EQ.5) GO TO 82                                                     D 321
       RHO=RHOA                                                                 D 322
82     TA=P*WO/(RHO*RUN1V*Z)                                                    D 323
       IF (K.EQ.5) GO TO 1                                                      D 324
       T=TA                                                                     D 325
C                                                                               D 326
C         COMPUTING A(M/SEC)                                                    D 327
C                                                                               D 328
83     IF (T-2100.) 84,84,87                                                    D 329
84     IF (T-1500.) 86,86,85                                                    D 330
85     IF (PLOG+1.) 87,87,86                                                    D 331
86     CON1=SQRT(T/273.15)                                                      D 332
       AOAO=-.0753808+CON1*(1.12644-.0552696*CON1)                              D 333
       AM=331.3115*AOAO                                                         D 334
       GO TO 108                                                                D 335
87     XA12=635.054-1220.46*SRLOG+803.882*B-180.845*D                           D 336
       XA23=373.702-663.358*SRLOG+408.854*B-86.8056*D                           D 337
       XA34=1703.78-2602.97*SRLOG+1337.93*B-231.422*D                           D 338
       XA22=1043.37-1820.34*SRLOG+1076.36*B-215.445*D                           D 339
       XA121=-10.*(PLOG-XA12)                                                   D 340
       XA231=-10.*(PLOG-XA23)                                                   D 341
       XA341=-10.*(PLOG-XA34)                                                   D 342
       XA221=-10.*(PLOG-XA22)                                                   D 343
       A1=-4409.6241+196.82259*PLOG+8746.4634*SRLOG-3.1650299*A-262.32947       D 344
      1*PLOG*SRLOG-5786.449*B+.02000486*C+2.1429826*A*SRLOG+87.589029*PL        D 345
```

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      20G*B+1277.6718*D                                                  D 346
       A21=-1814.5117+86.096078*PLOG+3315.6099*SRLOG-1.7593034*A-107.2534 D 347
      1*PLOG*SRLOG-2023.201*B+.016287679*C+1.1398134*A*SRLOG+37.659607*PL D 348
      20G*B+413.41945*D                                                  D 349
       A22=2651.2944-81.405596*PLOG-3099.0064*SRLOG+.69752668*A+48.062506 D 350
      1*PLOG*SRLOG+907.70889*B                                           D 351
       IF (XA221-40.) 89,88,88                                           D 352
88     TA22=0.0                                                          D 353
       GO TO 92                                                          D 354
89     IF (XA221+40.) 90,90,91                                           D 355
90     TA22=1.0                                                          D 356
       GO TO 92                                                          D 357
91     TA22=1./(1.+EXP(XA221))                                           D 358
92     A2=A21+(A22-A21)*TA22                                             D 359
       A3=-3217.8037+195.34964*PLOG+5348.2143*SRLOG-4.6268475*A-221.12705 D 360
      1*PLOG*SRLOG-2970.8649*B+.04461358*C+2.7079177*A*SRLOG+63.042803*B D 361
      2LOG*B+553.12007*D                                                 D 362
       A4=16976.939-476.10242*PLOG-17445.315*SRLOG+3.6534057*A+246.41125* D 363
      1PLOG*SRLOG+4486.3118*B                                            D 364
       IF (XA121-40.) 94,93,93                                           D 365
93     TA12=0.0                                                          D 366
       GO TO 97                                                          D 367
94     IF (XA121+40.) 95,95,96                                           D 368
95     TA12=1.0                                                          D 369
       GO TO 97                                                          D 370
96     TA12=1./(1.+EXP(XA121))                                           D 371
97     IF (XA231-40.) 99,98,98                                           D 372
98     TA23=0.0                                                          D 373
       GO TO 102                                                         D 374
99     IF (XA231+40.) 100,100,101                                        D 375
100    TA23=1.0                                                          D 376
       GO TO 102                                                         D 377
101    TA23=1./(1.+EXP(XA231))                                           D 378
102    IF (XA341-40.) 104,103,103                                        D 379
103    TA34=0.0                                                          D 380
       GO TO 107                                                         D 381
104    IF (XA341+40.) 105,105,106                                        D 382
105    TA34=1.0                                                          D 383
       GO TO 107                                                         D 384
106    TA34=1./(1.+EXP(XA341))                                           D 385
107    AOAO=A1+(A2-A1)*TA12+(A3-A2)*TA23+(A4-A3)*TA34                    D 386
       AM=331.3115*AOAO                                                  D 387
C                                                                        D 388
C         COMPUTING GAME                                                 D 389
C                                                                        D 390
108    GAME=W0*AM**2/(RUN1V*Z*T)                                         D 391
       IF (K.EQ.2) GO TO 109                                             D 392
       IF (K.EQ.3.OR.K.EQ.4) GO TO 110                                   D 393
       IF (K.EQ.5) GO TO 110                                             D 394
       H=HA                                                              D 395
       GO TO 110                                                         D 396
109    H=HA                                                              D 397
110    RETURN                                                            D 398
C                                                                        D 399
       END                                                               D 400-
       SUBROUTINE INTRP (N,X,Y,XINT,YINT)                                O   1
       DIMENSION X(N), Y(N)                                              O   2
       YINT=0.                                                           O   3
       DO 3 I=1,N                                                        O   4
       SUMN=1.                                                           O   5
       SUMD=1.                                                           O   6
       DO 2 J=1,N                                                        O   7
       IF (J-I) 1,2,1                                                    O   8
1      SUMN=SUMN*(XINT-X(J))                                             O   9
       SUMD=SUMD*(X(I)-X(J))                                             O  10
2      CONTINUE                                                          O  11
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```
3       YINT=YINT+Y(I)*SUMN/SUMD                                        0  12
        RETURN                                                          0  13
        END                                                             0  14-
        SUBROUTINE SC (R2I,UI,PI,HI,R1I,US,P,H,ISAV)                    D   1
        COMMON /BLK4/ LE,NON,LU,NDRIV,LB,LD,LG                          D   2
        COMMON /BLK5/ SR,TII,AI,ZI,GI,K,P2,ISP                          D   3
        R2I=10.*R1I                                                     D   4
        IF (LB.EQ.1) GO TO 5                                            D   5
        CALL SHOCK (R,C,D,R1I,US,P,H)                                   D   6
1       UI=US*(1.-R1I/R2I)                                              D   7
        PI=C-(R2I*(US-UI)**2)                                           D   8
        HI=D-.5*(US-UI)**2                                              D   9
        IF (LB.EQ.2) GO TO 3                                            D  10
        GO TO (2,3), ISAV                                               D  11
2       CALL SEARCH (PI,RNEW,HI,SR,TII,AI,ZI,GI,ZSI,ISP)                D  12
        GO TO 4                                                         D  13
3       CALL SAVE (PI,RNEW,HI,SR,TII,AI,ZI,GI,3)                        D  14
4       IF (ABS(1.-RNEW/R2I).LE..001) GO TO 9                           D  15
        R2I=RNEW                                                        D  16
        GO TO 1                                                         D  17
5       US=SQRT((PI-P)/(R1I*(1.-R1I/R2I)))                              D  18
        UI=US*(1.-R1I/R2I)                                              D  19
        HI=H+.5*(US**2-(US-UI)**2)                                      D  20
        GO TO (6,7), ISAV                                               D  21
6       CALL SEARCH (PI,RNEW,HI,SR,TII,AI,ZI,GI,ZSI,ISP)                D  22
        GO TO 8                                                         D  23
7       CALL SAVE (PI,RNEW,HI,SR,TII,AI,ZI,GI,3)                        D  24
8       IF (ABS(1.-RNEW/R2I).LE..001) GO TO 9                           D  25
        R2I=RNEW                                                        D  26
        GO TO 5                                                         D  27
9       RETURN                                                          D  28
        END                                                             D  29-
        SUBROUTINE SOLUT (U3,P3,U2,P2,M,N,UR,PR)                        S   1
        DIMENSION U3(20), P3(20), U2(10), P2(10), U(2)                  S   2
        FUNCD(PP,UU,R)=PP-UU*R                                          S   3
        FUNAB(P,PP,U,UU)=(P-PP)/(U-UU)                                  S   4
C                                                                       S   5
C       USE END POINTS FOR FIRST INTERSECTION                           S   6
C                                                                       S   7
        MR=1                                                            S   8
        NR=1                                                            S   9
        IF (P2(1).GT.P2(2)) NR=-NR                                      S  10
        IF (P3(1).GT.P3(2)) MR=-MR                                      S  11
        P31=P3(1)                                                       S  12
        P32=P3(M)                                                       S  13
        P21=P2(1)                                                       S  14
        P22=P2(N)                                                       S  15
        U21=U2(1)                                                       S  16
        U22=U2(N)                                                       S  17
        U31=U3(1)                                                       S  18
        U32=U3(M)                                                       S  19
1       AA=FUNAB(P22,P21,U22,U21)                                       S  20
        BB=FUNAB(P32,P31,U32,U31)                                       S  21
        CC=FUNCD(P21,U21,AA)                                            S  22
        DD=FUNCD(P31,U31,BB)                                            S  23
        UR=(CC-DD)/(BB-AA)                                              S  24
        PR=CC+UR*AA                                                     S  25
        CALL FTLUP (PR,U(1),NR,N,P2,U2)                                 S  26
        CALL FTLUP (PR,U(2),MR,M,P3,U3)                                 S  27
        IF (ABS((U(1)-U(2))/U(1))-.0001) 3,3,2                          S  28
2       P31=P32                                                         S  29
```

```
      P32=PR                                                          S   30
      P21=P22                                                         S   31
      P22=PR                                                          S   32
      U31=U32                                                         S   33
      U32=U(2)                                                        S   34
      U21=U22                                                         S   35
      U22=U(1)                                                        S   36
      GO TO 1                                                         S   37
3     P=PR                                                            S   38
      RETURN                                                          S   39
      END                                                             S   40-
-00
 L.E.T. PROGRAM FOR EQUILIBRIUM REAL AIR.
 $INP RUN=441.P1=3447.5.US1=2865.U5=5500.IREP=1.DELU5=330$
 $INP RUN=86.P1=6895.US1=4300.U5=7500.IREP=1.DELU5=500$
-
```

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 free-stream 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

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 06/19/74

L.E.T. PROGRAM FOR EQUILIBRIUM REAL AIR


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


SHOCK TUBE PHASE OF PROGRAM

MEASURED INPUTS FOR SHOCK TUBE PHASE

  RUN        P1         T1         US1        P2         P4          T4         XIS        DIA      ISAV  INU  LD
4.410E+02 3.447E+03 3.000E+02 2.865E+03 0.         0.         0.         4.650E+00 1.524E-01    2    2    4


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

CONDITIONS BEHIND INCIDENT SHOCK - REGION 2

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

  P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
2.895E+05 3.087E-01 3.175E+03 4.336E+06 3.302E+01 1.029E+00 1.151E+00 1.039E+03 2.493E+03 2.400E+00 8.604E+06

RATIO- 2 TO 1 CONDITIONS AND SHOCK VELOCITY
```

```
  P          RHO        T          H          A          MSI        USI
8.396E+01 7.710E+00 1.058E+01 1.443E+01 2.992E+00 8.252E+00 2.865E+03


SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY

   LMAX        L        L/LMAX      TIM        UT        LMAXT       LT       LT/LMAXT    TIMT       UIT        TIMI
7.324E+01 5.675E-01 7.748E-03 2.245E-04 2.527E+03 1.030E+00 4.235E-01 4.111E-01 1.580E-04 2.681E+03 2.419E-04


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

EXPANSION TUBE PHASE OF PROGRAM

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


INPUTS FOR EXPANSION TUBE PHASE

   US          PS          XAS        OELUS     ISAV IEXP IREP 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        Z          GAME       A          U          M          NRE
1.481E+03 7.307E-03 6.850E+02 6.979E+05 3.302E+01 1.029E+00 1.409E+00 5.345E+02 5.500E+03 1.029E+01 1.221E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

  P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
2.027E+05 8.157E-02 6.398E+03 1.681E+07 4.243E+01 1.353E+00 1.144E+00 1.686E+03 4.924E+02 2.921E-01 1.116E+01


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

  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.128E+05 8.510E-02 6.427E+03 1.693E+07 1.356E+00 1.144E+00 1.691E+03 1.867E+07 2.540E-02 3.323E-04


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

  P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
1.832E+05 4.111E-02 1.509E+04 1.535E+07 3.885E+01 1.029E+00 1.409E+00 2.506E+03 9.775E+02 3.900E-01 5.626E+00


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

  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.036E+05 4.431E-02 1.555E+04 1.582E+07 1.029E+00 1.409E+00 2.545E+03 1.705E+07 2.540E-02 3.323E-04

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


5 CONDITIONS FOR EQUILIBRIUM EXPANSION

  P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
4.457E+03 1.060E-02 1.464E+03 1.596E+06 3.302E+01 1.000E+00 1.306E+00 7.410E+02 5.500E+03 7.423E+00 1.122E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO

2.964E+05 1.186E-01 6.484E+03 1.660E+07 4.180E+01 1.342E+00 1.147E+00 1.693E+03 4.910E+02 2.900E-01 1.120E+01


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

  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
3.110E+05 1.237E-01 6.514E+03 1.672E+07 1.345E+00 1.147E+00 1.698E+03 2.229E+07 2.540E-02 4.807E-04


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
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APPENDIX A

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5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
4.457E+03  1.060E-02  1.464E+03  1.596E+06  3.302E+01  1.000E+00  1.306E+00  7.410E+02  4.840E+03  6.532E+00  9.870E+05


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
2.282E+05  1.074E-01  5.855E+03  1.319E+07  4.019E+01  1.264E+00  1.163E+00  1.572E+03  4.775E+02  3.038E-01  1.013E+01


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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.407E+05  1.124E-01  5.890E+03  1.331E+07  1.266E+00  1.162E+00  1.578E+03  1.553E+07  2.540E-02  6.342E-04


ACCELERATION AIR CONDITIONS (REGION 20) AND P10
   P20        RHO20      T20        H20        Z20        M20        P10        US10       MS10       RATIO
4.457E+03  1.986E-03  5.493E+03  1.767E+07  1.423E+00  3.477E+00  1.178E+01  5.908E+03  1.702E+01  1.452E+01


ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

   XAS        XA         LMAX       L          L/LMAX     TIM        UI         UI/US      US20/UI    TIMI
1.698E+01  1.698E+00  2.038E-01  6.847E-02  3.359E-01  1.193E-05  5.738E+03  1.043E+00  1.030E+00  2.127E-05
1.698E+01  3.396E+00  2.038E-01  1.080E-01  5.299E-01  1.863E-05  5.798E+03  1.054E+00  1.019E+00  4.253E-05
1.698E+01  5.094E+00  2.038E-01  1.365E-01  6.699E-01  2.306E-05  5.832E+03  1.060E+00  1.013E+00  6.380E-05
1.698E+01  6.792E+00  2.038E-01  1.531E-01  7.509E-01  2.615E-05  5.854E+03  1.064E+00  1.009E+00  8.507E-05
1.698E+01  8.490E+00  2.038E-01  1.664E-01  8.163E-01  2.835E-05  5.869E+03  1.067E+00  1.007E+00  1.063E-04
1.698E+01  1.019E+01  2.038E-01  1.761E-01  8.638E-01  2.995E-05  5.880E+03  1.069E+00  1.005E+00  1.276E-04
1.698E+01  1.189E+01  2.038E-01  1.832E-01  8.987E-01  3.112E-05  5.887E+03  1.070E+00  1.004E+00  1.489E-04
1.698E+01  1.358E+01  2.038E-01  1.884E-01  9.245E-01  3.198E-05  5.892E+03  1.071E+00  1.003E+00  1.701E-04
1.698E+01  1.528E+01  2.038E-01  1.923E-01  9.436E-01  3.262E-05  5.896E+03  1.072E+00  1.002E+00  1.914E-04
1.698E+01  1.698E+01  2.038E-01  1.952E-01  9.578E-01  3.310E-05  5.899E+03  1.073E+00  1.001E+00  2.127E-04


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPH

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
1.751E+06  1.294E+00  4.307E+03  7.267E+06  3.380E+01  1.094E+00  1.201E+00  1.275E+03  5.946E+02  4.665E-01  6.781E+06

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

EXPANSION TUBE PHASE OF PROGRAM

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


INPUTS FOR EXPANSION TUBE PHASE

   US         PS         XAS        DELUS      ISAV IEXP IREP 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        Z          GAME       A          U          M          NRE
1.400E+02  1.762E-03  2.529E+02  2.643E+05  3.380E+01  1.094E+00  1.430E+00  3.370E+02  5.500E+03  1.632E+01  6.015E+05


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
4.868E+04  1.972E-02  6.122E+03  1.803E+07  4.512E+01  1.405E+00  1.131E+00  1.671E+03  4.913E+02  2.941E-01  1.119E+01


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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
5.111E+04  2.058E-02  6.166E+03  1.815E+07  1.408E+00  1.131E+00  1.676E+03  9.826E+06  2.540E-02  2.015E-04
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APPENDIX A

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STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
4.385E+04 9.794E-03 1.426E+04 1.490E+07 4.147E+01 1.094E+00 1.430E+00 2.530E+03 9.896E+02 3.911E-01 5.558E+00


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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
4.883E+04 1.056E-02 1.472E+04 1.539E+07 1.094E+00 1.430E+00 2.571E+03 8.117E+06 2.540E-02 2.015E-04

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


5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
6.052E+03 1.126E-02 1.870E+03 2.111E+06 3.380E+01 1.000E+00 1.278E+00 8.284E+02 5.500E+03 6.639E+00 1.002E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
3.156E+05 1.236E-01 6.571E+03 1.711E+07 4.200E+01 1.354E+00 1.147E+00 1.711E+03 5.009E+02 2.927E-01 1.097E+01


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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
3.315E+05 1.289E-01 6.602E+03 1.725E+07 1.357E+00 1.147E+00 1.717E+03 2.375E+07 2.540E-02 5.475E-04


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
6.052E+03 1.126E-02 1.870E+03 2.111E+06 3.380E+01 1.000E+00 1.278E+00 8.284E+02 4.840E+03 5.842E+00 8.817E+05


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK
   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
2.431E+05 1.113E-01 5.969E+03 1.370E+07 4.041E+01 1.275E+00 1.160E+00 1.592E+03 4.897E+02 3.077E-01 9.882E+00


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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.568E+05 1.166E-01 6.005E+03 1.382E+07 1.277E+00 1.159E+00 1.598E+03 1.668E+07 2.540E-02 7.245E-04


ACCELERATION AIR CONDITIONS (REGION 20) AND P10
    P20        RHO20       T20        H20        Z20        M20        P10        US10       MS10       RATIO
6.052E+03 2.667E-03 5.565E+03 1.769E+07 1.421E+00 3.455E+00 1.599E+01 5.912E+03 1.703E+01 1.436E+01


ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

   XAS        XA         LMAX       L          L/LMAX     TIM        UI         UI/U5     US20/UI    TIMI
1.698E+01 1.698E+00 2.765E-01 7.471E-02 2.702E-01 1.307E-05 5.717E+03 1.039E+00 1.034E+00 2.149E-05
1.698E+01 3.396E+00 2.765E-01 1.221E-01 4.414E-01 2.113E-05 5.776E+03 1.050E+00 1.024E+00 4.298E-05
1.698E+01 5.094E+00 2.765E-01 1.562E-01 5.649E-01 2.688E-05 5.812E+03 1.057E+00 1.017E+00 6.448E-05
1.698E+01 6.792E+00 2.765E-01 1.819E-01 6.577E-01 3.116E-05 5.836E+03 1.061E+00 1.013E+00 8.597E-05
1.698E+01 8.490E+00 2.765E-01 2.016E-01 7.289E-01 3.444E-05 5.853E+03 1.064E+00 1.010E+00 1.075E-04
1.698E+01 1.019E+01 2.765E-01 2.169E-01 7.843E-01 3.697E-05 5.866E+03 1.067E+00 1.008E+00 1.290E-04
1.698E+01 1.189E+01 2.765E-01 2.289E-01 8.278E-01 3.896E-05 5.876E+03 1.068E+00 1.006E+00 1.504E-04
1.698E+01 1.358E+01 2.765E-01 2.384E-01 8.622E-01 4.052E-05 5.883E+03 1.070E+00 1.005E+00 1.719E-04
1.698E+01 1.528E+01 2.765E-01 2.460E-01 8.895E-01 4.176E-05 5.889E+03 1.071E+00 1.004E+00 1.934E-04
1.698E+01 1.698E+01 2.765E-01 2.520E-01 9.112E-01 4.275E-05 5.894E+03 1.072E+00 1.003E+00 2.149E-04


XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
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APPENDIX A

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CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPH

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

      P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
2.654E+06 1.639E+00 4.984E+03 8.887E+06 3.451E+01 1.132E+00 1.225E+00 1.408E+03 0.          0.          0.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

EXPANSION TUBE PHASE OF PROGRAM

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INPUTS FOR EXPANSION TUBE PHASE

      U5          P5          KAS          DELU5      ISAV IEXP IREP 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          Z          GAME          A          U          M          NRE
8.689E+01 1.266E-03 2.112E+02 2.242E+05 3.451E+01 1.132E+00 1.441E+00 3.145E+02 5.500E+03 1.749E+01 5.016E+05

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
3.491E+04 1.394E-02 6.097E+03 1.882E+07 4.605E+01 1.431E+00 1.127E+00 1.680E+03 4.991E+02 2.971E-01 1.101E+01

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

      P          RHO          T          H          Z          GAME          A          QT          RN          TIMI
3.669E+04 1.457E-02 6.120E+03 1.895E+07 1.433E+00 1.128E+00 1.685E+03 8.694E+06 2.540E-02 1.872E-04

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
3.137E+04 6.906E-03 1.398E+04 1.484E+07 4.232E+01 1.132E+00 1.441E+00 2.559E+03 1.009E+03 3.942E-01 5.453E+00

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

      P          RHO          T          H          Z          GAME          A          QT          RN          TIMI
3.502E+04 7.452E-03 1.466E+04 1.535E+07 1.132E+00 1.441E+00 2.602E+03 6.855E+06 2.540E-02 1.872E-04

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

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

      P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
7.729E+03 1.188E-02 2.256E+03 2.676E+06 3.451E+01 1.003E+00 1.225E+00 8.925E+02 5.500E+03 6.163E+00 9.309E+05

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
3.338E+05 1.278E-01 6.656E+03 1.767E+07 4.222E+01 1.367E+00 1.146E+00 1.730E+03 5.111E+02 2.954E-01 1.075E+01

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

      P          RHO          T          H          Z          GAME          A          QT          RN          TIMI
3.508E+05 1.334E-01 6.688E+03 1.780E+07 1.370E+00 1.146E+00 1.736E+03 2.523E+07 2.540E-02 5.980E-04

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
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APPENDIX A

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

P	RHO	T	H	S/R	Z	GAME	A	U	M	NRE
7.729E+03	1.188E-02	2.256E+03	2.676E+06	3.451E+01	1.003E+00	1.225E+00	8.925E+02	4.840E+03	5.423E+00	8.192E+05

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

P	RHO	T	H	S/R	Z	GAME	A	U	M	RATIO
2.571E+05	1.143E-01	6.085E+03	1.426E+07	4.067E+01	1.288E+00	1.156E+00	1.613E+03	5.029E+02	3.118E-01	9.623E+00

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

P	RHO	T	H	Z	GAME	A	QT	RN	TIMI
2.720E+05	1.200E-01	6.121E+03	1.439E+07	1.290E+00	1.156E+00	1.619E+03	1.788E+07	2.540E-02	7.932E-04

ACCELERATION AIR CONDITIONS (REGION 20) AND P10

P20	RHO20	T20	H20	Z20	M20	P10	US10	MS10	RATIO
7.729E+03	3.375E-03	5.623E+03	1.772E+07	1.419E+00	3.437E+00	2.040E+01	5.916E+03	1.704E+01	1.424E+01

ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

XAS	XA	LMAX	L	L/LMAX	TIM	UI	UI/U5	US20/UI	TIMI
1.698E+01	1.698E+00	3.529E-01	7.945E-02	2.251E-01	1.394E-05	5.700E+03	1.036E+00	1.038E+00	2.167E-05
1.698E+01	3.396E+00	3.529E-01	1.330E-01	3.769E-01	2.310E-05	5.758E+03	1.047E+00	1.028E+00	4.335E-05
1.698E+01	5.094E+00	3.529E-01	1.735E-01	4.916E-01	2.995E-05	5.794E+03	1.053E+00	1.021E+00	6.502E-05
1.698E+01	6.792E+00	3.529E-01	2.053E-01	5.817E-01	3.528E-05	5.819E+03	1.058E+00	1.017E+00	8.670E-05
1.698E+01	8.490E+00	3.529E-01	2.307E-01	6.537E-01	3.952E-05	5.838E+03	1.061E+00	1.013E+00	1.084E-04
1.698E+01	1.019E+01	3.529E-01	2.513E-01	7.122E-01	4.295E-05	5.852E+03	1.064E+00	1.011E+00	1.300E-04
1.698E+01	1.189E+01	3.529E-01	2.682E-01	7.600E-01	4.574E-05	5.864E+03	1.066E+00	1.009E+00	1.517E-04
1.698E+01	1.358E+01	3.529E-01	2.821E-01	7.994E-01	4.804E-05	5.873E+03	1.068E+00	1.007E+00	1.734E-04
1.698E+01	1.528E+01	3.529E-01	2.936E-01	8.320E-01	4.993E-05	5.880E+03	1.069E+00	1.006E+00	1.951E-04
1.698E+01	1.698E+01	3.529E-01	3.032E-01	8.591E-01	5.151E-05	5.886E+03	1.070E+00	1.005E+00	2.167E-04

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

RUN	P1	T1	US1	P2	P4	T4	XIS	DIA	ISAV	INU	LD
8.600E+01	6.895E+03	3.000E+02	4.300E+03	0.	0.	0.	4.650E+00	1.524E-01	2	2	4

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

CONDITIONS BEHIND INCIDENT SHOCK - REGION 2

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

P	RHO	T	H	S/R	Z	GAME	A	U	M	NRE
1.337E+06	7.865E-01	5.114E+03	9.450E+06	3.566E+01	1.158E+00	1.224E+00	1.442E+03	3.862E+03	2.678E+00	2.302E+07

RATIO- 2 TO 1 CONDITIONS AND SHOCK VELOCITY

P	RHO	T	H	A	MS1	US1
1.939E+02	9.823E+00	1.705E+01	3.144E+01	4.154E+00	1.238E+01	4.300E+03

SHOCK TUBE FLOW PARAMETERS USING MIRELS THEORY

LMAX	L	L/LMAX	TIM	UI	LMAXT	LT	LT/LMAXT	TIMT	UIT	TIMI
1.210E+02	4.540E-01	3.753E-03	1.167E-04	3.890E+03	1.018E+00	3.523E-01	3.462E-01	8.689E-05	4.054E+03	1.226E-04

APPENDIX A

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EXPANSION TUBE PHASE OF PROGRAM

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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

   P          RHO         T           H          S/R        Z          GAME       A          U          M          NRE
1.165E+04  2.980E-02  1.177E+03  1.262E+06  3.566E+01  1.158E+00  1.449E+00  7.527E+02  7.500E+03  9.964E+00  4.882E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO         T           H          S/R        Z          GAME       A          U          M          RATIO
1.550E+06  3.613E-01  8.740E+03  3.316E+07  4.687E+01  1.710E+00  1.185E+00  2.254E+03  6.191E+02  2.746E-01  1.212E+01


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

   P          RHO         T           H          Z          GAME       A          QT         RN         TIMI
1.620E+06  3.753E-01  8.783E+03  3.336E+07  1.713E+00  1.186E+00  2.262E+03  1.024E+08  2.540E-02  2.526E-04


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

   P          RHO         T           H          S/R        Z          GAME       A          U          M          RATIO
1.367E+06  1.556E-01  2.644E+04  2.835E+07  4.094E+01  1.158E+00  1.449E+00  3.568E+03  1.437E+03  4.027E-01  5.220E+00


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

   P          RHO         T           H          Z          GAME       A          QT         RN         TIMI
1.534E+06  1.685E-01  2.740E+04  2.939E+07  1.158E+00  1.449E+00  3.632E+03  8.770E+07  2.540E-02  2.526E-04

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


5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P          RHO         T           H          S/R        Z          GAME       A          U          M          NRE
4.177E+04  4.314E-02  3.184E+03  4.948E+06  3.566E+01  1.058E+00  1.157E+00  1.058E+03  7.500E+03  7.087E+00  3.597E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO         T           H          S/R        Z          GAME       A          U          M          RATIO

2.269E+06  5.264E-01  8.905E+03  3.288E+07  4.611E+01  1.693E+00  1.187E+00  2.266E+03  6.176E+02  2.726E-01  1.216E+01


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

   P          RHO         T           H          Z          GAME       A          QT         RN         TIMI
2.371E+06  5.444E-01  8.948E+03  3.308E+07  1.696E+00  1.187E+00  2.274E+03  1.228E+08  2.540E-02  3.719E-04


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FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

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5 CONDITIONS FOR EQUILIBRIUM EXPANSION

   P          RHO         T           H          S/R        Z          GAME       A          U          M          NRE
4.177E+04  4.314E-02  3.184E+03  4.948E+06  3.566E+01  1.058E+00  1.157E+00  1.058E+03  6.500E+03  6.142E+00  3.117E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK
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APPENDIX A

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   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
1.699E+06 4.748E-01 8.107E+03 2.590E+07 4.375E+01 1.538E+00 1.167E+00 2.044E+03 5.903E+02 2.888E-01 1.100E+01

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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
1.783E+06 4.950E-01 8.146E+03 2.608E+07 1.541E+00 1.168E+00 2.051E+03 8.379E+07 2.540E-02 5.080E-04

ACCELERATION AIR CONDITIONS (REGION 20) AND P10
    P20        RHO20      T20        H20        Z20        M20        P10        US10       MS10       RATIO
4.177E+04 1.156E-02 7.125E+03 3.206E+07 1.768E+00 3.668E+00 6.000E+01 7.984E+03 2.300E+01 1.658E+01

ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

   XAS        XA         LMAX       L          L/LMAX     TIM        UI         UI/U5      US20/UI    TIMI
1.698E+01 1.698E+00 9.757E-01 8.203E-02 8.408E-02 1.073E-05 7.644E+03 1.019E+00 1.045E+00 1.365E-05
1.698E+01 3.396E+00 9.757E-01 1.492E-01 1.529E-01 1.939E-05 7.693E+03 1.026E+00 1.038E+00 2.731E-05
1.698E+01 5.094E+00 9.757E-01 2.078E-01 2.129E-01 2.689E-05 7.727E+03 1.030E+00 1.033E+00 4.096E-05
1.698E+01 6.792E+00 9.757E-01 2.600E-01 2.665E-01 3.353E-05 7.753E+03 1.034E+00 1.030E+00 5.461E-05
1.698E+01 8.490E+00 9.757E-01 3.072E-01 3.148E-01 3.951E-05 7.775E+03 1.037E+00 1.027E+00 6.827E-05
1.698E+01 1.019E+01 9.757E-01 3.501E-01 3.588E-01 4.493E-05 7.793E+03 1.039E+00 1.025E+00 8.192E-05
1.698E+01 1.189E+01 9.757E-01 3.895E-01 3.992E-01 4.988E-05 7.809E+03 1.041E+00 1.022E+00 9.557E-05
1.698E+01 1.358E+01 9.757E-01 4.257E-01 4.363E-01 5.442E-05 7.822E+03 1.043E+00 1.021E+00 1.092E-04
1.698E+01 1.528E+01 9.757E-01 4.591E-01 4.705E-01 5.860E-05 7.835E+03 1.045E+00 1.019E+00 1.229E-04
1.698E+01 1.698E+01 9.757E-01 4.901E-01 5.023E-01 6.247E-05 7.846E+03 1.046E+00 1.018E+00 1.365E-04

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CONDITIONS BEHIND STANDING SHOCK AT SECONDARY DIAPH

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
1.062E+07 3.761E+00 7.707E+03 1.658E+07 3.709E+01 1.276E+00 1.178E+00 1.824E+03 8.073E+02 4.427E-01 0.

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EXPANSION TUBE PHASE OF PROGRAM

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INPUTS FOR EXPANSION TUBE PHASE

   U5         P5         XAS        DELU5     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

   P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
7.181E+02 5.821E-03 3.368E+02 3.784E+05 3.709E+01 1.276E+00 1.484E+00 4.278E+02 7.500E+03 1.753E+01 2.168E+06

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
3.006E+05 6.913E-02 8.327E+03 3.623E+07 5.100E+01 1.819E+00 1.176E+00 2.261E+03 6.310E+02 2.791E-01 1.188E+01

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

   P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
3.146E+05 7.185E-02 8.371E+03 3.642E+07 1.822E+00 1.176E+00 2.269E+03 4.933E+07 2.540E-02 1.370E-04

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

   P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
2.635E+05 2.949E-02 2.439E+04 2.741E+07 4.432E+01 1.276E+00 1.484E+00 3.641E+03 1.480E+03 4.066E-01 5.066E+00

STAGNATION CONDITIONS BEHIND BOW SHOCK-REGION T5
FROZEN EXPANSION-- FROZEN POST SHOCK
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APPENDIX A

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  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.972E+05 3.198E-02 2.537E+04 2.850E+07 1.276E+00 1.484E+00 3.713E+03 3.743E+07 2.540E-02 1.370E-04

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


NO SOLUTION ON TAPE FOR THE CONDITIONS

      S/R=   37.090681                                          EVALUATE
     Z(6)=  2.54208103E+00                                        Z(6)


PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

  P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
4.730E+04 4.146E-02 3.559E+03 6.461E+06 3.709E+01 1.115E+00 1.171E+00 1.155E+03 7.500E+03 6.492E+00 3.162E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
2.181E+06 4.866E-01 9.044E+03 3.438E+07 4.675E+01 1.727E+00 1.189E+00 2.309E+03 6.390E+02 2.768E-01 1.174E+01


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

  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
2.282E+06 5.056E-01 9.090E+03 3.459E+07 1.730E+00 1.190E+00 2.318E+03 1.261E+08 2.540E-02 4.122E-04


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FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX


5 CONDITIONS FOR EQUILIBRIUM EXPANSION

  P          RHO        T          H          S/R        Z          GAME       A          U          M          NRE
4.730E+04 4.146E-02 3.559E+03 6.461E+06 3.709E+01 1.115E+00 1.171E+00 1.155E+03 6.500E+03 5.627E+00 2.740E+06


STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

  P          RHO        T          H          S/R        Z          GAME       A          U          M          RATIO
1.634E+06 4.396E-01 8.222E+03 2.740E+07 4.445E+01 1.575E+00 1.171E+00 2.086E+03 6.125E+02 2.936E-01 1.060E+01


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

  P          RHO        T          H          Z          GAME       A          QT         RN         TIMI
1.718E+06 4.591E-01 8.263E+03 2.759E+07 1.578E+00 1.172E+00 2.094E+03 8.708E+07 2.540E-02 5.646E-04


ACCELERATION AIR CONDITIONS (REGION 20) AND P10
   P20        RHO20      T20        H20        Z20        M20        P10        US10       MS10       RATIO
4.730E+04 1.301E-02 7.170E+03 3.208E+07 1.766E+00 3.657E+00 6.792E+01 7.987E+03 2.300E+01 1.650E+01


ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

  XAS        XA         LMAX       L          L/LMAX     TIM        UI         UI/U5      US20/UI    TIMI
1.698E+01 1.698E+00 1.104E+00 8.353E-02 7.564E-02 1.094E-05 7.637E+03 1.018E+00 1.046E+00 1.372E-05
1.698E+01 3.396E+00 1.104E+00 1.528E-01 1.384E-01 1.988E-05 7.685E+03 1.025E+00 1.039E+00 2.744E-05
1.698E+01 5.094E+00 1.104E+00 2.138E-01 1.936E-01 2.770E-05 7.718E+03 1.029E+00 1.035E+00 4.117E-05
1.698E+01 6.792E+00 1.104E+00 2.686E-01 2.432E-01 3.468E-05 7.743E+03 1.032E+00 1.031E+00 5.489E-05
1.698E+01 8.490E+00 1.104E+00 3.184E-01 2.883E-01 4.101E-05 7.765E+03 1.035E+00 1.029E+00 6.861E-05
1.698E+01 1.019E+01 1.104E+00 3.641E-01 3.297E-01 4.678E-05 7.783E+03 1.038E+00 1.026E+00 8.233E-05
1.698E+01 1.189E+01 1.104E+00 4.062E-01 3.678E-01 5.209E-05 7.798E+03 1.040E+00 1.024E+00 9.605E-05
1.698E+01 1.358E+01 1.104E+00 4.452E-01 4.032E-01 5.699E-05 7.812E+03 1.042E+00 1.022E+00 1.098E-04
1.698E+01 1.528E+01 1.104E+00 4.815E-01 4.360E-01 6.153E-05 7.824E+03 1.043E+00 1.021E+00 1.235E-04
1.698E+01 1.698E+01 1.104E+00 5.152E-01 4.666E-01 6.576E-05 7.835E+03 1.045E+00 1.019E+00 1.372E-04


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APPENDIX A

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CONDITIONS BEHIND REFLECTED SHOCK AT SECONDARY DIAPH

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      P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
1.541E+07 4.721E+00 8.480E+03 1.989E+07 3.806E+01 1.341E+00 1.176E+00 1.959E+03 0.          0.          0.

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

EXPANSION TUBE PHASE OF PROGRAM

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

INPUTS FOR EXPANSION TUBE PHASE

      U5          P5          XAS          DELU5      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

      P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
1.785E+02 2.444E-03 1.897E+02 2.185E+05 3.806E+01 1.341E+00 1.502E+00 3.312E+02 7.500E+03 2.264E+01 1.448E+06

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION--EQUILIBRIUM POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
1.258E+05 2.829E-02 8.234E+03 3.826E+07 5.344E+01 1.881E+00 1.164E+00 2.275E+03 6.477E+02 2.847E-01 1.158E+01

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

      P          RHO          T          H          Z          GAME          A          QT          RN          TIMI
1.318E+05 2.943E-02 8.282E+03 3.847E+07 1.884E+00 1.165E+00 2.284E+03 3.374E+07 2.540E-02 1.046E-04

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
FROZEN EXPANSION-- FROZEN POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
1.098E+05 1.208E-02 2.361E+04 2.719E+07 4.607E+01 1.341E+00 1.502E+00 3.696E+03 1.517E+03 4.105E-01 4.944E+00

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

      P          RHO          T          H          Z          GAME          A          QT          RN          TIMI
1.243E+05 1.312E-02 2.461E+04 2.834E+07 1.341E+00 1.502E+00 3.773E+03 2.407E+07 2.540E-02 1.046E-04

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


NO SOLUTION ON TAPE FOR THE CONDITIONS

      S/R=    38.059235                                                EVALUATE
    Z(4)=  2.54208103E+00                                                Z(6)


PERFECT AIR RELATIONS USED FOR NUMERICAL INTEGRATION

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

      P          RHO          T          H          S/R          Z          GAME          A          U          M          NRE
5.576E+04 4.272E-02 3.919E+03 7.698E+06 3.806E+01 1.159E+00 1.205E+00 1.254E+03 7.500E+03 5.981E+00 3.011E+06

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

      P          RHO          T          H          S/R          Z          GAME          A          U          M          RATIO
2.247E+06 4.859E-01 9.196E+03 3.561E+07 4.716E+01 1.752E+00 1.192E+00 2.348E+03 6.591E+02 2.807E-01 1.138E+01

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

P	RHO	T	H	Z	GAME	A	QT	RN	TIMI
2.355E+06	5.055E-01	9.246E+03	3.583E+07	1.755E+00	1.192E+00	2.357E+03	1.327E+08	2.540E-02	4.545E-04

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FOLLOWING EQUILIBRIUM CONDITIONS INCLUDE FLOW ATTN

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

5 CONDITIONS FOR EQUILIBRIUM EXPANSION

P	RHO	T	H	S/R	Z	GAME	A	U	M	NRE
5.576E+04	4.272E-02	3.919E+03	7.698E+06	3.806E+01	1.159E+00	1.205E+00	1.254E+03	6.500E+03	5.184E+00	2.609E+06

STATIC CONDITIONS BEHIND BOW SHOCK - REGION 5S
EQUILIBRIUM EXPANSION--EQUILIBRIUM POST SHOCK

P	RHO	T	H	S/R	Z	GAME	A	U	M	RATIO
1.685E+06	4.387E-01	8.347E+03	2.862E+07	4.491E+01	1.603E+00	1.174E+00	2.124E+03	6.329E+02	2.980E-01	1.027E+01

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

P	RHO	T	H	Z	GAME	A	QT	RN	TIMI
1.775E+06	4.587E-01	8.391E+03	2.883E+07	1.607E+00	1.175E+00	2.132E+03	9.251E+07	2.540E-02	6.244E-04

ACCELERATION AIR CONDITIONS (REGION 20) AND P10

P20	RHO20	T20	H20	Z20	M20	P10	US10	MS10	RATIO
5.576E+04	1.523E-02	7.231E+03	3.210E+07	1.763E+00	3.642E+00	8.004E+01	7.990E+03	2.301E+01	1.639E+01

ACCELERATION AIR FLOW PARAMETERS USING MIRELS THEORY

XAS	XA	LMAX	L	L/LMAX	TIM	UI	UI/U5	US20/UI	TIMI
1.698E+01	1.698E+00	1.301E+00	8.546E-02	6.568E-02	1.120E-05	7.629E+03	1.017E+00	1.047E+00	1.381E-05
1.698E+01	3.396E+00	1.301E+00	1.574E-01	1.210E-01	2.051E-05	7.674E+03	1.023E+00	1.041E+00	2.763E-05
1.698E+01	5.094E+00	1.301E+00	2.215E-01	1.702E-01	2.874E-05	7.706E+03	1.027E+00	1.037E+00	4.144E-05
1.698E+01	6.792E+00	1.301E+00	2.796E-01	2.149E-01	3.617E-05	7.731E+03	1.031E+00	1.034E+00	5.525E-05
1.698E+01	8.490E+00	1.301E+00	3.329E-01	2.559E-01	4.295E-05	7.751E+03	1.033E+00	1.031E+00	6.907E-05
1.698E+01	1.019E+01	1.301E+00	3.822E-01	2.937E-01	4.920E-05	7.769E+03	1.036E+00	1.029E+00	8.288E-05
1.698E+01	1.189E+01	1.301E+00	4.280E-01	3.289E-01	5.498E-05	7.784E+03	1.038E+00	1.026E+00	9.669E-05
1.698E+01	1.358E+01	1.301E+00	4.707E-01	3.617E-01	6.036E-05	7.798E+03	1.040E+00	1.025E+00	1.105E-04
1.698E+01	1.528E+01	1.301E+00	5.107E-01	3.925E-01	6.539E-05	7.810E+03	1.041E+00	1.023E+00	1.243E-04
1.698E+01	1.698E+01	1.301E+00	5.482E-01	4.213E-01	7.009E-05	7.821E+03	1.043E+00	1.022E+00	1.381E-04

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):

a, percent	2.78
h, percent	1.96
T, percent	2.24
Z^*, percent	0.75
γ_E, percent	≈5.00
ρ, percent	2.52

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

regions (2) and (2s), 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 (2) 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 $(e^-, Ar, N, N^+, N_2, O, O^+, O_2, NO, \text{and } NO^+)$ air model is employed in reference 5, the air composition by volume being 78.08 percent N_2, 20.95 percent O_2, and 0.97 percent Ar. This composition yields an undissociated molecular weight W_u of 28.97 in agreement with references 9 and 11. As expected, thermodynamic properties in region (4) were in perfect agreement between the two programs for both driver gases. The maximum uncertainties observed between flow quantities in region (2) and $U_{s,1}$, as determined from the present program and reference 5, are

p_2, percent	0.3
ρ_2, percent	2.3
T_2, percent	2.6
h_2, percent	0.5
$s_2 W_u/R$, percent	0.2
a_2, percent	1.6
U_2, percent	0.2
$U_{s,1}$, percent	0.5

The ratios of flow conditions in region (2) to conditions in region (1) 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 $s_2 W_u/R$ are in good agreement for the two sources of real-air thermodynamic properties. However, agreement for ρ_2/ρ_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 (2s) and (2r) calculated by using the curve-fit expressions

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 (t5) 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

Method	ISAV	IEXP
(1)	1	1
(2)	2	1
(3)	2	2

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 ΔU 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 $p_{5,f}$ 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 (t5) were calculated with these three methods for the following basic inputs:

$p_1 = 1.724$ kN/m^2

$T_1 = 300$ K

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

U_5 = 4, 5, 6, and 7 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 I.- PERCENT DIFFERENCE BETWEEN FLOW QUANTITIES IN REGIONS (5), (5s), AND (t5) AS CALCULATED BY METHODS (1), (2), AND (3) AND REFERENCE 5

Flow quantity	Percent difference between methods (1) and (2) for U_5, km/sec, of –				Percent difference between methods (1) and (3) for U_5, km/sec, of –				Percent difference between method (1) and reference 5 for U_5, km/sec, of –			
	4	5	6	7	4	5	6	7	4	5	6	7
p_5	5.47	5.48	5.50	5.54	1.67	7.85	7.47	8.70	0.09	0.15	0.14	0.50
ρ_5	5.43	5.43	5.48	5.49	3.98	7.28	6.45	7.24	.18	.28	.22	.51
T_5	.04	.00	.08	.03	2.77	.45	1.01	1.51	.04	.06	.00	.05
h_5	.03	.05	.00	.03	.49	.30	.71	1.11	.00	.00	.08	.06
Z_5	.00	.00	.00	.00	.30	.00	.00	.00	.00	.00	.00	.00
$\gamma_{E,5}$	.00	.00	.00	.00	3.67	6.88	.68	.65	.00	.00	.00	.07
a_5	.05	.01	.01	.00	.60	3.26	.19	.45	.01	.01	.04	.02
M_5	.05	.02	.01	.00	.59	3.26	.19	.43	.02	.02	.04	.00
$N_{Re,5}$	5.44	5.46	5.47	5.44	5.87	7.02	5.88	6.26	.75	.38	.72	.00
p_{5s}	5.32	5.40	5.46	5.47	3.79	7.22	4.28	7.19	.14	.20	.21	.51
ρ_{5s}	4.63	4.61	5.25	5.18	1.96	6.46	.62	6.83	.11	.18	.25	.57
T_{5s}	.87	.88	.53	.93	.74	.93	.59	1.03	.13	.07	.05	.05
h_{5s}	.00	.00	.00	.00	.19	.07	.05	.04	.00	.00	.00	.00
$s_{5s}W_u/R$	.05	.12	.29	.48	.79	.17	.31	.46	.00	.05	.04	.02
Z_{5s}	.25	.15	.42	.75	.25	.15	.42	.75	.00	.00	.00	.00
$\gamma_{E,5s}$	.91	.17	.26	.00	.99	.17	.26	.00	.08	.09	.00	.09
a_{5s}	.86	.31	.23	.16	.80	.37	.29	.22	.00	.00	.00	.05
$p_{t,5}$	5.37	5.42	5.65	5.49	3.85	7.31	6.54	7.24	.15	.23	.21	.50
$\rho_{t,5}$	4.55	4.58	5.27	5.18	3.13	6.43	6.20	6.85	.14	.26	.27	.56
$T_{t,5}$	.99	.86	.54	.93	.84	.92	.60	1.02	.13	.06	.03	.05
$h_{t,5}$	.00	.00	.00	.00	.09	.07	.05	.04	.00	.00	.00	.00

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 $U_{s,1}$ 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.

Flow quantity	IAC of –			
	10	20	30	50
p_5	5.74	0.82	0.63	0.00
ρ_5	4.23	.62	.45	.00
T_5	1.58	.22	.17	.00
h_5	1.65	.23	.18	.00
Z_5	.00	.00	.00	.00
$\gamma_{E,5}$	.07	.00	.00	.00
a_5	.77	.10	.08	.00
M_5	.07	.14	.07	.00
$N_{Re,5}$	3.29	.39	.39	.00

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

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 (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 LF = 2 and ISAV = IEXP = 1, and the values from method (3) were used for 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

$p_1 = 6.895$ kN/m^2

$T_1 = 300$ K

$U_{s,1} = 500$ m/sec

$U_5 = 700$, 900, and 1100 m/sec

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), (5s), and (t5) 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 (6s) and (t6) as was used to obtain conditions in regions (5s) and (t5).

APPENDIX C

LANGLEY LIBRARY SUBROUTINE ITR1

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 ITR1 (X, DELTX, FOFX, E1, E2, MAXI, ICODE)

X	An initial guess supplied by the user. On a normal return to the calling program from ITR1, X contains the root.
DELTX	An increment supplied by the user so that $\frac{f(x + DELTX) - f(x)}{DELTX}$ 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 ITR1 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

$$x_{n+1} = q_n + (1 - q)\, f(x_n)$$

$$q = \frac{a}{a - 1}$$

$$a = \frac{f(x_n) - f(x_{n-1})}{x_n - x_{n-1}}$$

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

If

$$\left|f(x_n)\right| \geqq \epsilon_1$$

then

$$\left|\frac{f(x_n) - x_n}{f(x_n)}\right| \leqq \epsilon_1 \tag{C1}$$

and if

$$\left|f(x_n)\right| < \epsilon_1$$

then

$$\left|f(x_n) - x_n\right| \leqq \epsilon_2 \tag{C2}$$

Reference: (a) Scarborough, James B.: Numerical Mathematical Analysis. Fourth ed. Johns Hopkins Press, 1958, p. 192.

Storage: 137_8 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.
DELTX	ΔX, the size of the scanning interval.
FOFX	The name of 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 ITR2 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 iterations are exceeded ICODE = 2: DELTX = 0, or negative ICODE = 3: a root cannot be found within the given bounds ICODE = 4: A > B

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

Method: The given function F(X) is evaluated at a given starting point a and at intervals of a specified ΔX thereafter, up to and including a specified end point b. A change of sign of the function across a ΔX 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 ΔX be given such that no more than one root be present within a ΔX 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

$$\left|X_i\right| > \epsilon_1$$

then

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

and if

$$\left|X_i\right| \leqq \epsilon_1$$

then

$$\left|X_i - X_{i-1}\right| \leqq \epsilon_2$$

Reference: Scarborough, James B.: Numerical Mathematical Analysis. Fourth ed. John Hopkins Press, 1958.

Storage: 260_8 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,. . .,N. For M = 0 or $N \leq 1$, y = F(VARI(1)) 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

References: (a) Nielson, Kaj L.: Methods in Numerical Analysis. Macmillan Co., c.1956, pp. 87-91.

(b) Milne, William Edmund: Numerical Calculus. Princeton Univ. Press, 1949, pp. 69-73.

Storage: 430_8 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_xth- and K_zth-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,

x_i $(i = 1,2,\ldots,L)$

y_j $(i = 1,2,\ldots,M)$

z_k $(k = 1,2,\ldots,N)$

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_{max}. With a zero in this position, extrapolation occurs when $z > z_{max}$. 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.

(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 $x < x_1$, the routine chooses the following points for extrapolation:

$$x_1, x_2, \cdots, x_{k+1} \quad \text{and} \quad y_1, y_2, \cdots, y_{k+1}$$

(2) If $x > x_n$, the routine chooses the following points for extrapolation:

$$x_{n-k}, x_{n-k+1}, \cdots, x_n \quad \text{and} \quad y_{n-k}, y_{n-k+1}, \cdots, y_n$$

(3) If $x \leq x_n$, the routine chooses the following points for interpolation:
When k is odd,

$$x_{i-\frac{k+1}{2}}, x_{i-\frac{k+1}{2}+1}, \cdots, x_{i-\frac{k+1}{2}+k} \quad \text{and} \quad y_{i-\frac{k+1}{2}}, y_{i-\frac{k+1}{2}+1}, \cdots, y_{i-\frac{k+1}{2}+k}$$

When k is even,

$$x_{i-\frac{k}{2}}, x_{i-\frac{k}{2}+1}, \cdots, x_{i-\frac{k}{2}+k} \quad \text{and} \quad y_{i-\frac{k}{2}}, y_{i-\frac{k}{2}+1}, \cdots, y_{i-\frac{k}{2}+k}$$

(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.

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

$$x_{d-k}, x_{d-k+1}, \cdots, x_d \quad \text{and} \quad y_{d-k}, y_{d-k+1}, \cdots, y_d$$

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

$$x_{d+1}, x_{d+2}, \cdots, x_{d+k} \quad \text{and} \quad y_{d+1}, y_{d+2}, \cdots, y_{d+k}$$

(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 multiline 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 multiline function with no extrapolation above the top line.

Accuracy: A function of the order of interpolation used.

Reference: (a) Nielsen, Kaj L.: Methods in Numerical Analysis. Macmillan Co., c.1956.

Storage: 555_8 locations.

Subprograms used:

UNS	40_8 locations.
DISSER	110_8 locations.
LAGRAN	55_8 locations.

Subroutine date: August 1, 1968.

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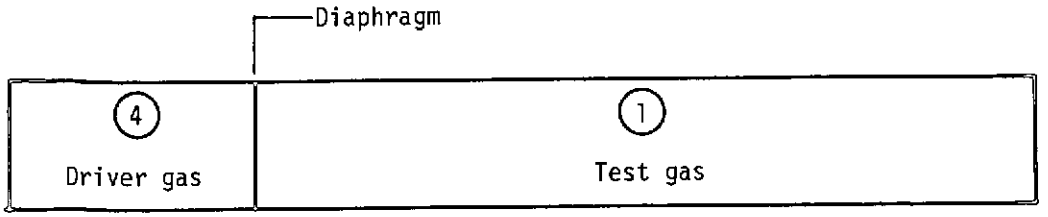
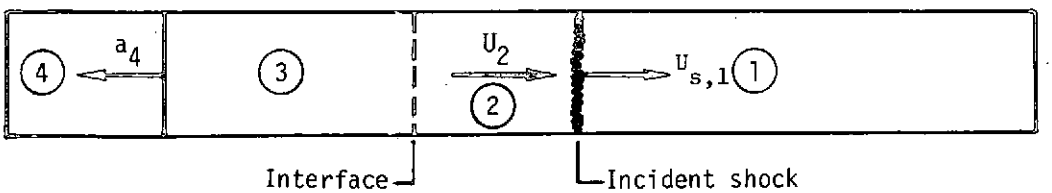
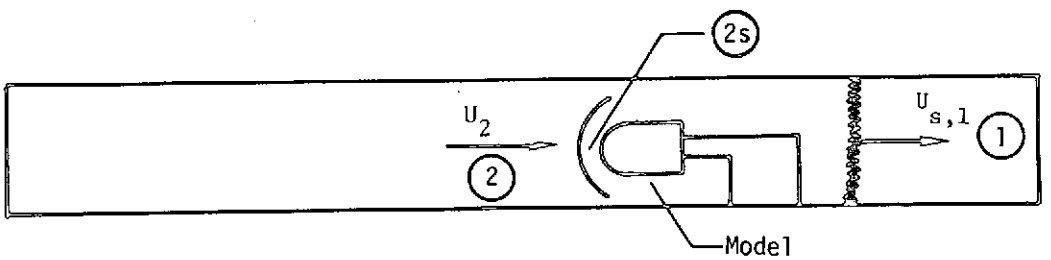


(a) Prior to diaphragm rupture.



(b) Incident (moving) normal shock in test gas.



(c) Standing normal shock at test model.

(d) Reflected normal shock from end wall.

Figure 1.- Sketches illustrating shock-tube regions of interest: Regions (2), (2s), and (2r).

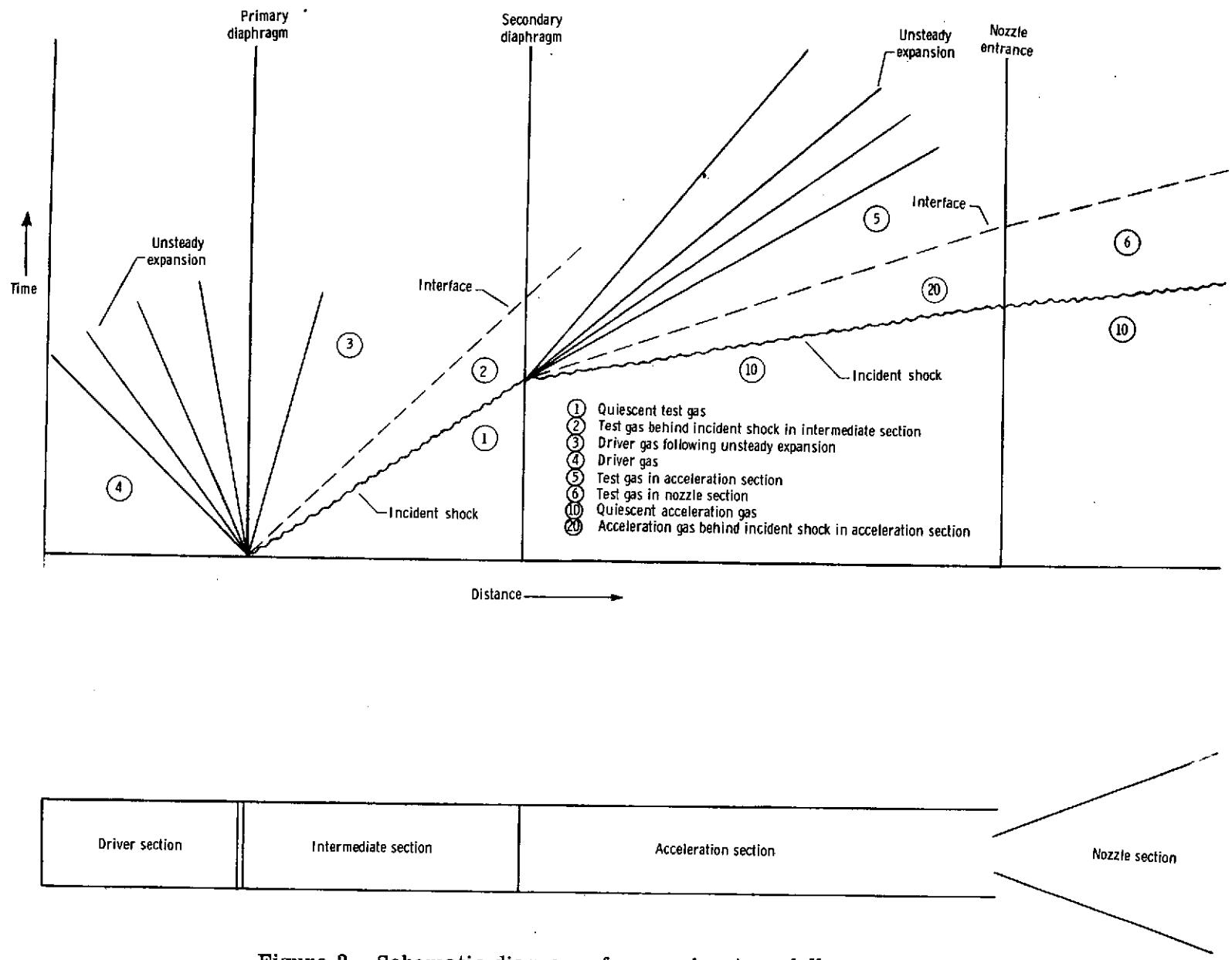
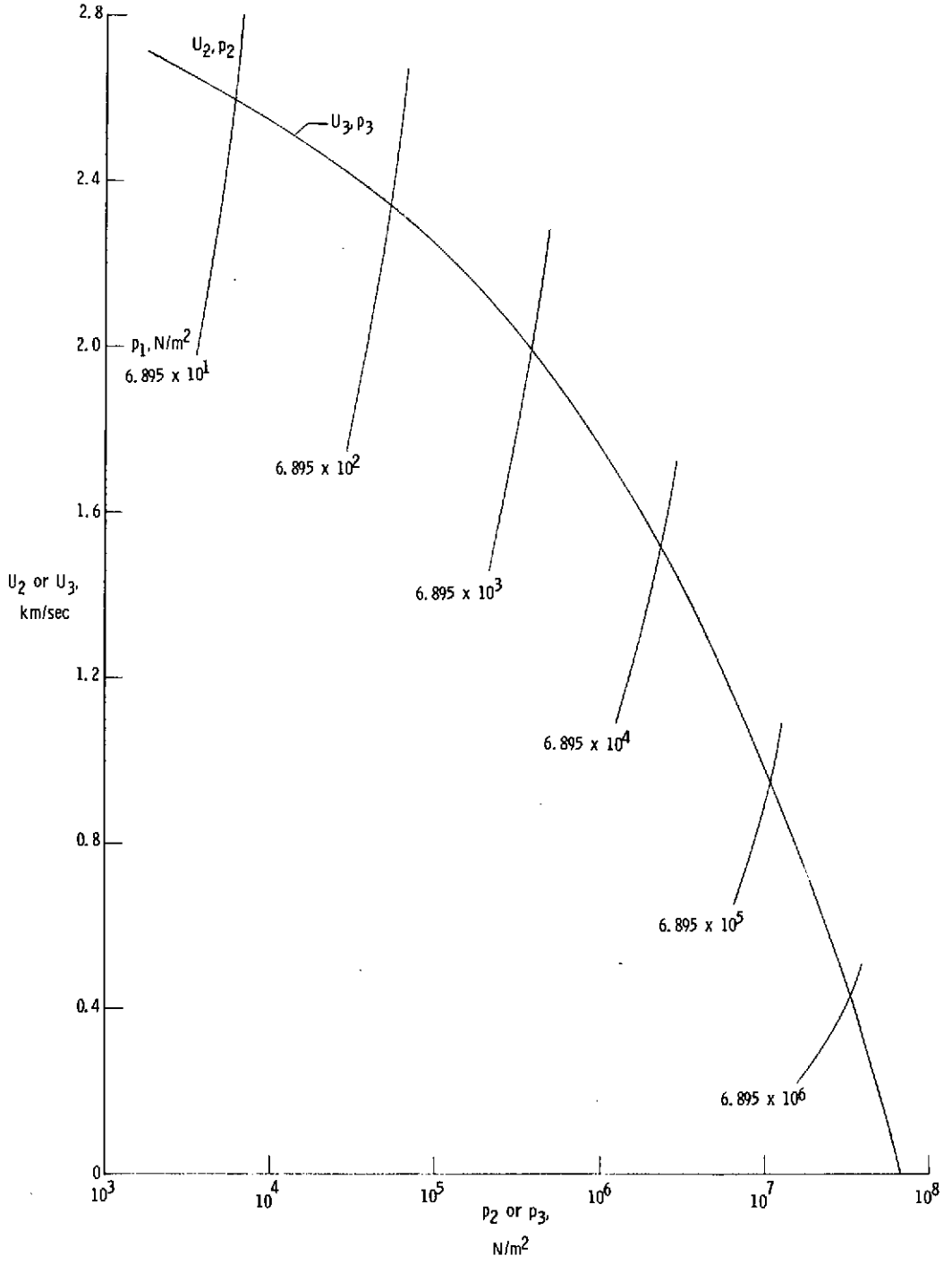
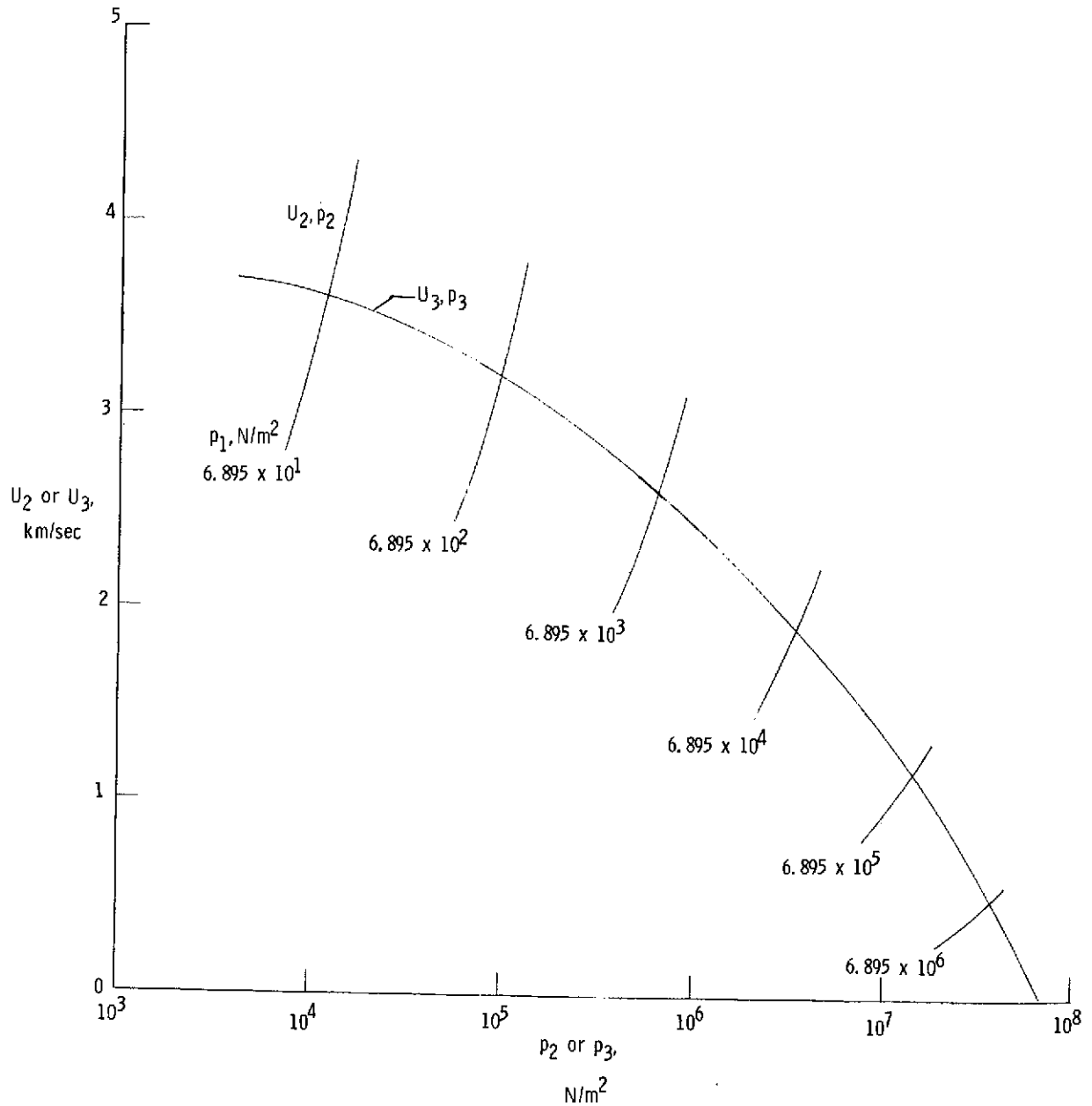


Figure 2.- Schematic diagram of expansion tunnel flow sequence.



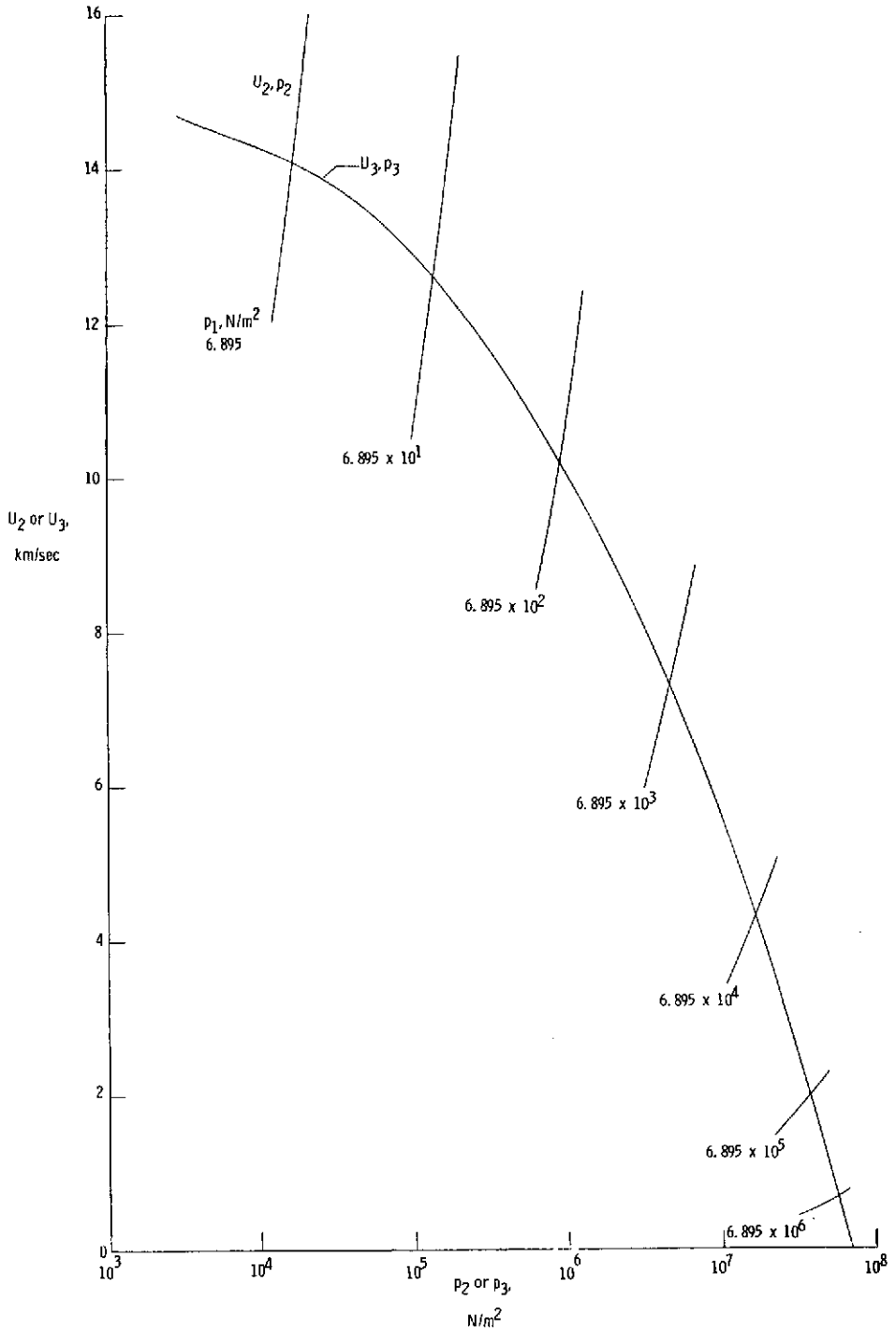
(a) Helium driver gas with $T_4 = 300$ K.

Figure 3.- Velocity U_3 as a function of pressure p_3 for isentropic unsteady expansion of helium and hydrogen driver gases for $p_4 = 68.95$ MN/m^2 and various T_4; velocity U_2 as a function of pressure p_2 for incident normal shock in real air.



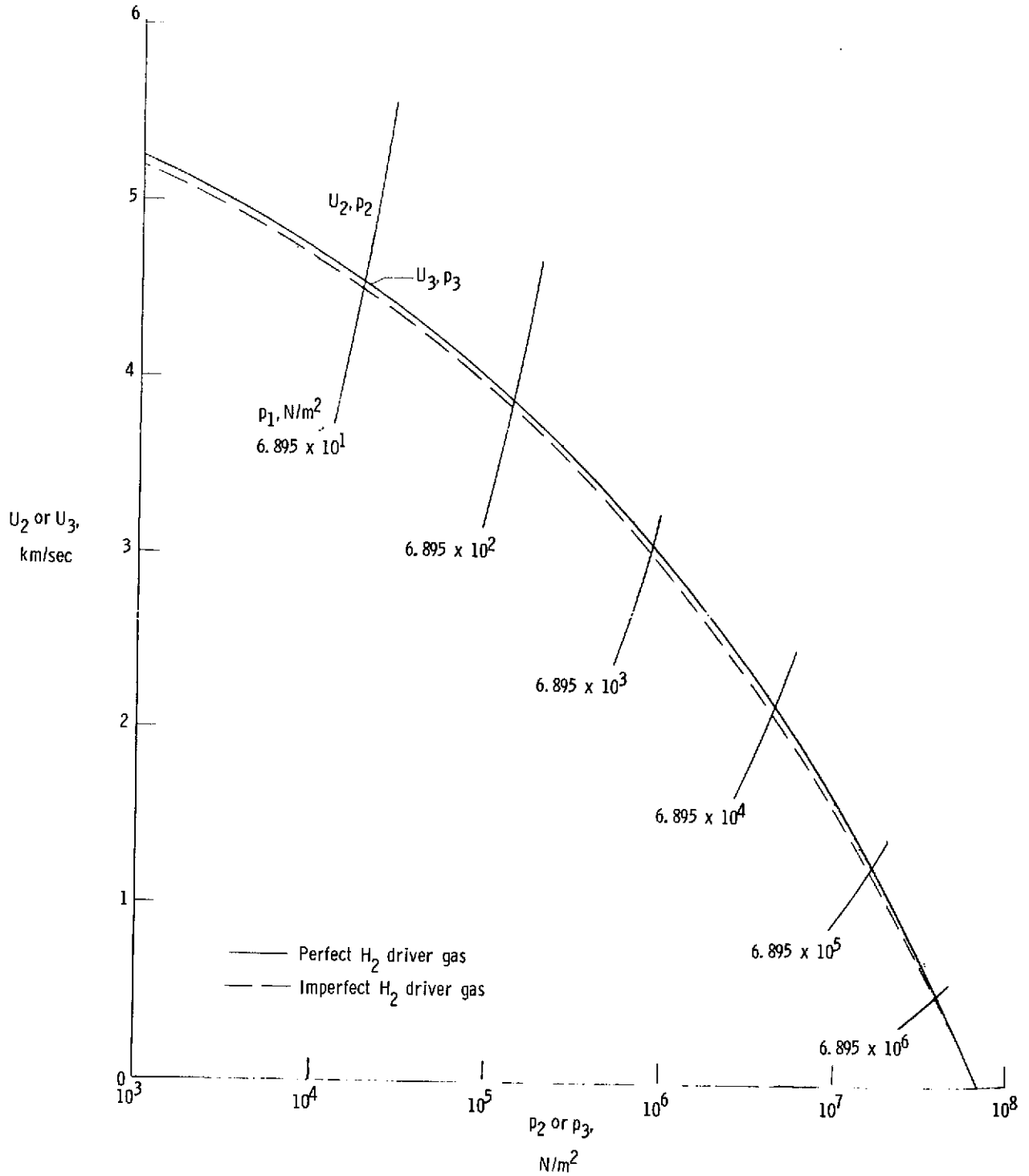
(b) Helium driver gas with T_4 = 600 K.

Figure 3.- Continued.



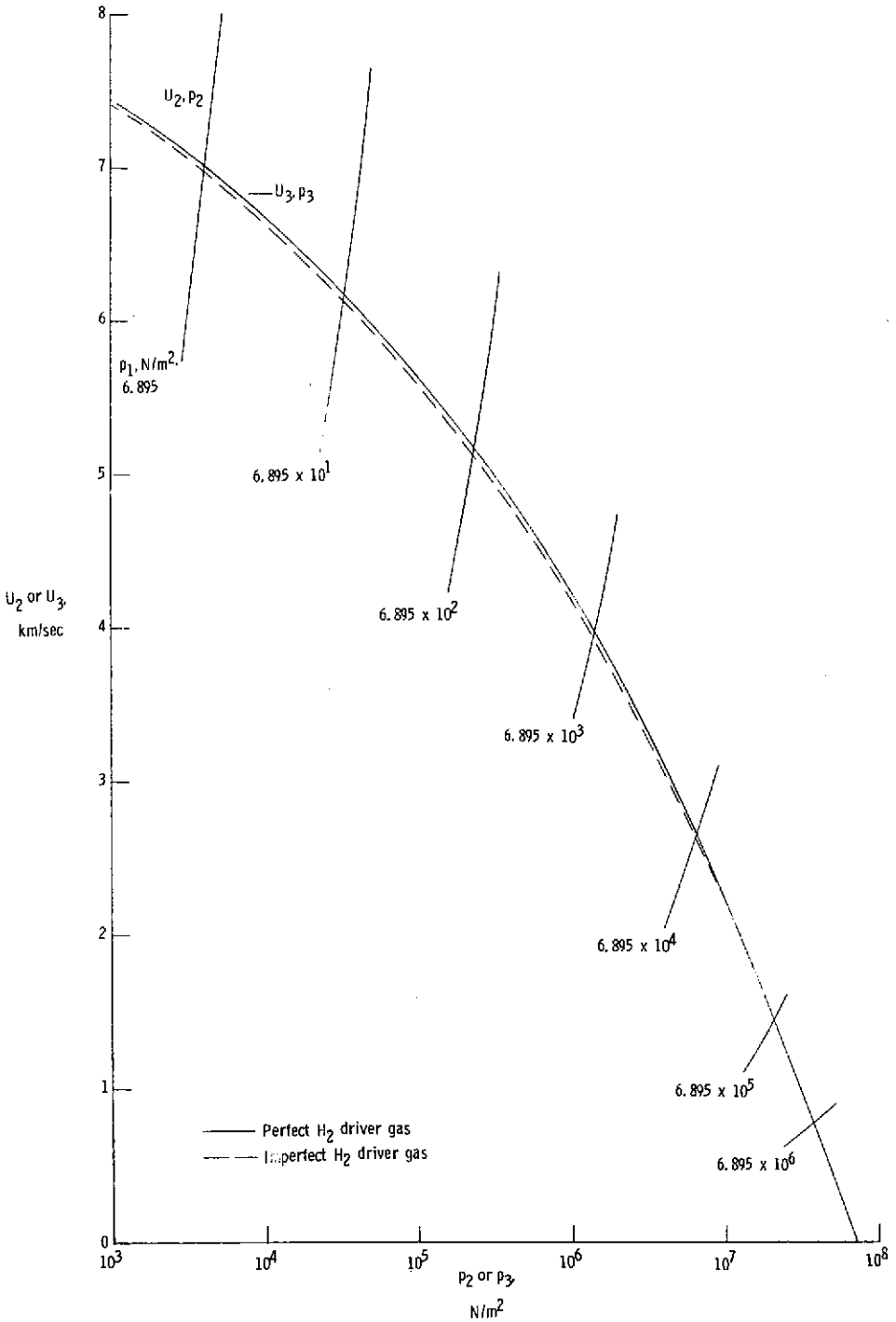
(c) Helium driver gas with T_4 = 10 000 K.

Figure 3.- Continued.



(d) Hydrogen driver gas with $T_4 = 300$ K.

Figure 3.- Continued.



(e) Hydrogen driver gas with T_4 = 600 K.

Figure 3.- Concluded.

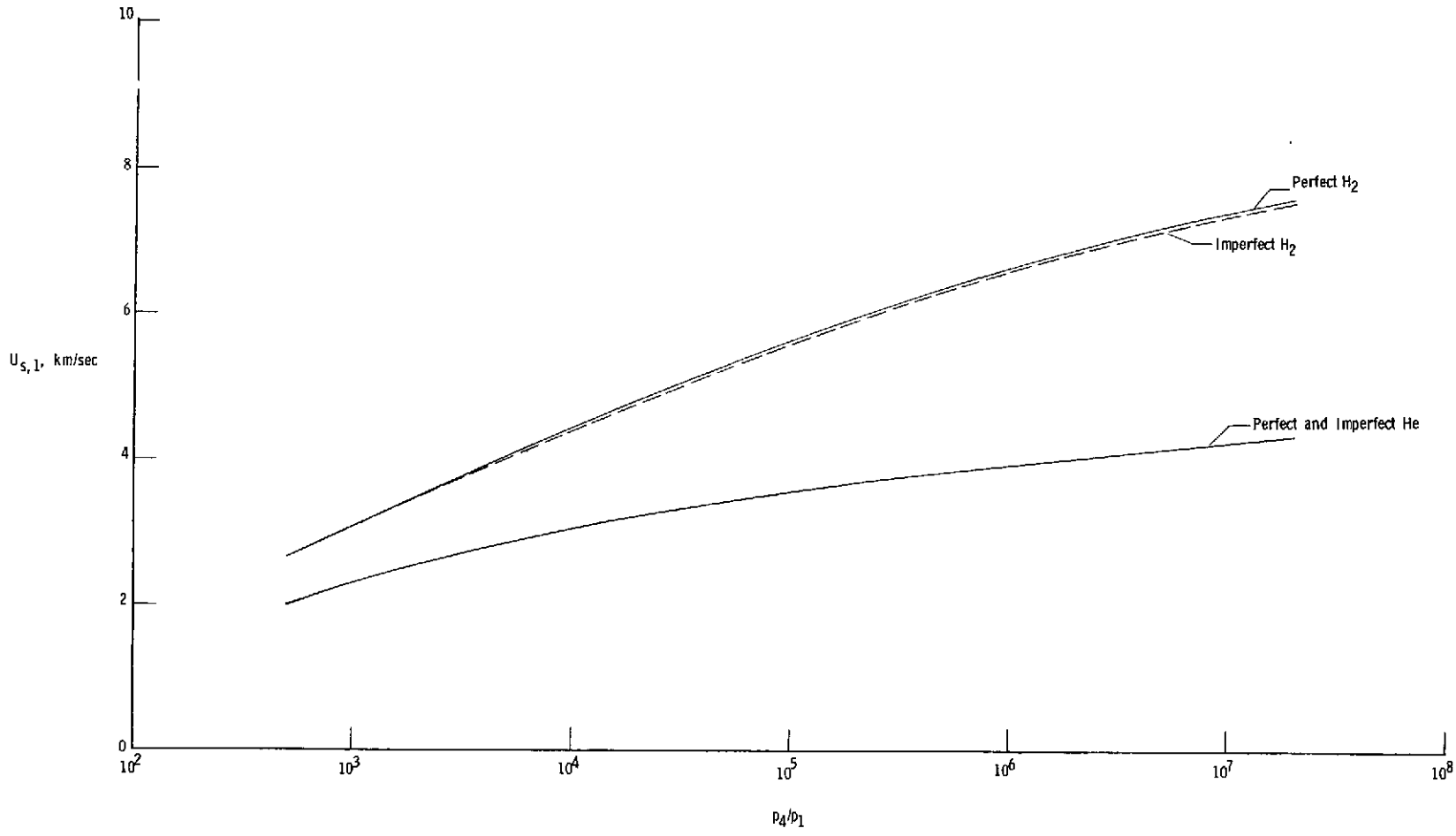
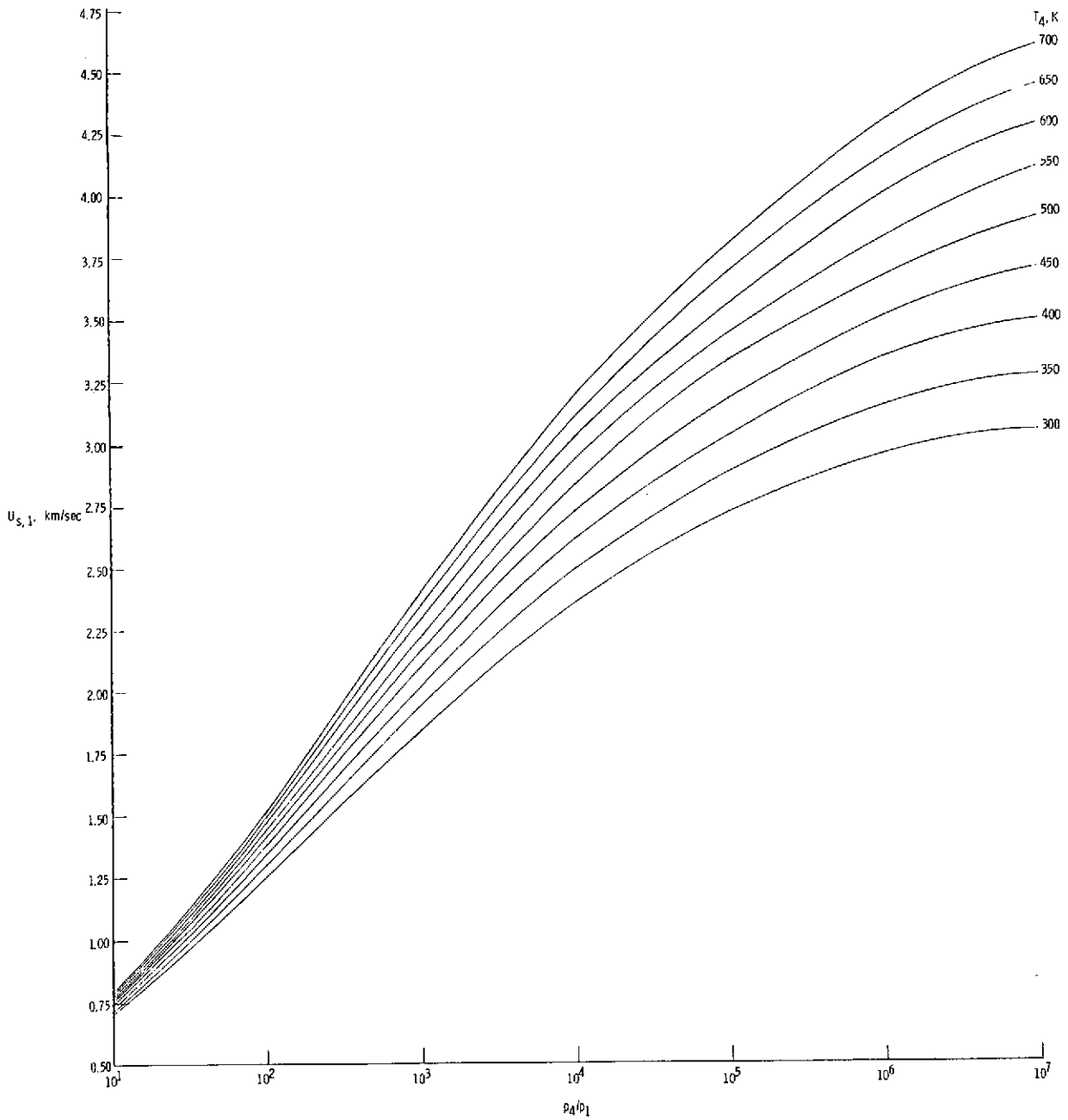
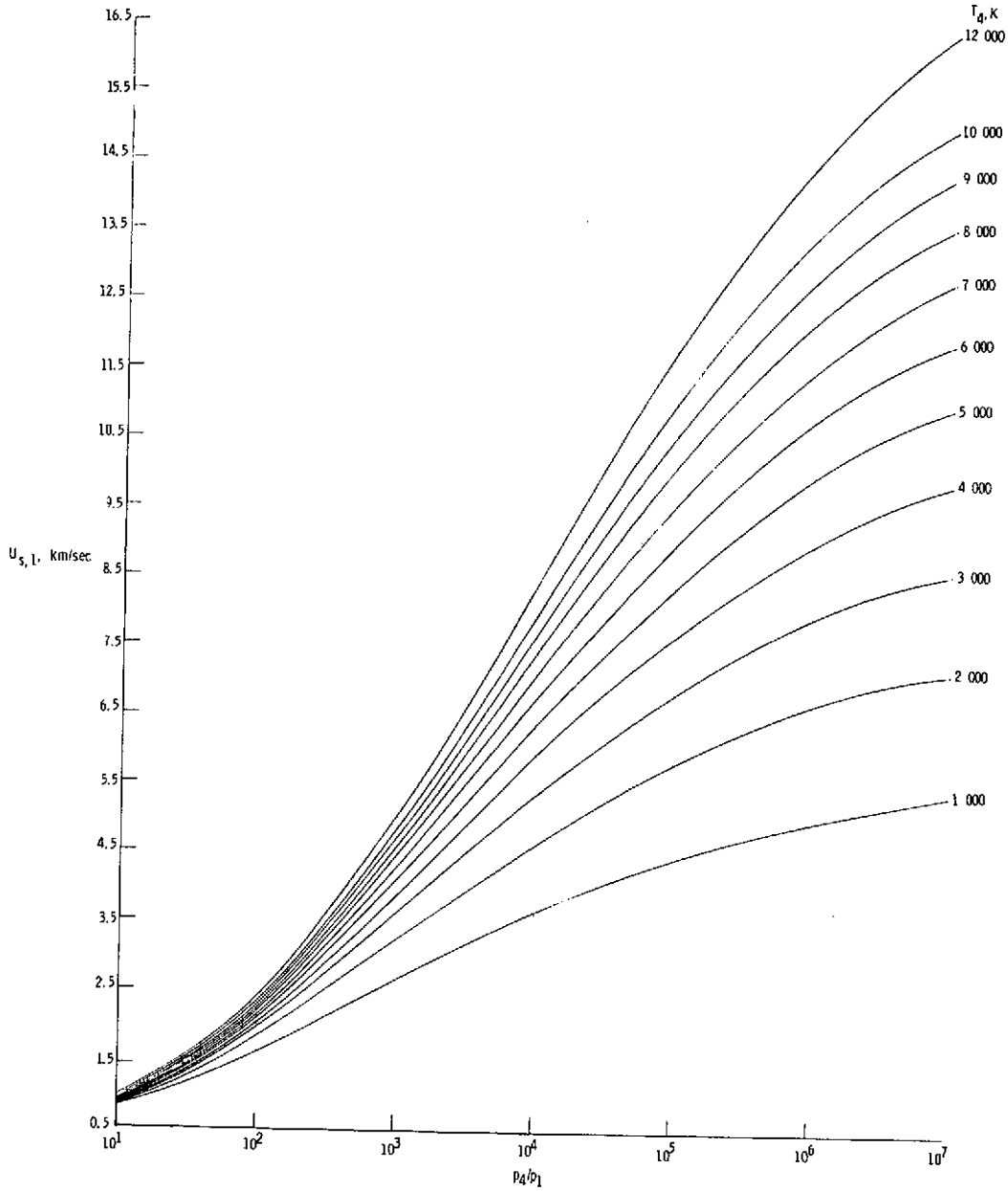


Figure 4.- Incident normal shock velocity as a function of ratio of driver gas pressure to quiescent test air pressure for helium and hydrogen driver gases. T_4 = 600 K.



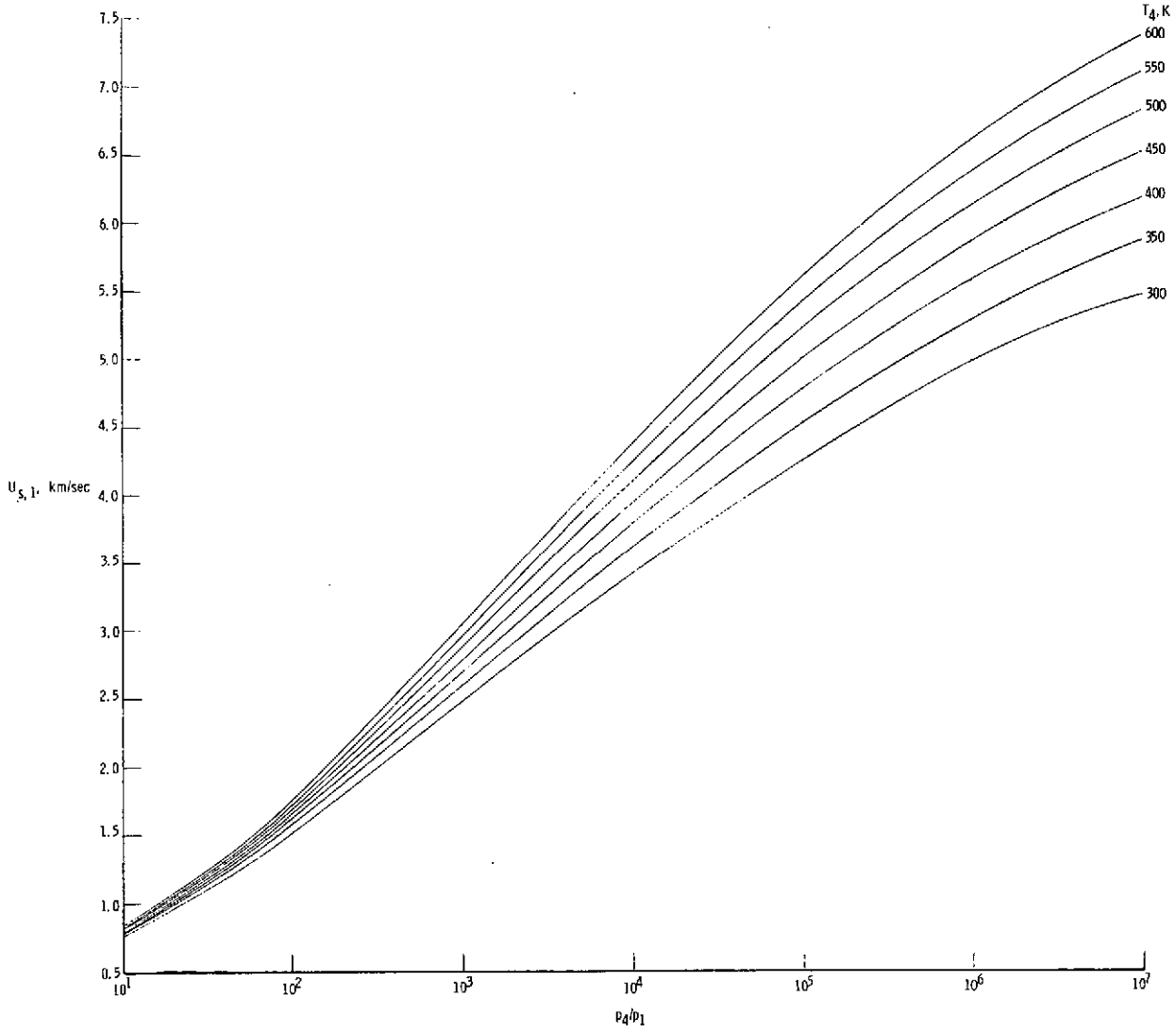
(a) Helium driver gas with 300 K $\leqq T_4 \leqq$ 700 K.

Figure 5.- Shock tube performance for real-air test gas and helium and hydrogen driver gases over range of T_4. $p_4 = 68.95$ MN/m^2.



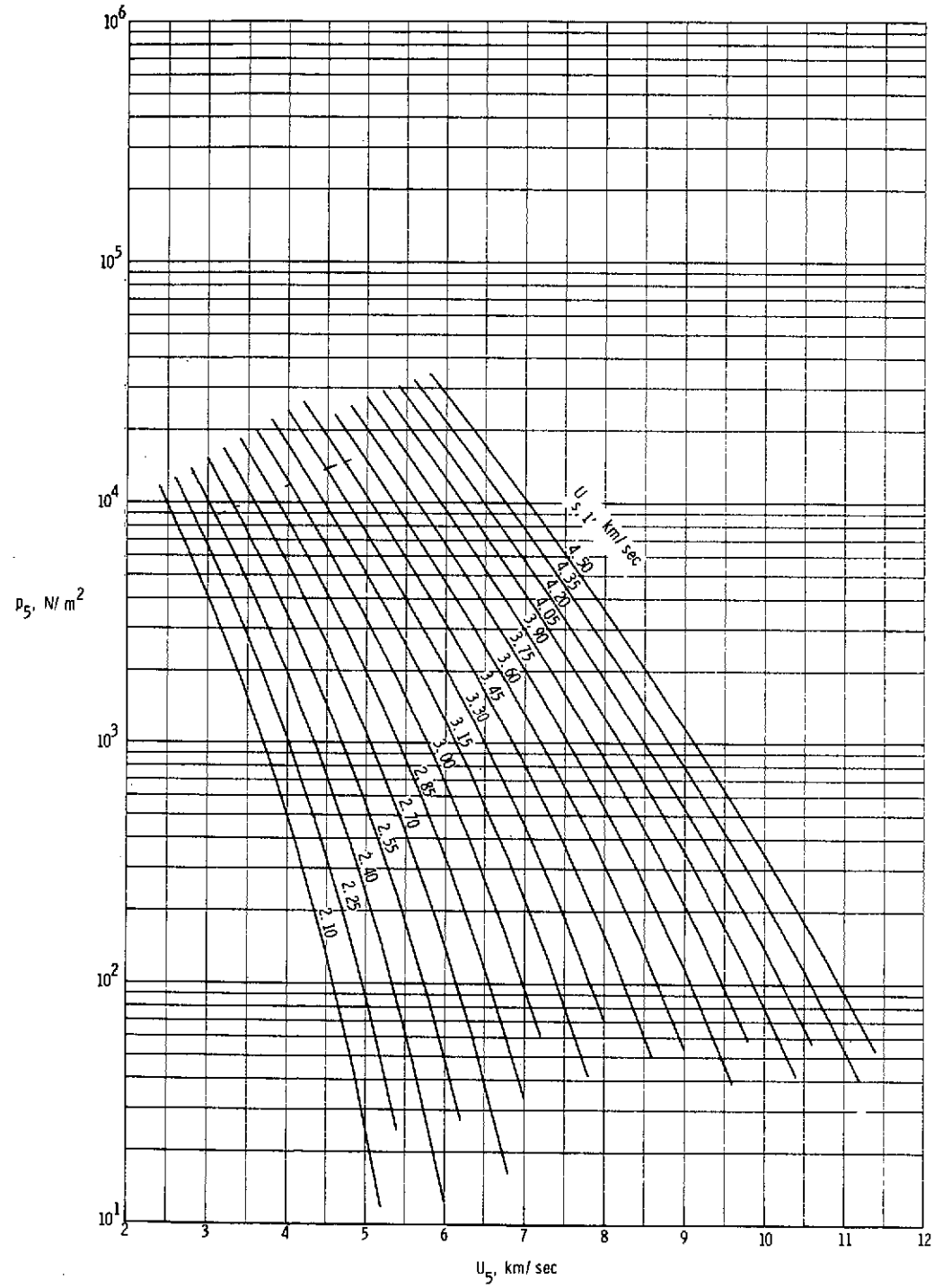
(b) Helium driver gas with 1000 K $\leqq T_4 \leqq$ 12 000 K.

Figure 5.- Continued.



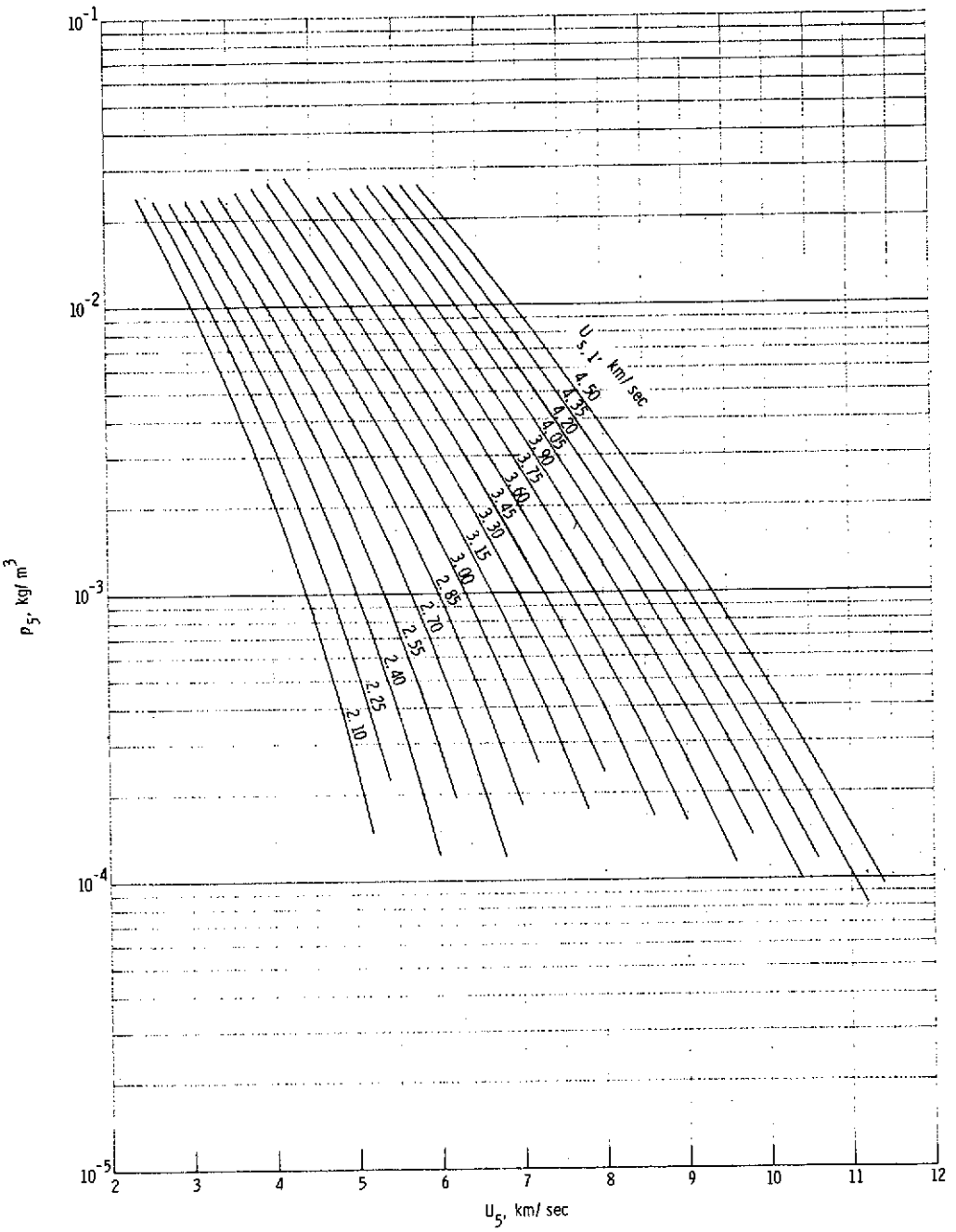
(c) Hydrogen driver gas with 300 K $\leqq T_4 \leqq$ 600 K.

Figure 5.- Concluded.



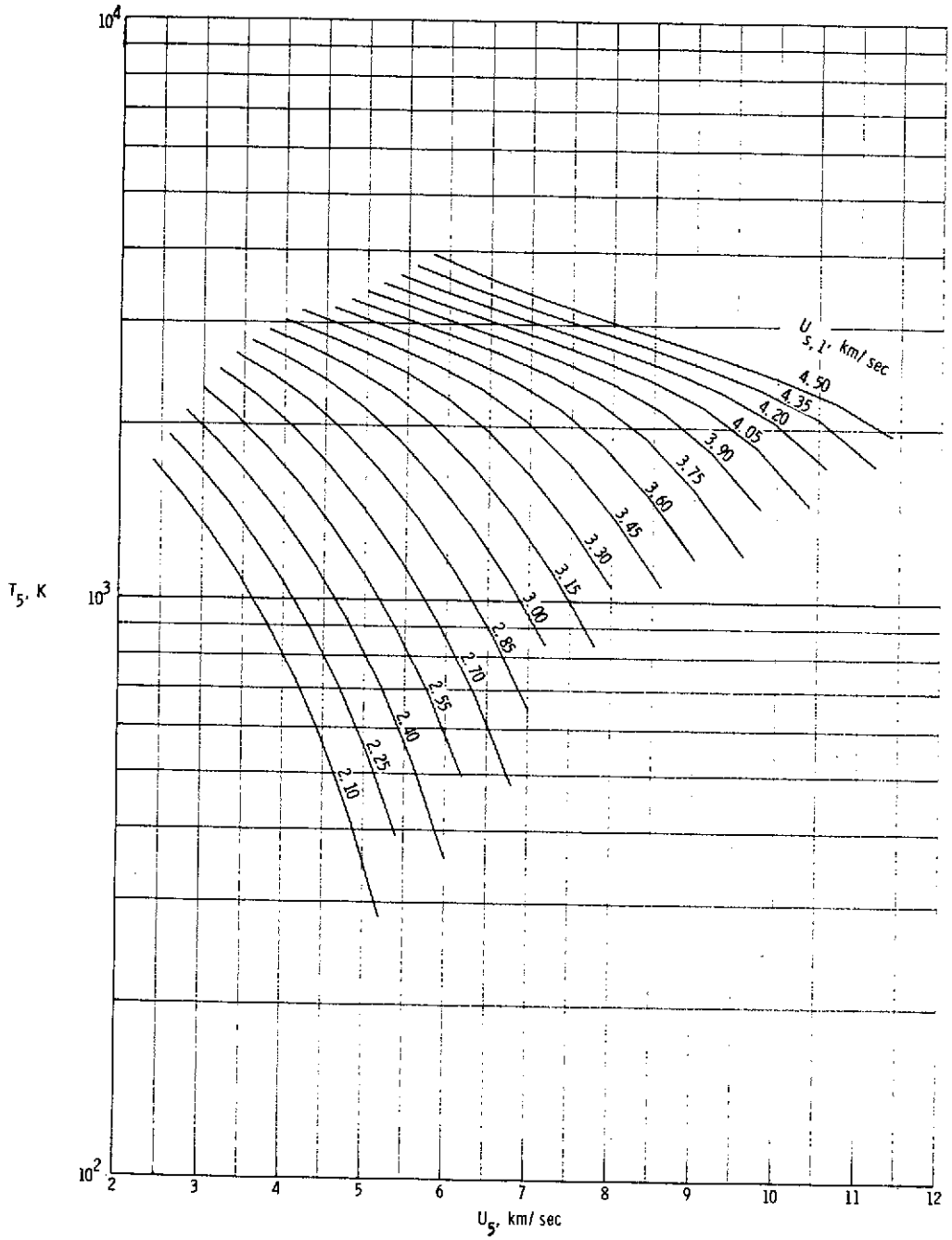
(a) Static pressure in region (5).

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. $p_1 = 0.6895$ kN/m^2.



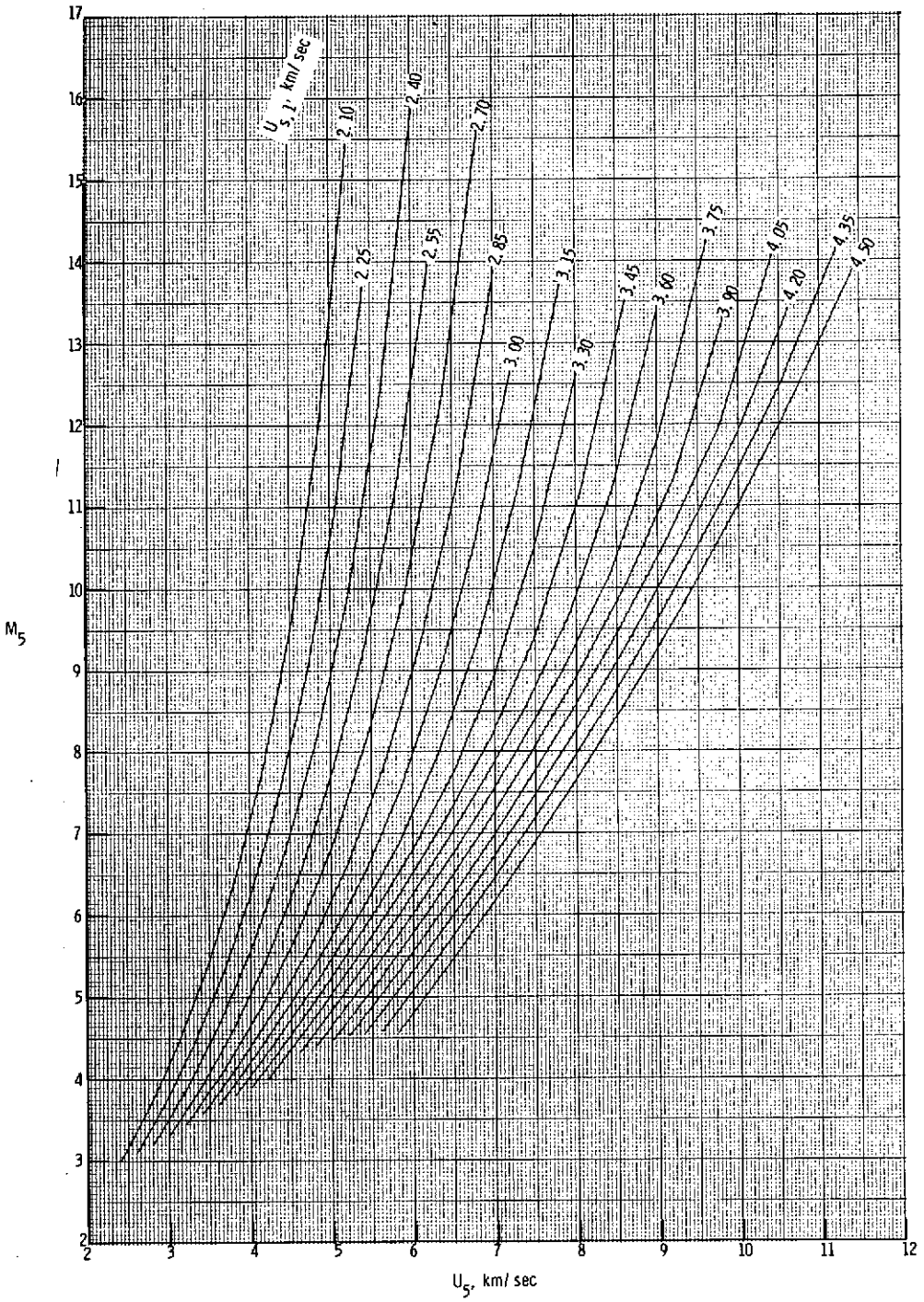
(b) Static density in region (5).

Figure 6.- Continued.



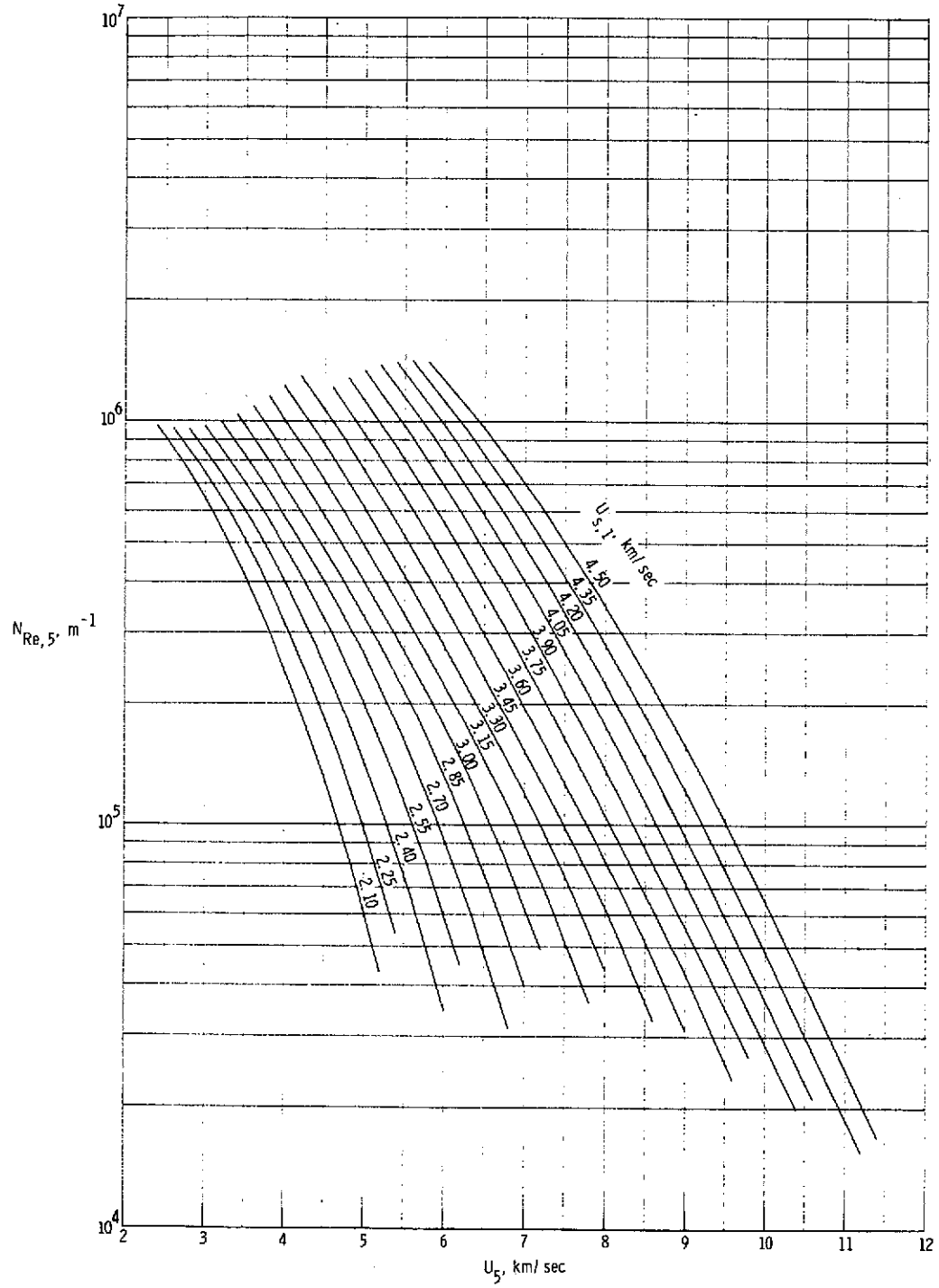
(c) Static temperature in region (5).

Figure 6.- Continued.



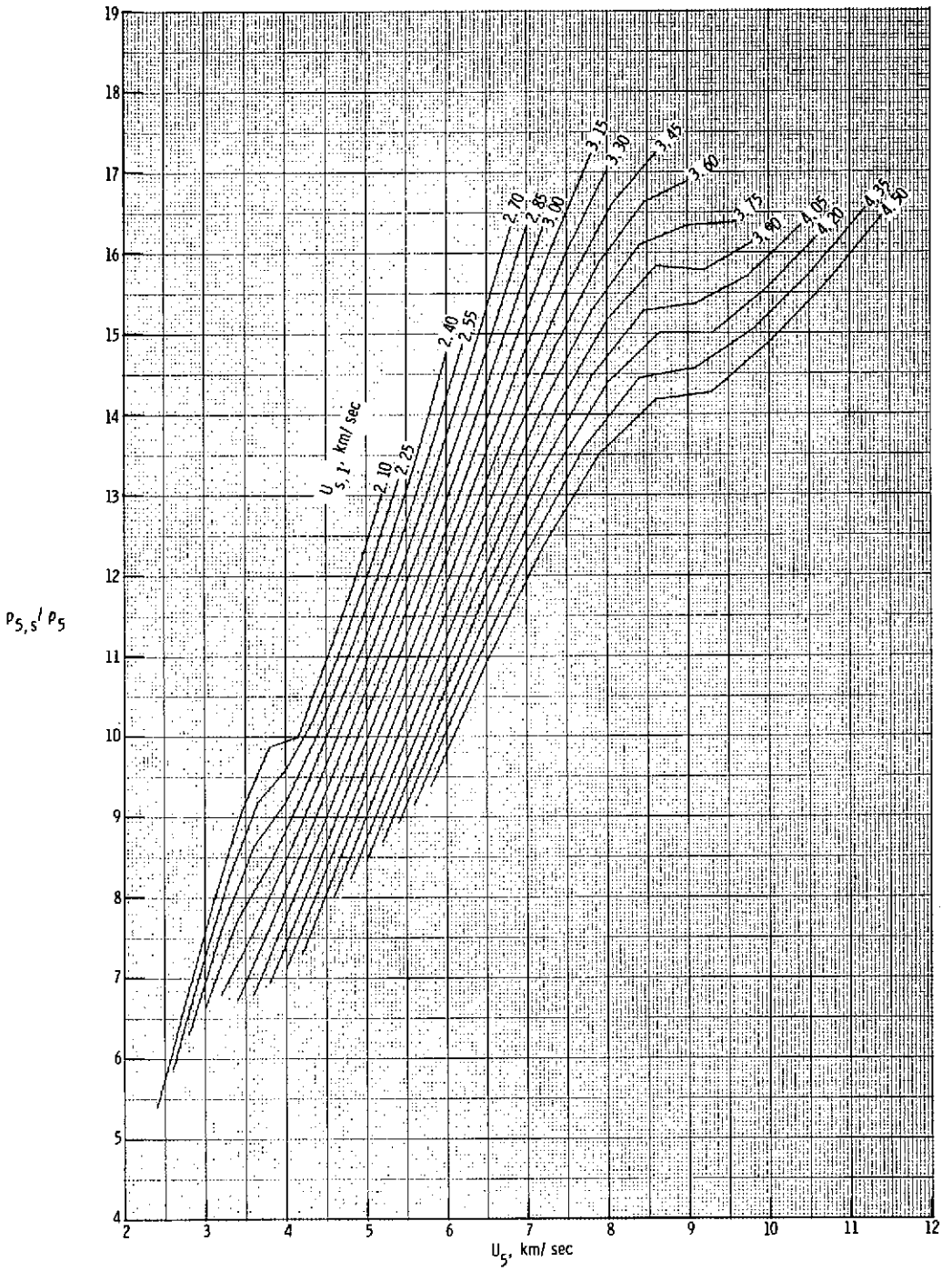
(d) Mach number in region (5).

Figure 6.- Continued.



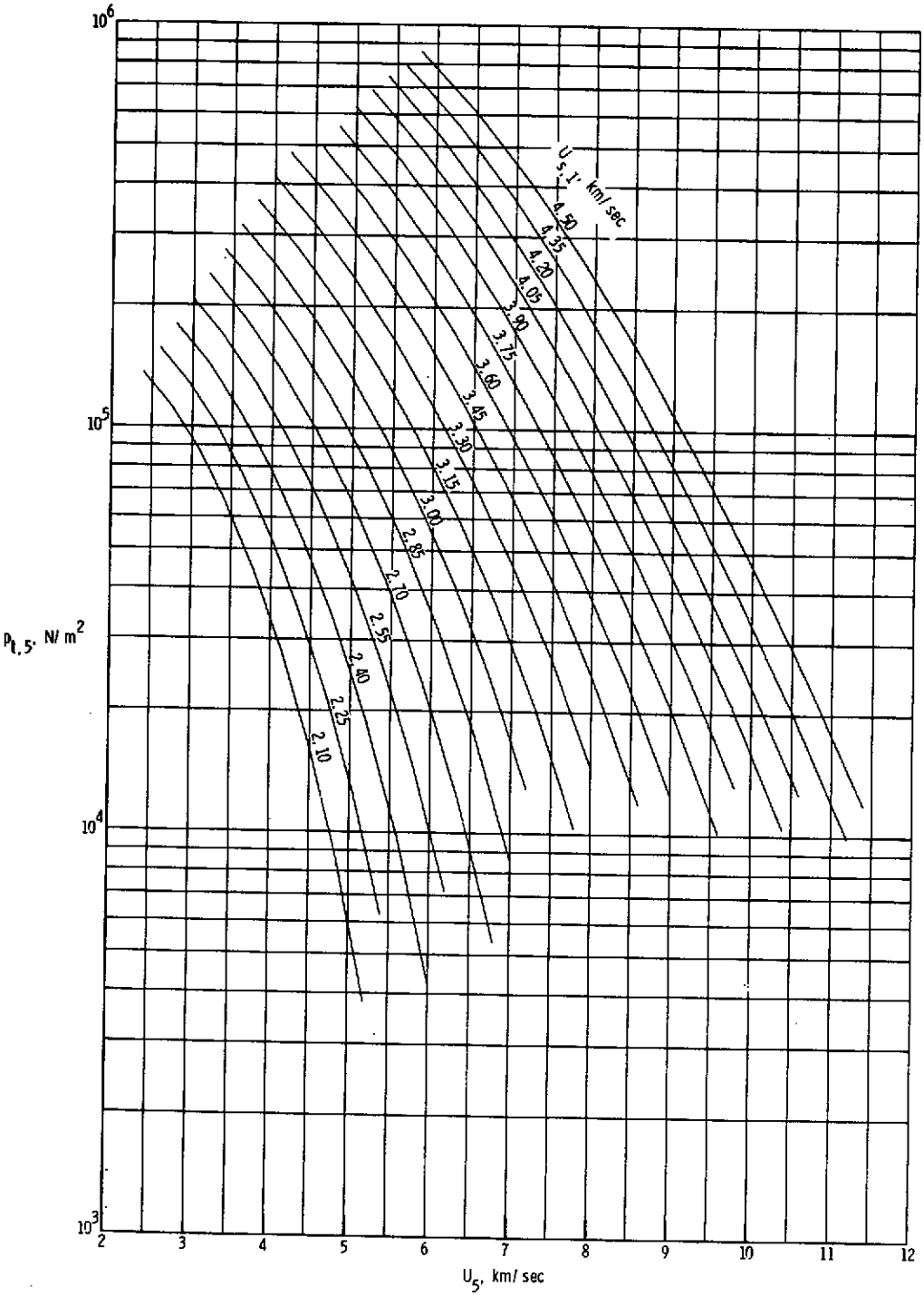
(e) Unit Reynolds number in region (5).

Figure 6.- Continued.



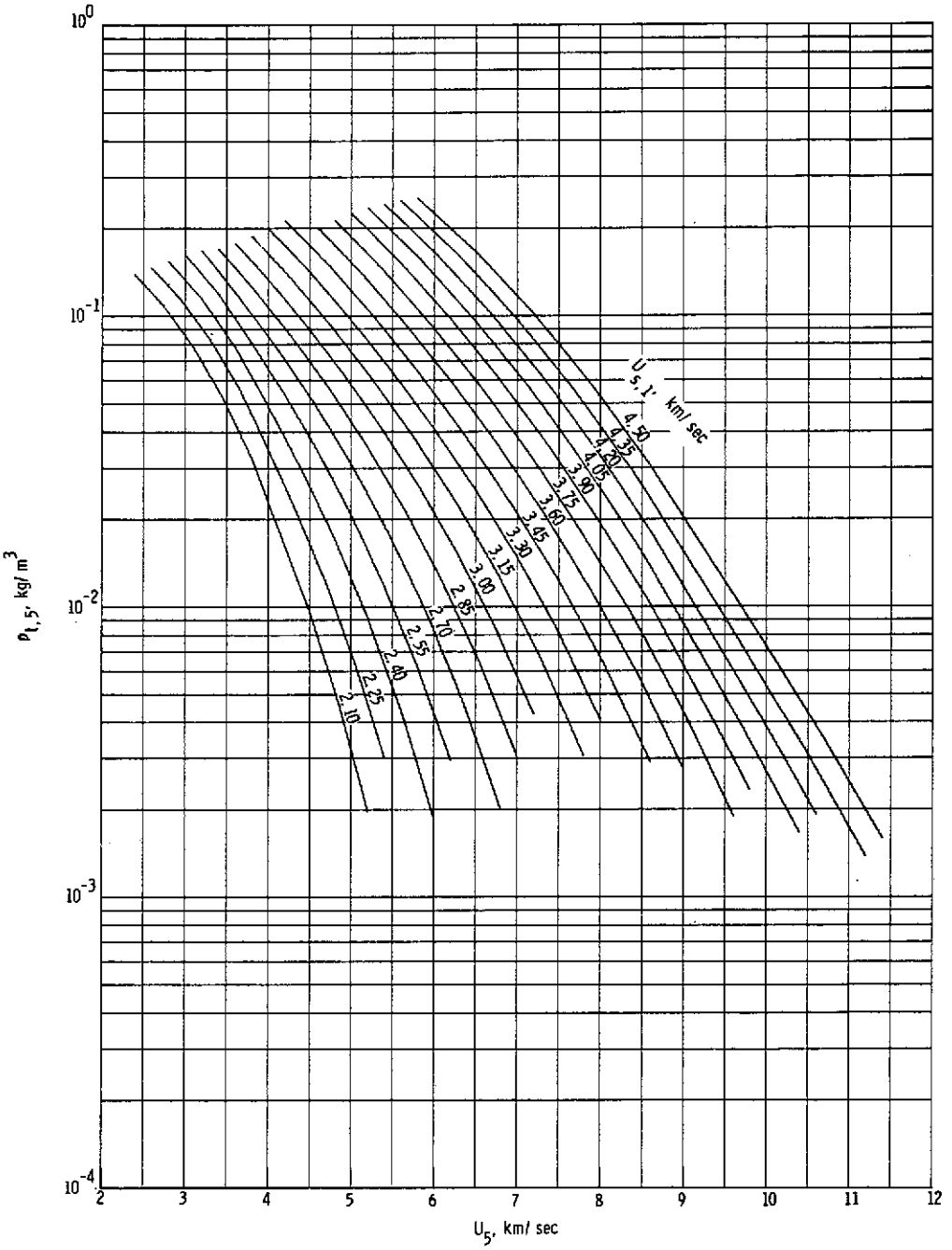
(f) Normal-shock density ratio.

Figure 6.- Continued.



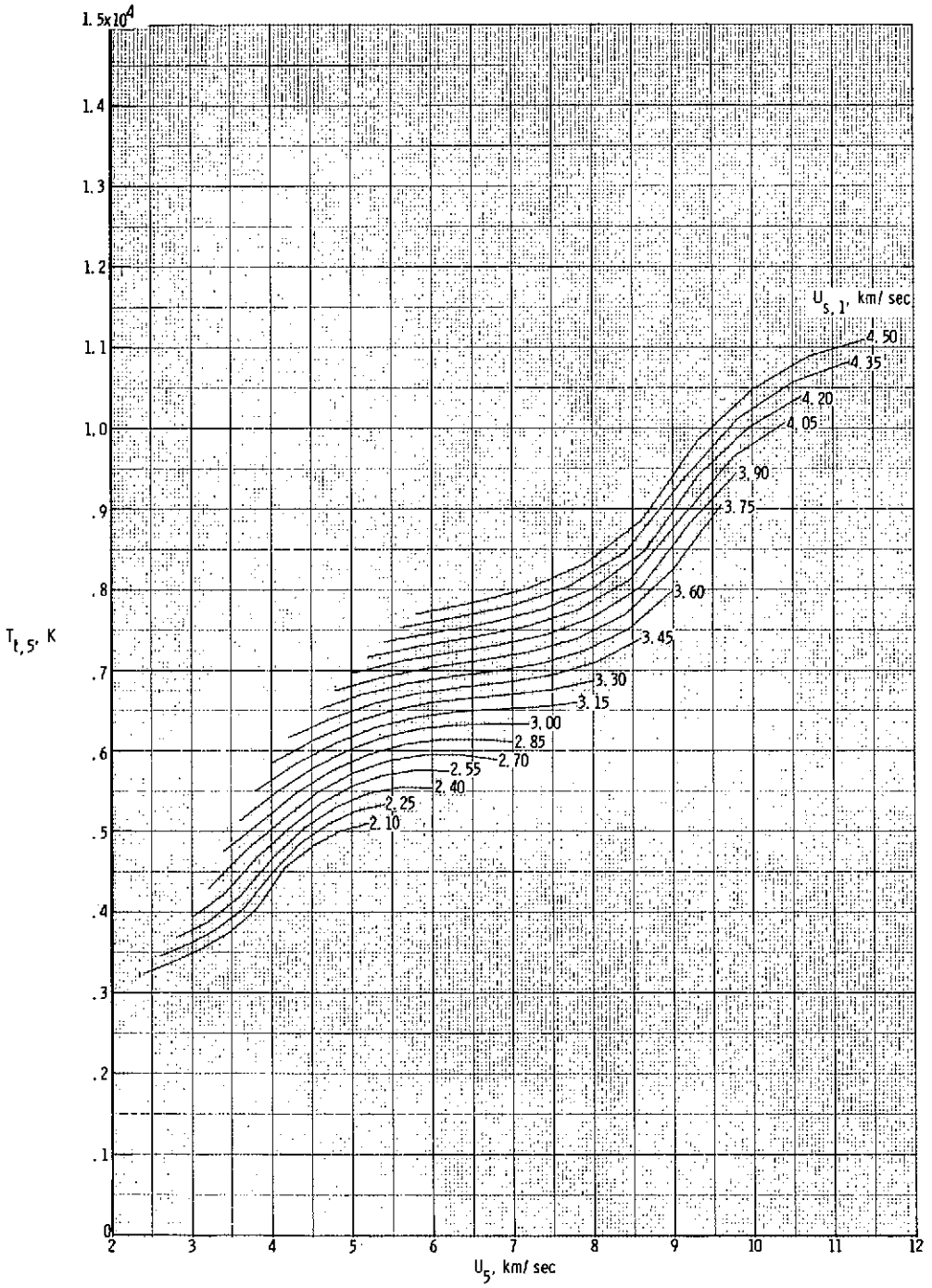
(g) Stagnation pressure behind normal bow shock.

Figure 6.- Continued.



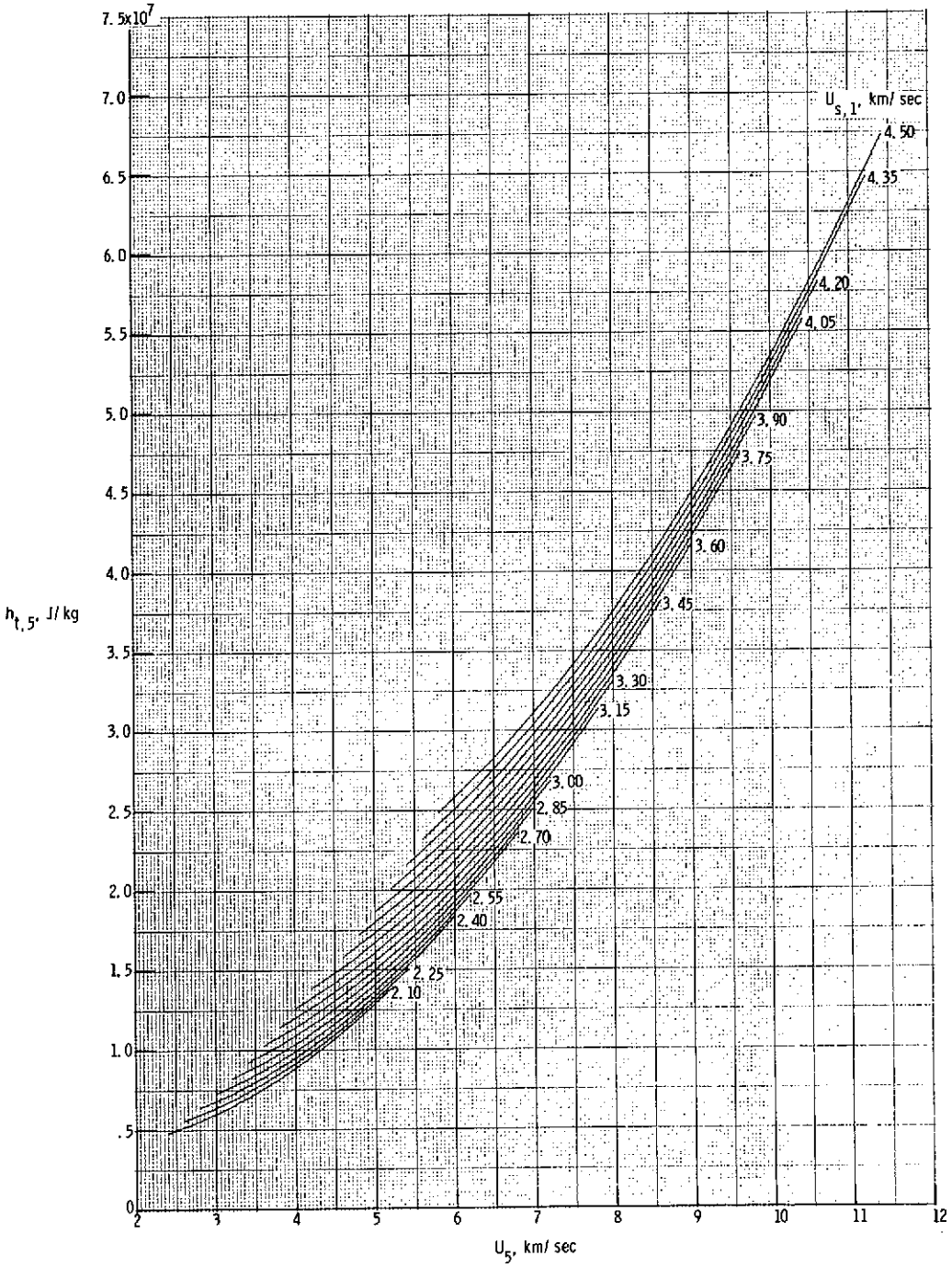
(h) Stagnation density behind normal bow shock.

Figure 6.- Continued.



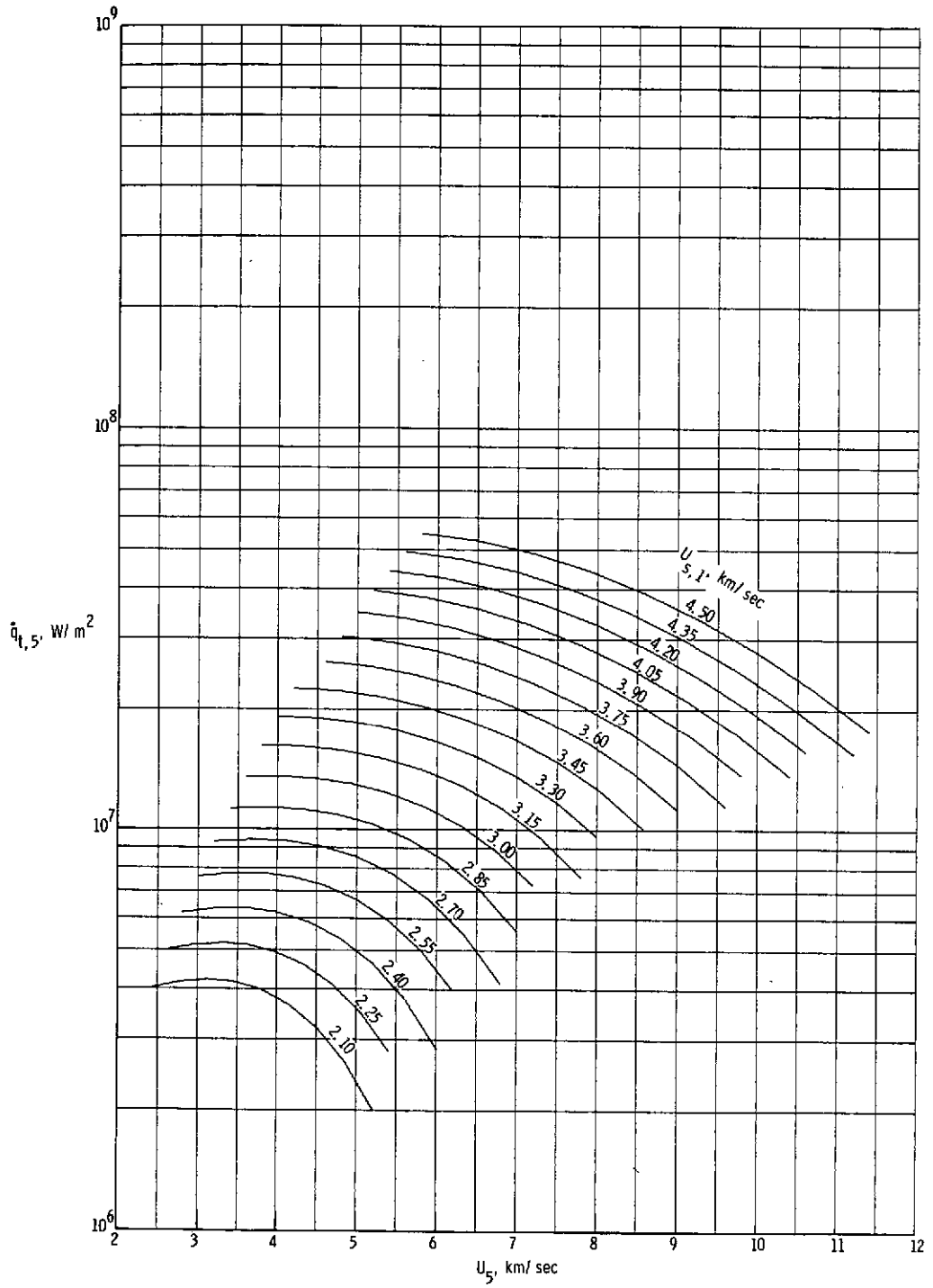
(i) Stagnation temperature behind normal bow shock.

Figure 6.- Continued.



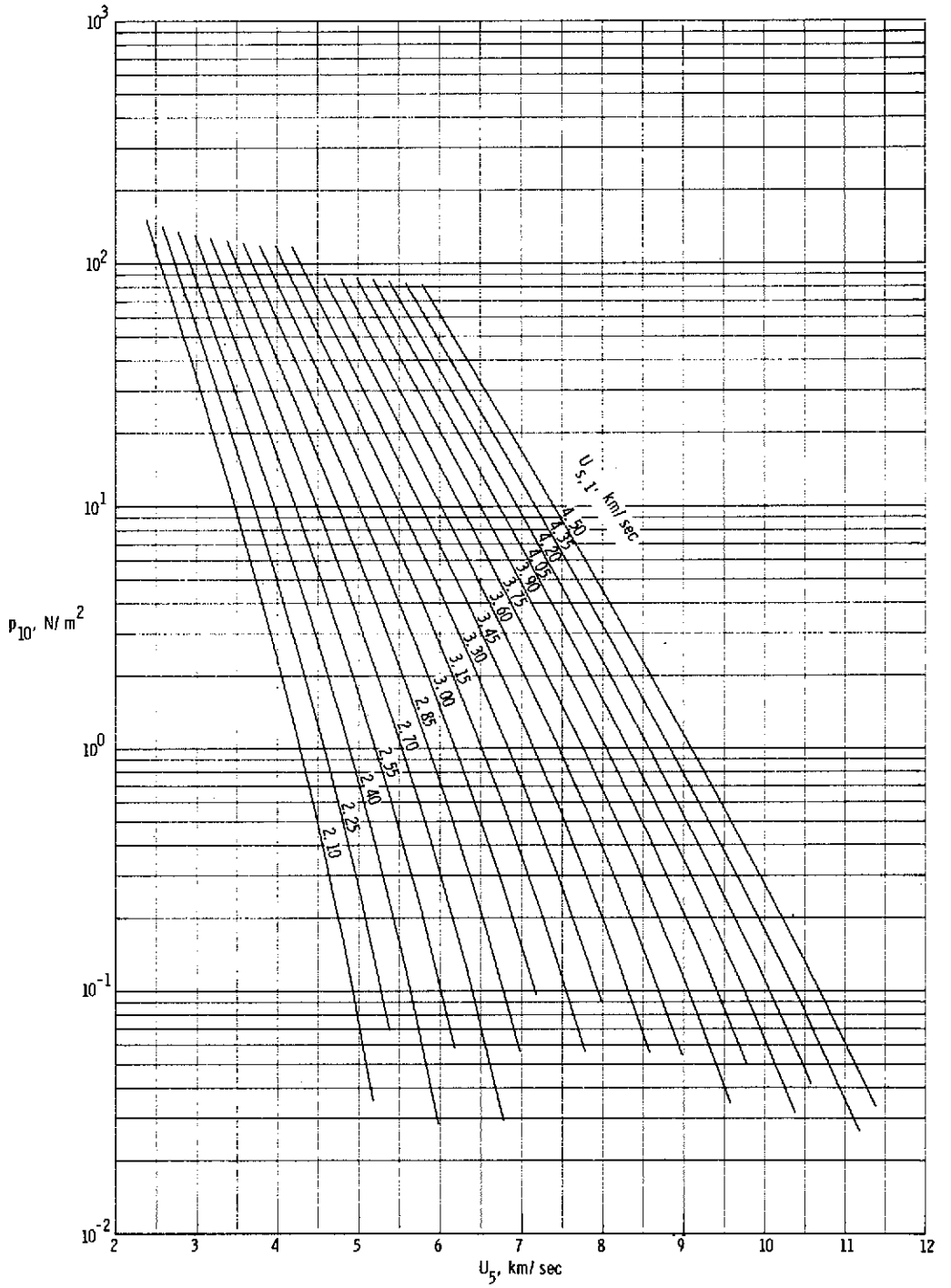
(j) Stagnation enthalpy behind normal bow shock.

Figure 6.- Continued.



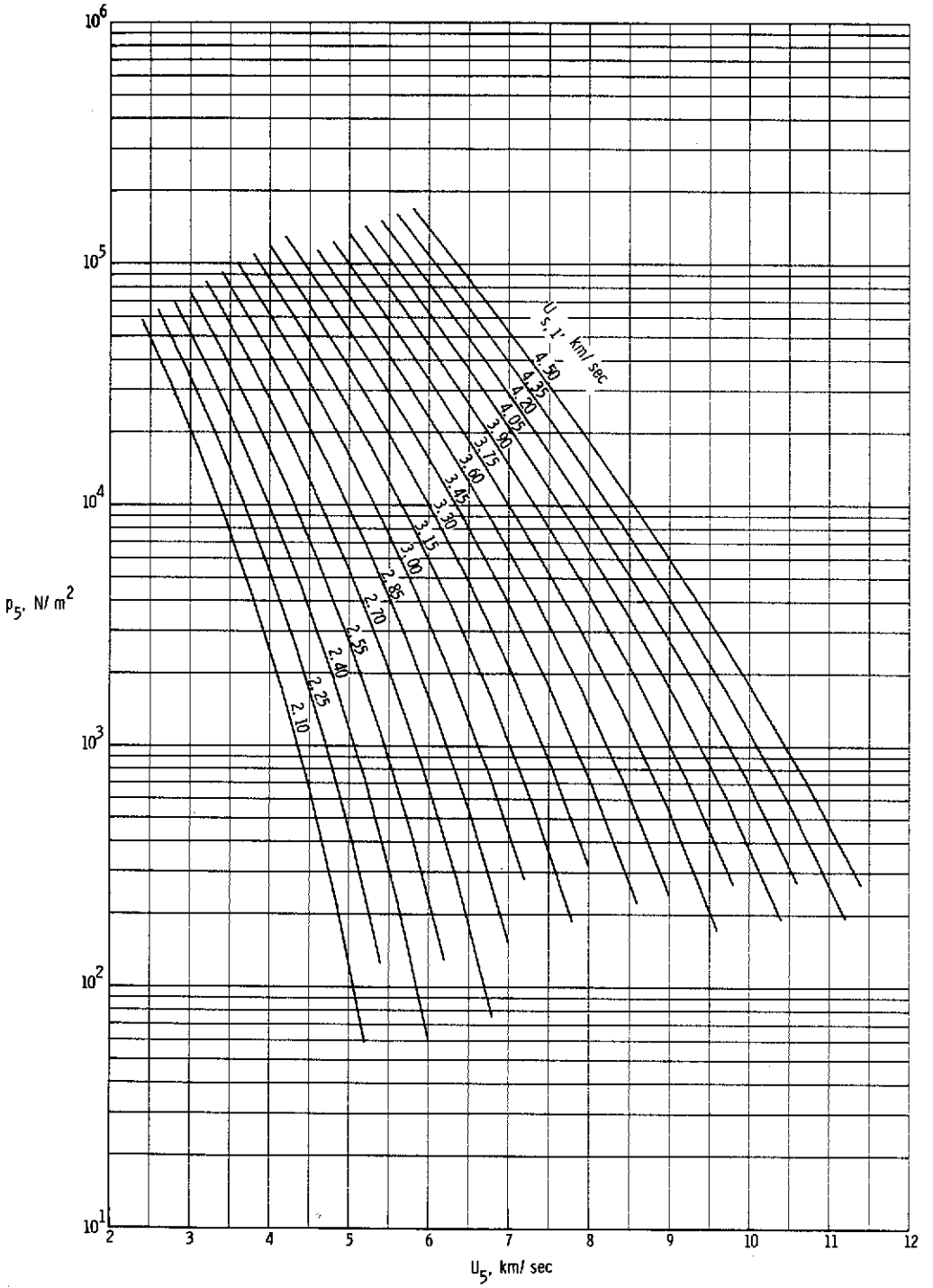
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 6.- Continued.



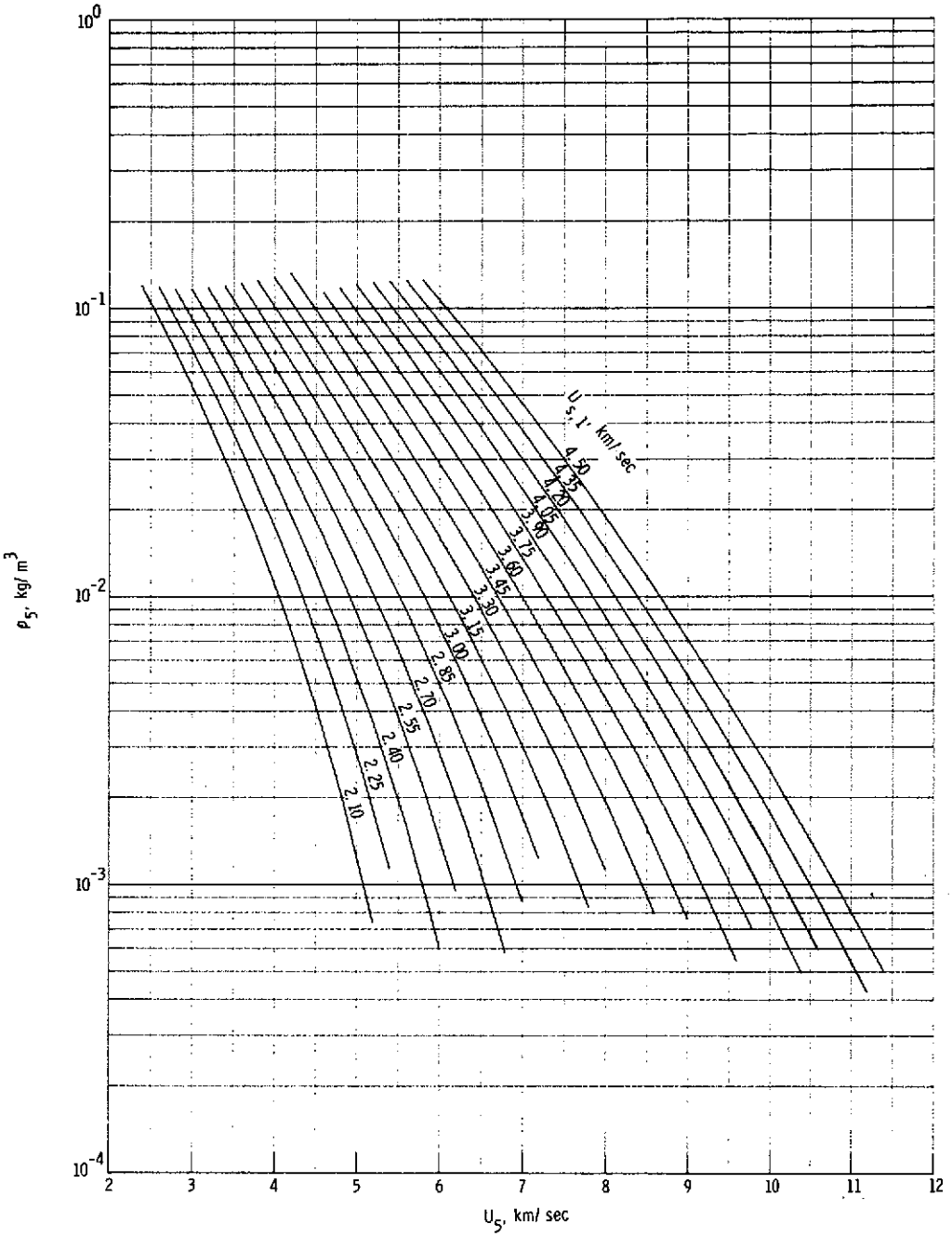
(l) Quiescent acceleration air pressure in region (10).

Figure 6.- Concluded.



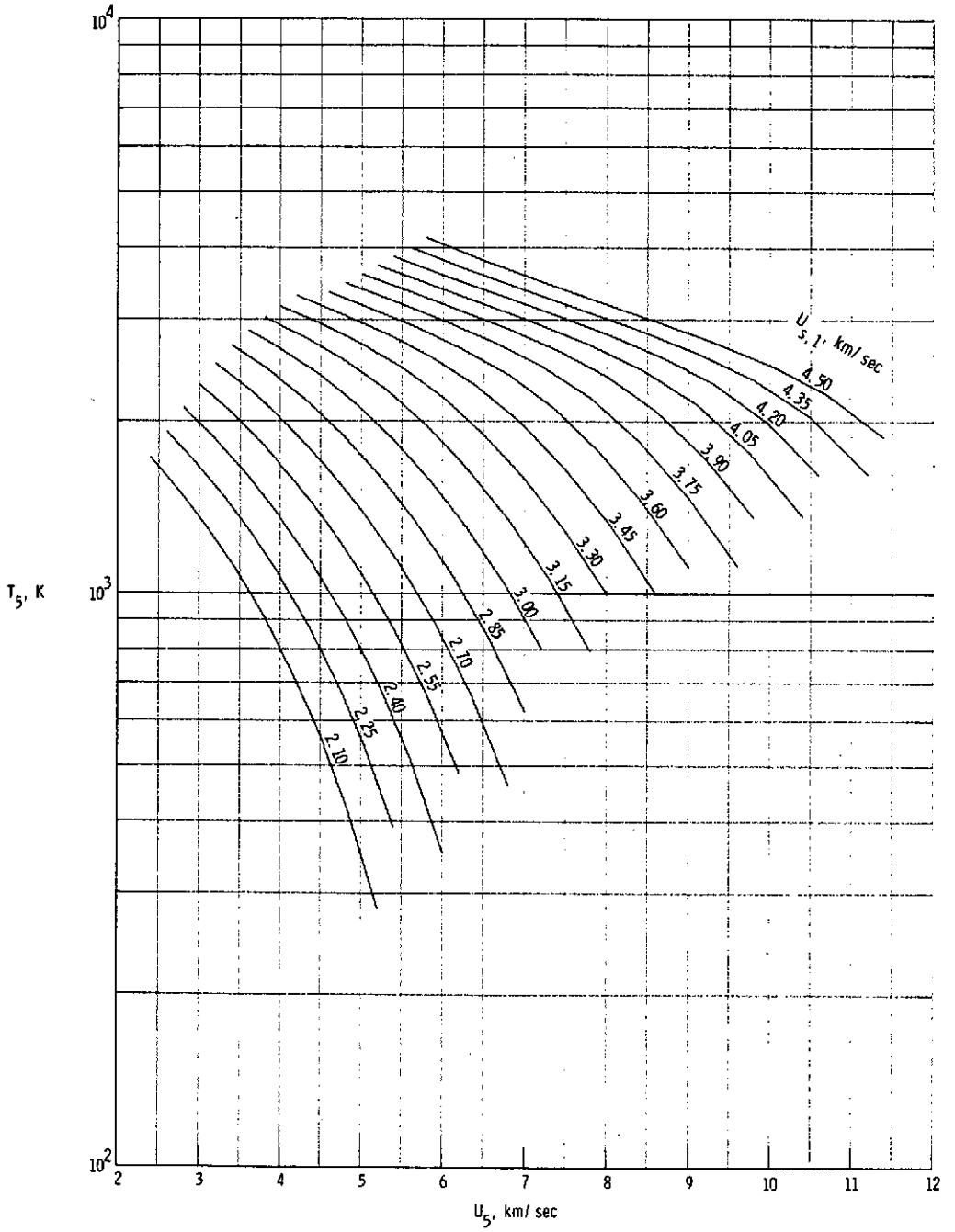
(a) Static pressure in region (5).

Figure 7.- 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. $p_1 = 3.45$ kN/m^2.



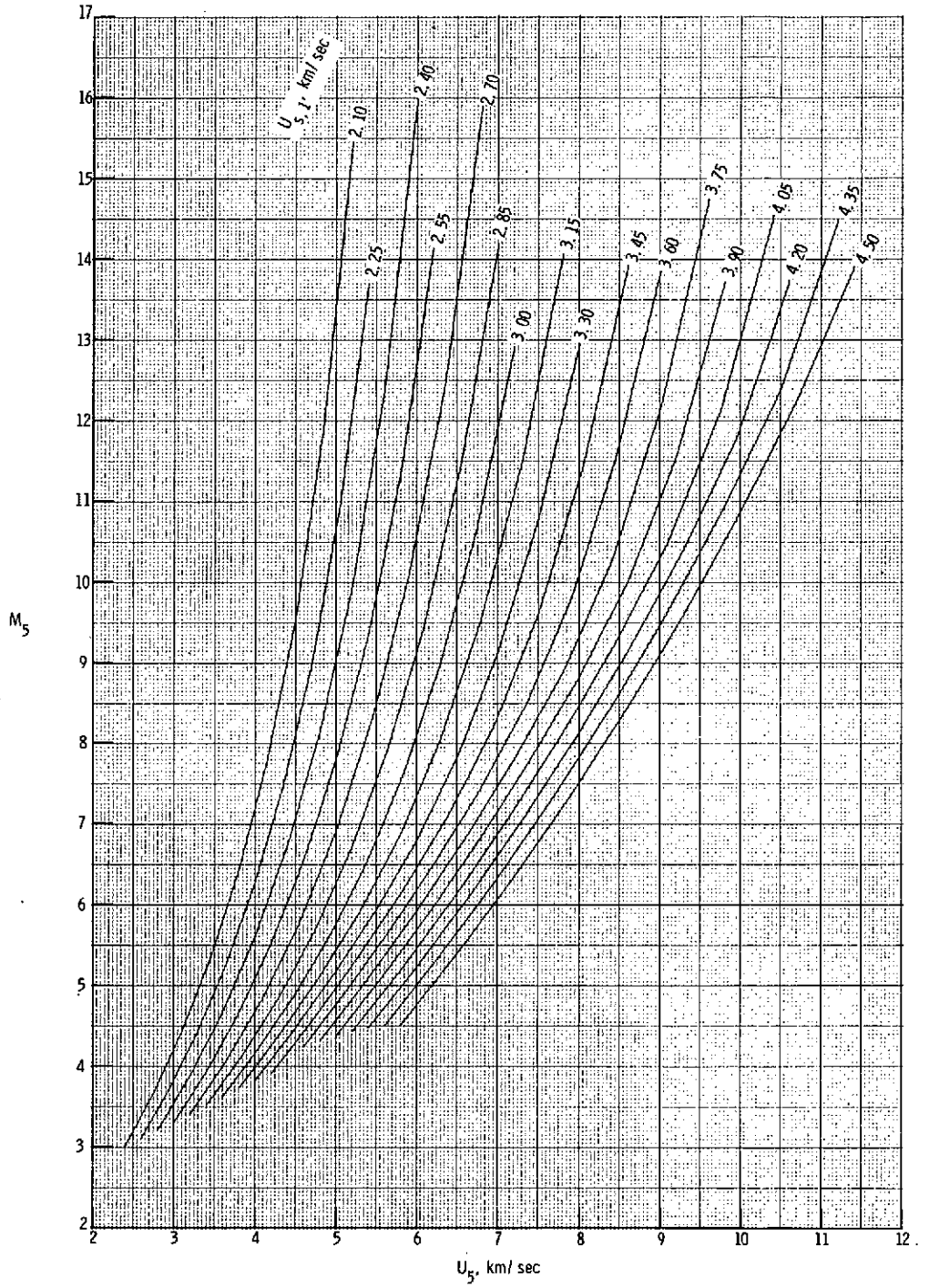
(b) Static density in region (5).

Figure 7.- Continued.



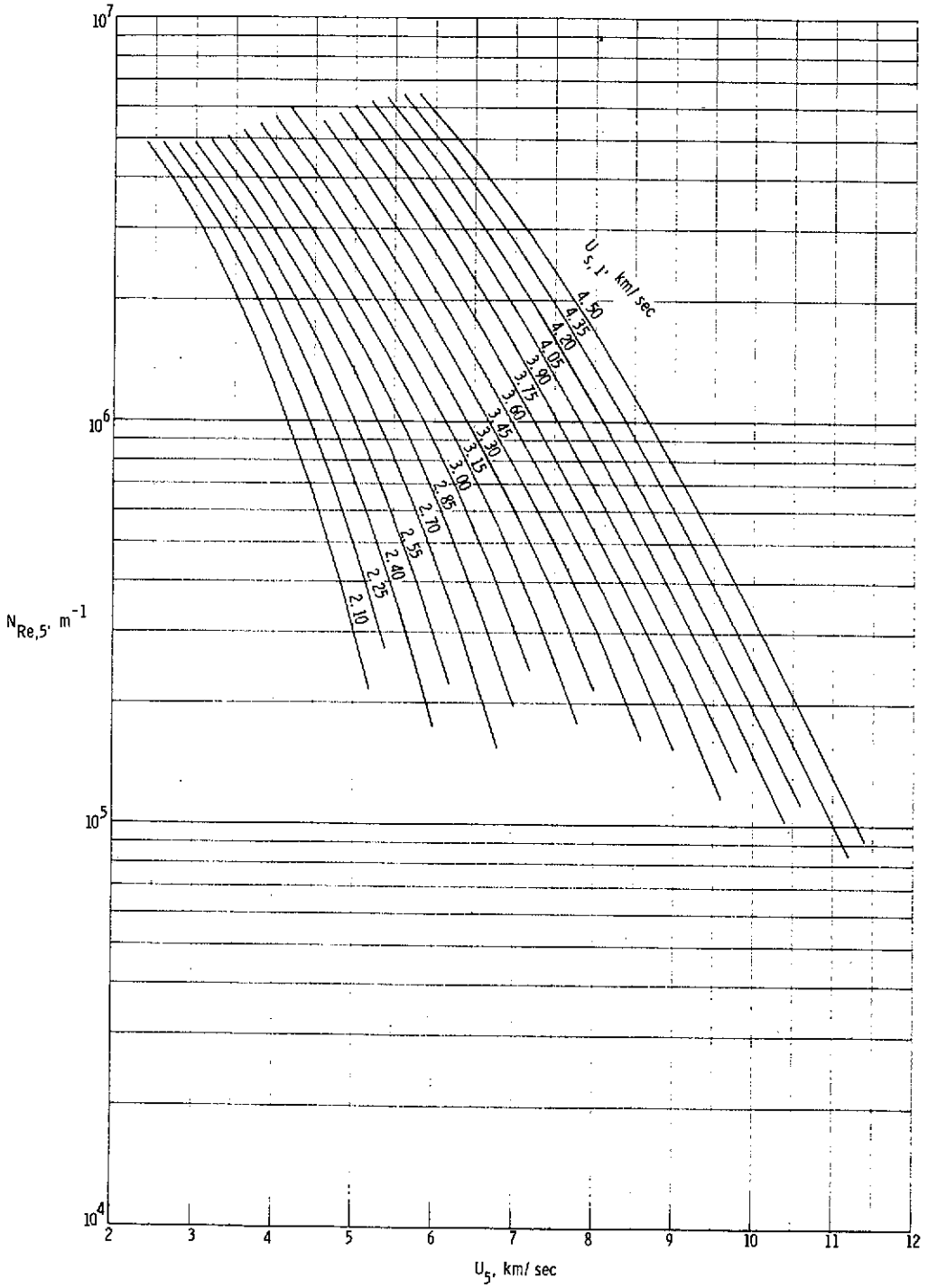
(c) Static temperature in region (5).

Figure 7.- Continued.



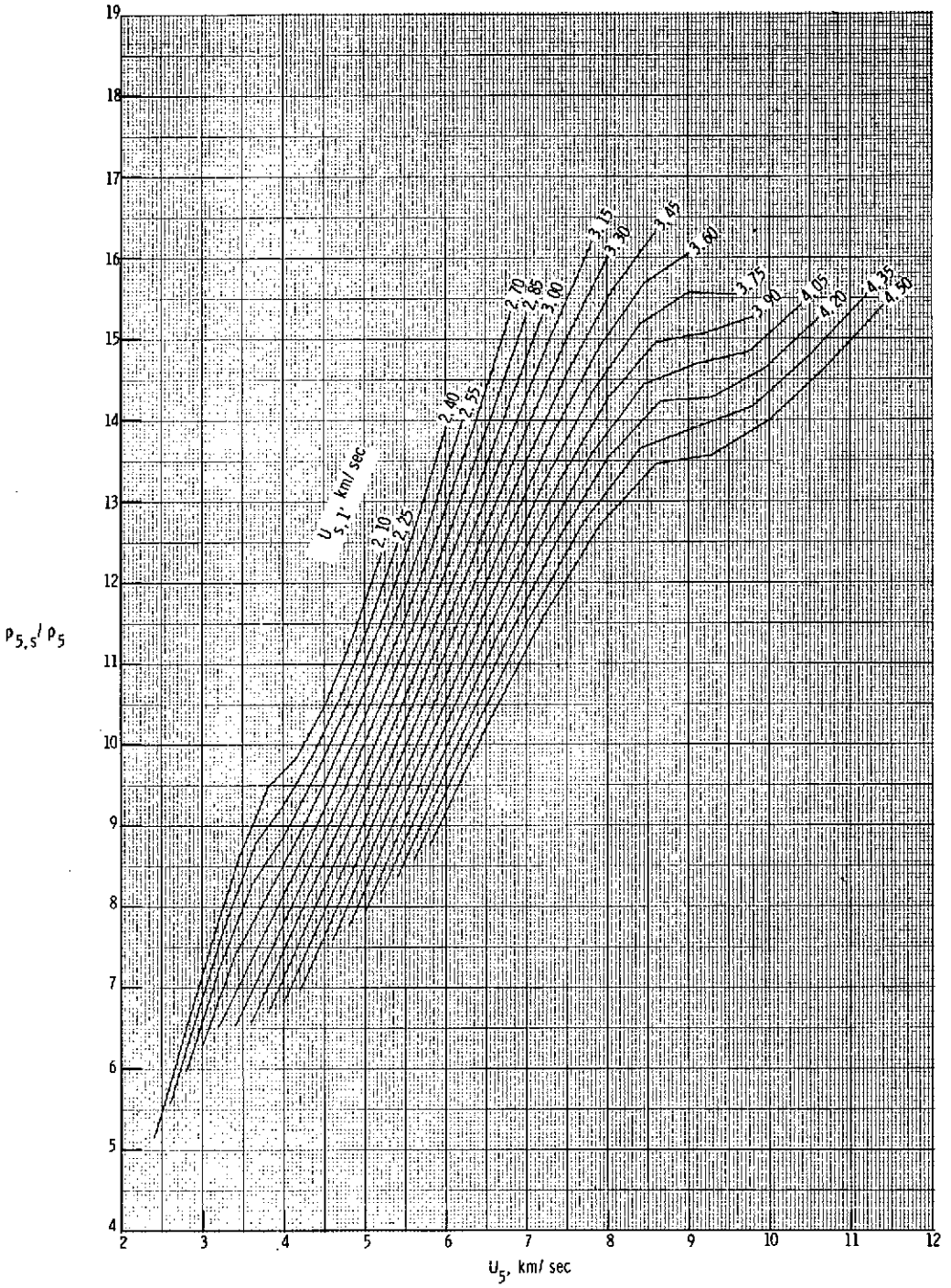
(d) Mach number in region (5).

Figure 7.- Continued.



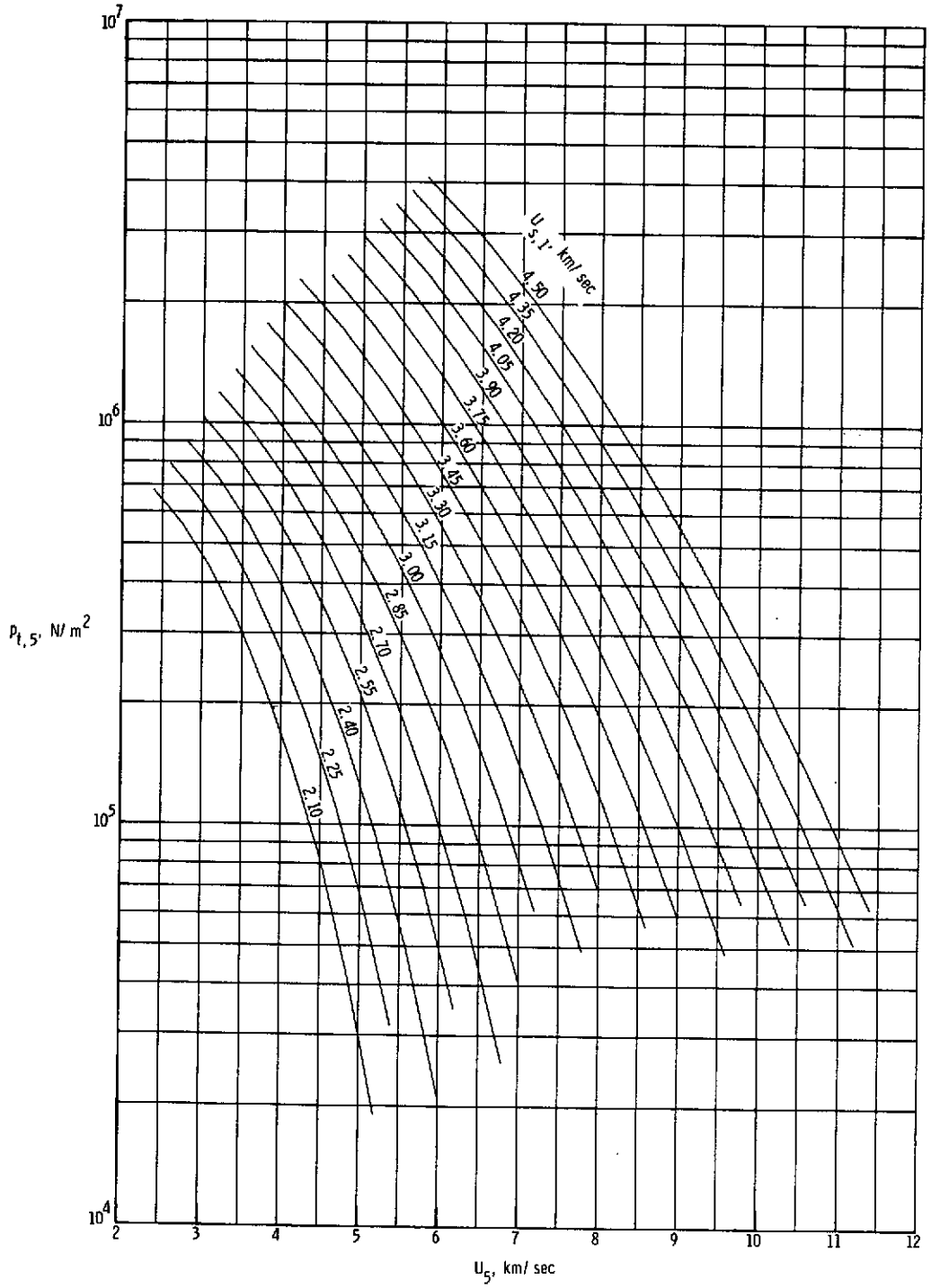
(e) Unit Reynolds number in region (5).

Figure 7.- Continued.



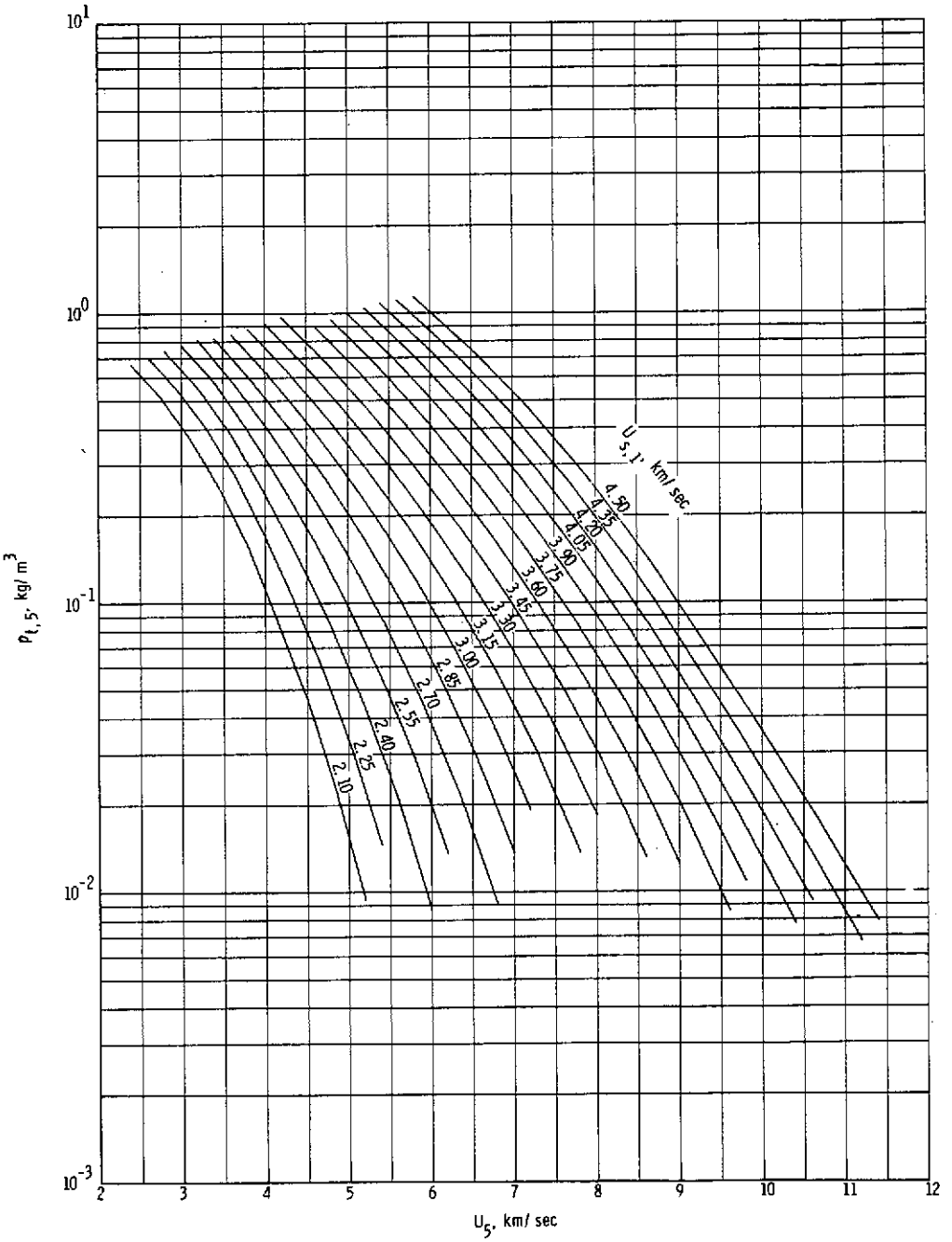
(f) Normal shock density ratio.

Figure 7.- Continued.



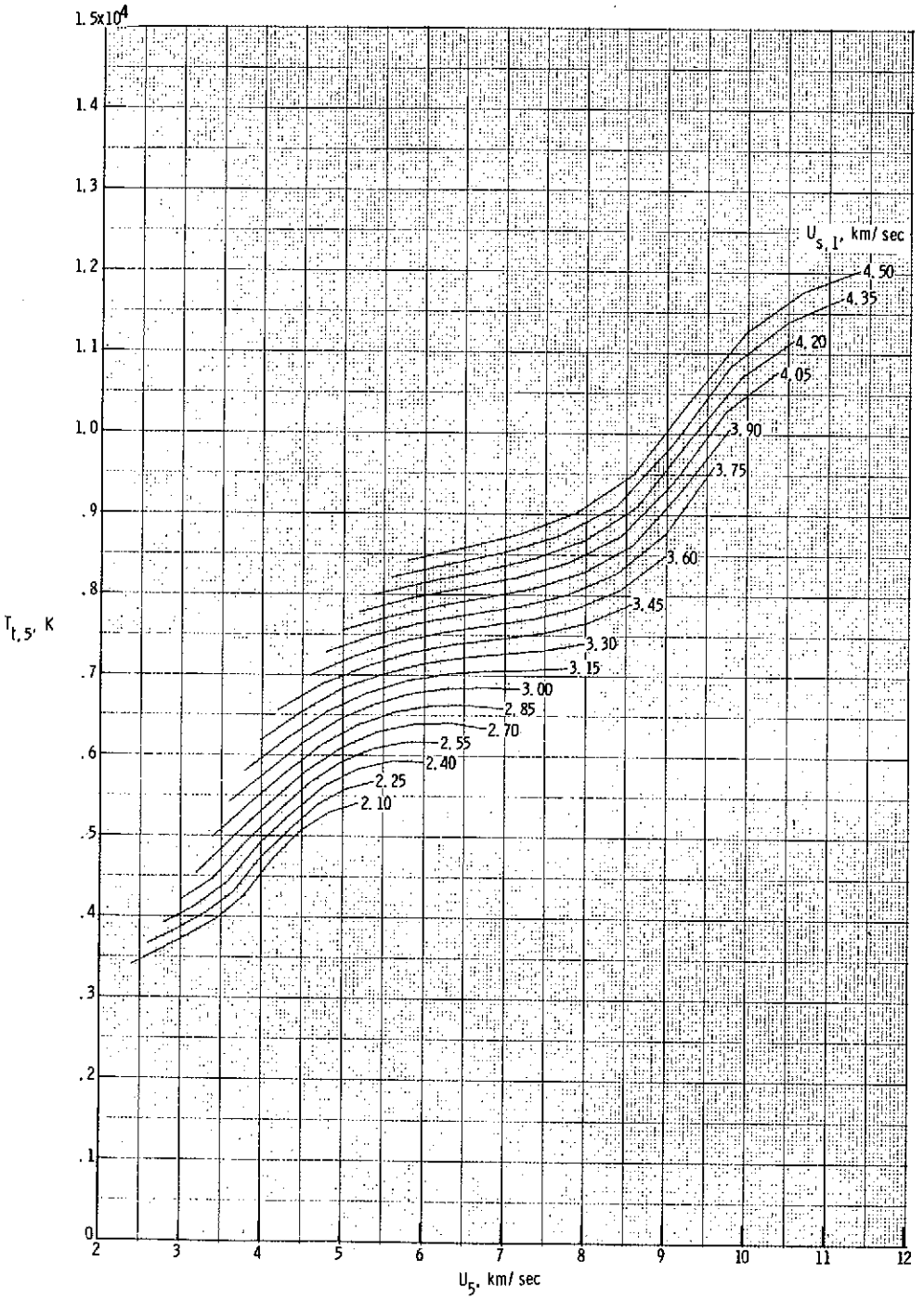
(g) Stagnation pressure behind normal bow shock.

Figure 7.- Continued.



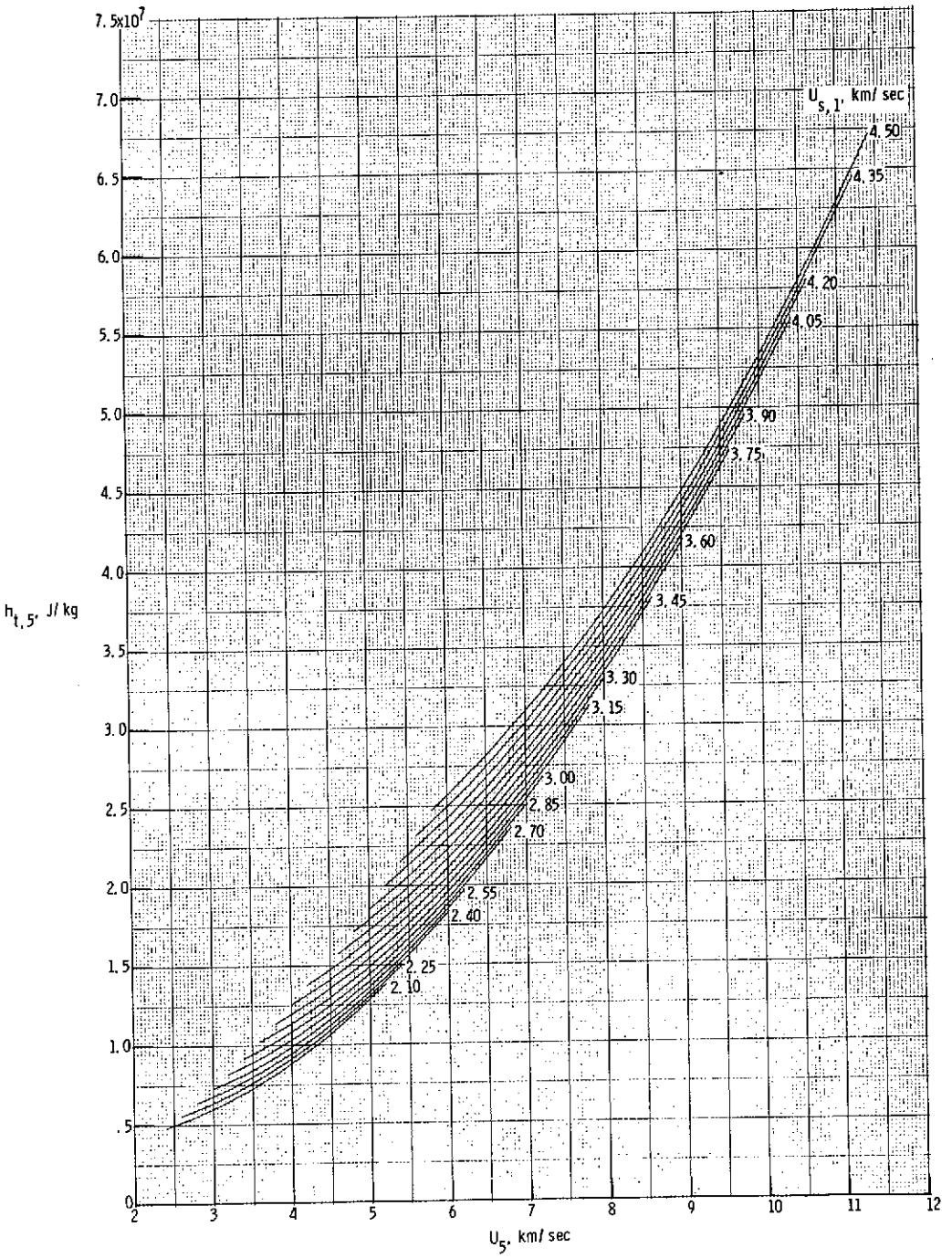
(h) Stagnation density behind normal bow shock.

Figure 7.- Continued.



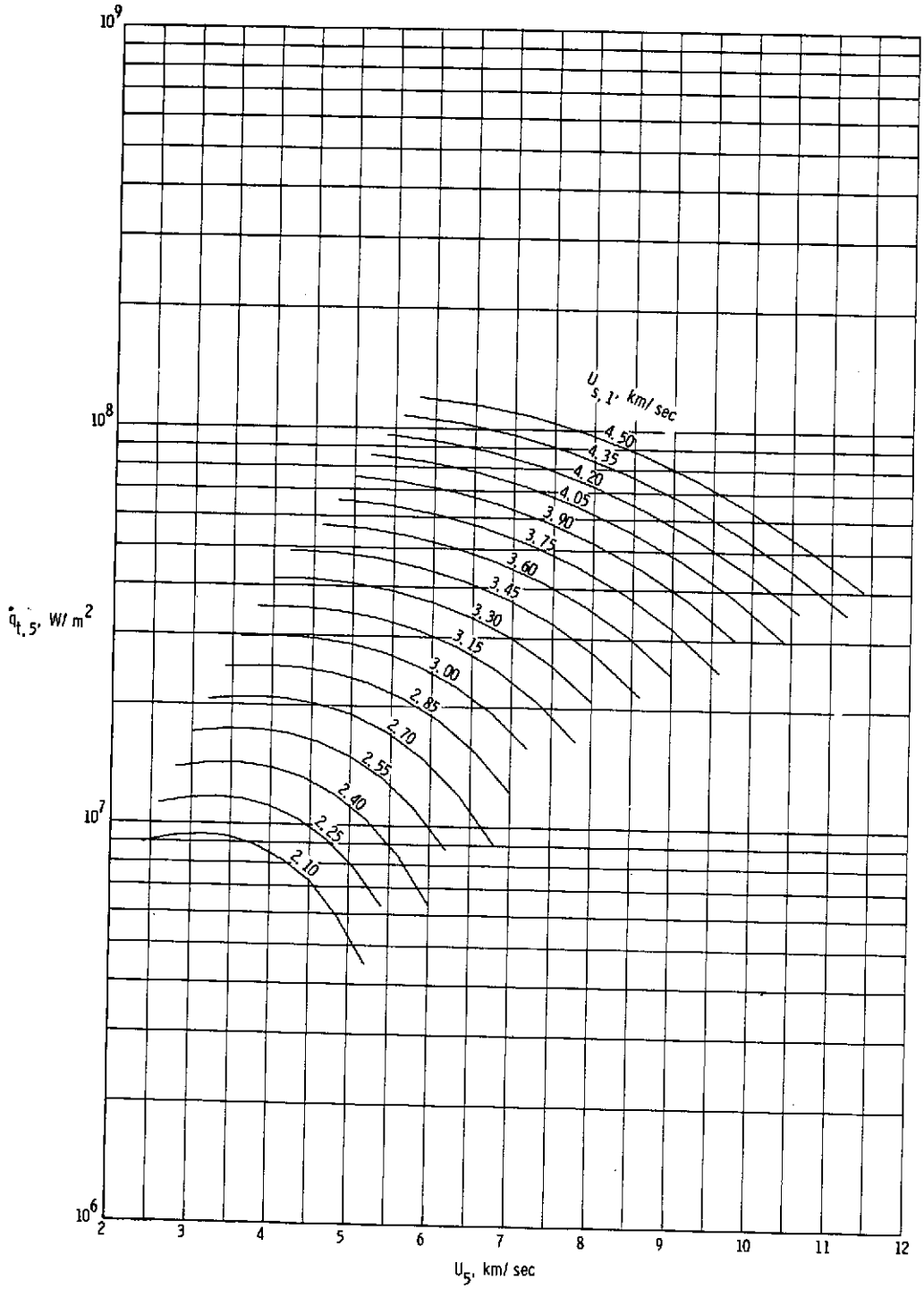
(i) Stagnation temperature behind normal bow shock.

Figure 7.- Continued.



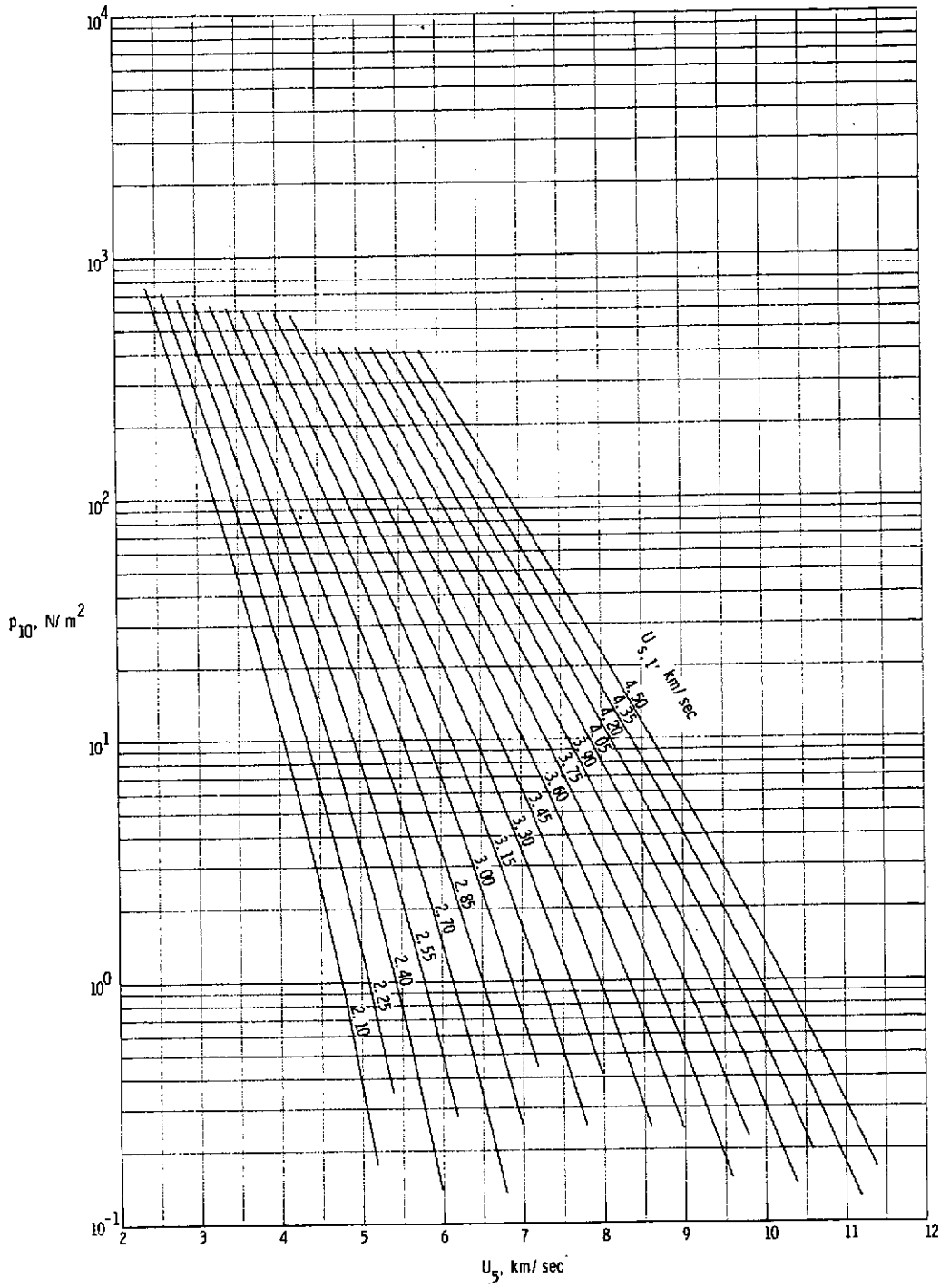
(j) Stagnation enthalpy behind normal bow shock.

Figure 7.- Continued.



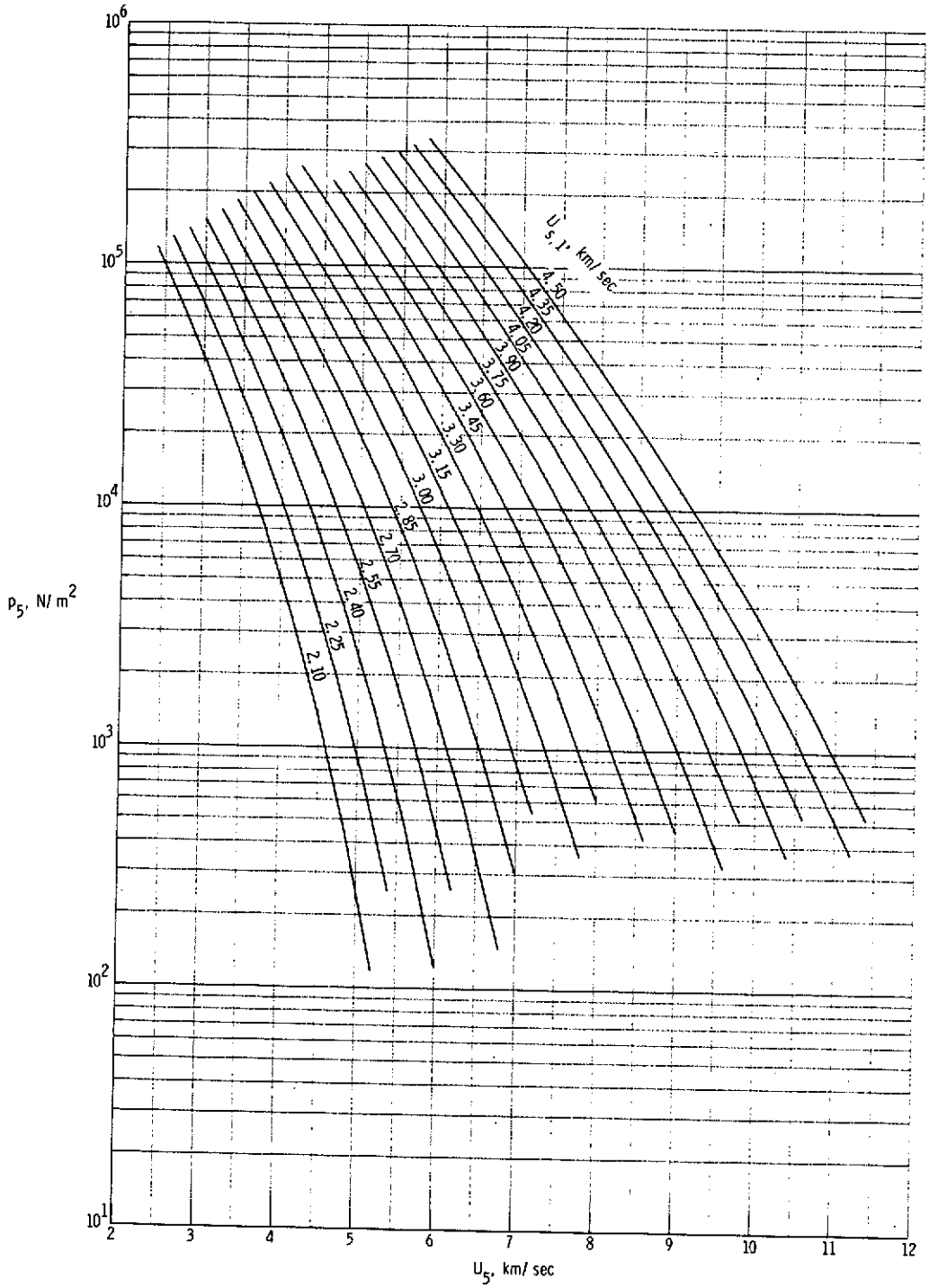
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 7.- Continued.



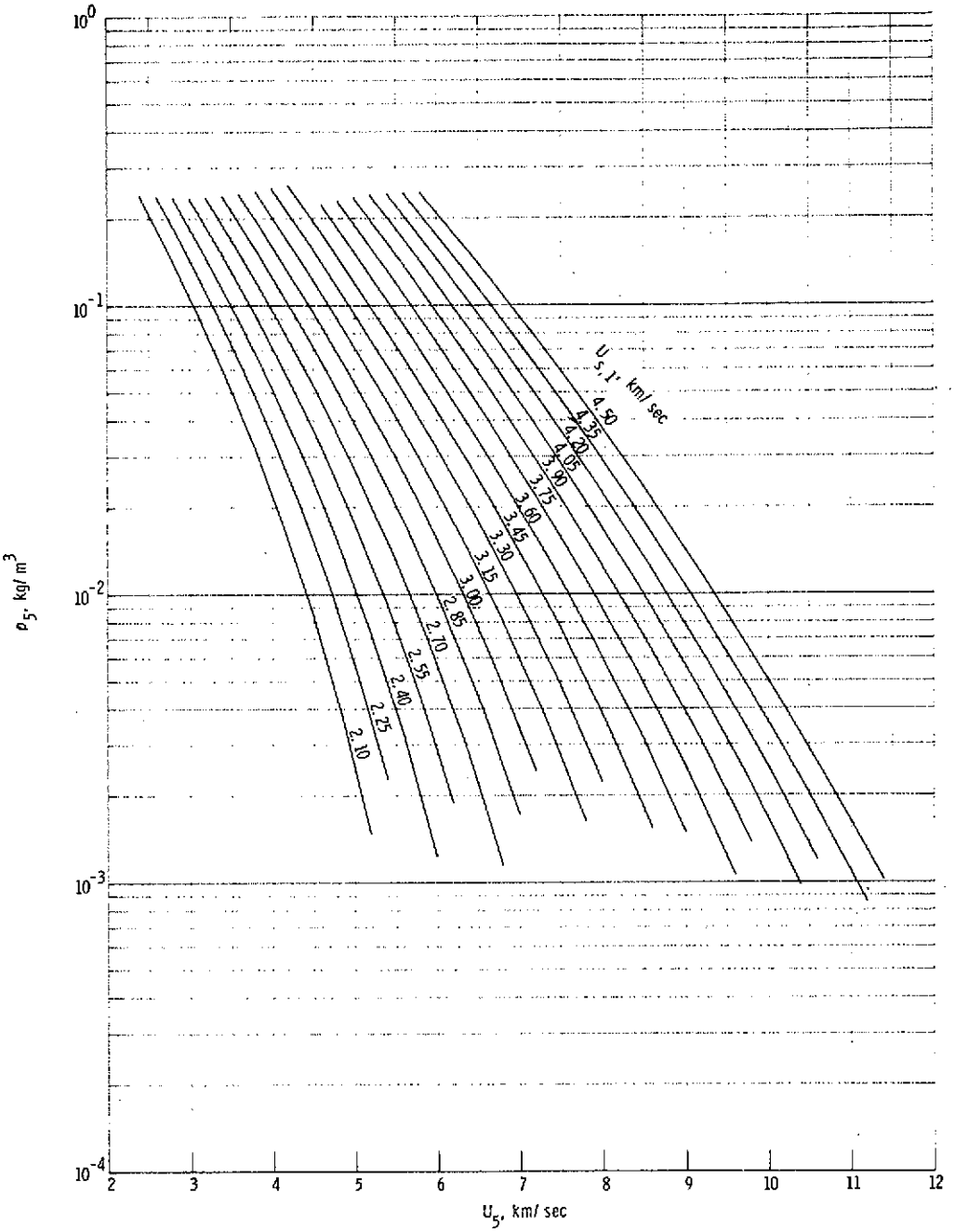
(l) Quiescent acceleration air pressure in region (10).

Figure 7.- Concluded.



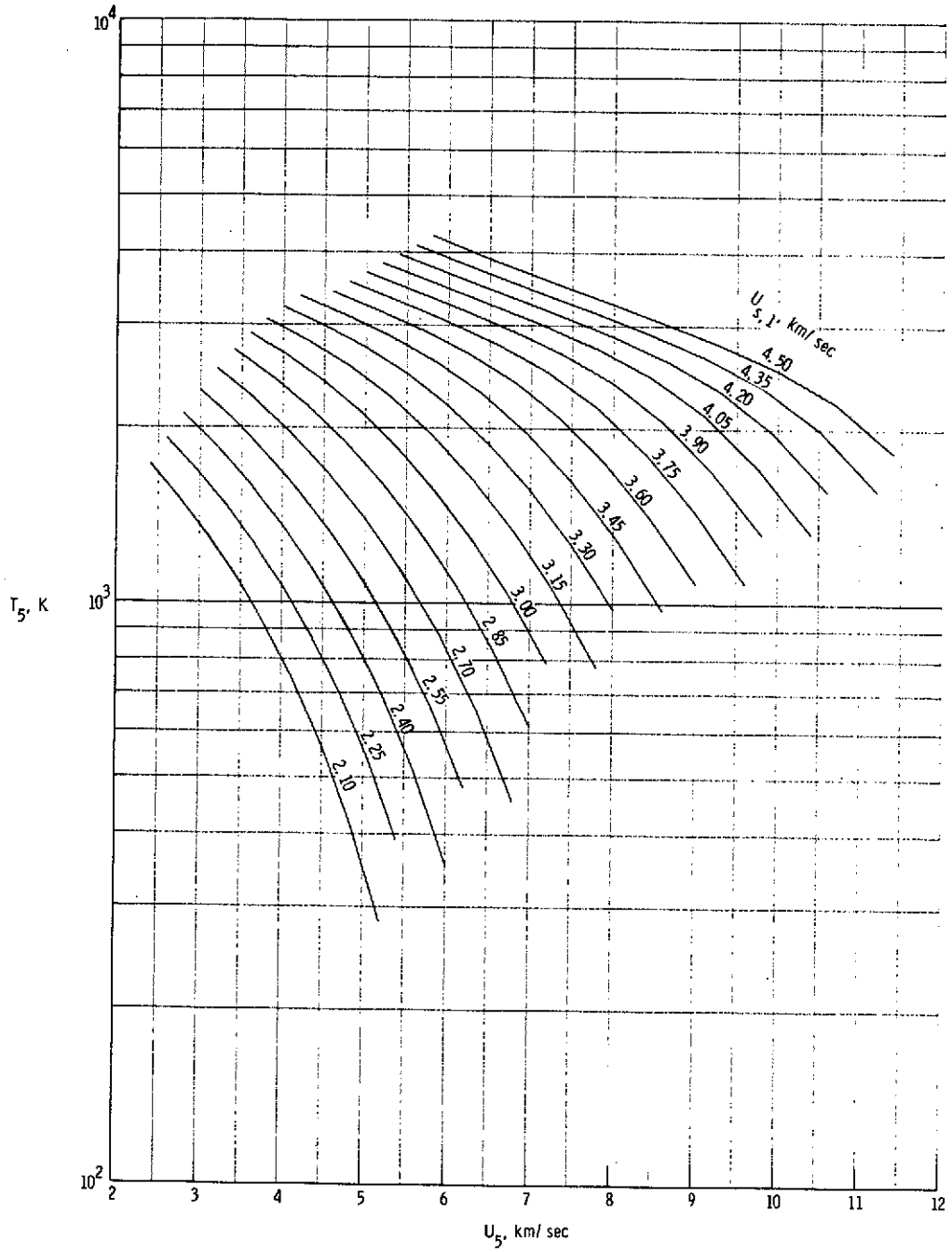
(a) Static pressure in region (5).

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. $p_1 = 6.90$ kN/m^2.



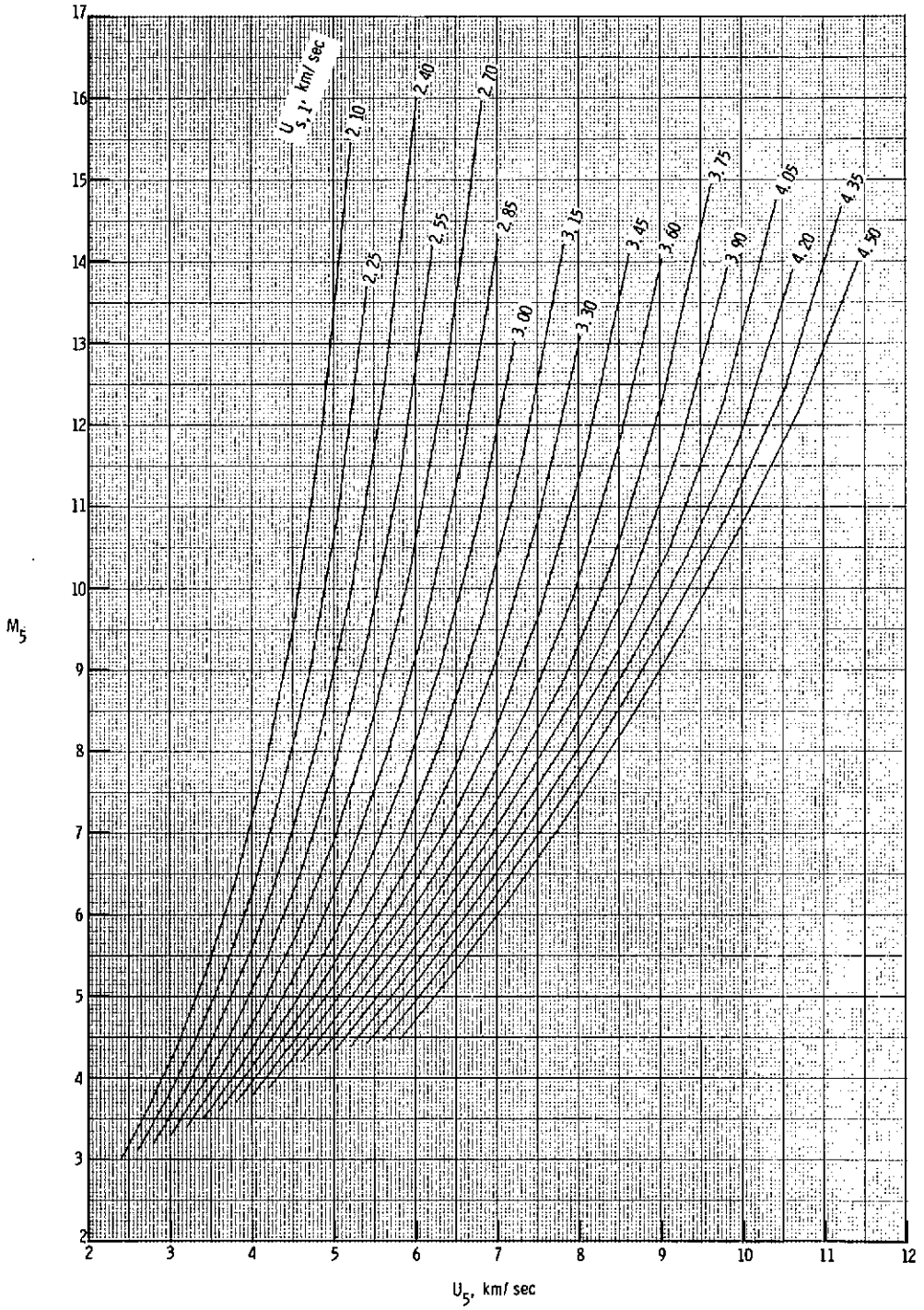
(b) Static density in region (5).

Figure 8.- Continued.



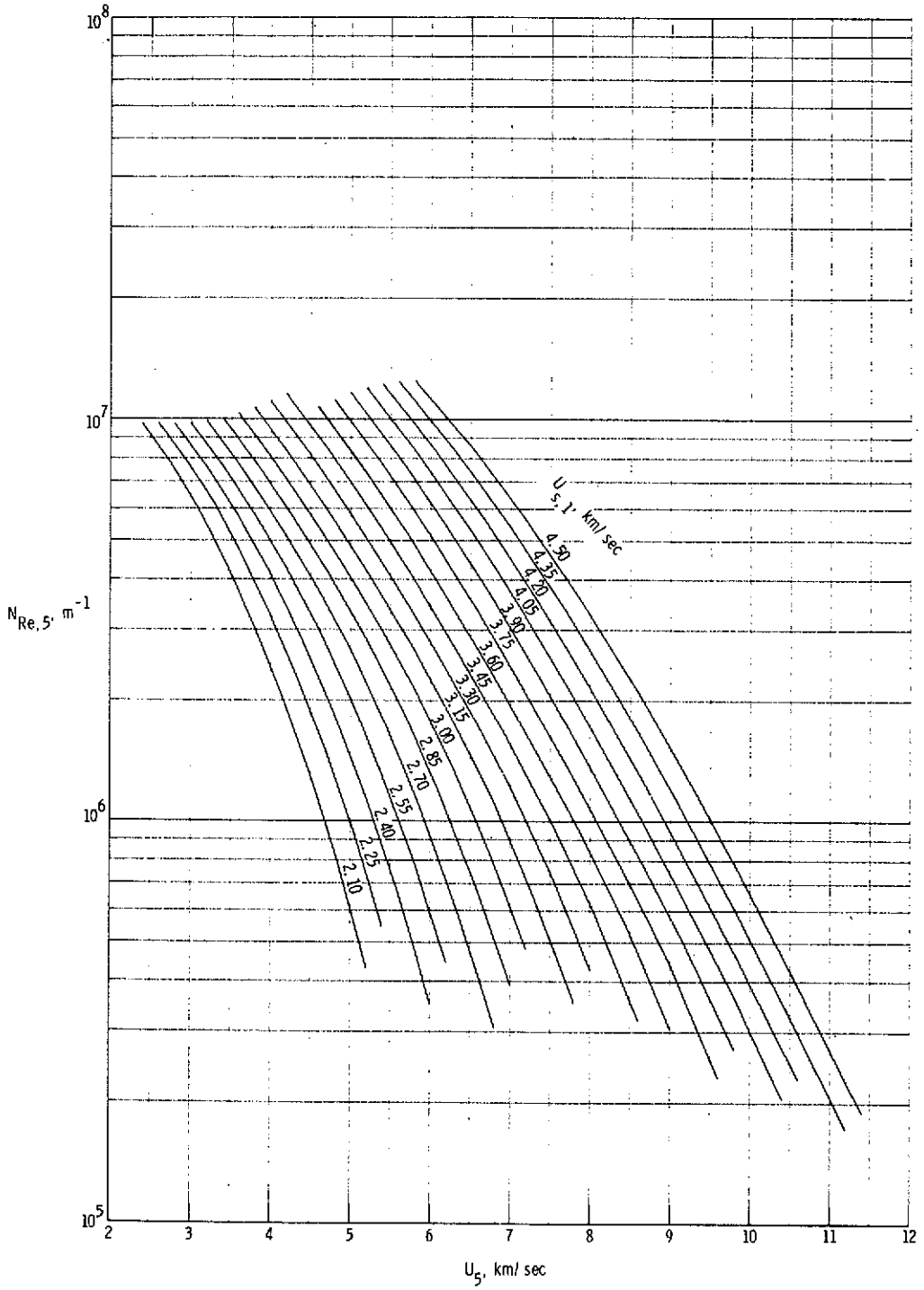
(c) Static temperature in region (5).

Figure 8.- Continued.



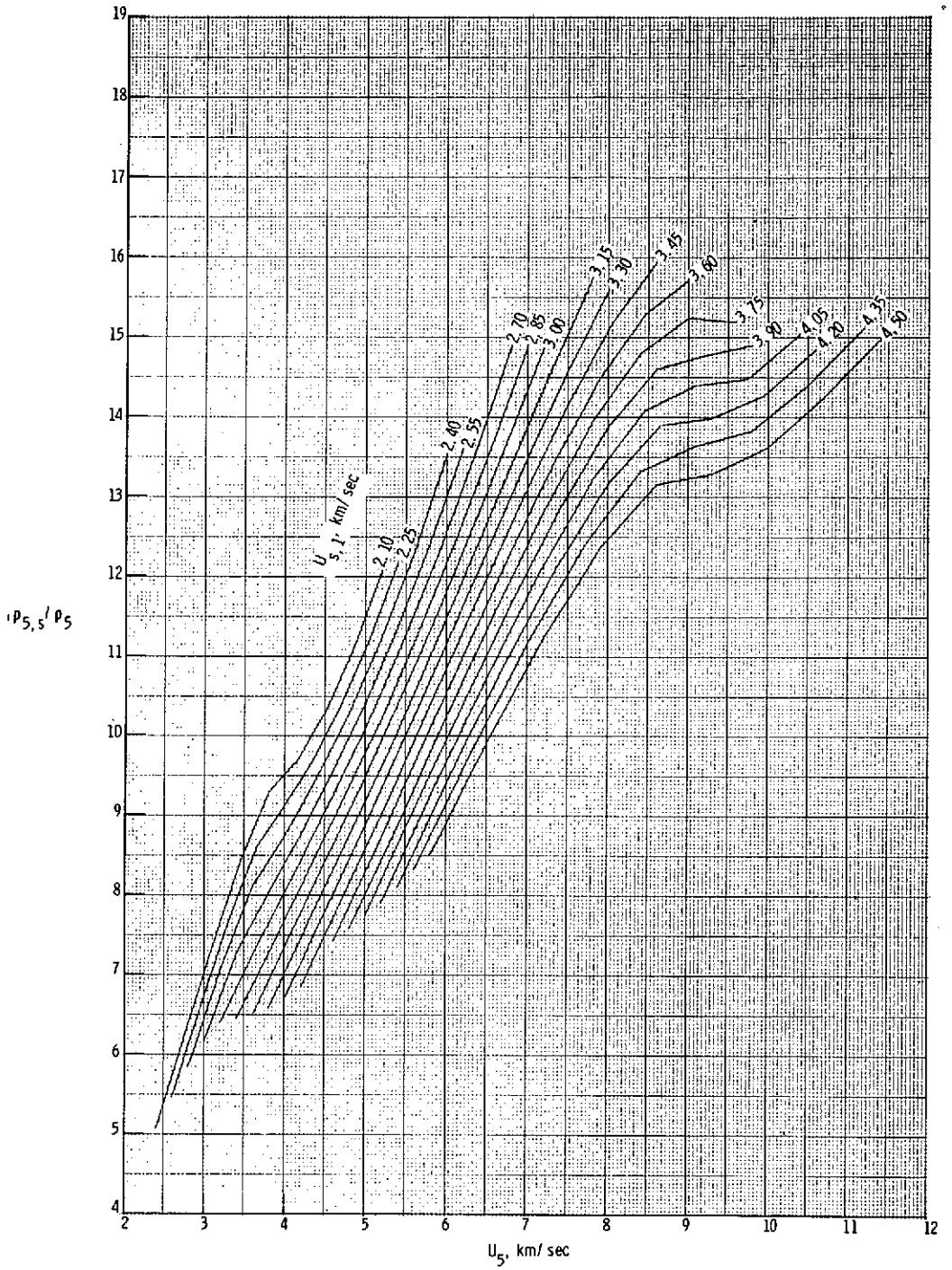
(d) Mach number in region (5).

Figure 8.- Continued.



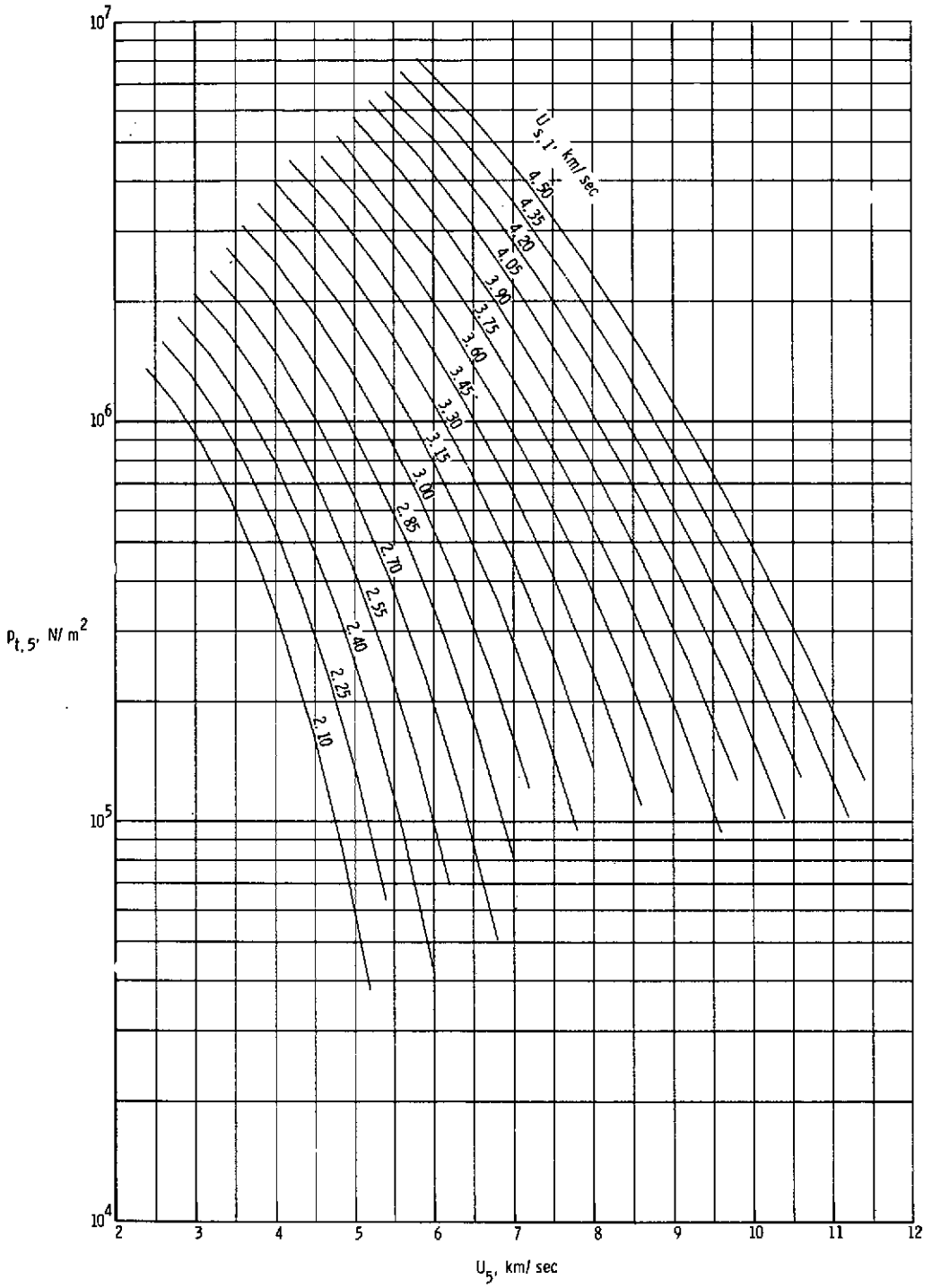
(e) Unit Reynolds number in region (5).

Figure 8.- Continued.



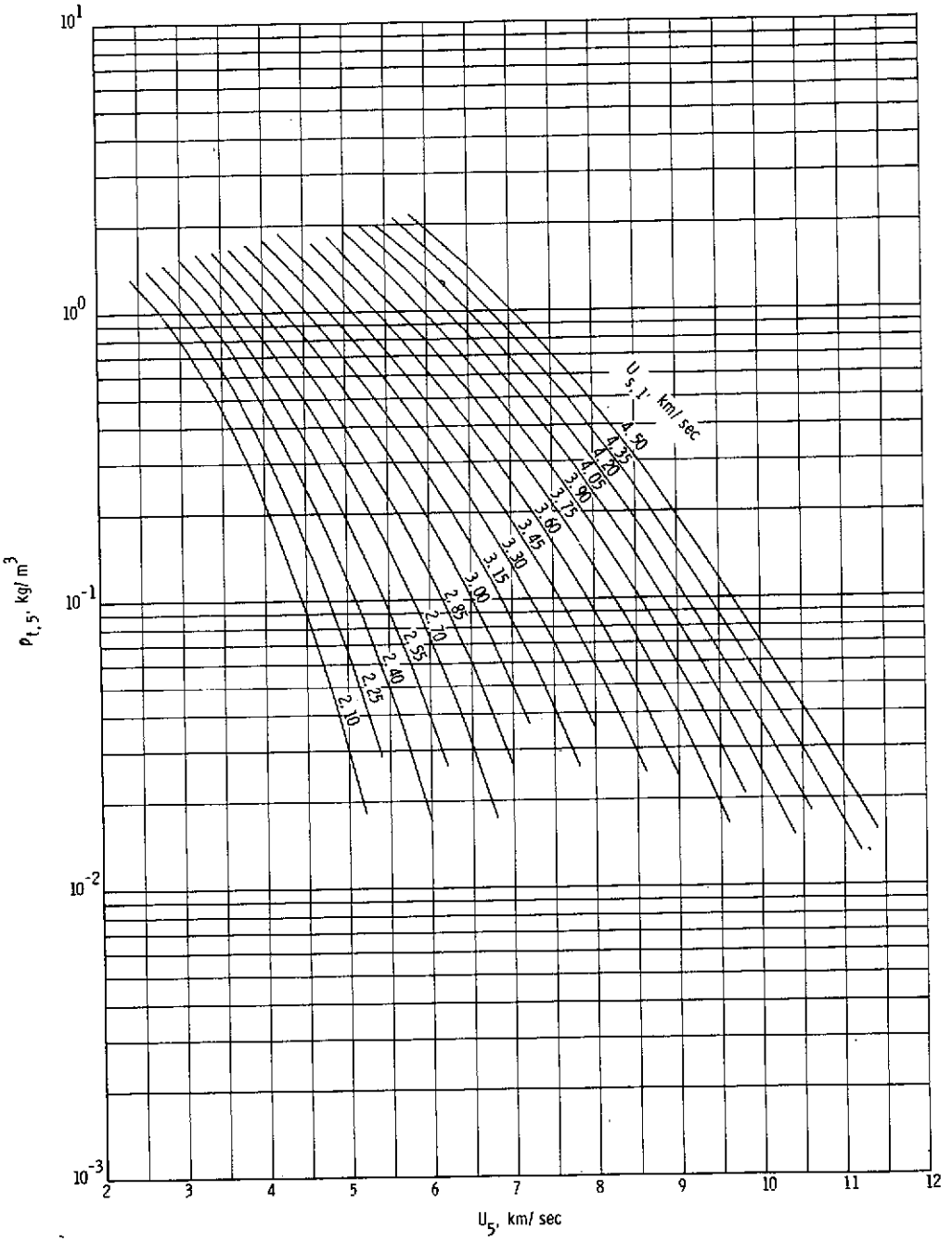
(f) Normal shock density ratio.

Figure 8.- Continued.



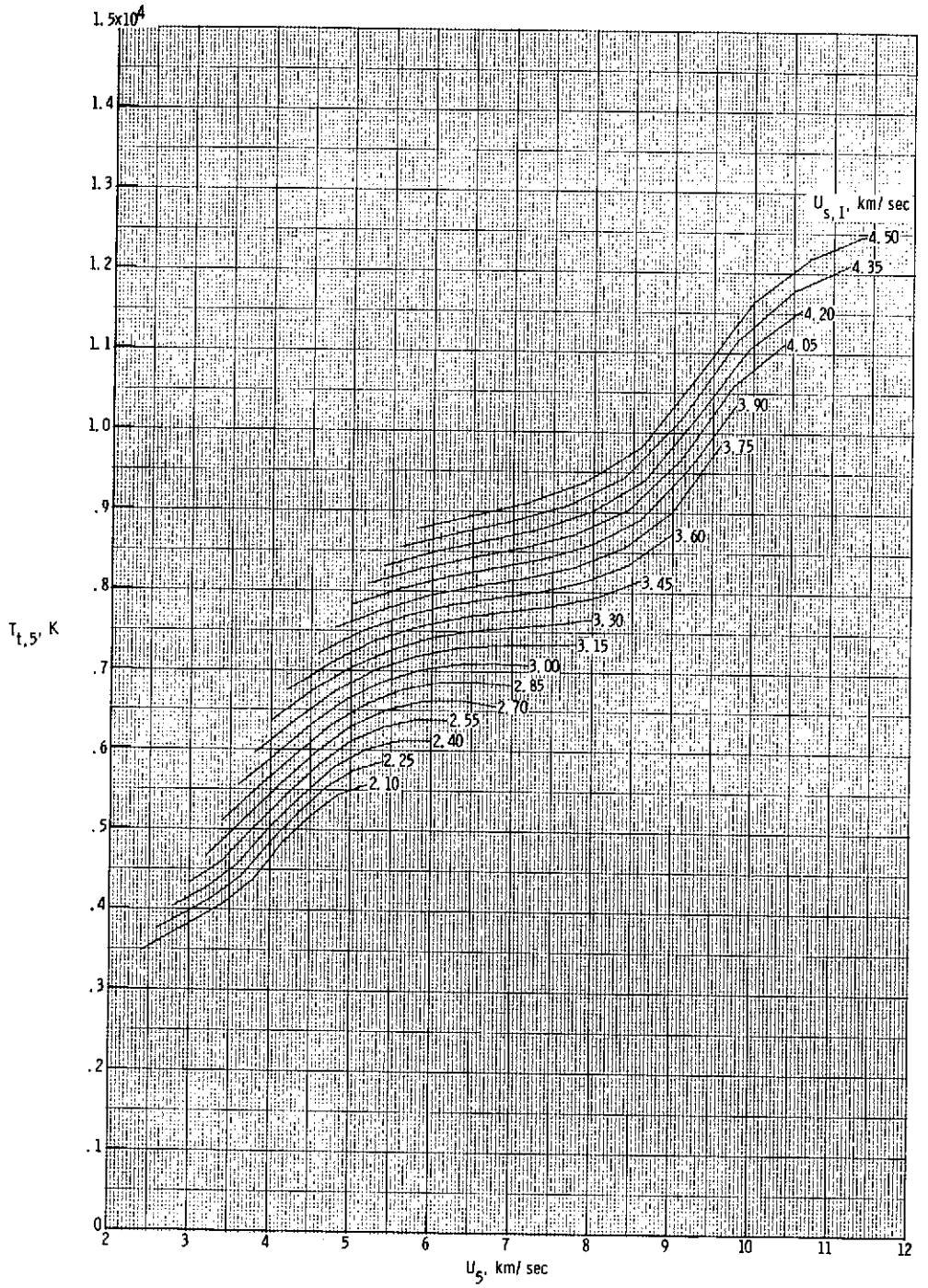
(g) Stagnation pressure behind normal bow shock.

Figure 8.- Continued.



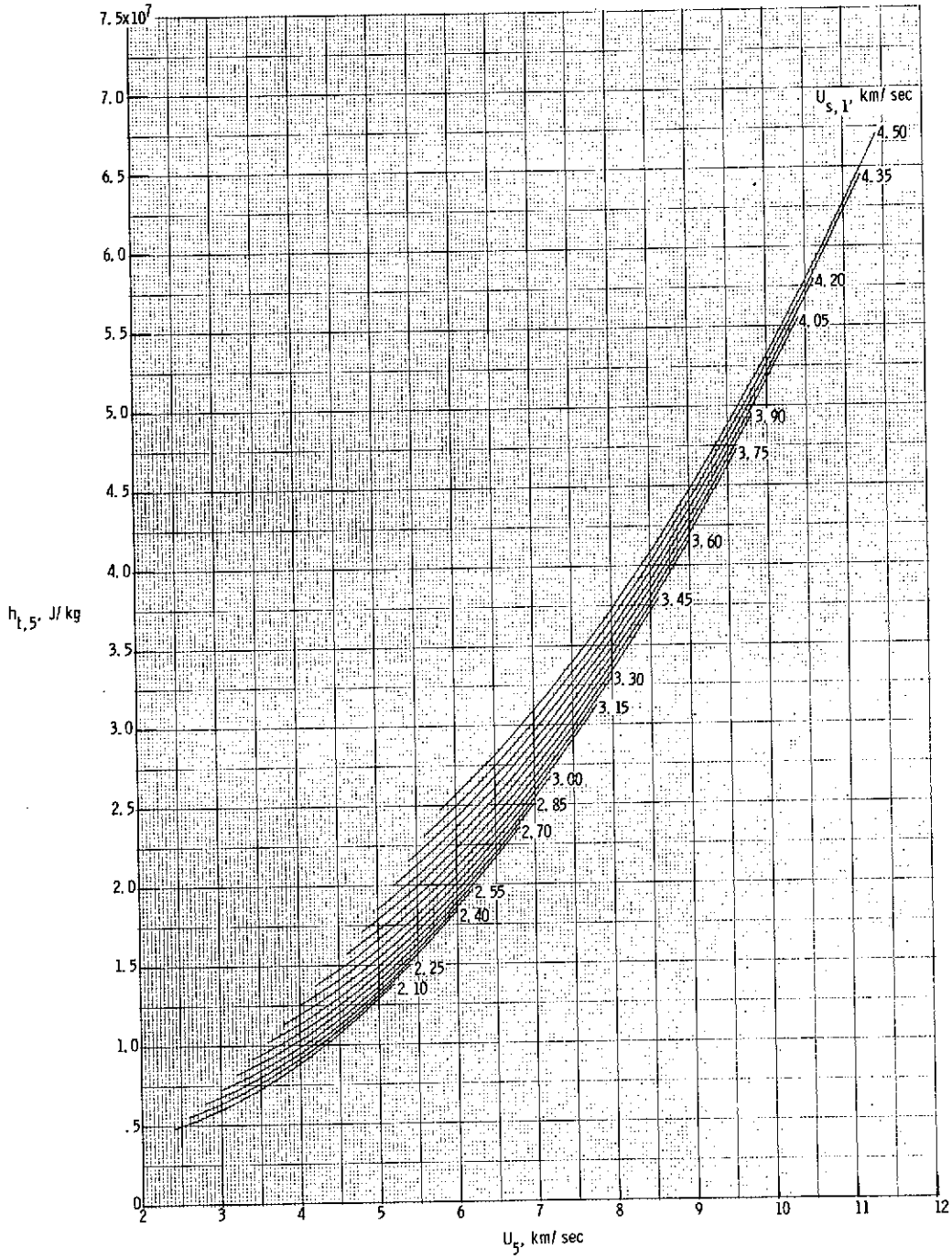
(h) Stagnation density behind normal bow shock.

Figure 8.- Continued.



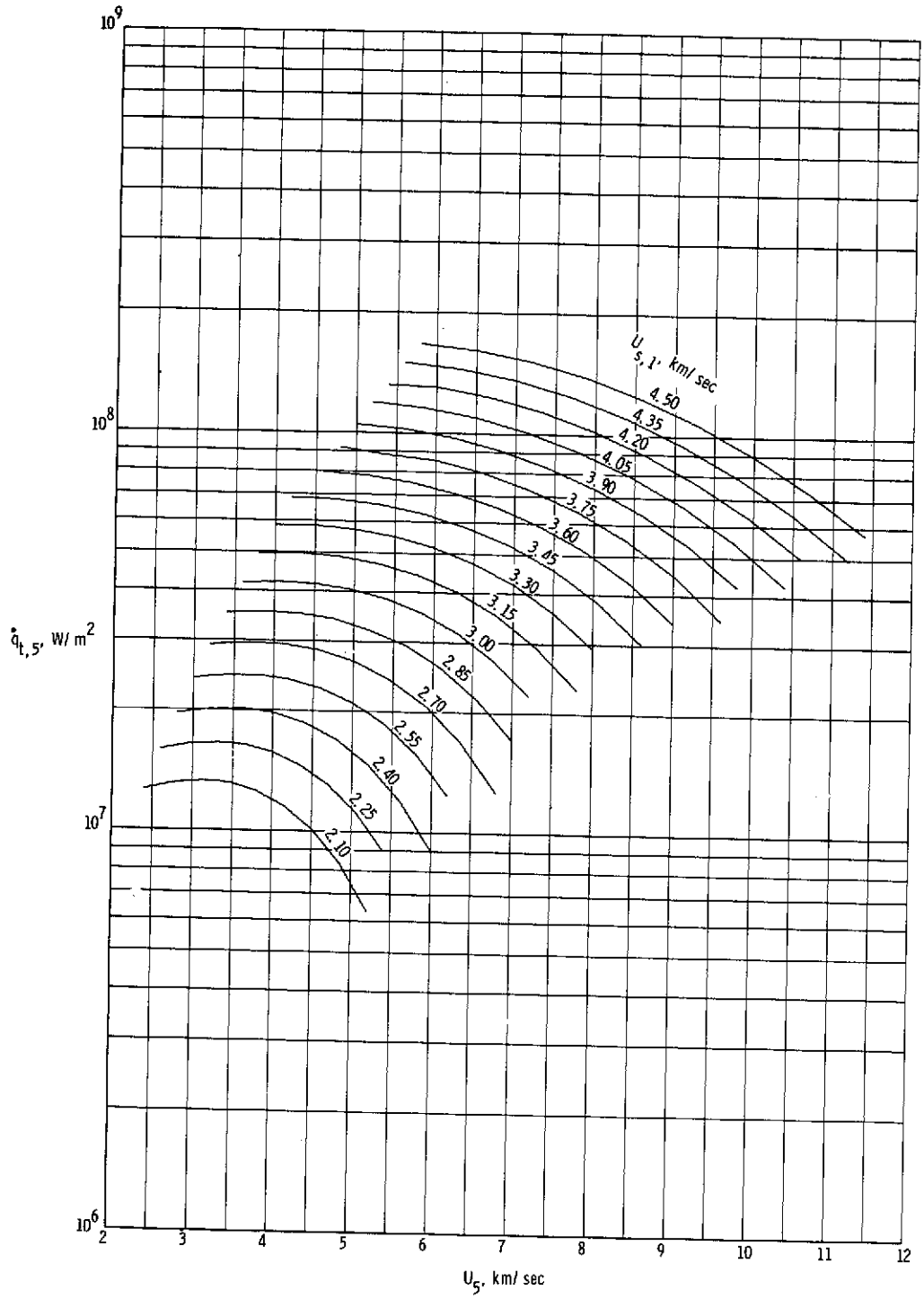
(i) Stagnation temperature behind normal bow shock.

Figure 8.- Continued.



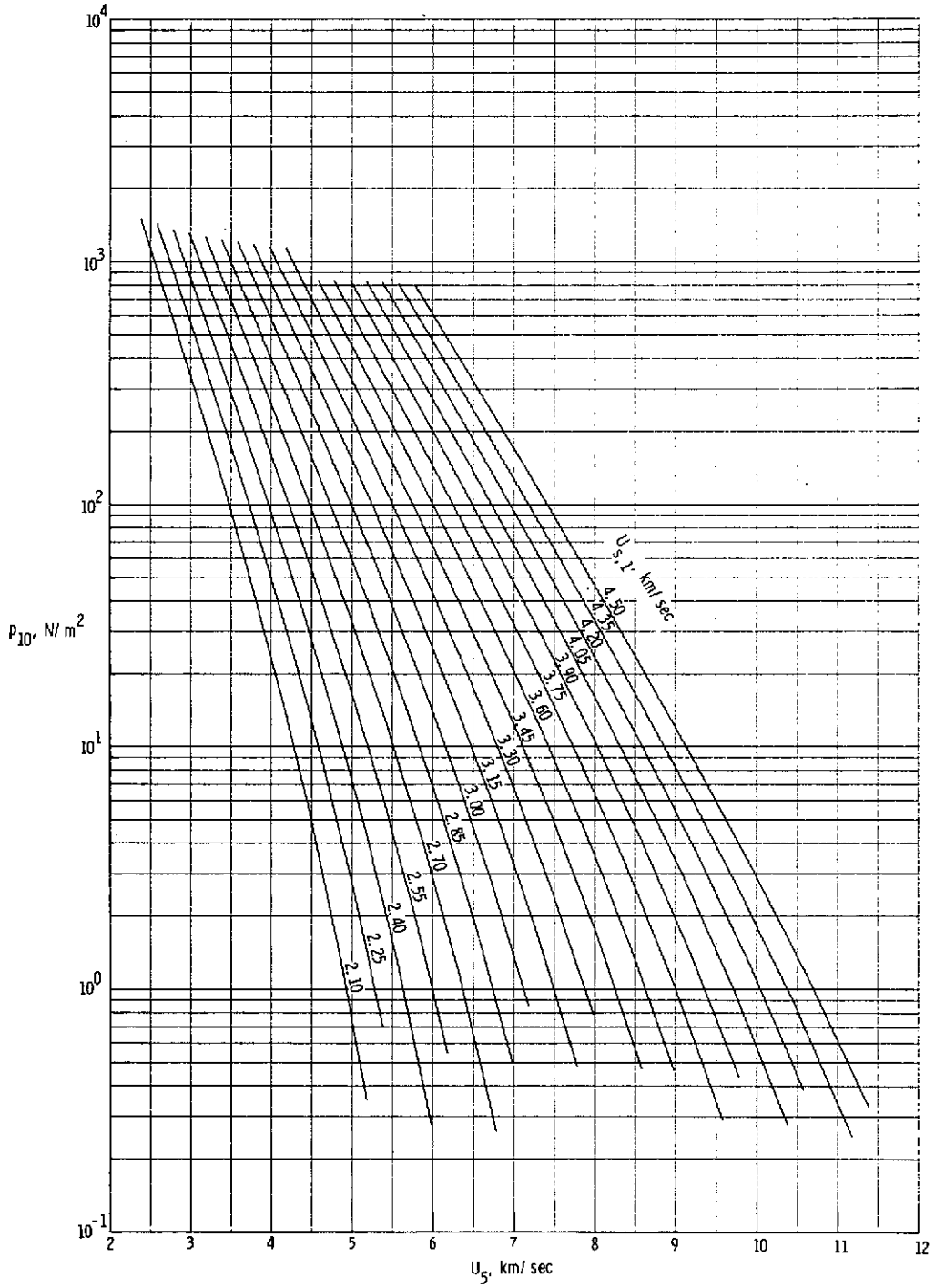
(j) Stagnation enthalpy behind normal bow shock.

Figure 8.- Continued.



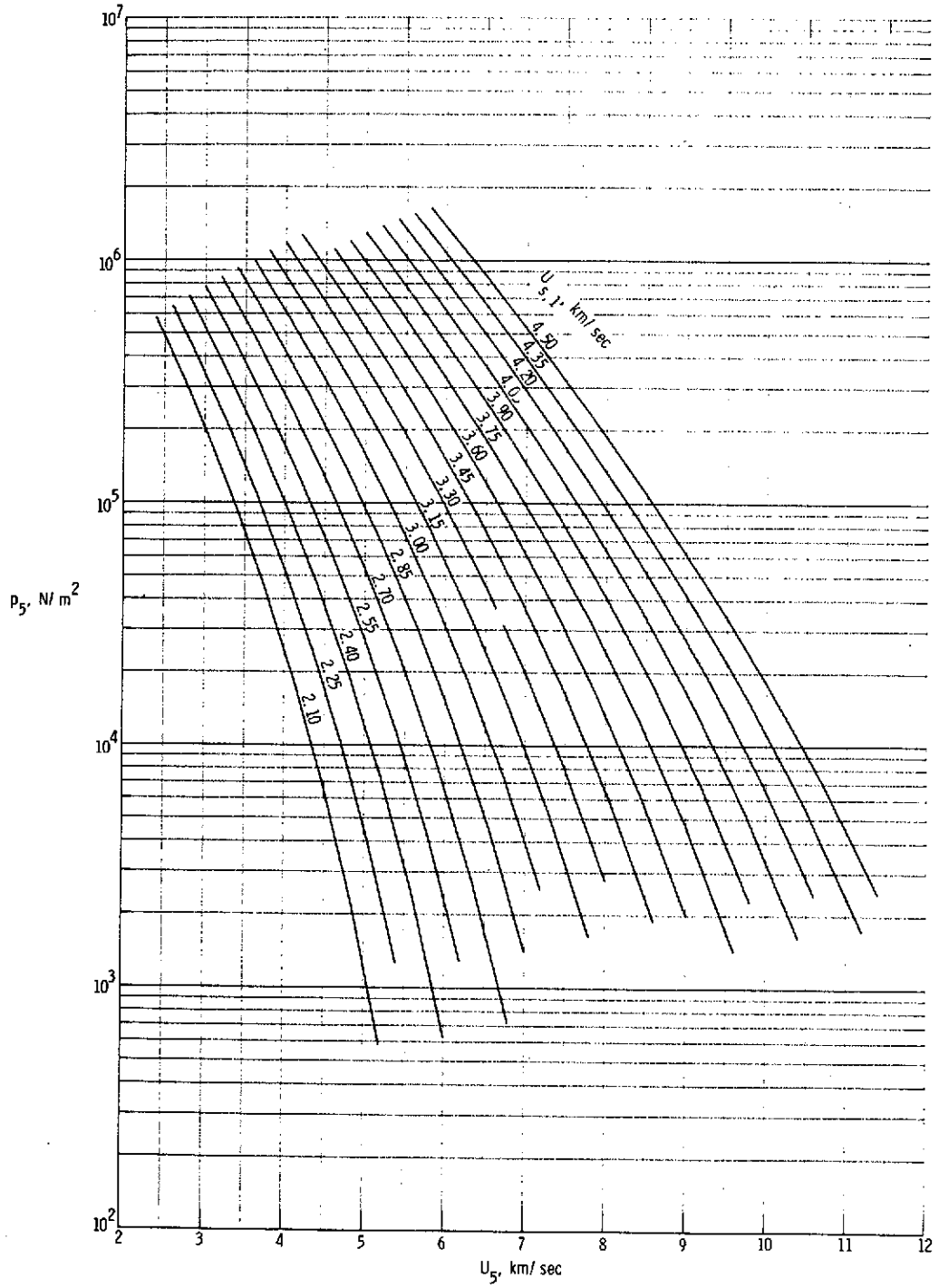
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 8.- Continued.



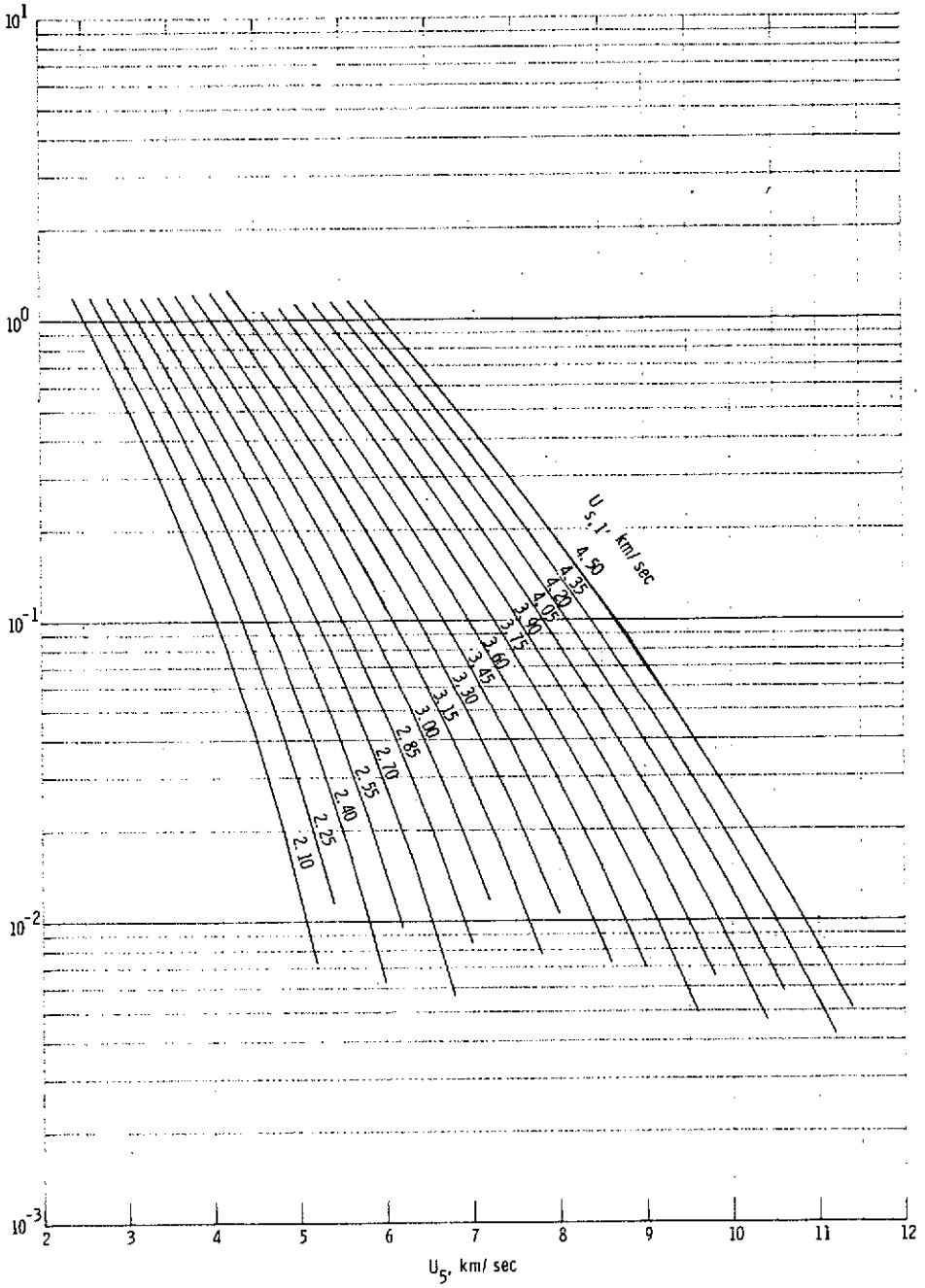
(l) Quiescent acceleration air pressure in region (10).

Figure 8.- Concluded.



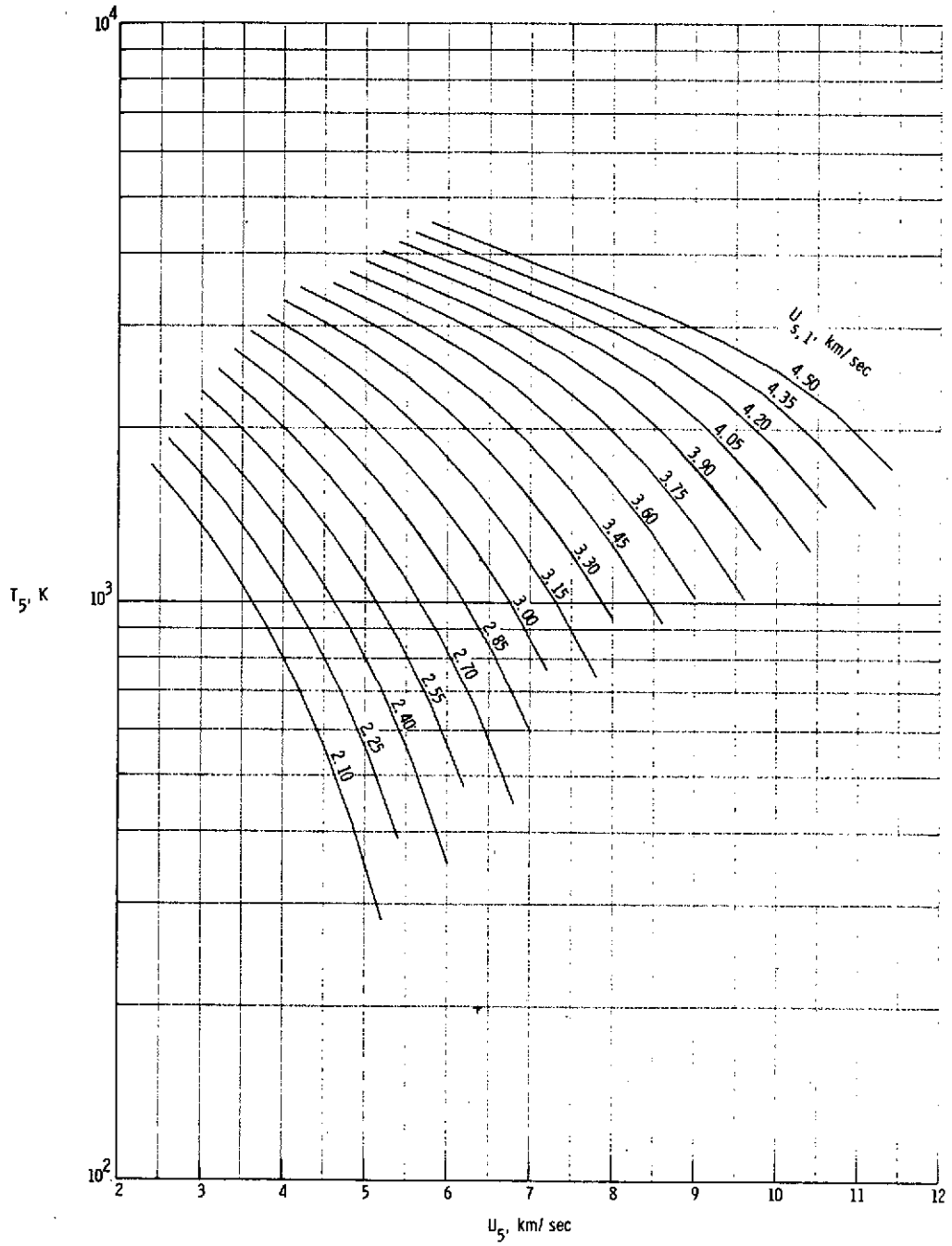
(a) Static pressure in region (5).

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. $p_1 = 34.47$ kN/m^2.



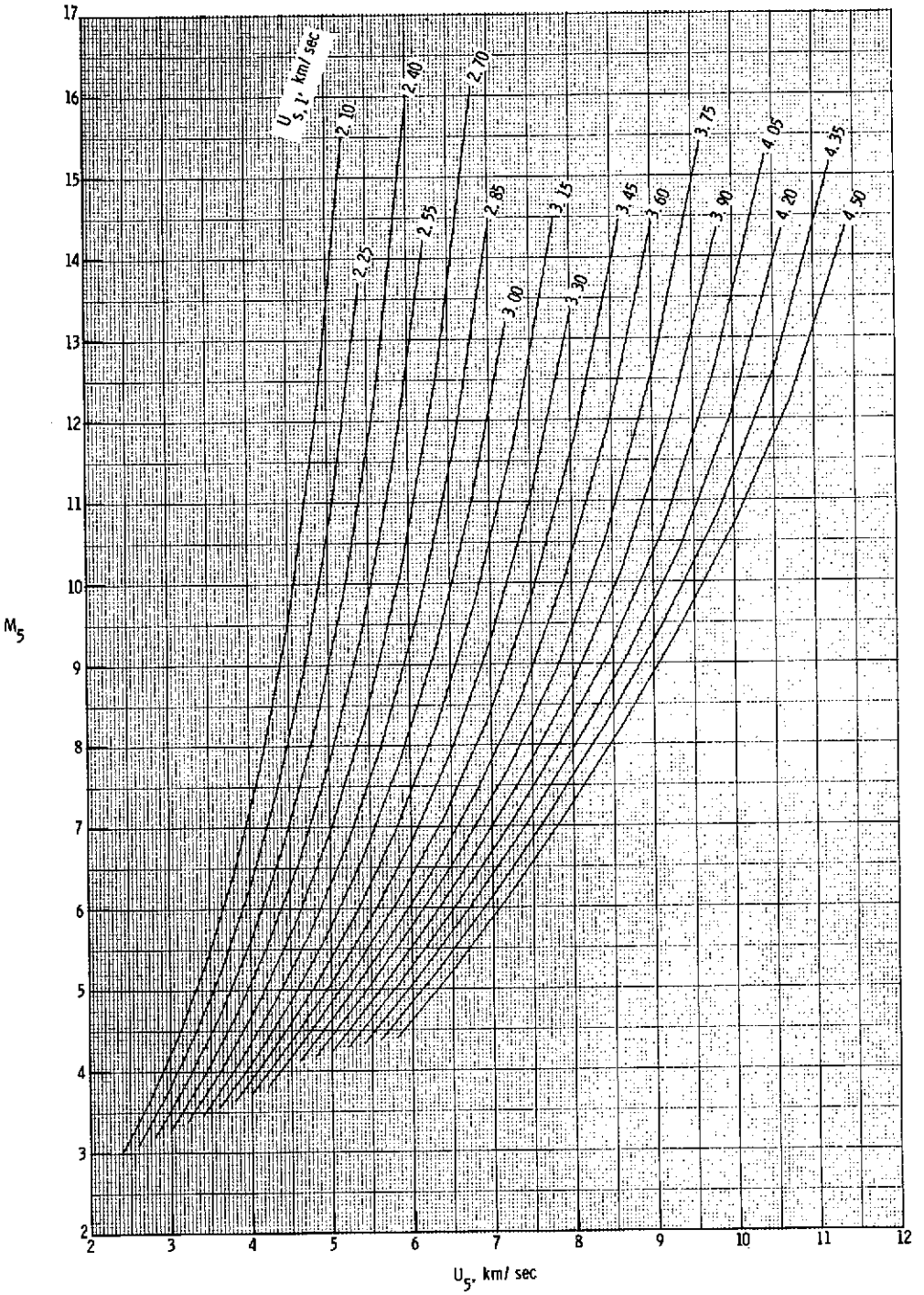
(b) Static density in region (5).

Figure 9.- Continued.



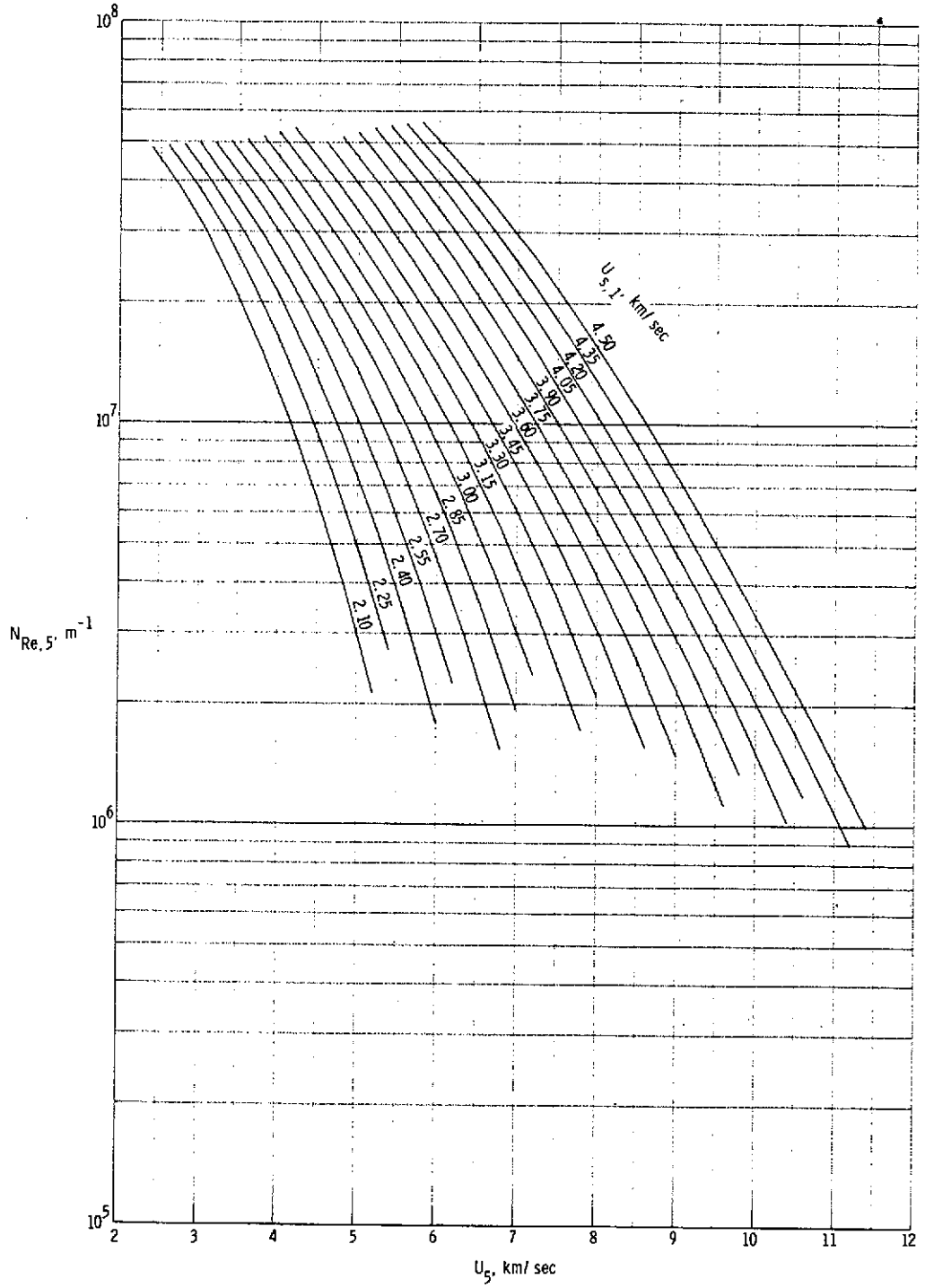
(c) Static temperature in region (5).

Figure 9.- Continued.



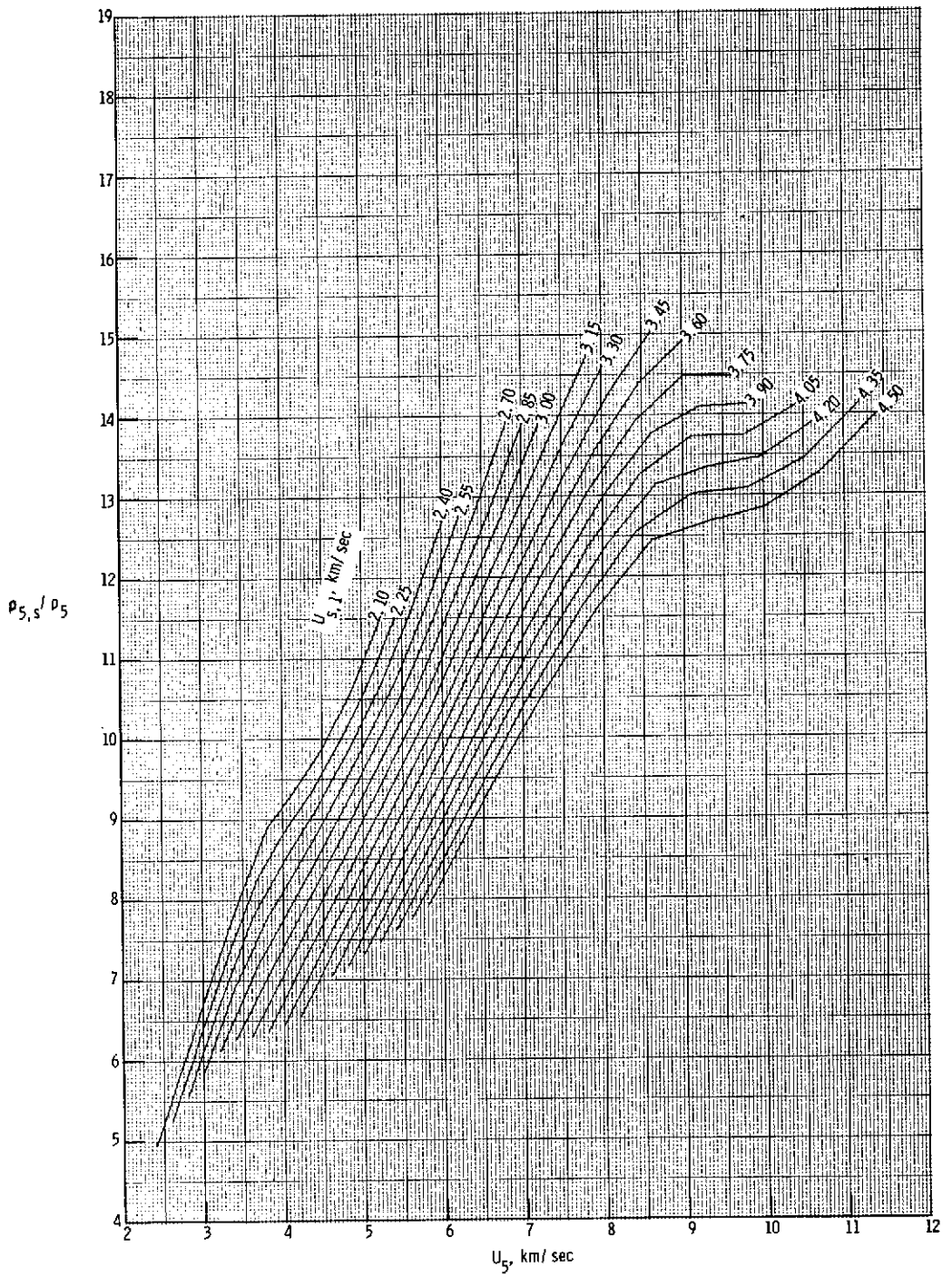
(d) Mach number in region (5).

Figure 9.- Continued.



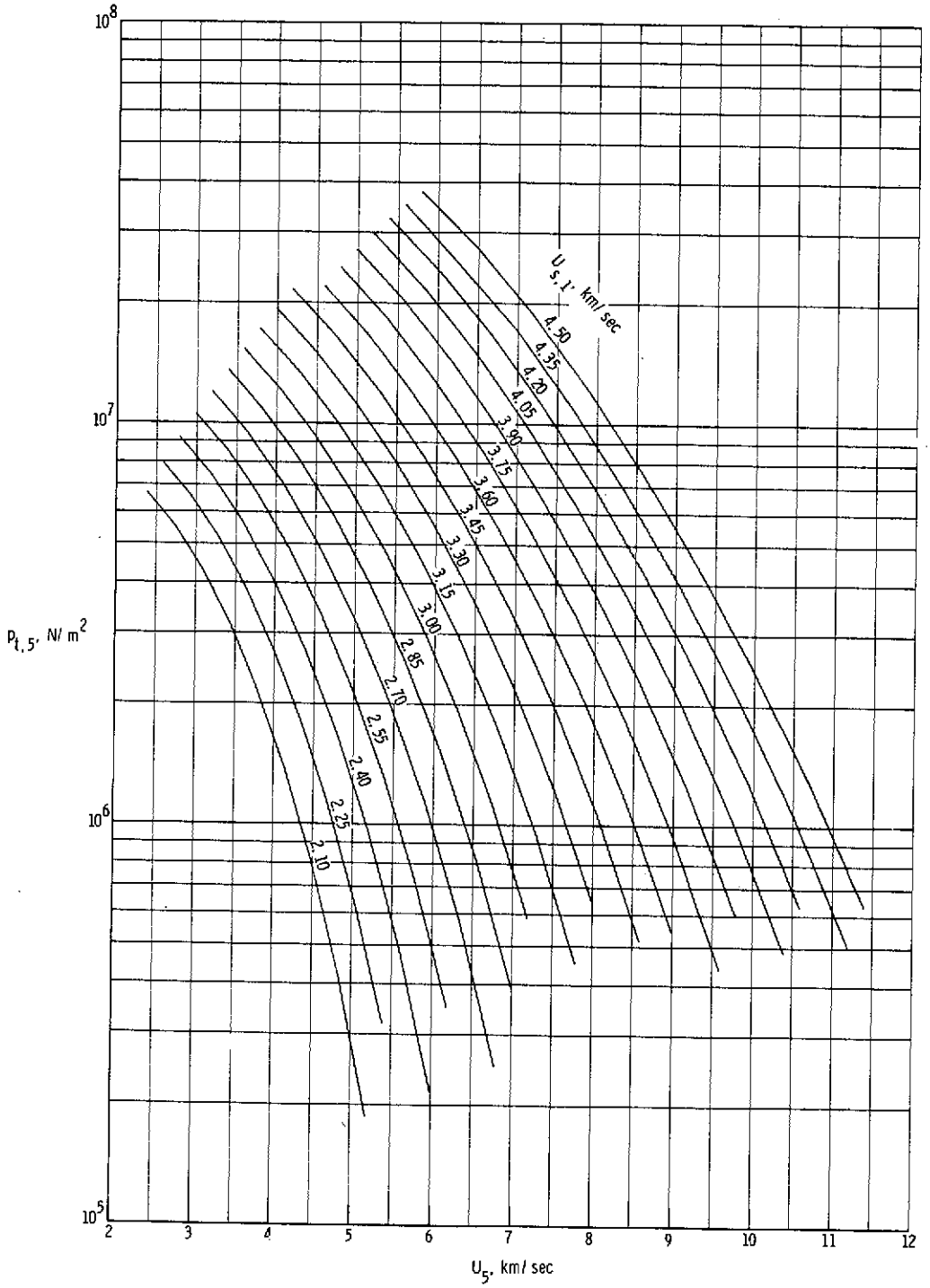
(e) Unit Reynolds number in region (5).

Figure 9.- Continued.



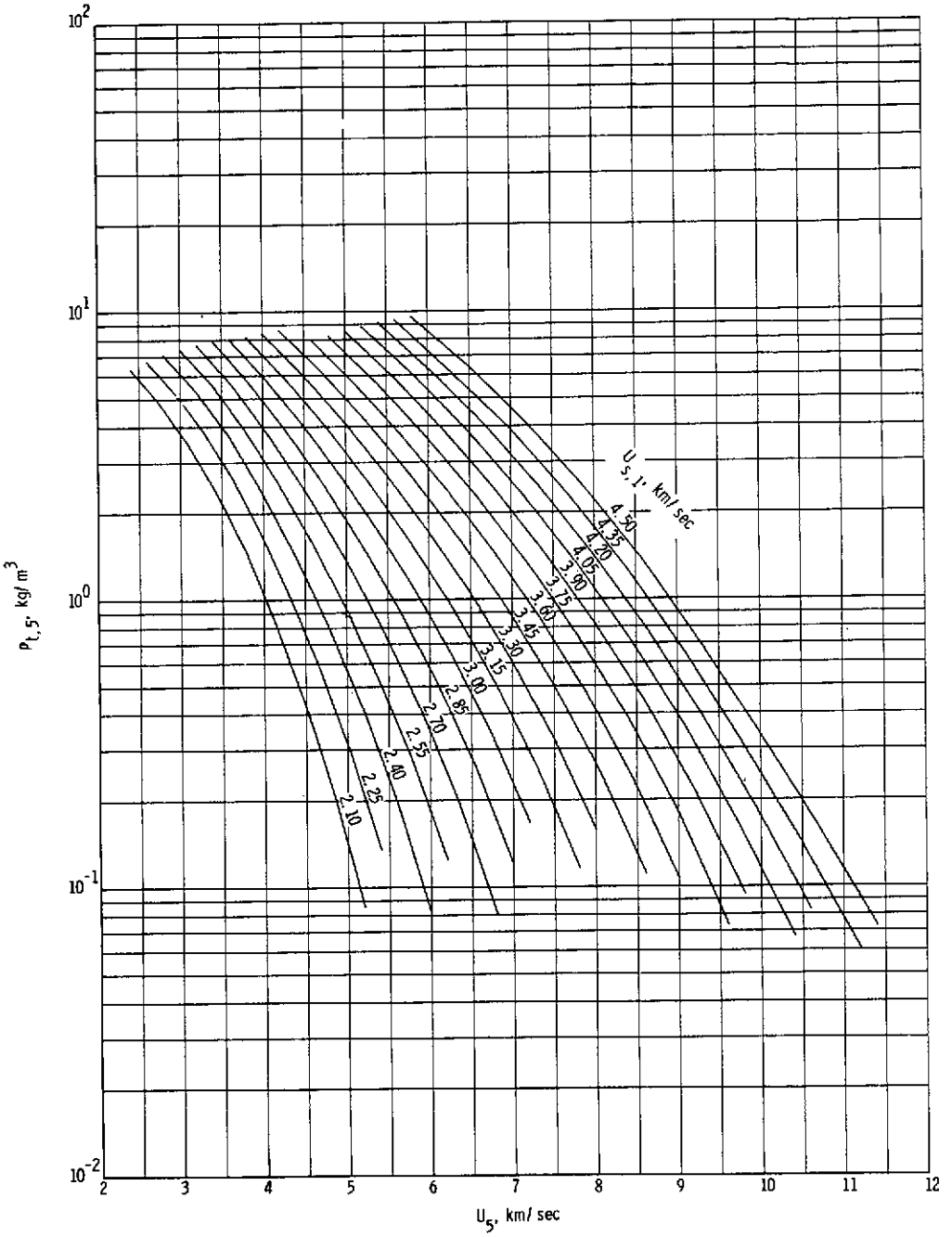
(f) Normal shock density ratio.

Figure 9.- Continued.



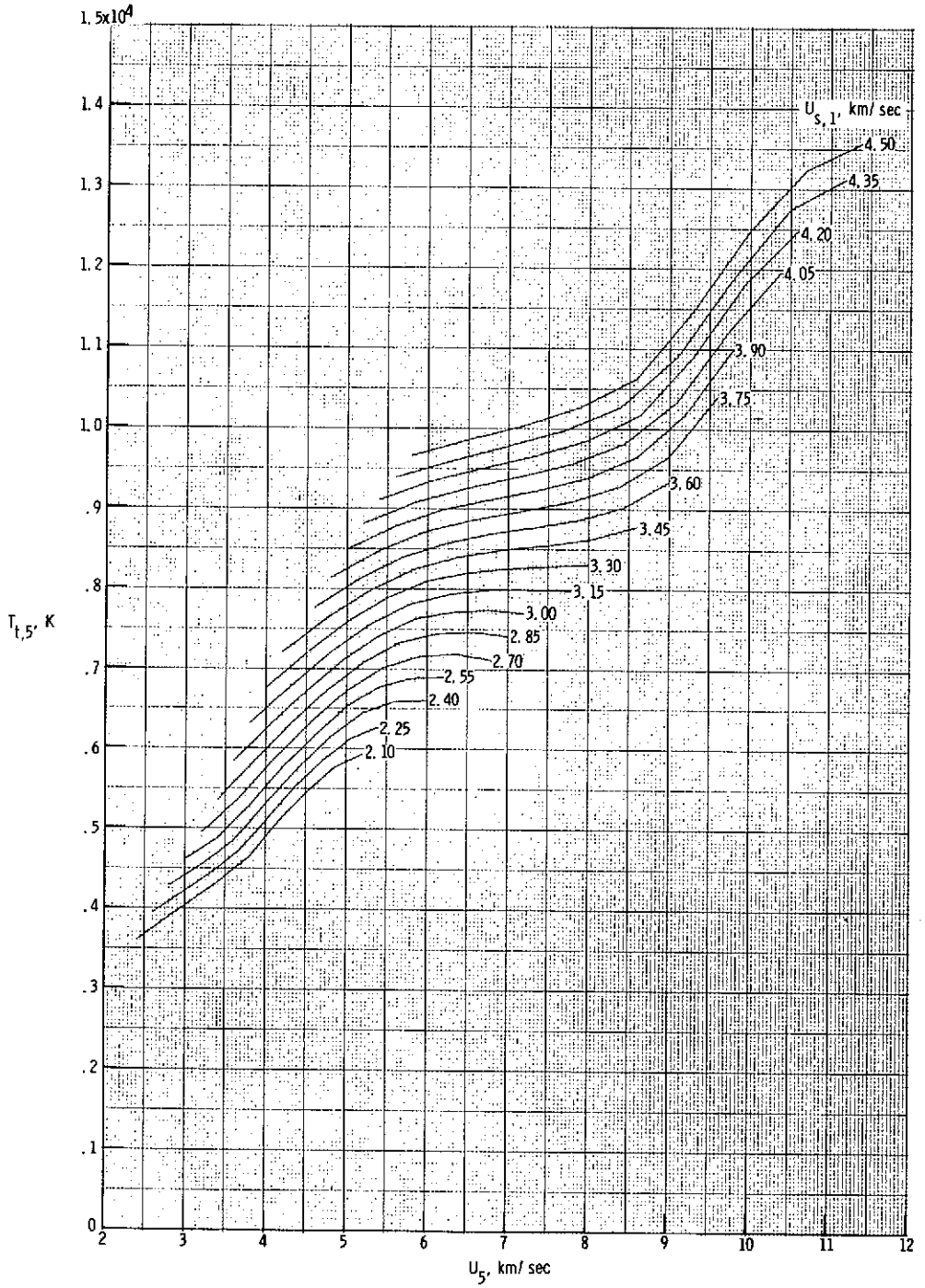
(g) Stagnation pressure behind normal bow shock.

Figure 9.- Continued.



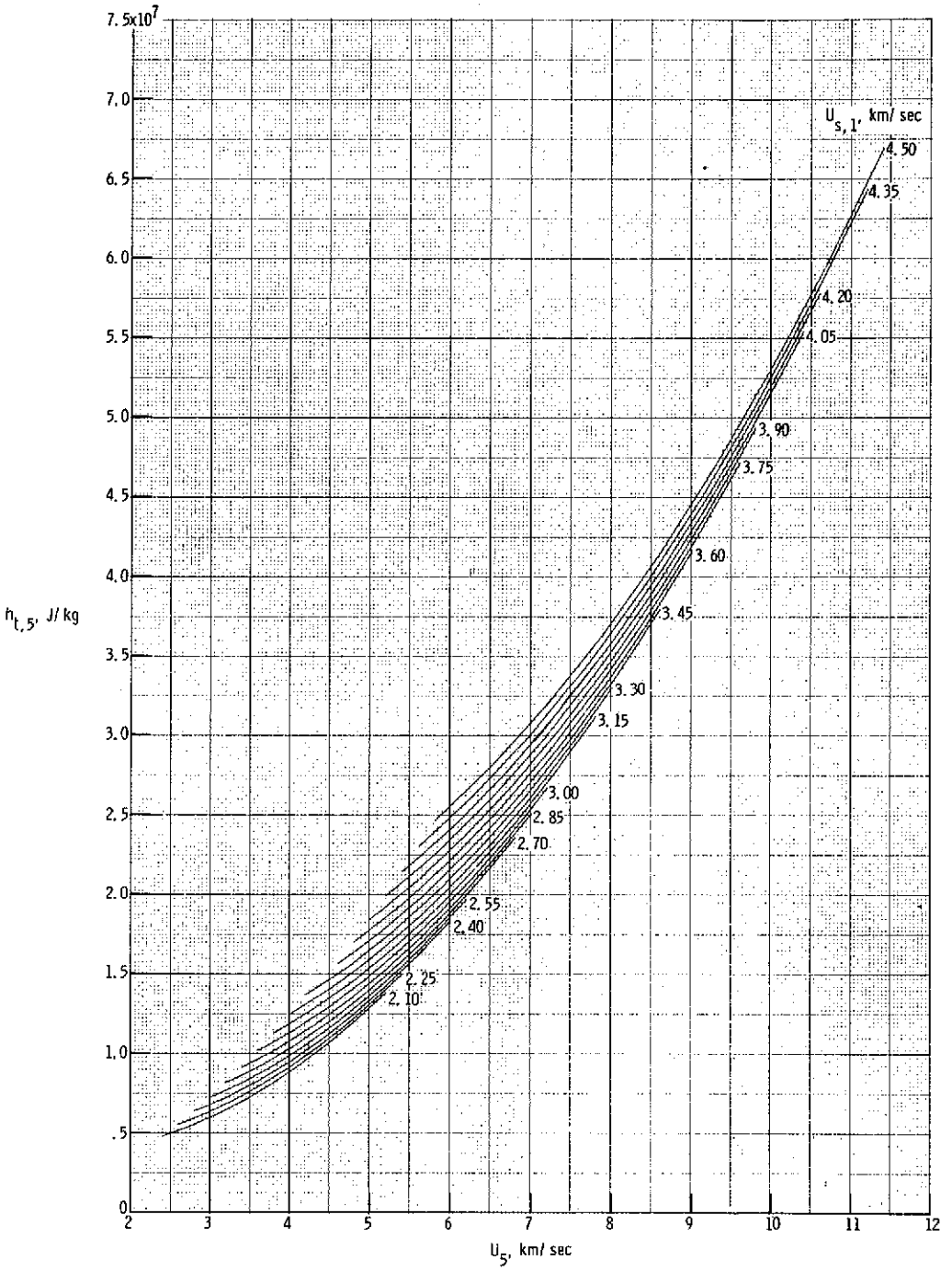
(h) Stagnation density behind normal bow shock.

Figure 9.- Continued.



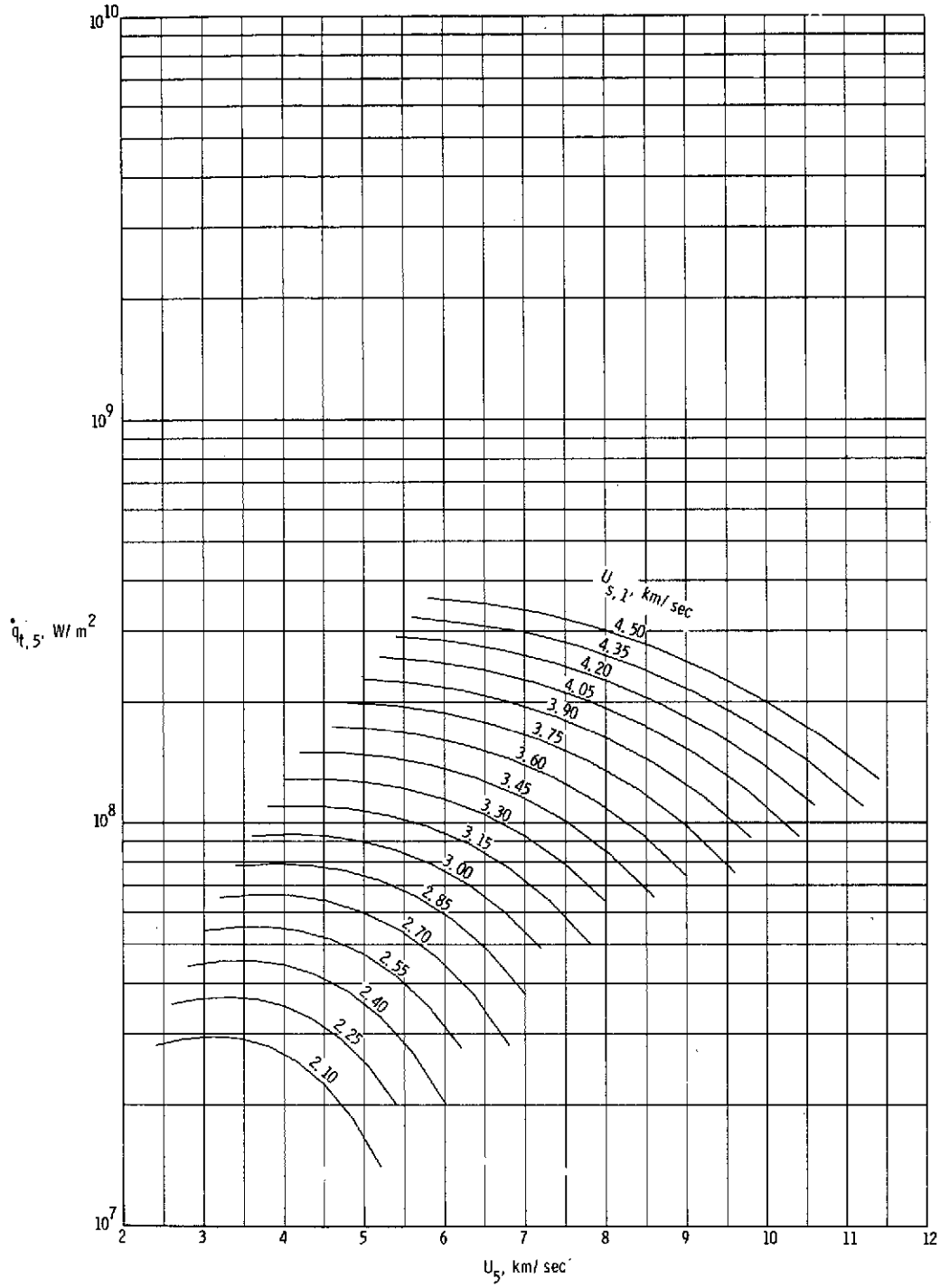
(i) Stagnation temperature behind normal bow shock.

Figure 9.- Continued.



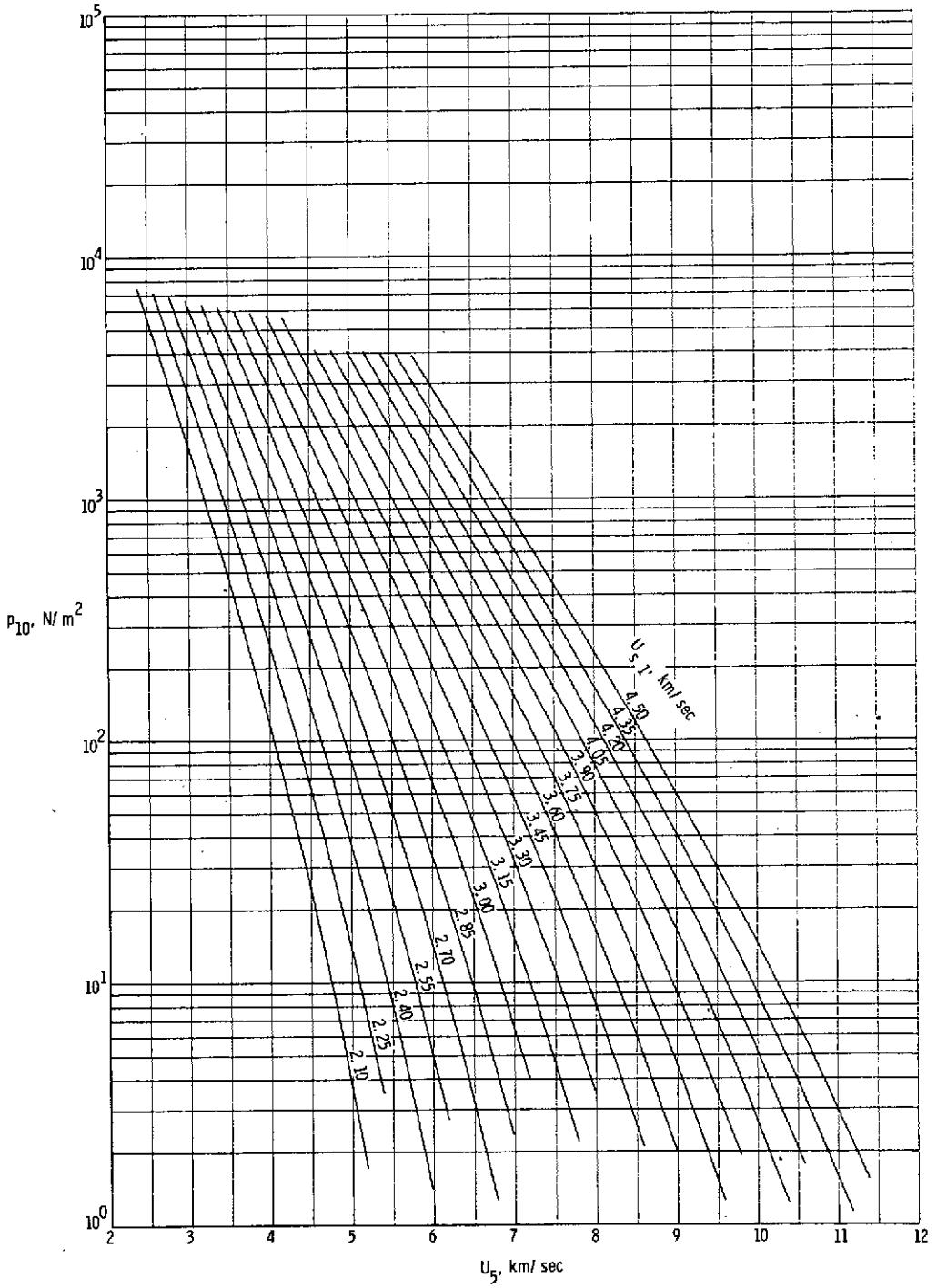
(j) Stagnation enthalpy behind normal bow shock.

Figure 9.- Continued.



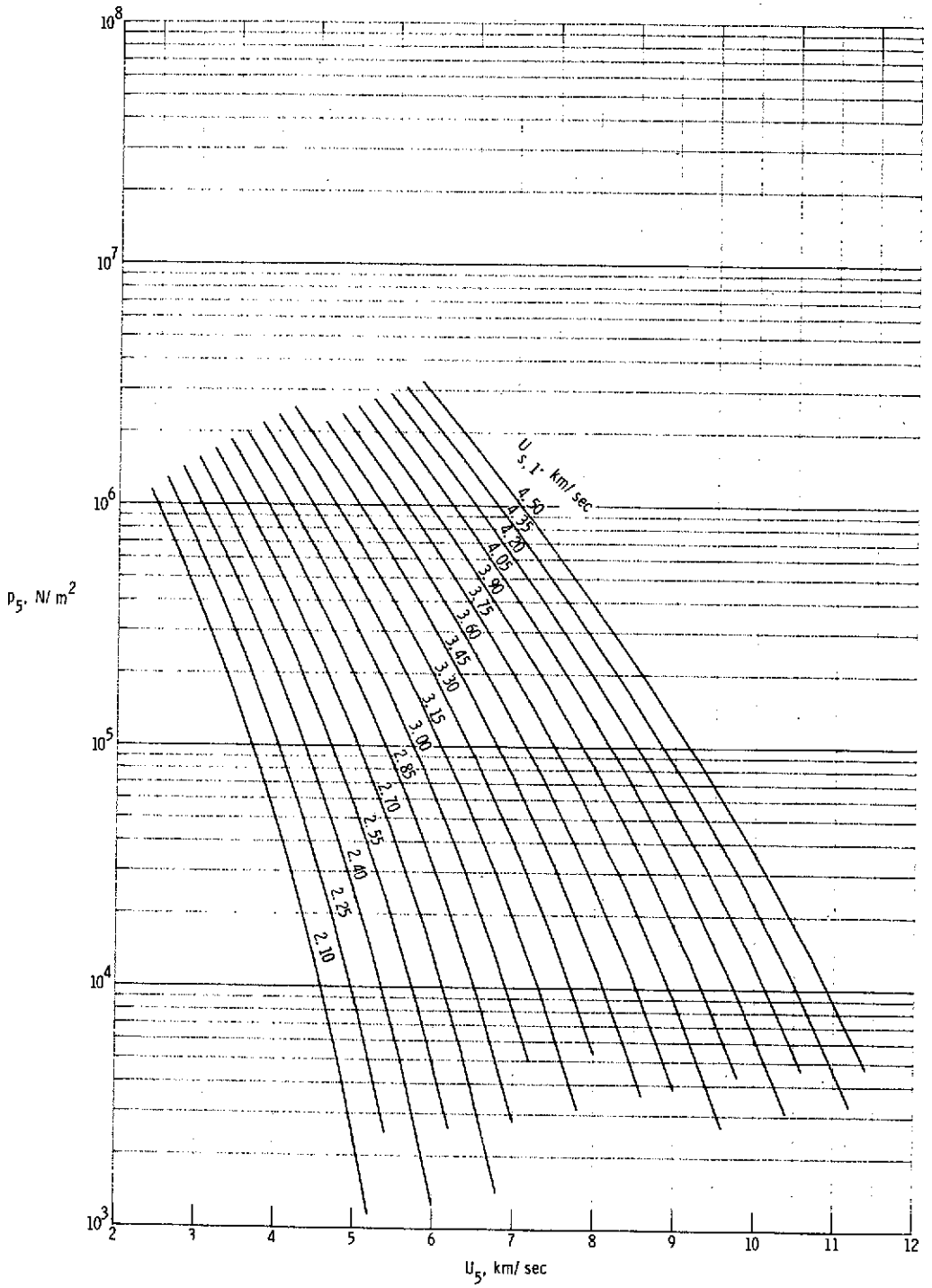
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 9.- Continued.



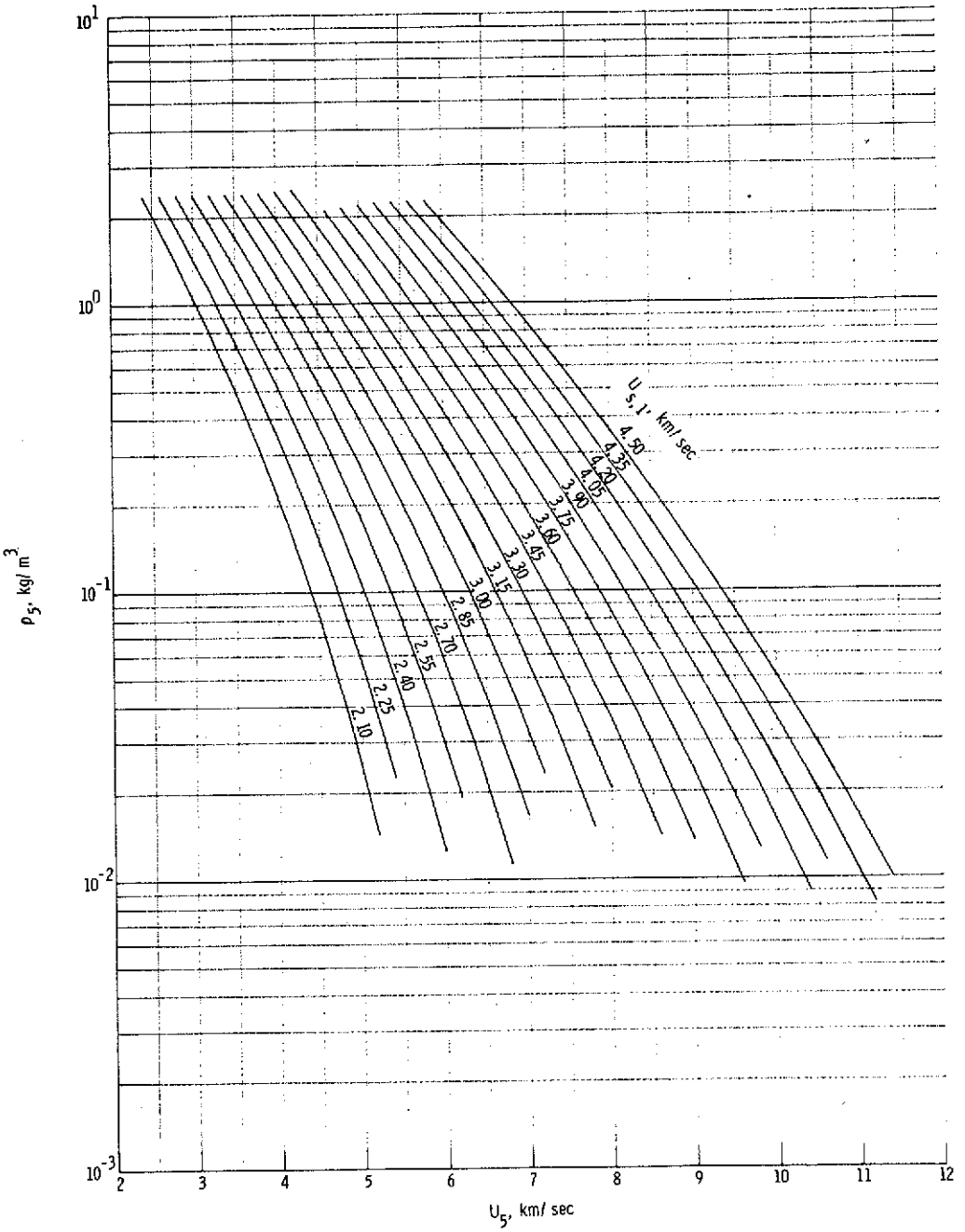
(1) Quiescent acceleration air pressure in region (10).

Figure 9.- Concluded.



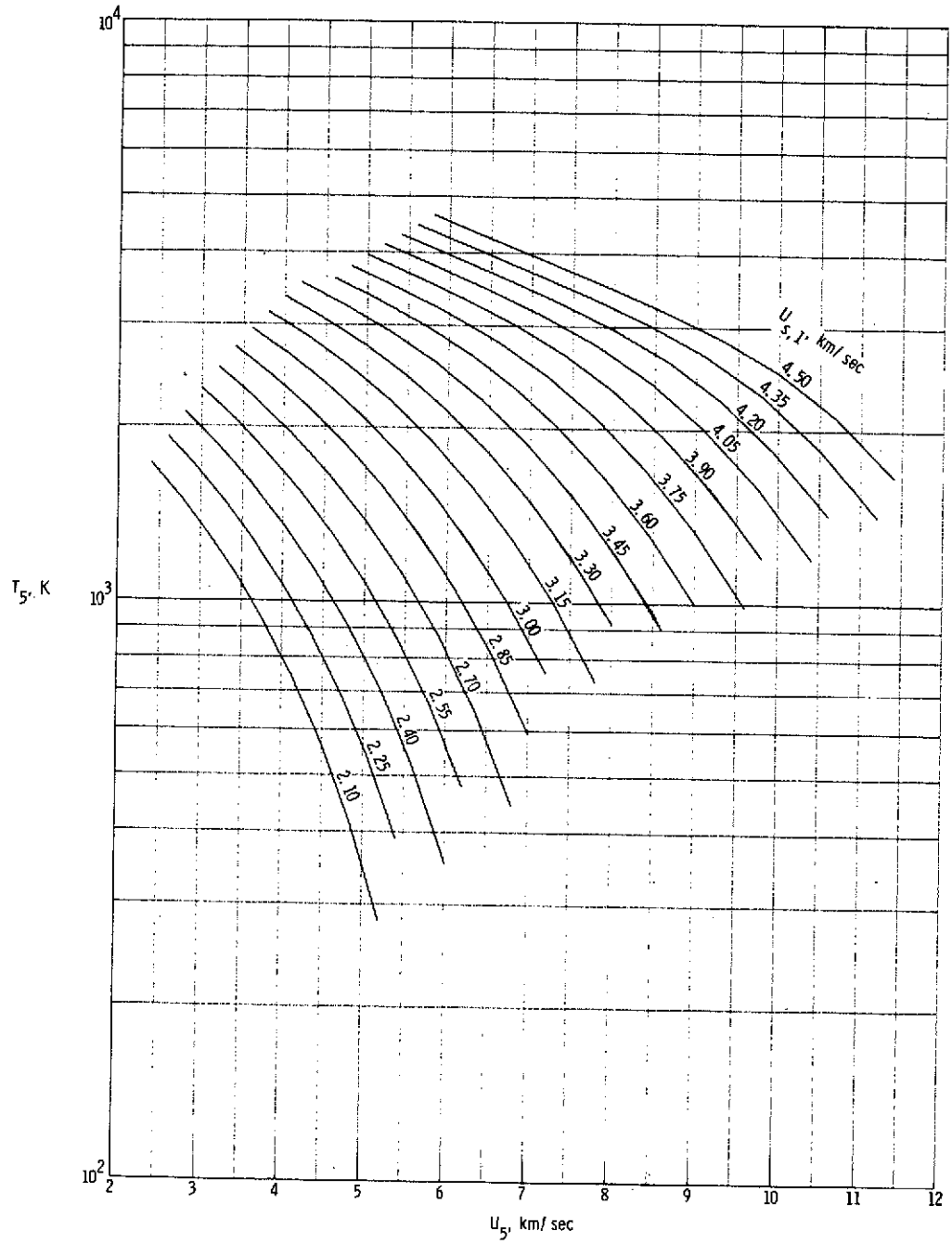
(a) Static pressure in region (5).

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. $p_1 = 68.95$ kN/m^2.



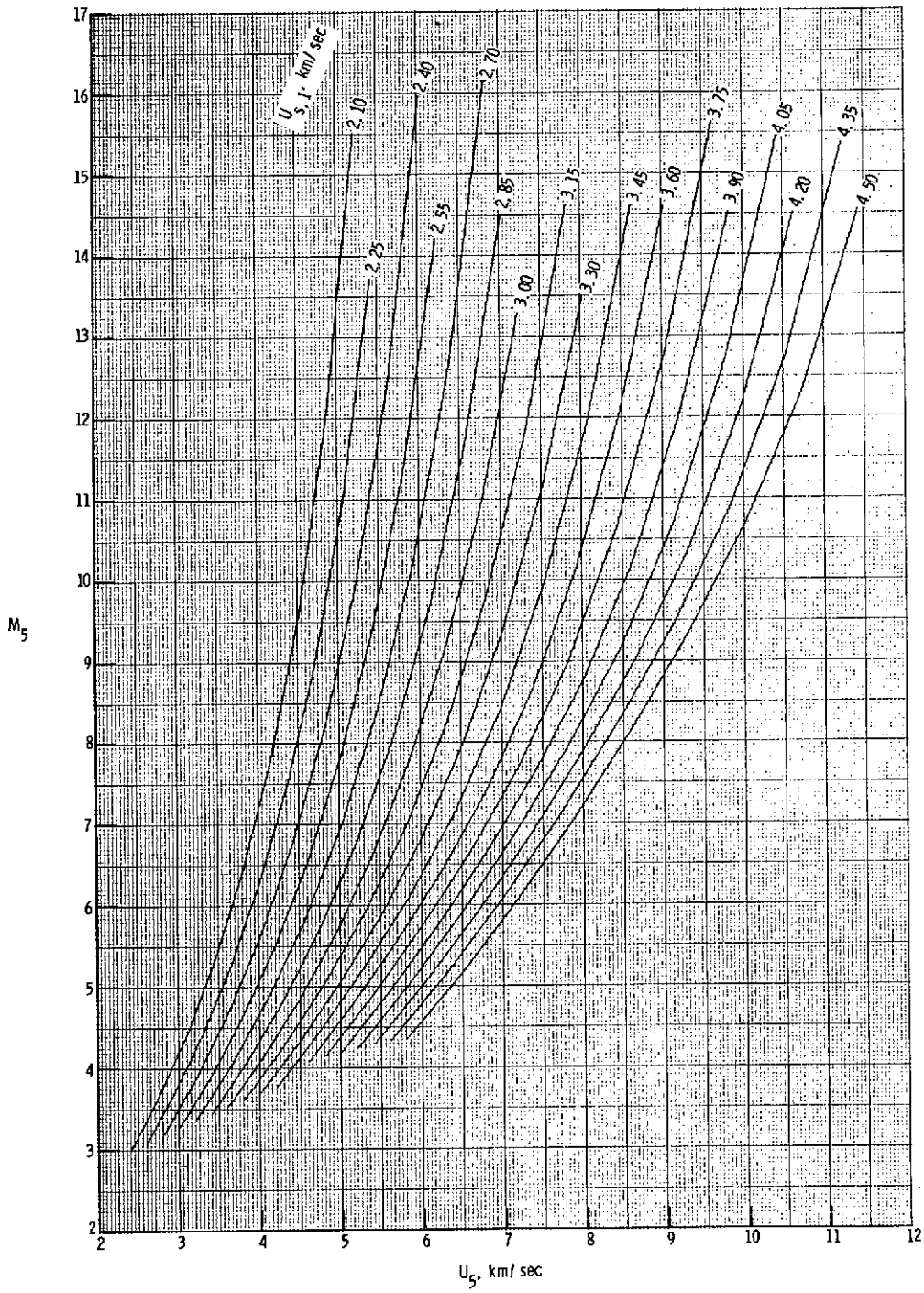
(b) Static density in region (5).

Figure 10.- Continued.



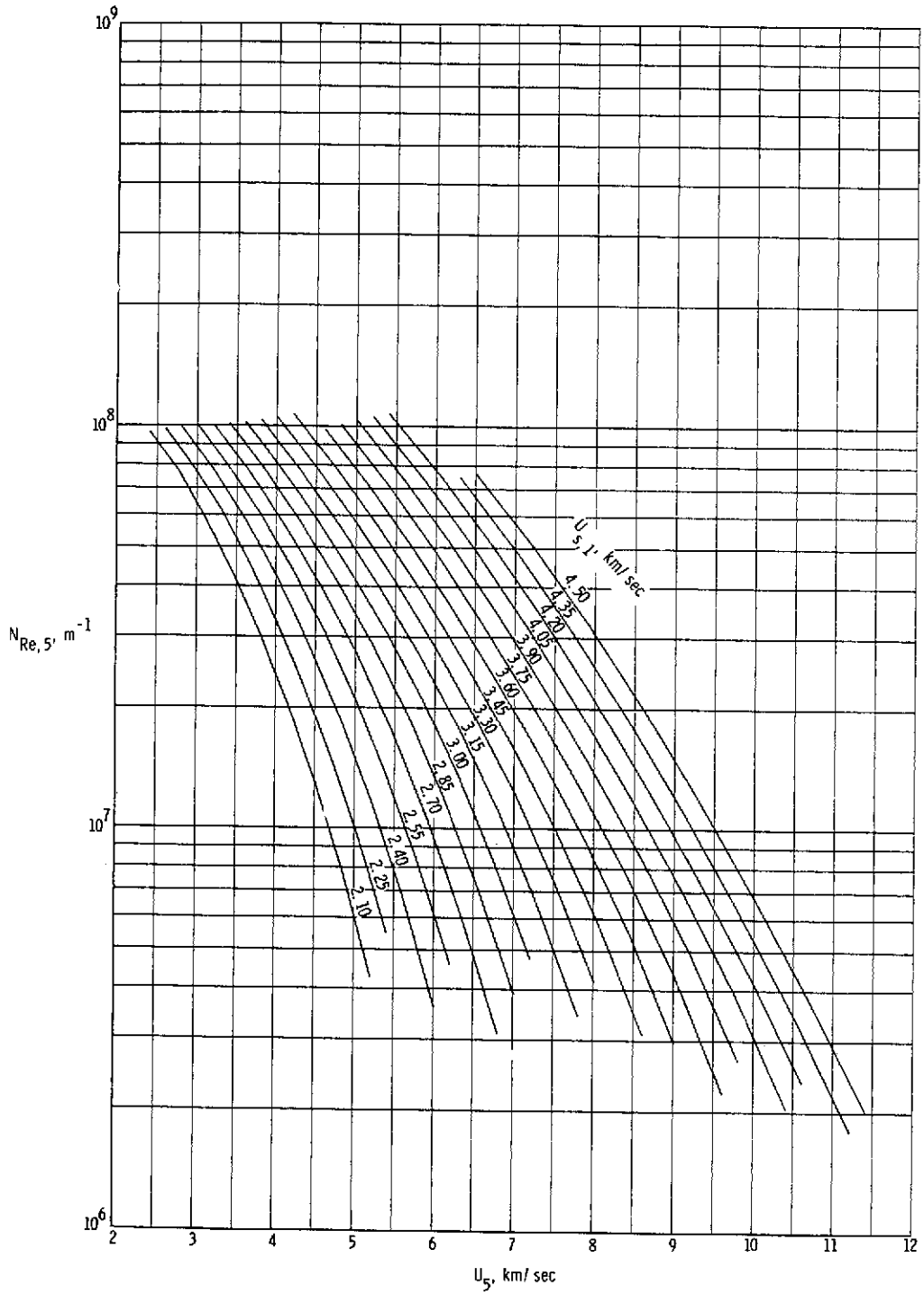
(c) Static temperature in region (5).

Figure 10.- Continued.



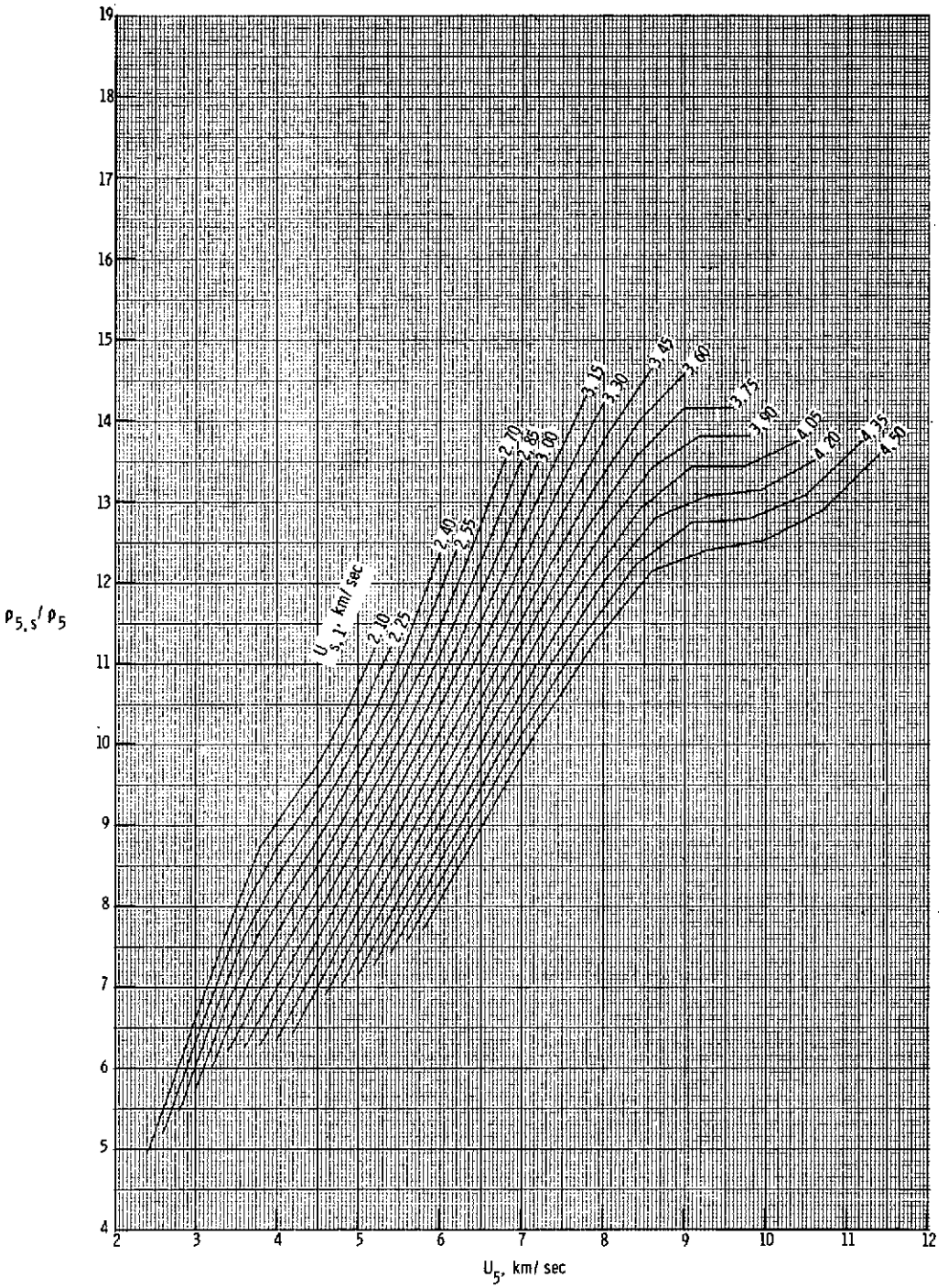
(d) Mach number in region (5).

Figure 10.- Continued.



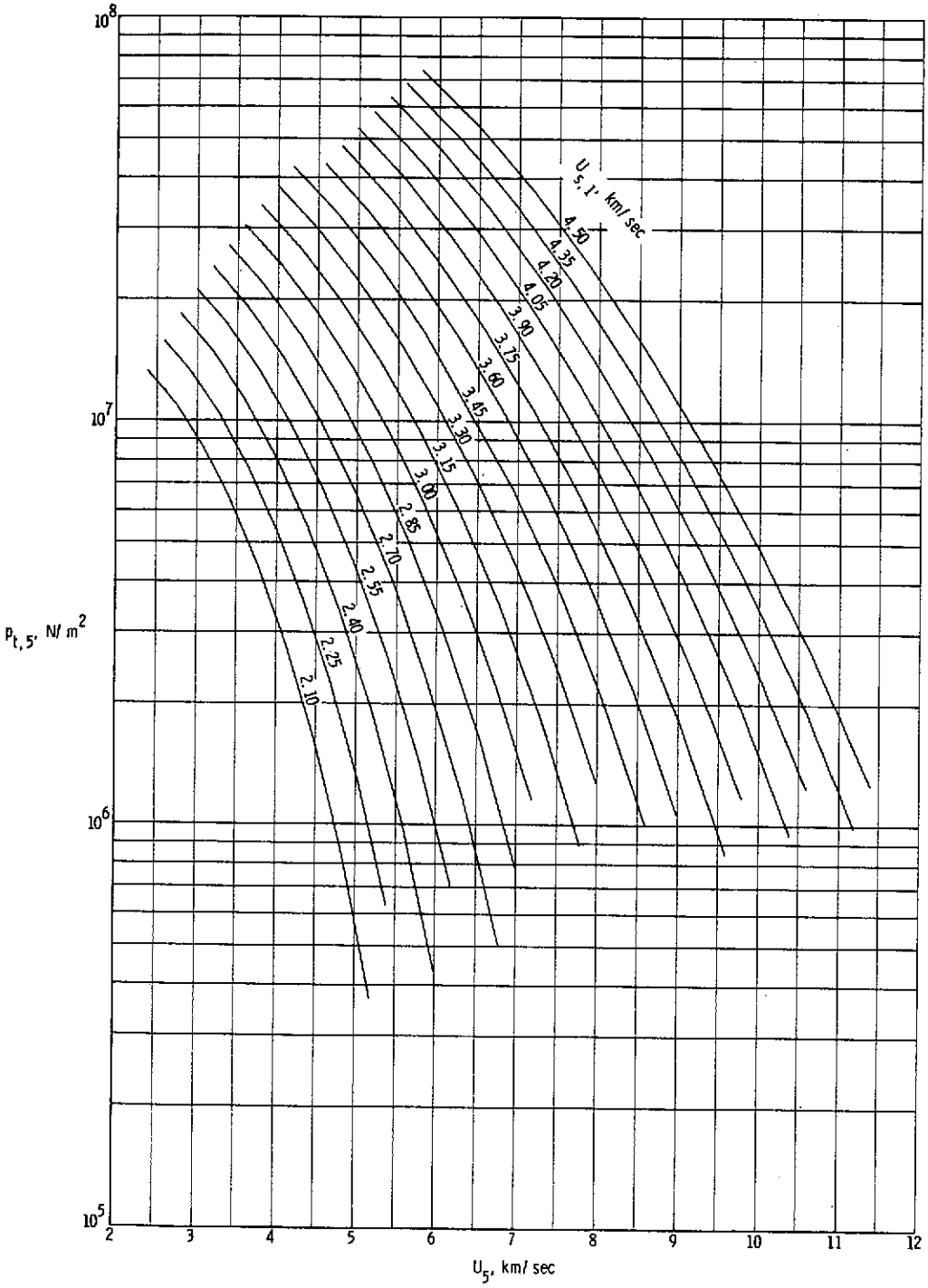
(e) Unit Reynolds number in region (5).

Figure 10.- Continued.



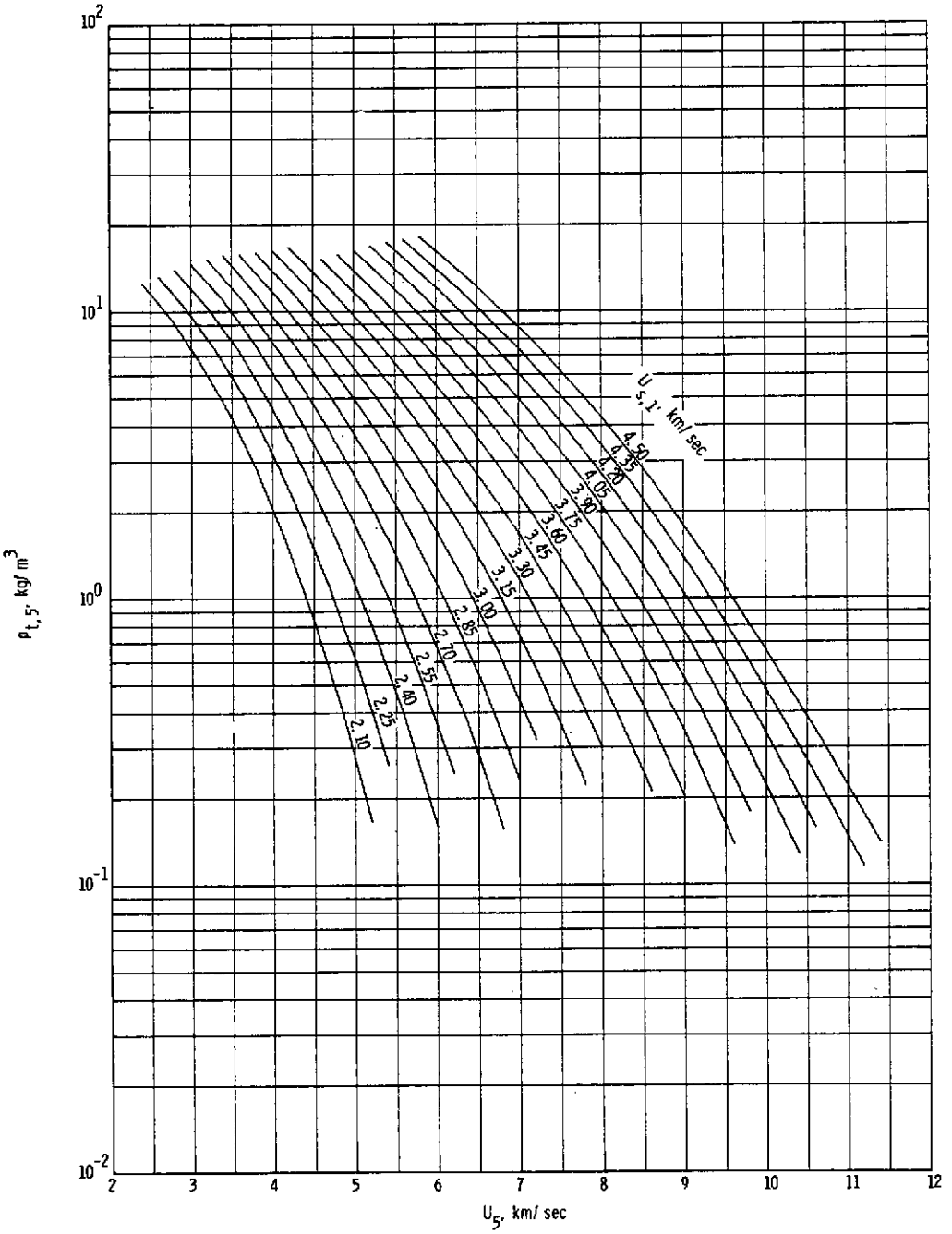
(f) Normal shock density ratio.

Figure 10.- Continued.



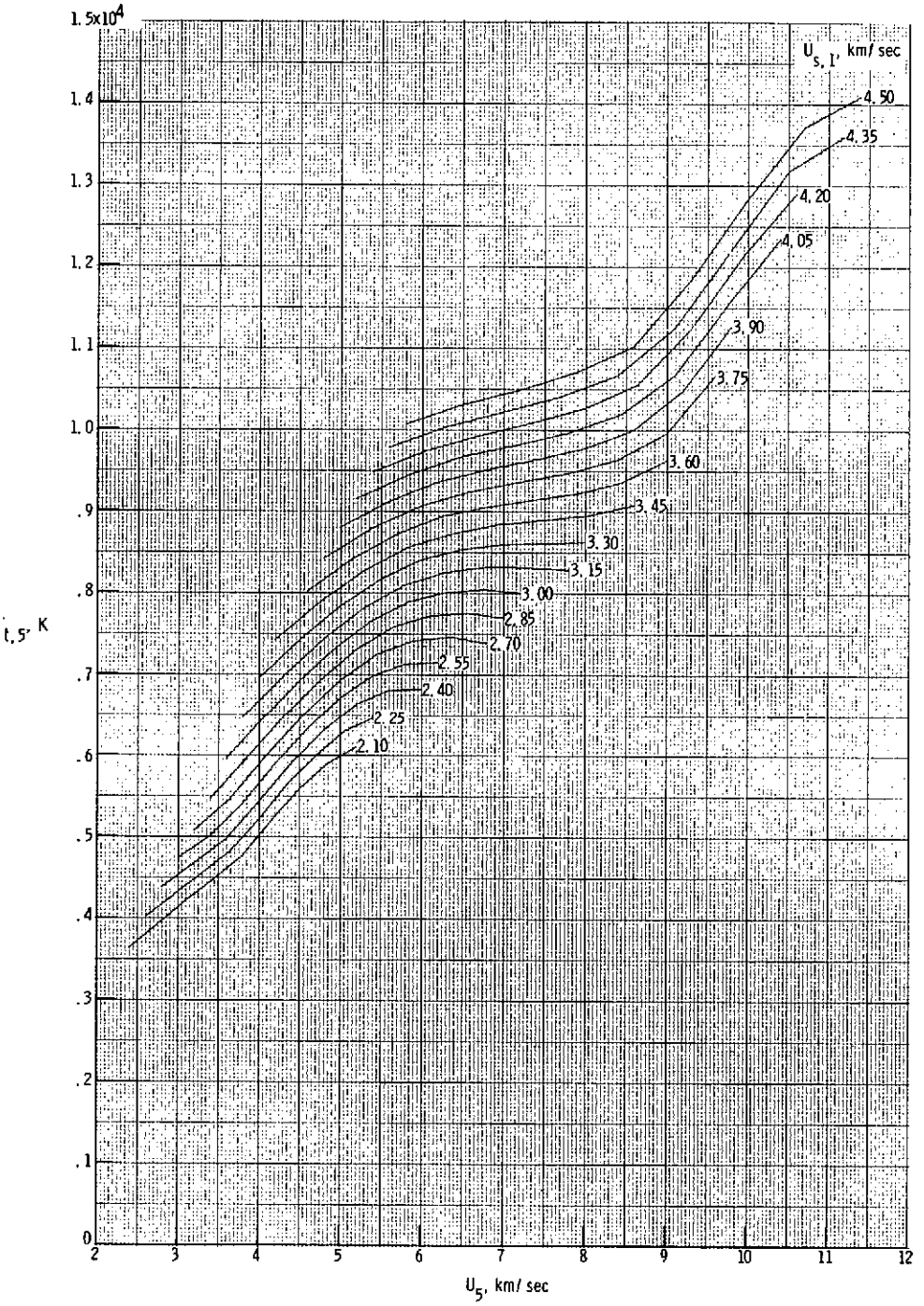
(g) Stagnation pressure behind normal bow shock.

Figure 10.- Continued.



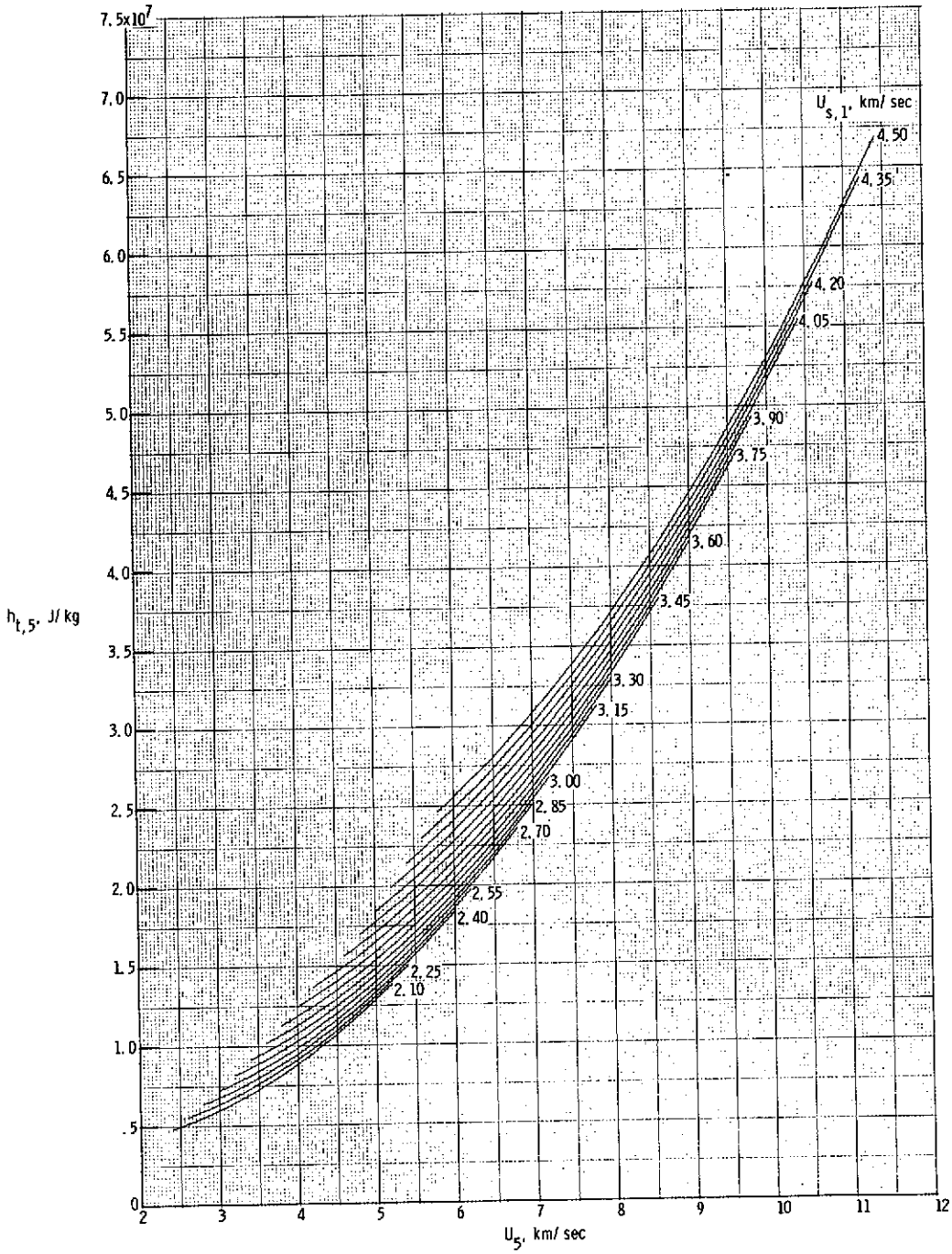
(h) Stagnation density behind normal bow shock.

Figure 10.- Continued.



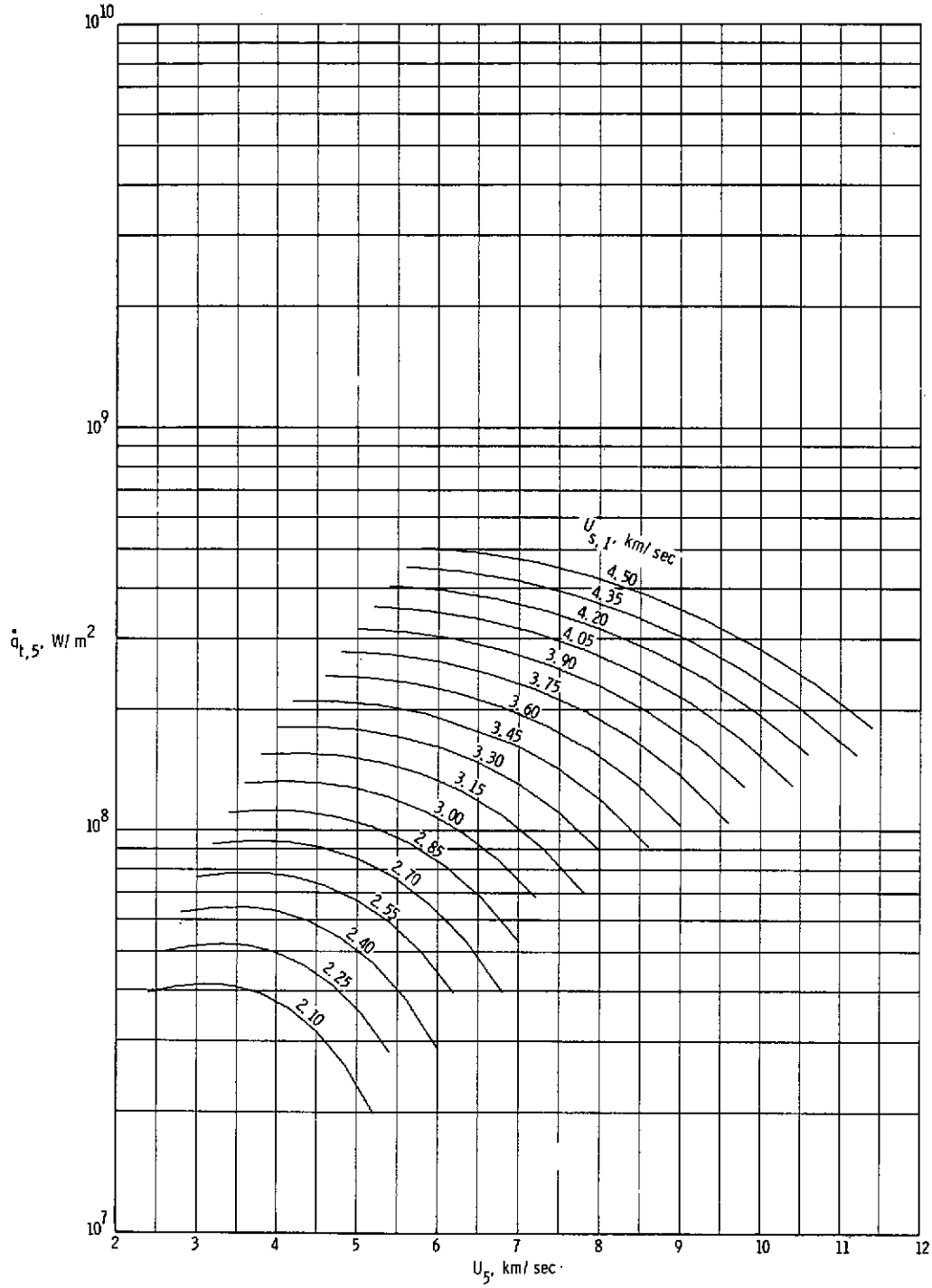
(i) Stagnation temperature behind normal bow shock.

Figure 10.- Continued.



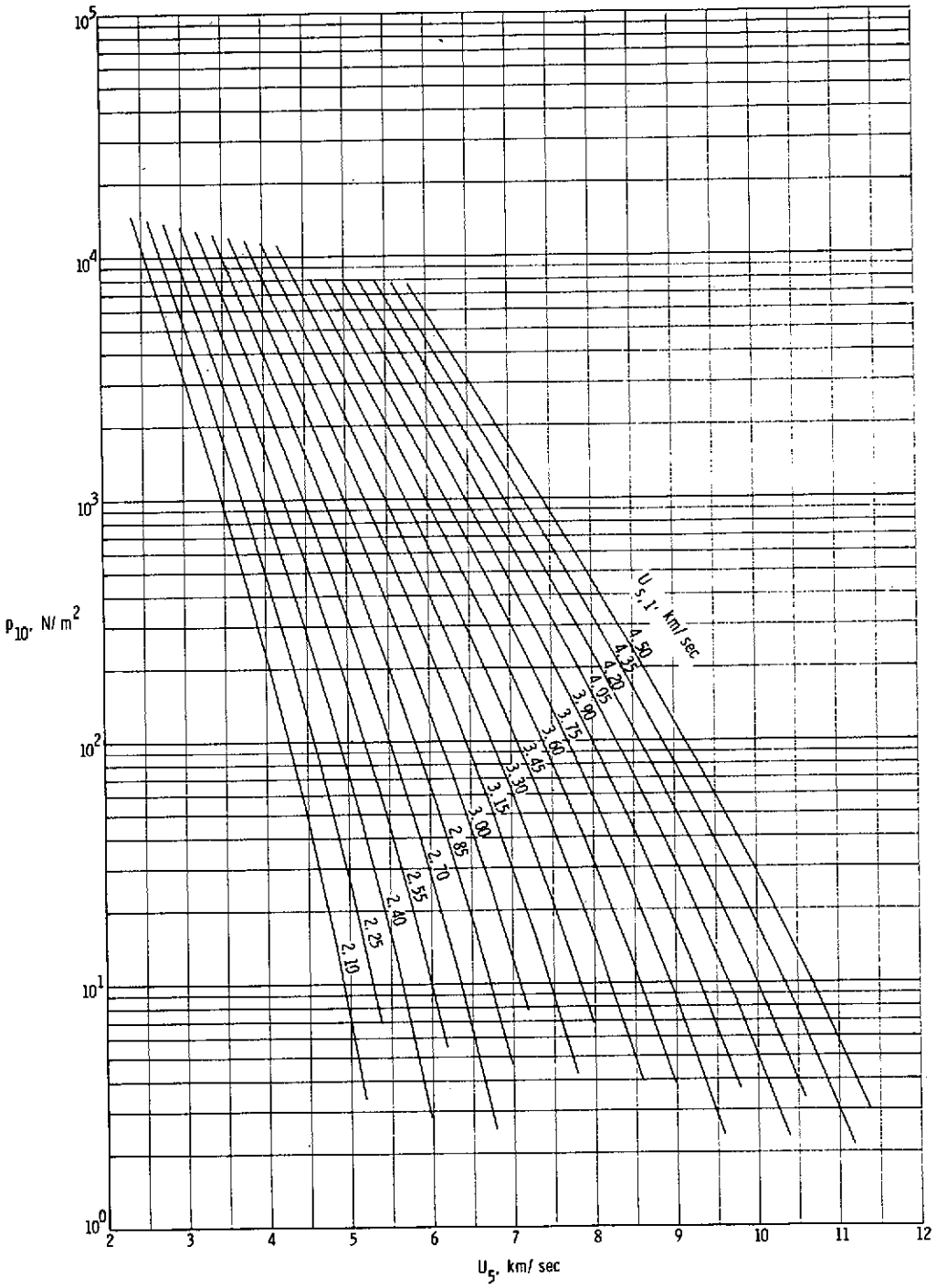
(j) Stagnation enthalpy behind normal bow shock.

Figure 10.- Continued.



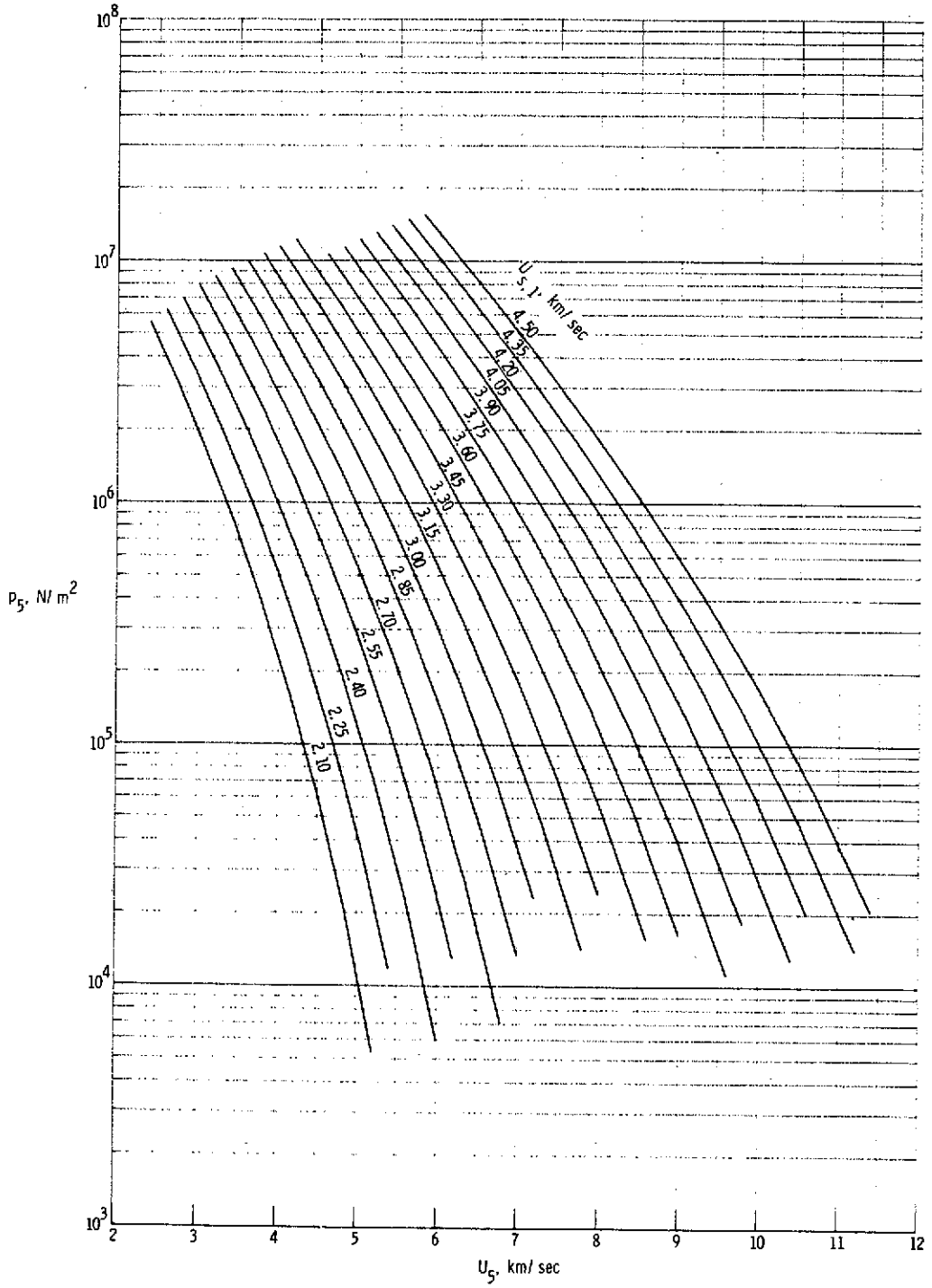
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 10.- Continued.



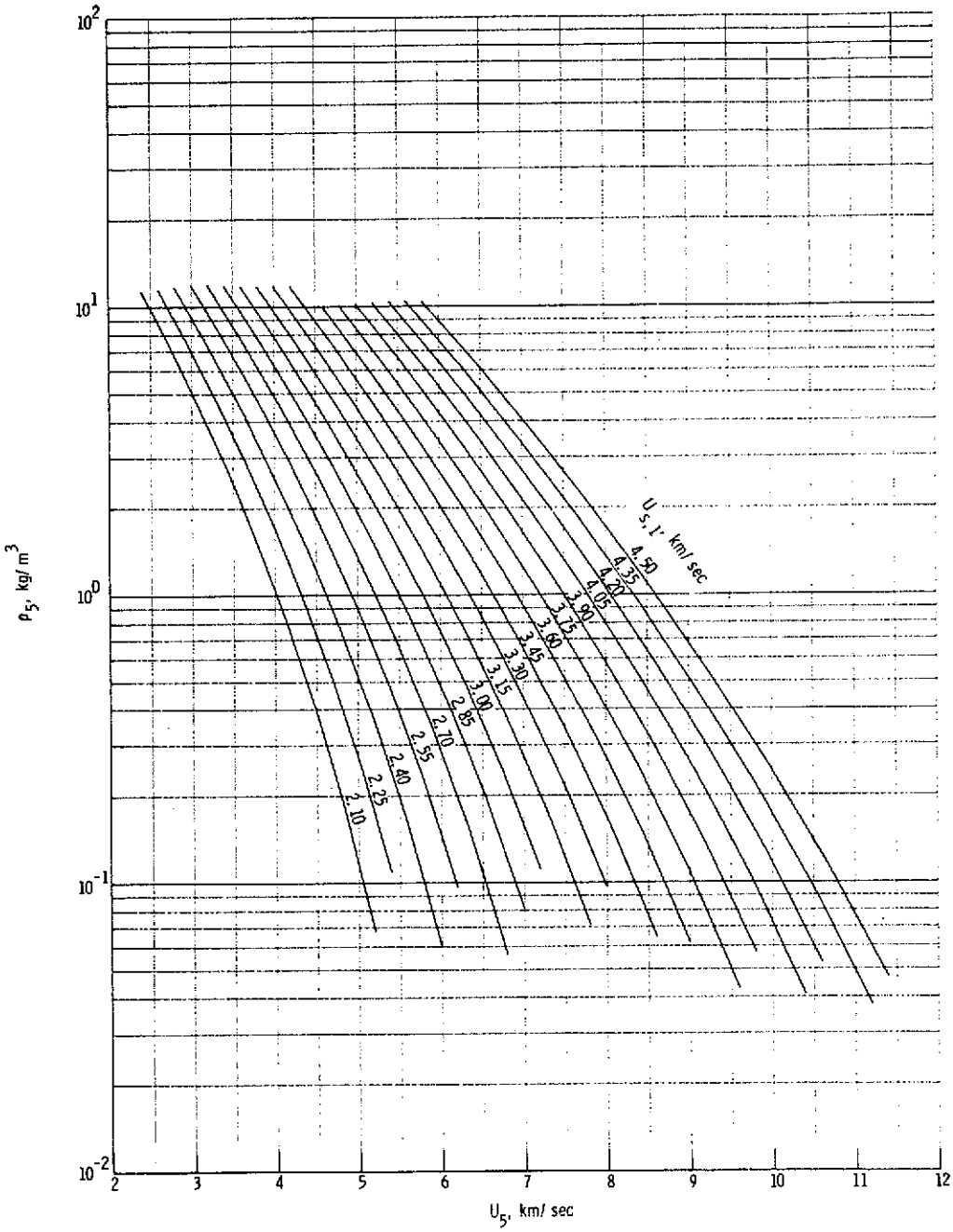
(l) Quiescent acceleration air pressure in region (10).

Figure 10.- Concluded.



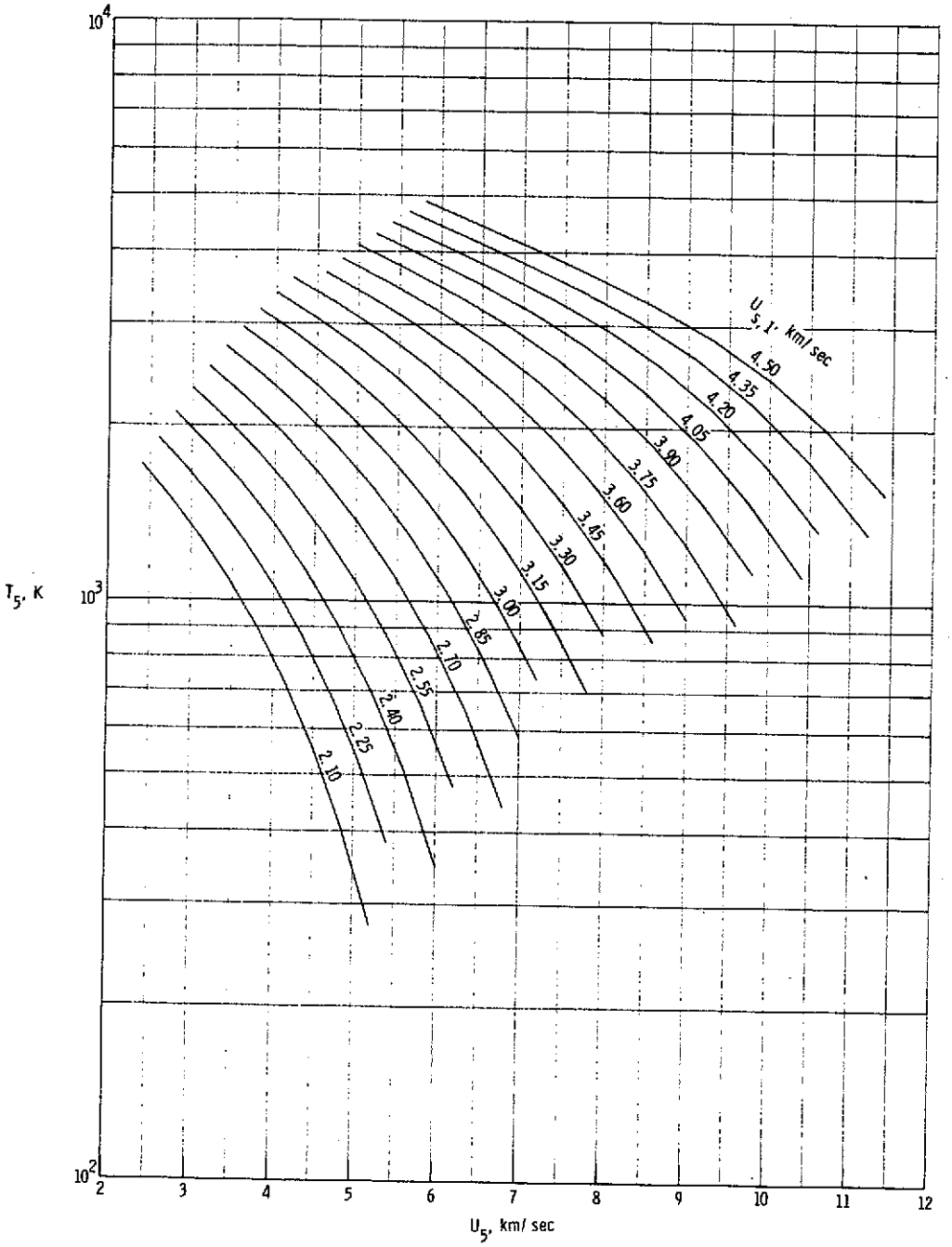
(a) Static pressure in region (5).

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.



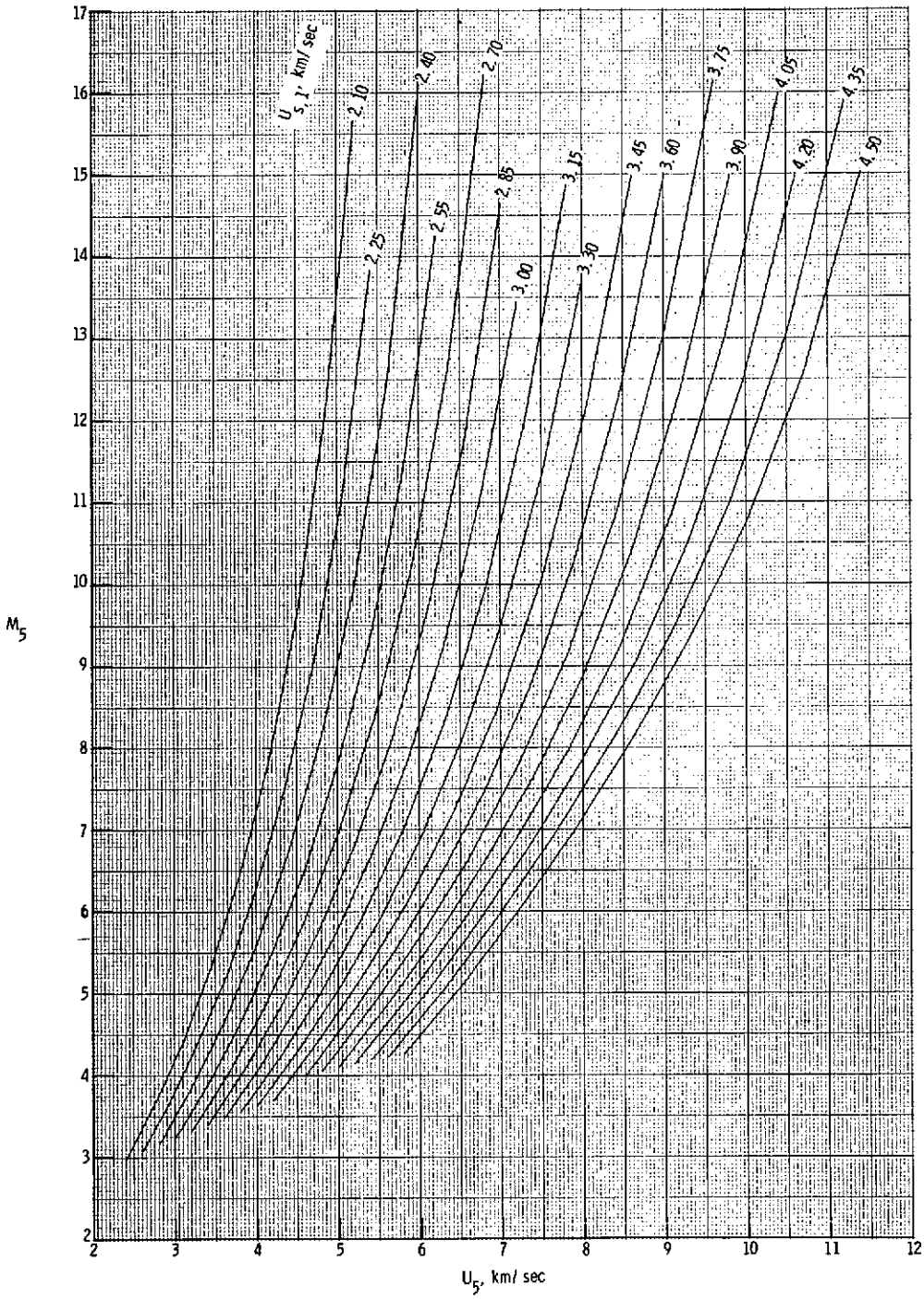
(b) Static density in region (5).

Figure 11.- Continued.



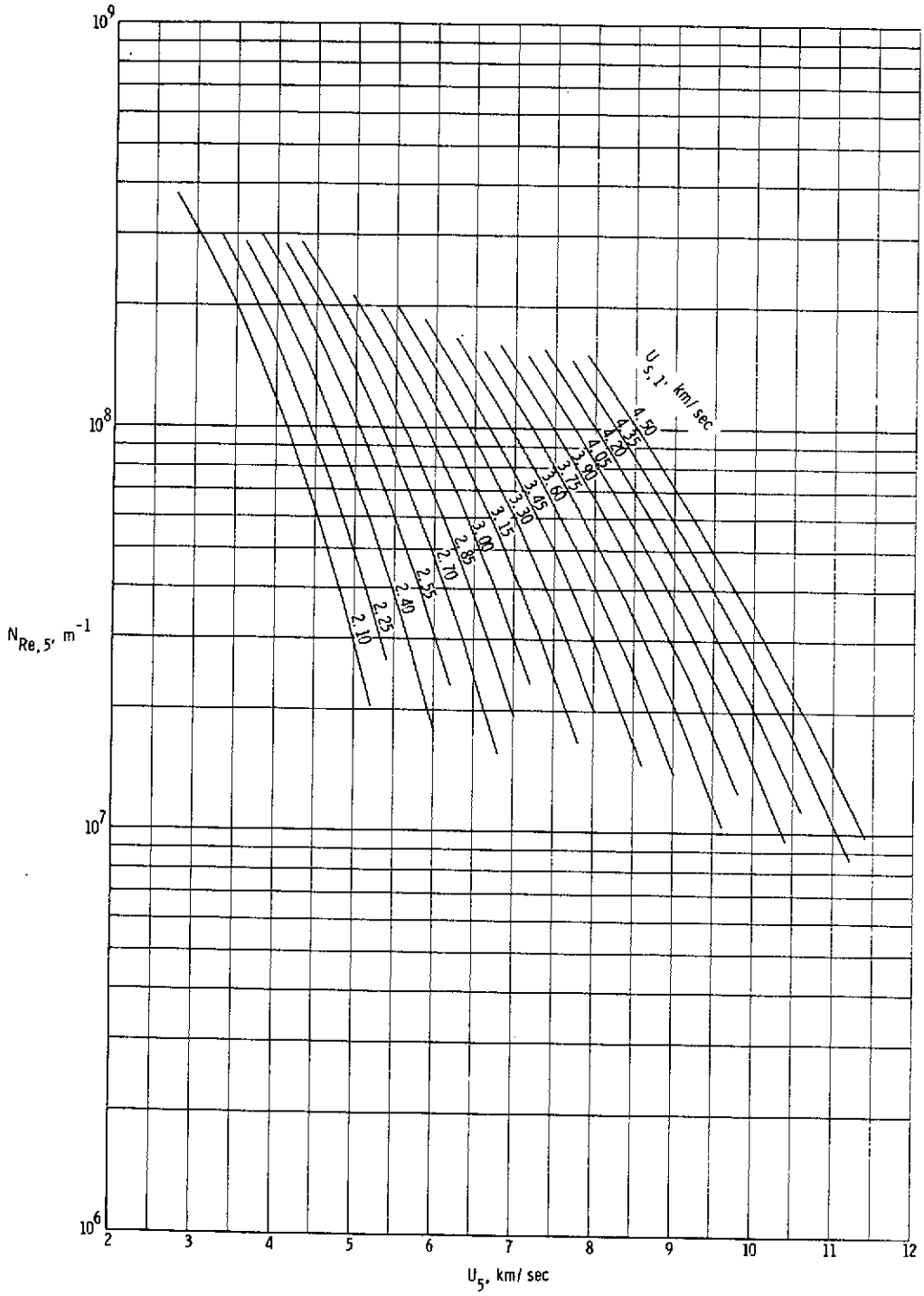
(c) Static temperature in region (5).

Figure 11.- Continued.



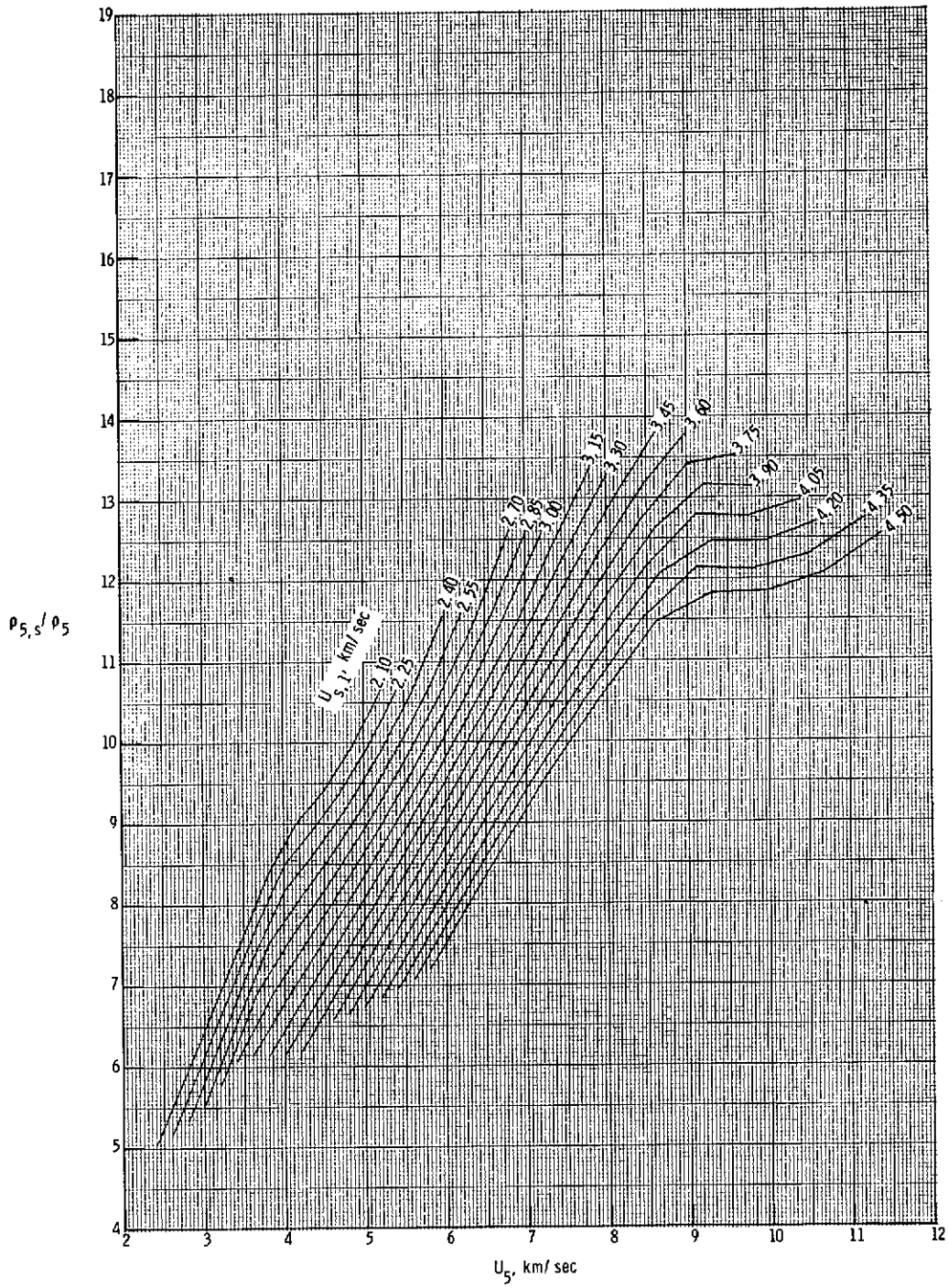
(d) Mach number in region (5).

Figure 11.- Continued.



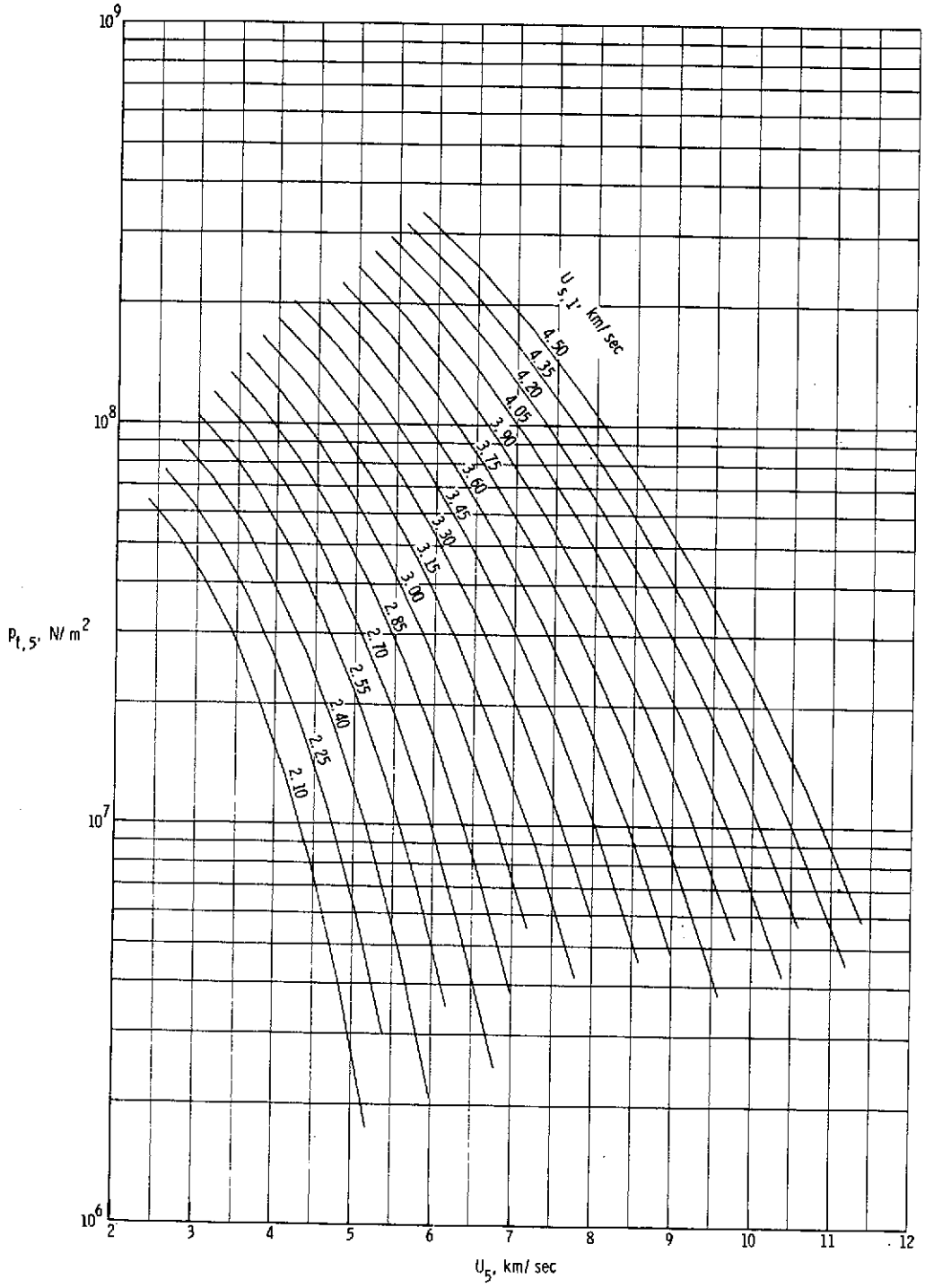
(e) Unit Reynolds number in region (5).

Figure 11.- Continued.



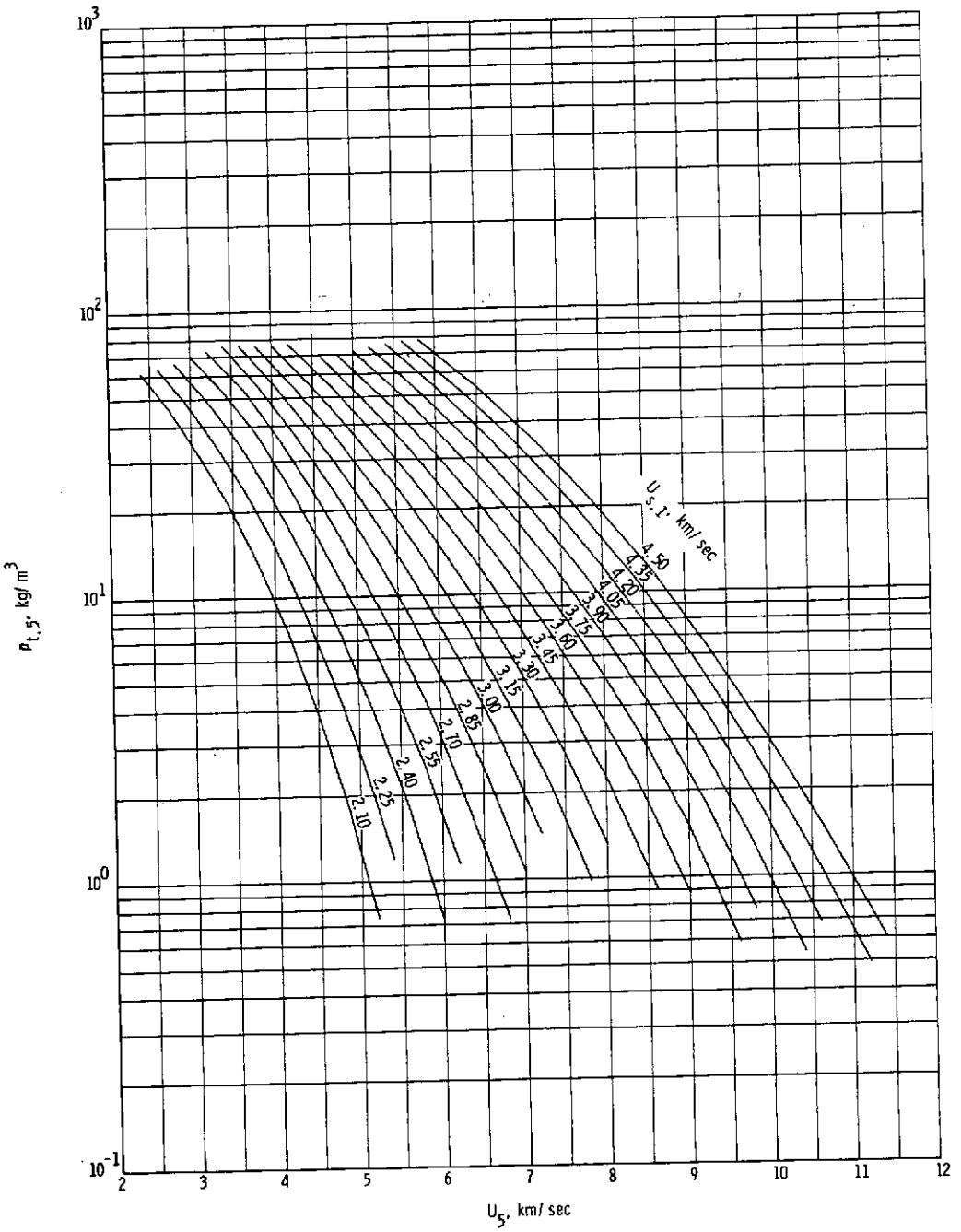
(f) Normal shock density ratio.

Figure 11.- Continued.



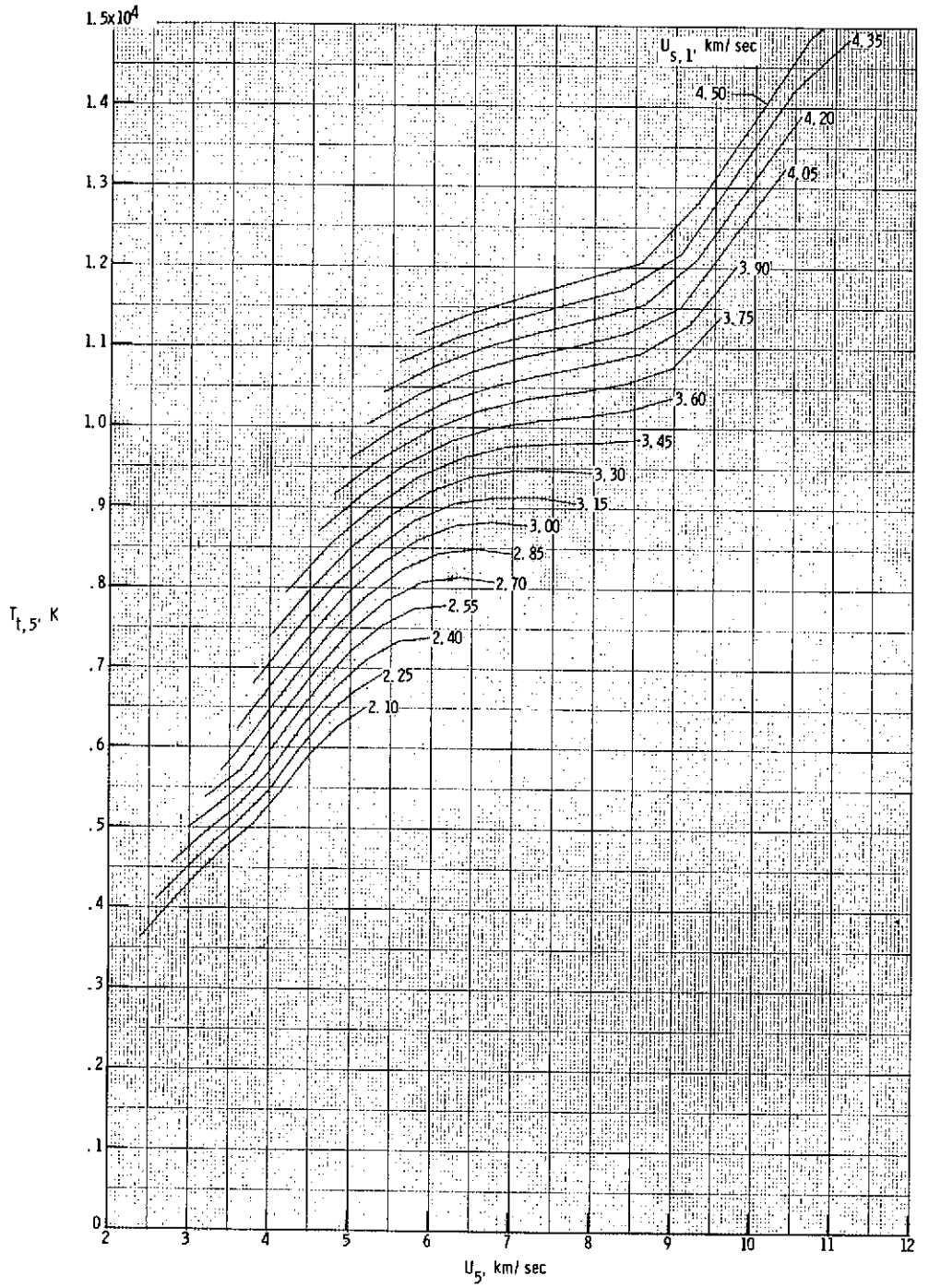
(g) Stagnation pressure behind normal bow shock.

Figure 11.- Continued.



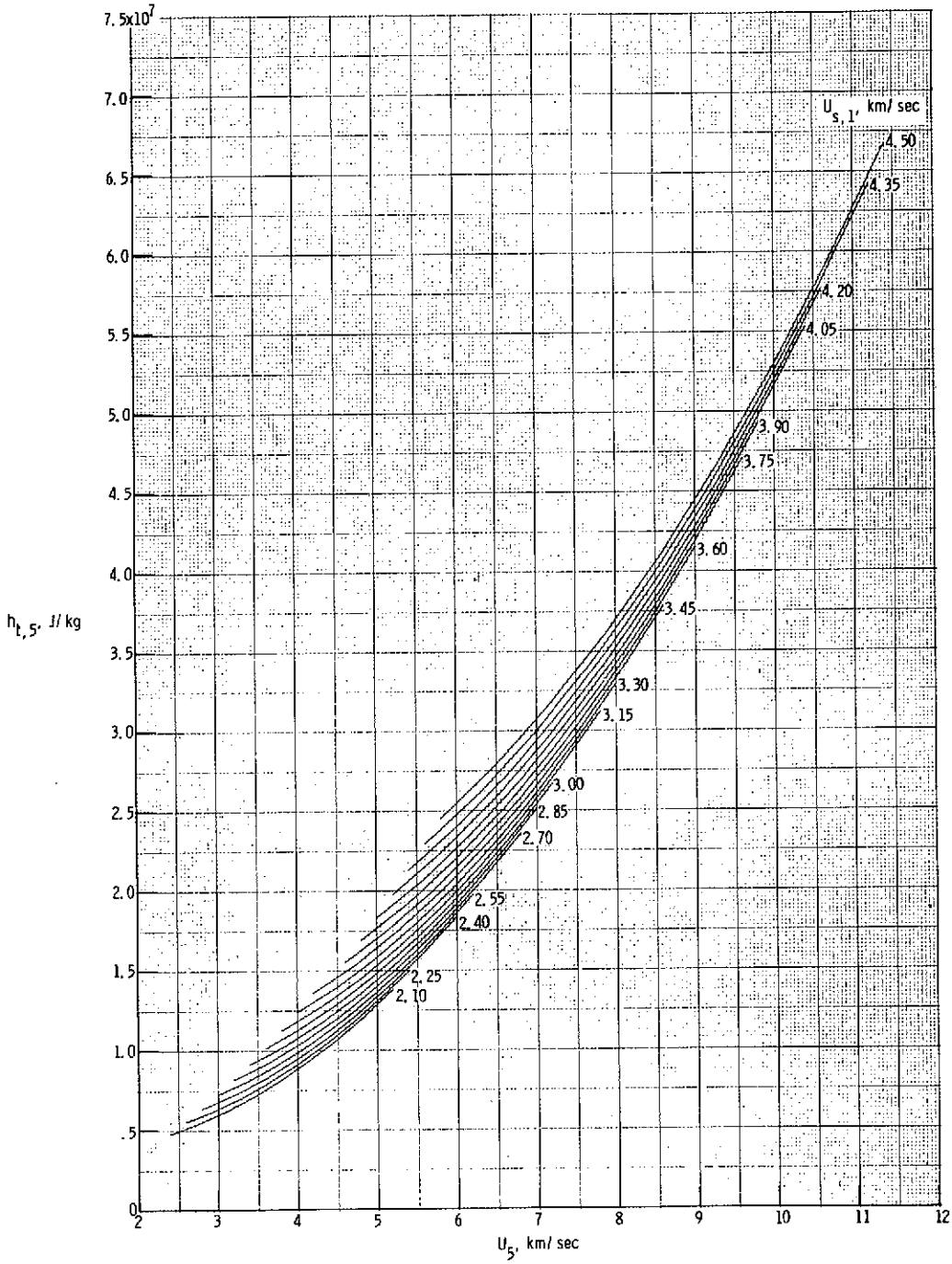
(h) Stagnation density behind normal bow shock.

Figure 11.- Continued.



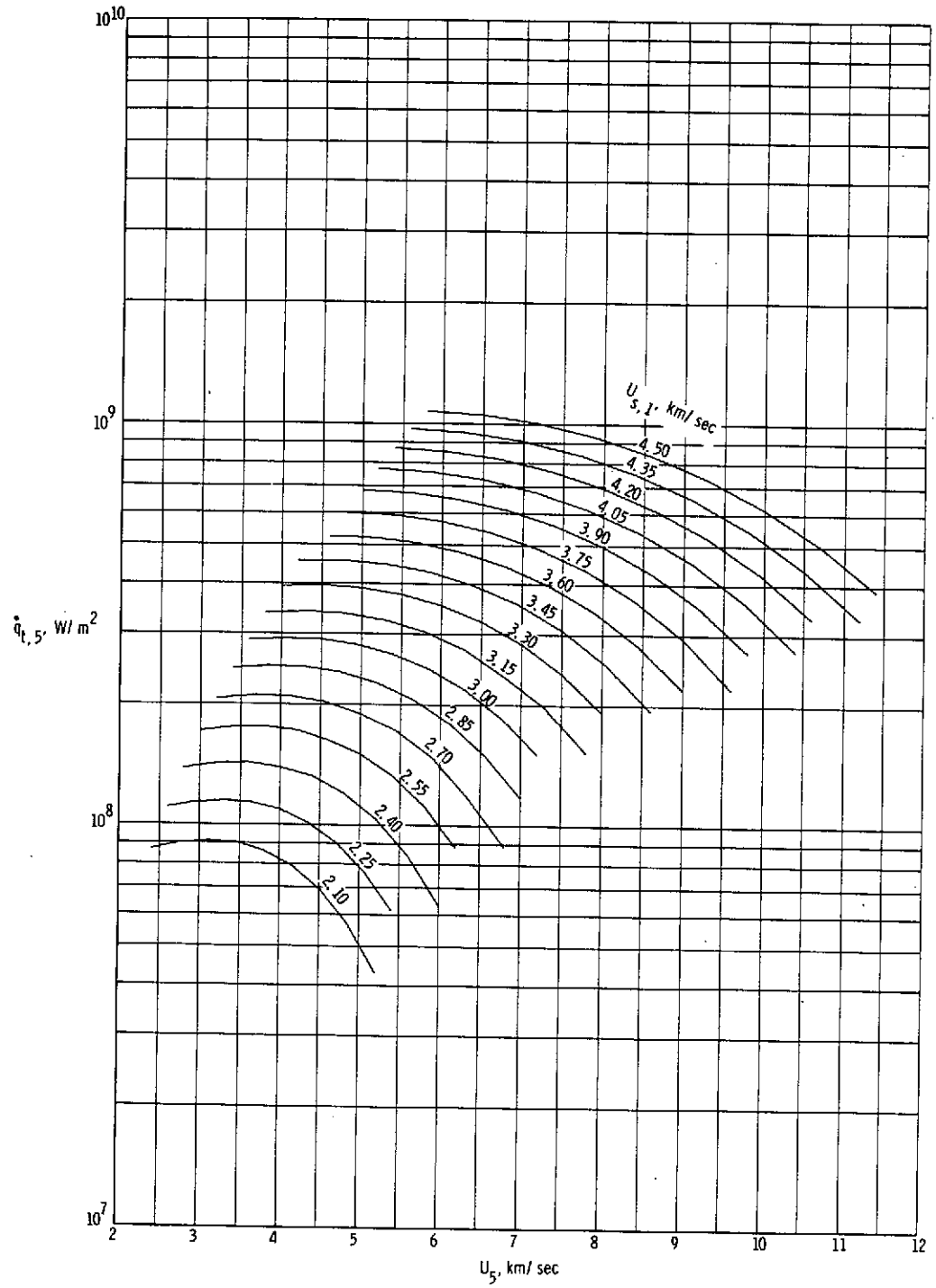
(i) Stagnation temperature behind normal bow shock.

Figure 11.- Continued.



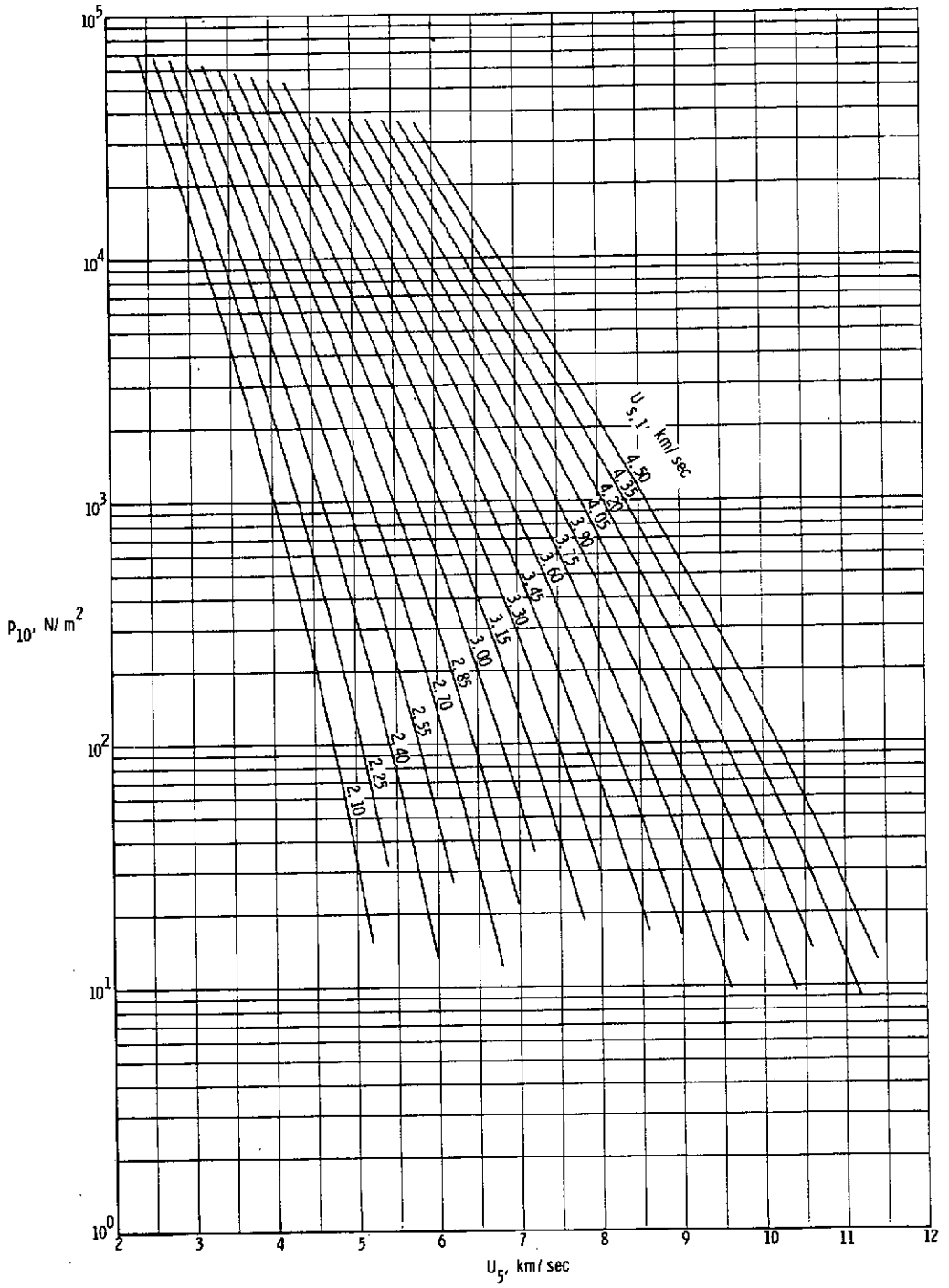
(j) Stagnation enthalpy behind normal bow shock.

Figure 11.- Continued.



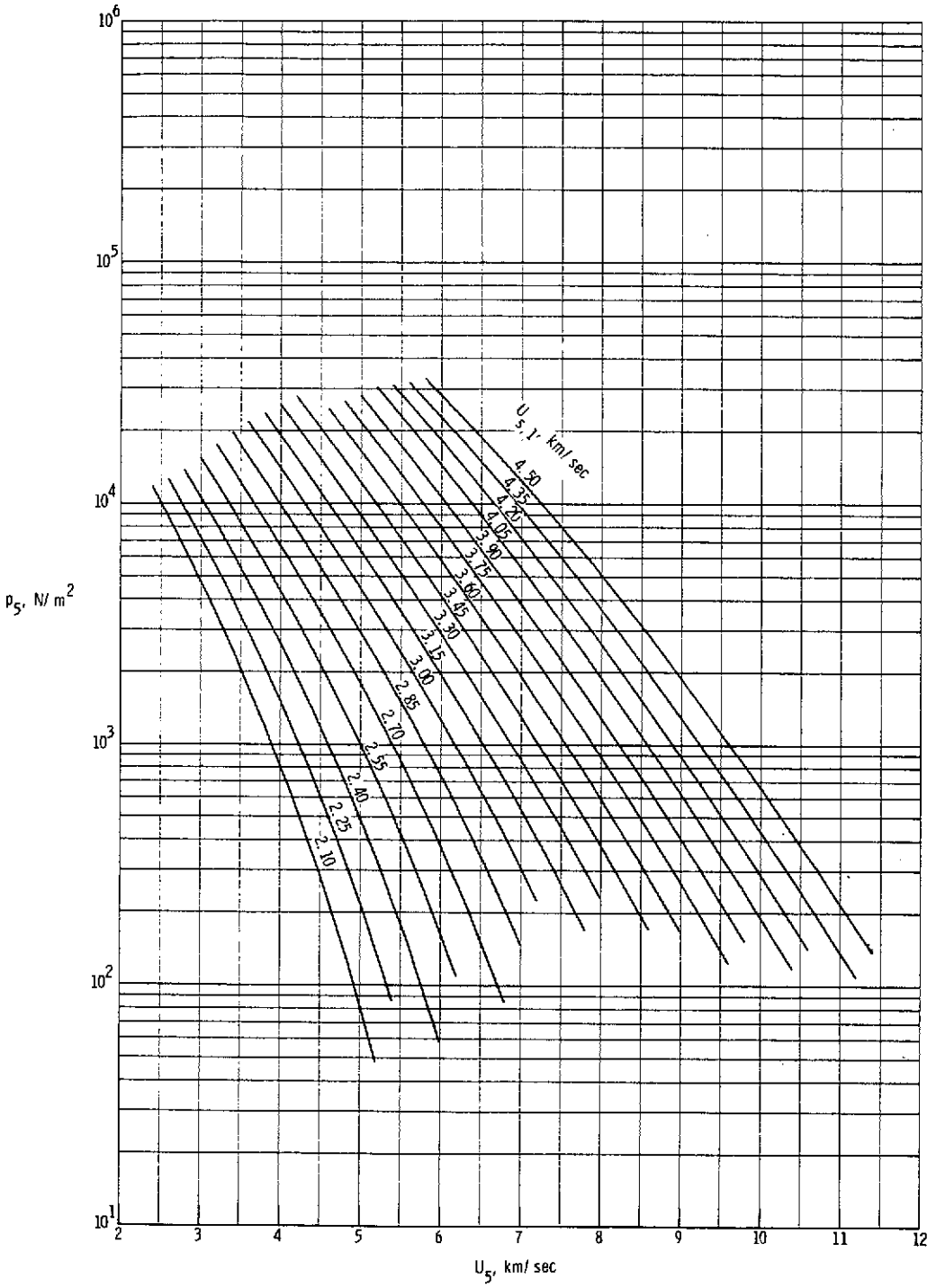
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 11.- Continued.



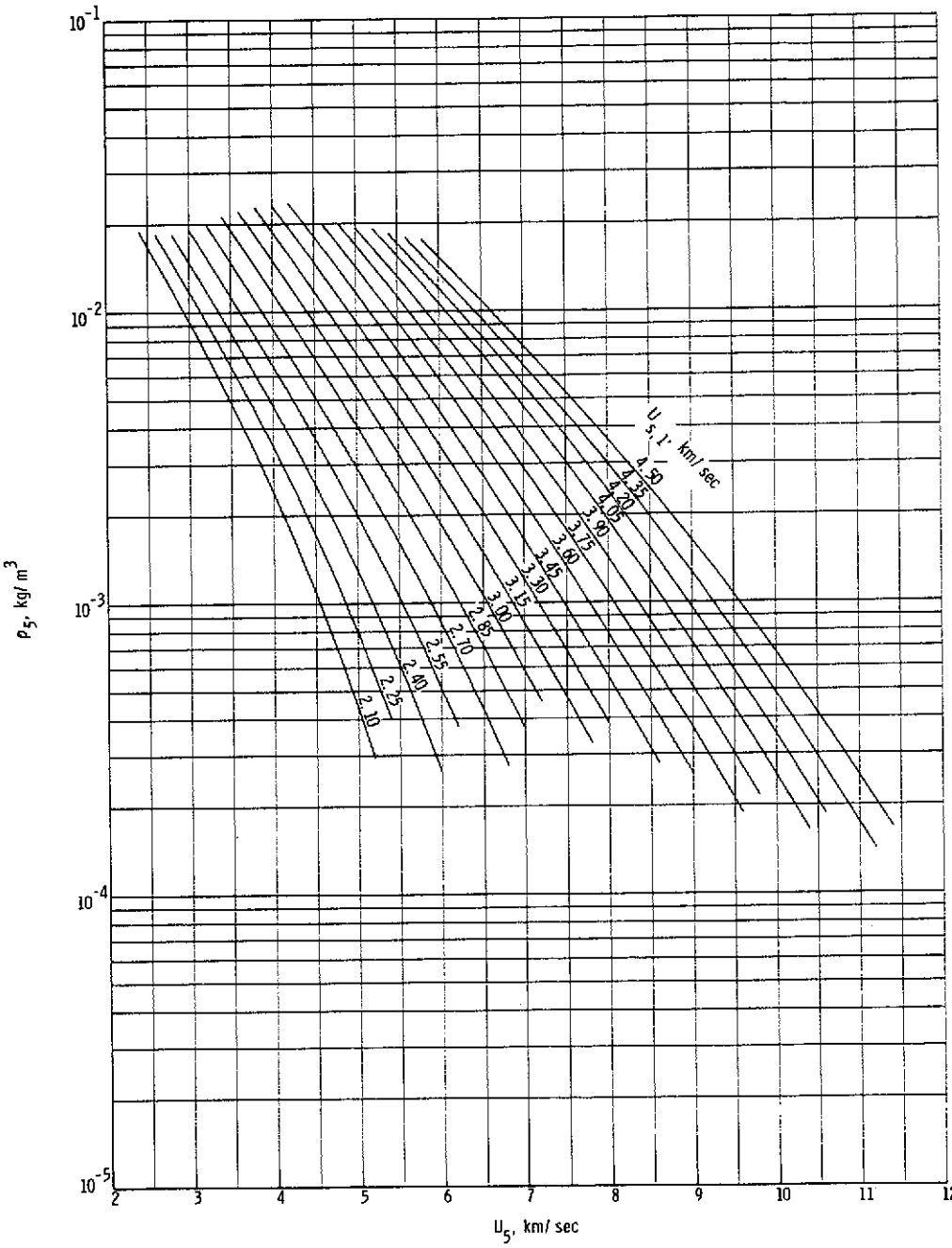
(l) Quiescent acceleration air pressure in region (10).

Figure 11.- Concluded.



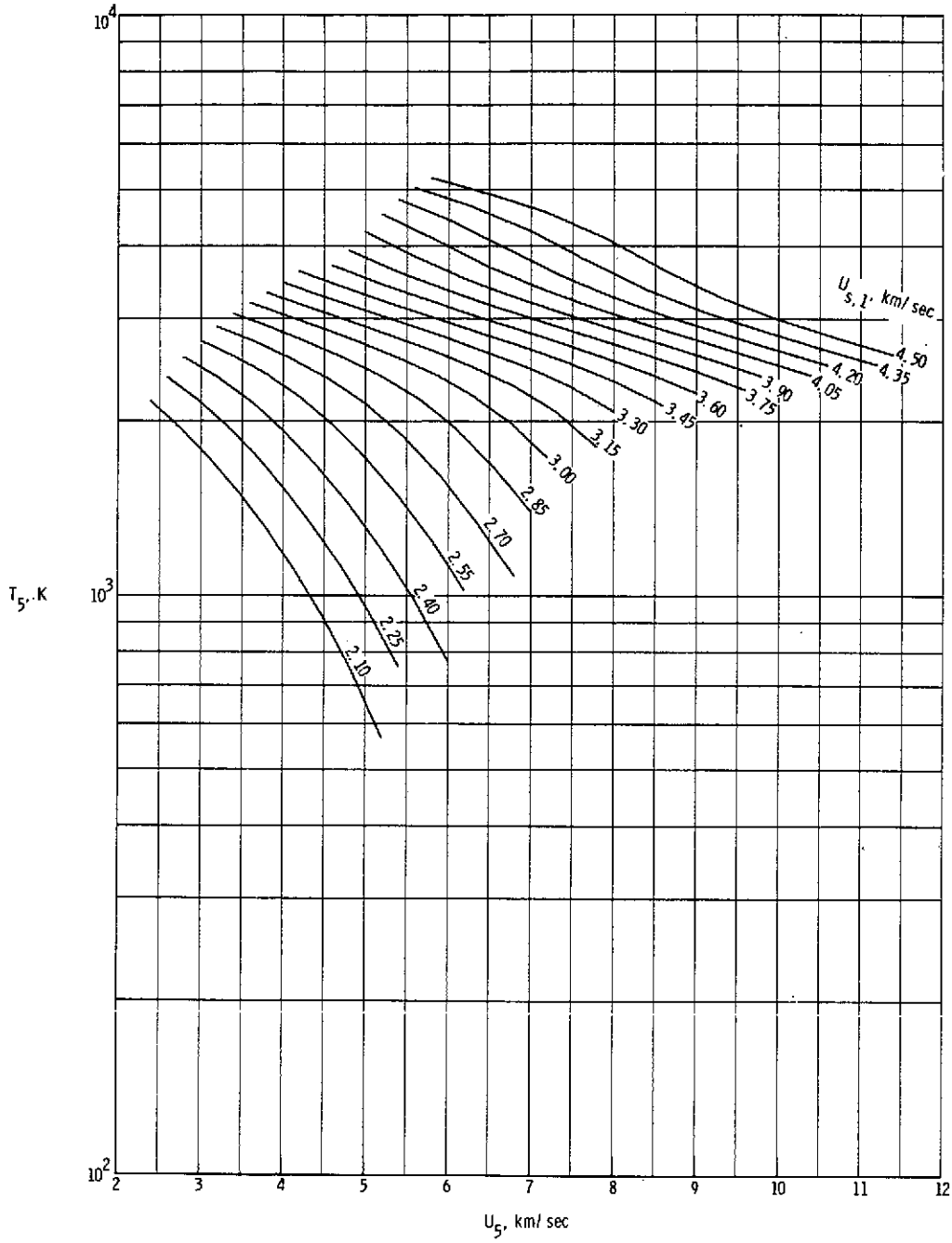
(a) Static pressure in region (5).

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. $p_1 = 689.5$ N/m^2.



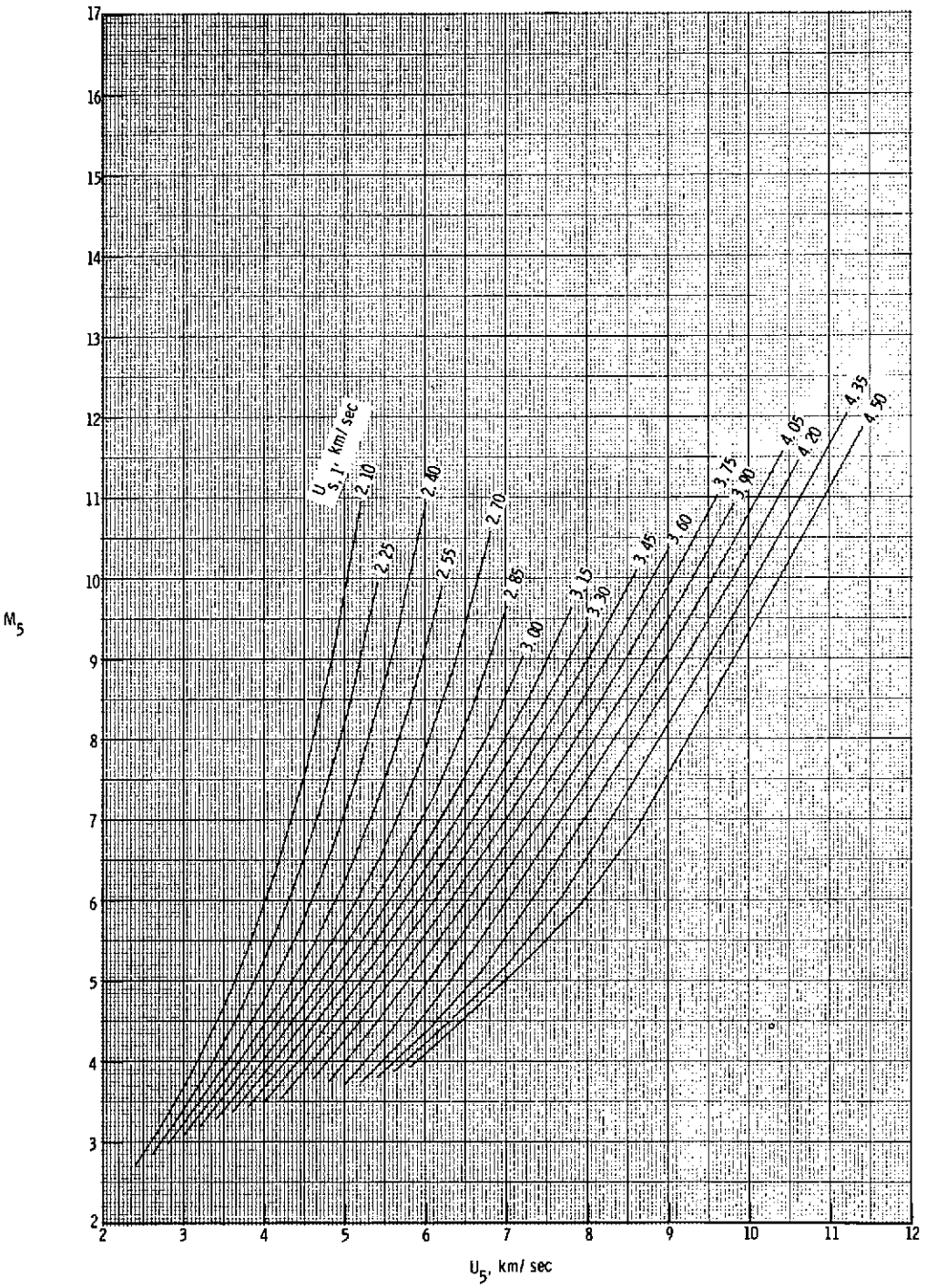
(b) Static density in region (5).

Figure 12.- Continued.



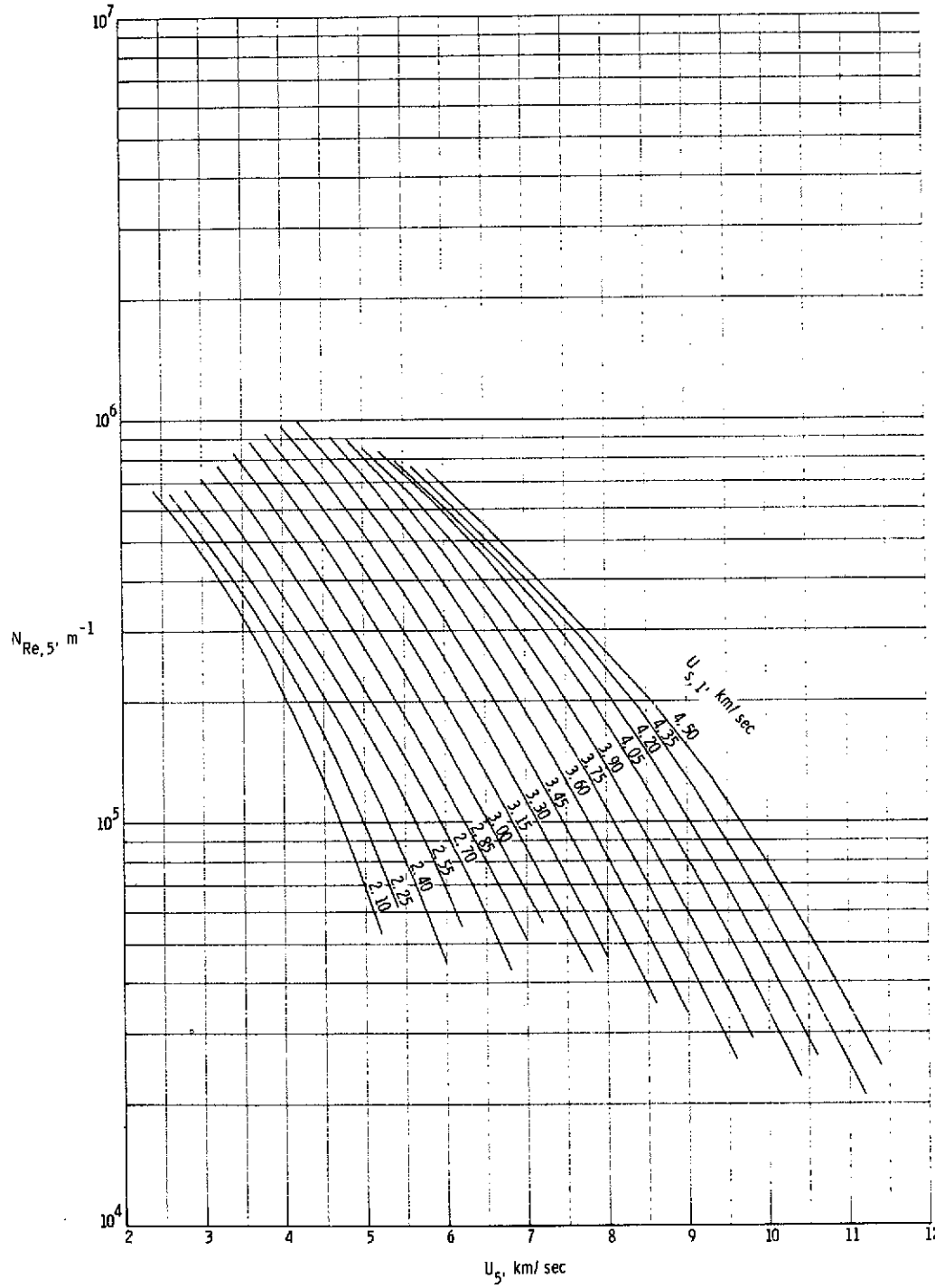
(c) Static temperature in region (5).

Figure 12.- Continued.



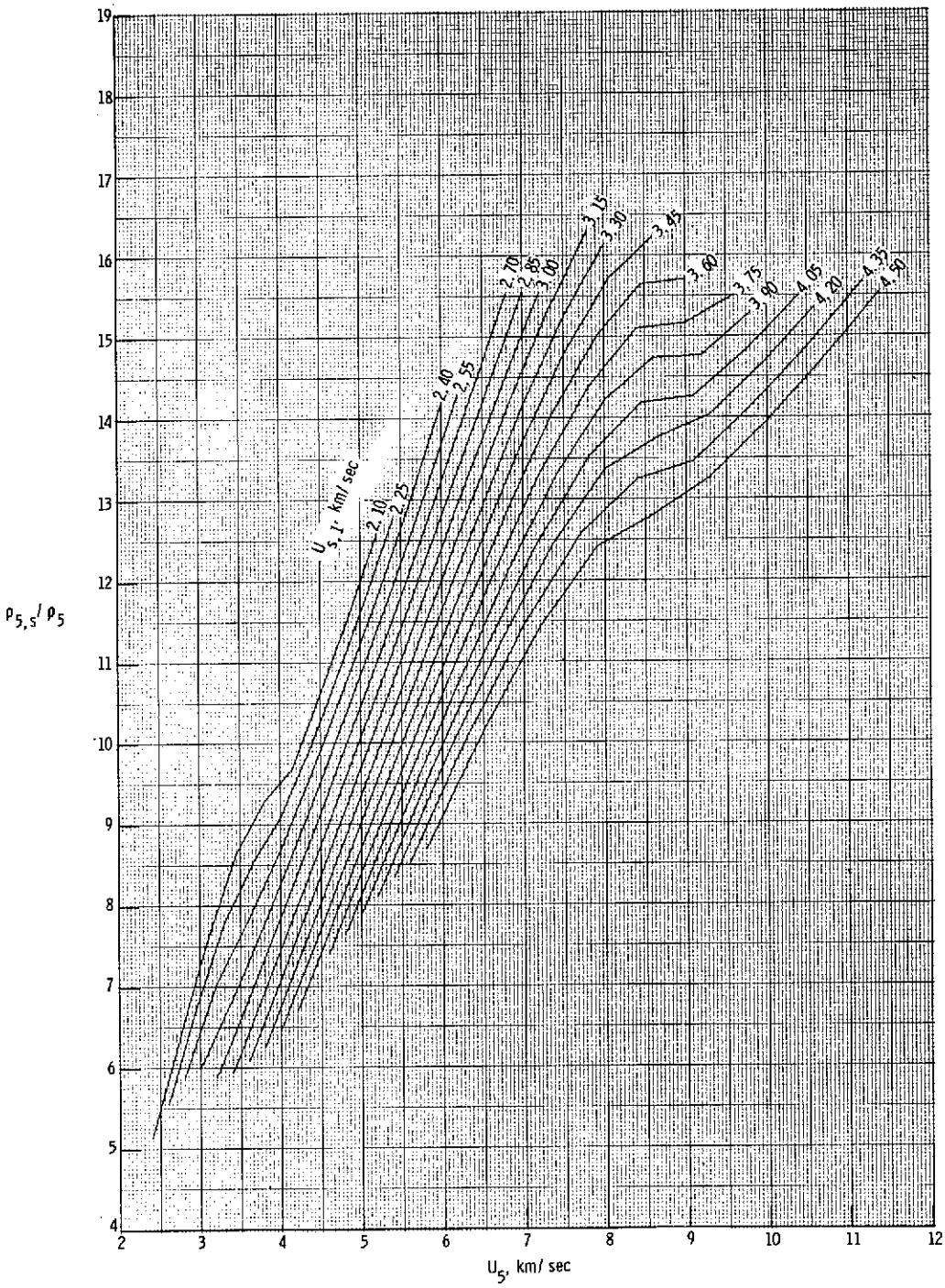
(d) Mach number in region (5).

Figure 12.- Continued.



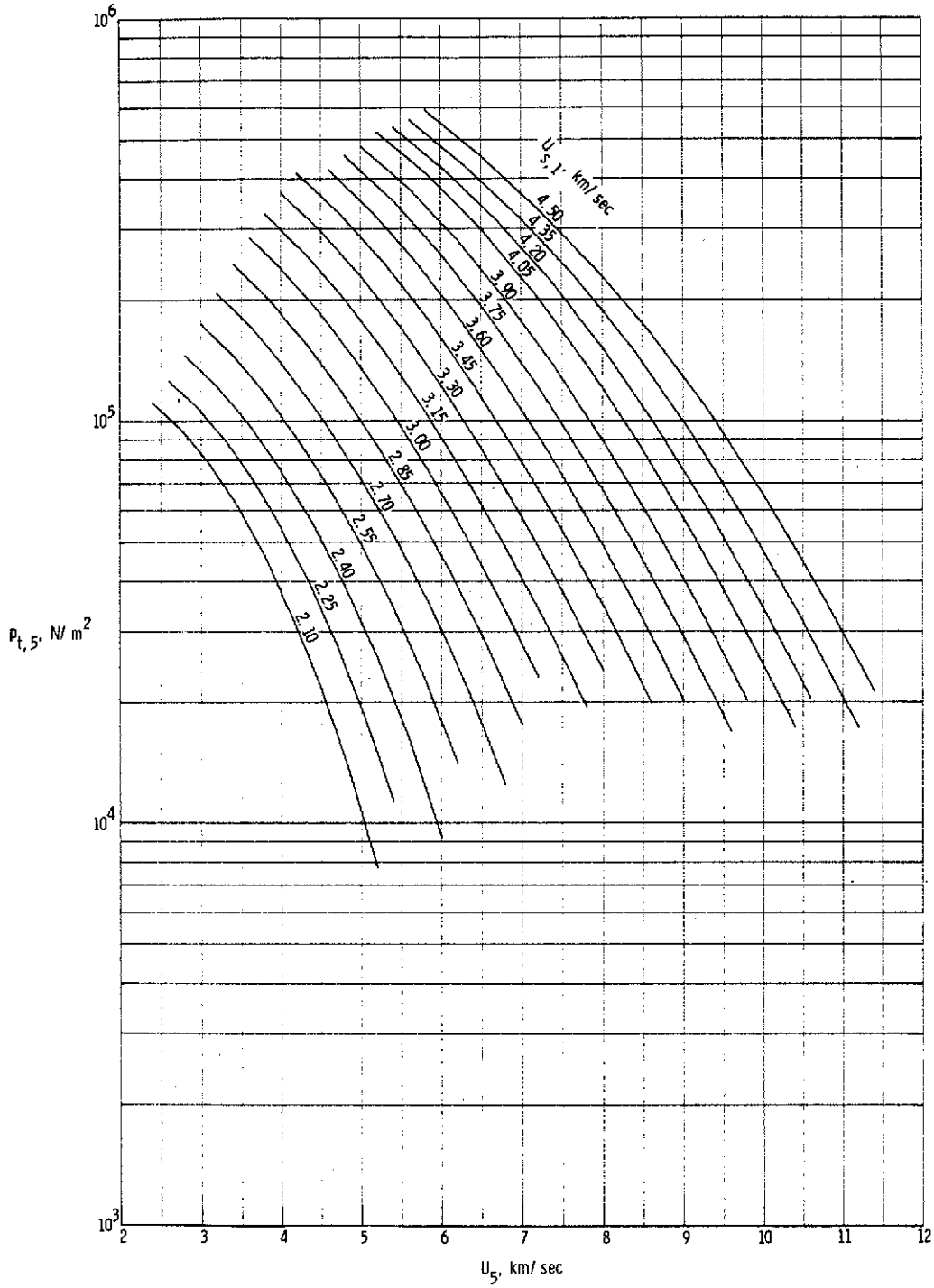
(e) Unit Reynolds number in region (5).

Figure 12.- Continued.



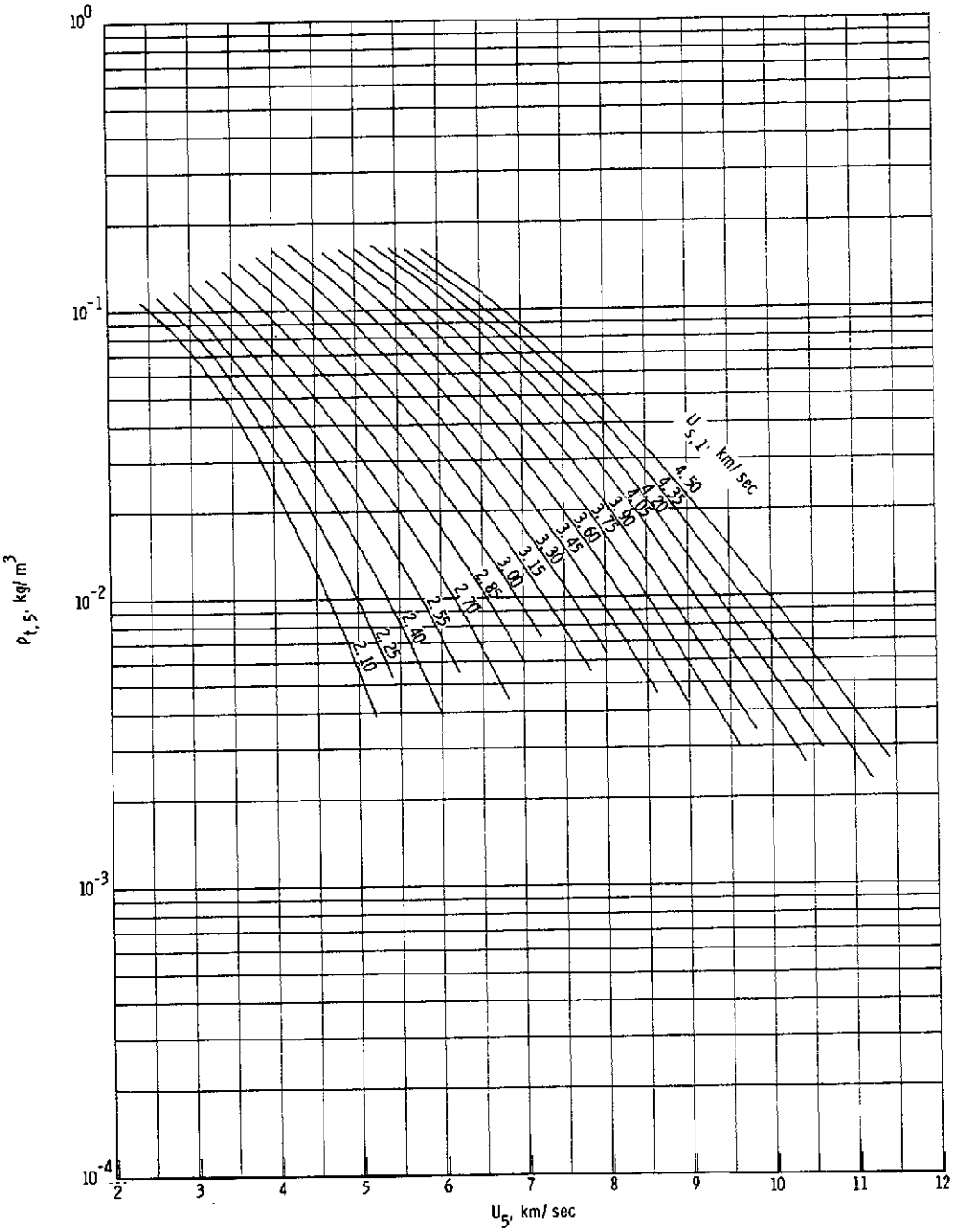
(f) Normal shock density ratio.

Figure 12.- Continued.



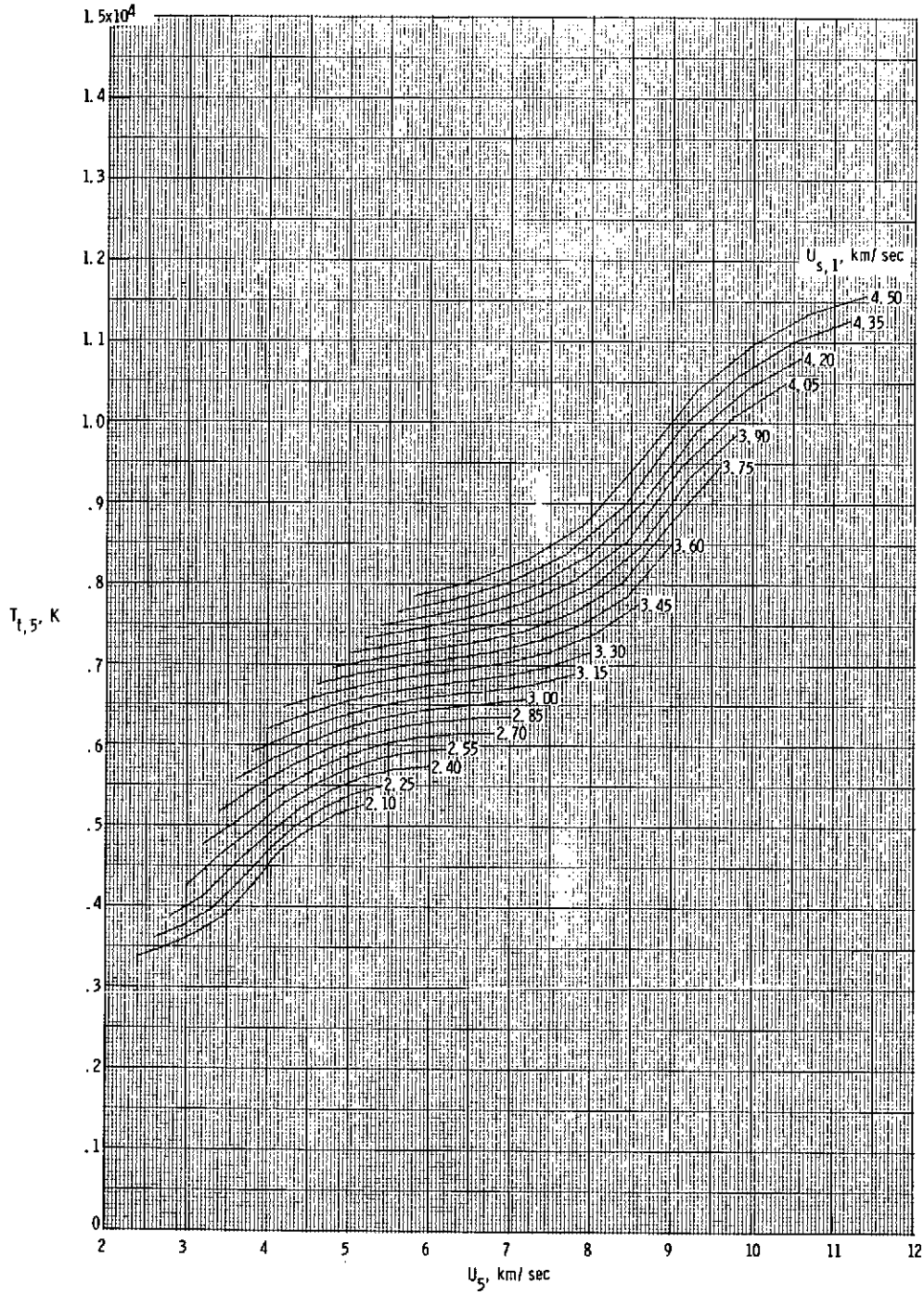
(g) Stagnation pressure behind normal bow shock.

Figure 12.- Continued.



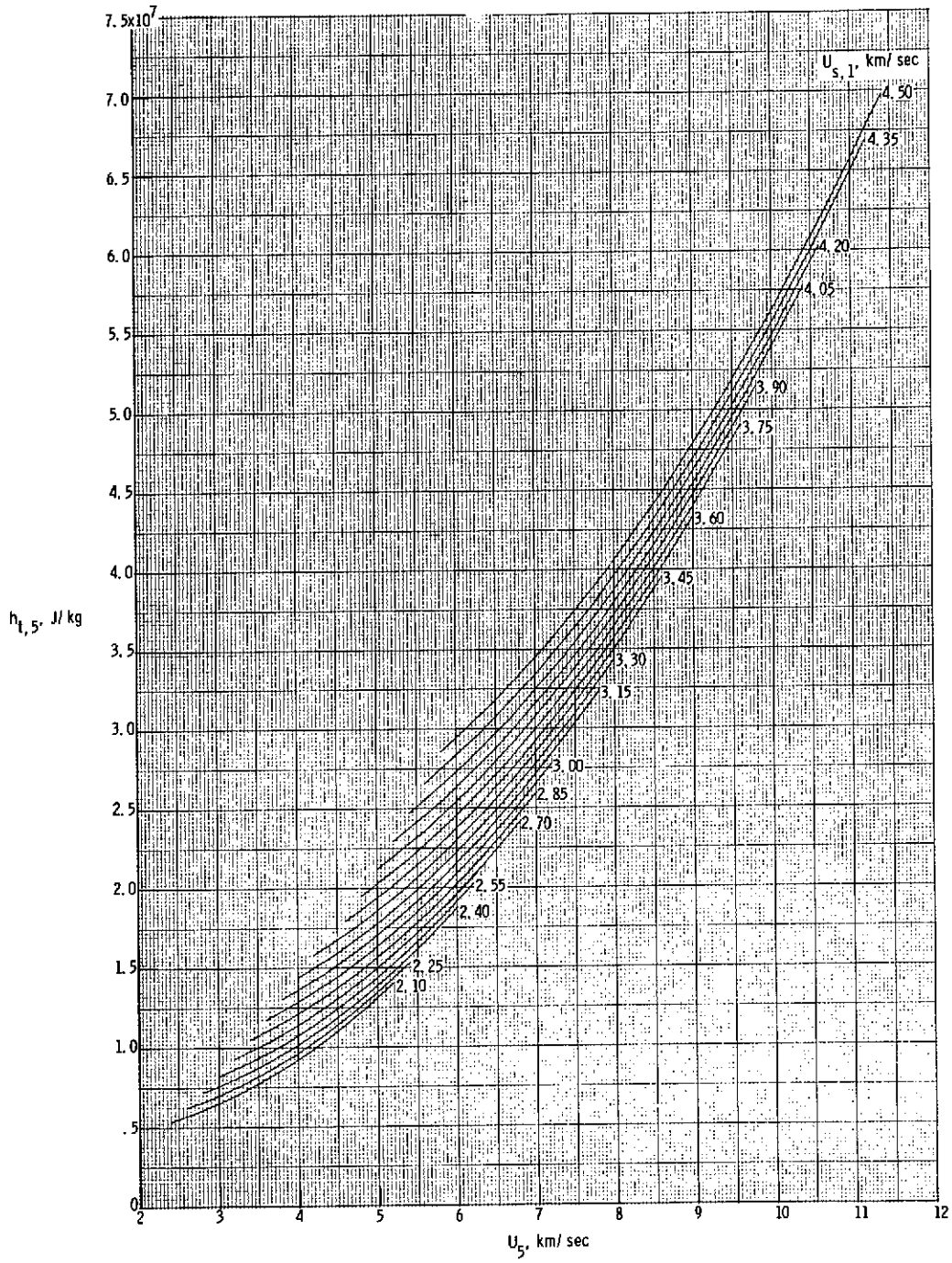
(h) Stagnation density behind normal bow shock.

Figure 12.- Continued.



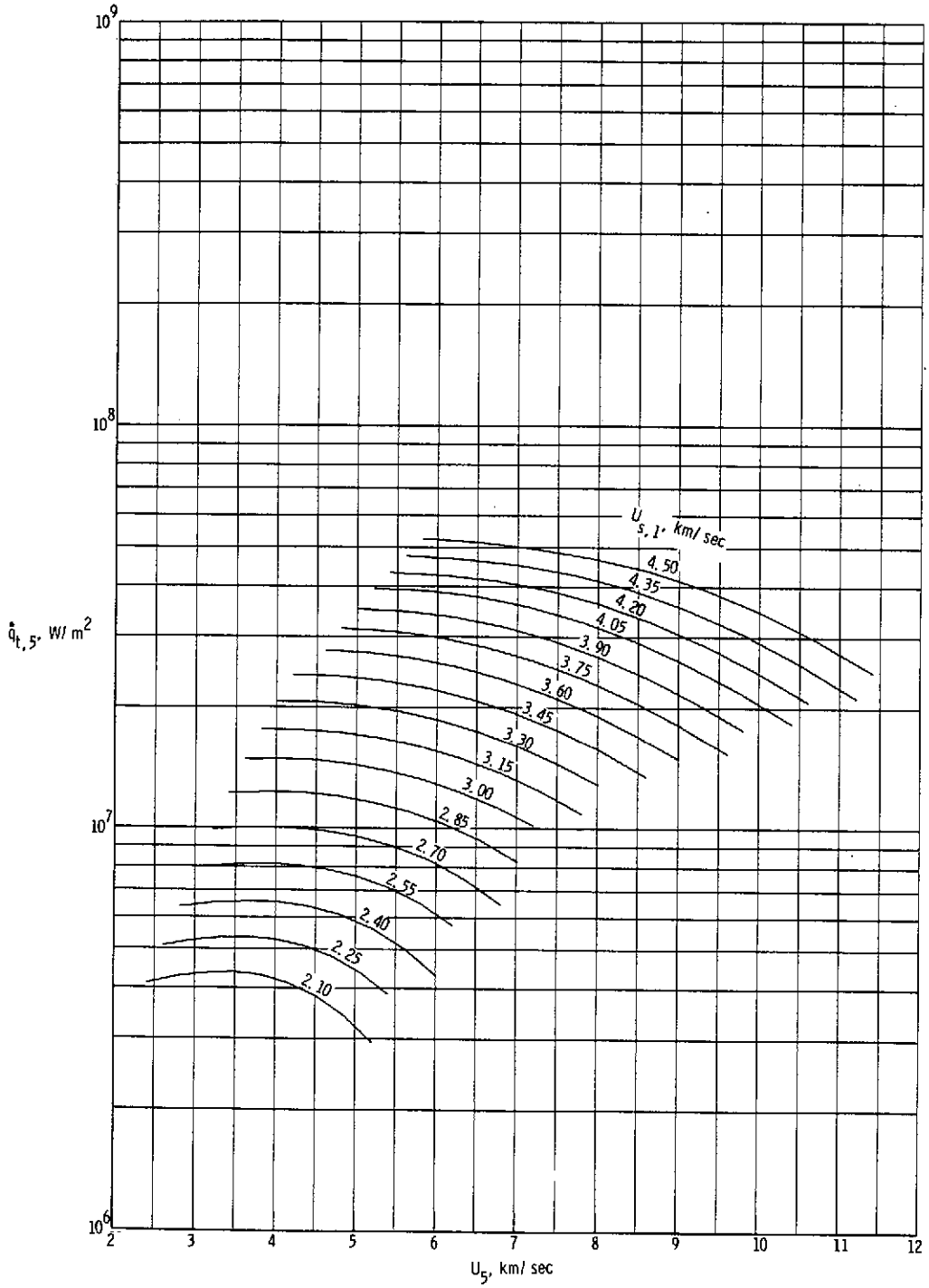
(i) Stagnation temperature behind normal bow shock.

Figure 12.- Continued.



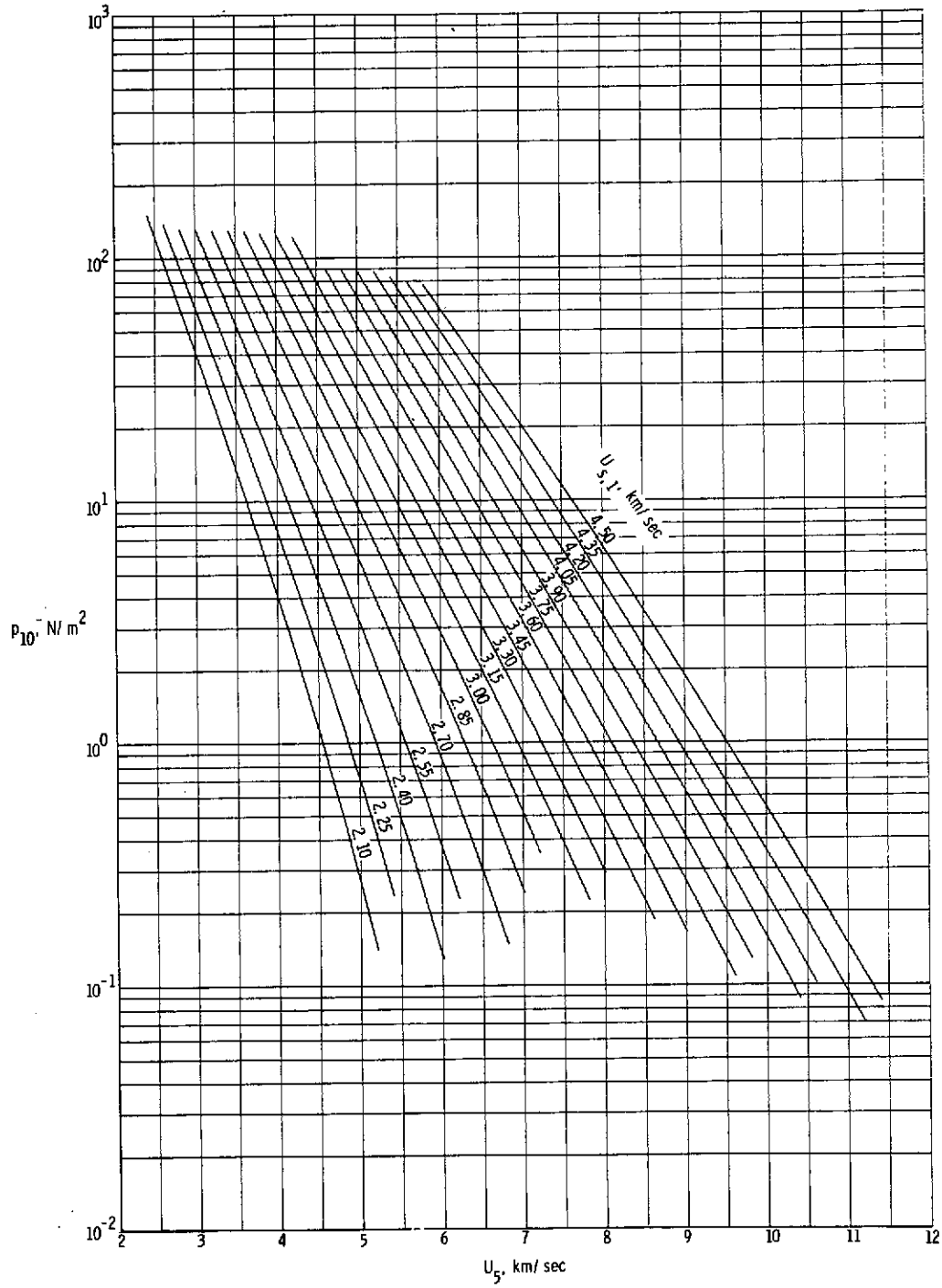
(j) Stagnation enthalpy behind normal bow shock.

Figure 12.- Continued.



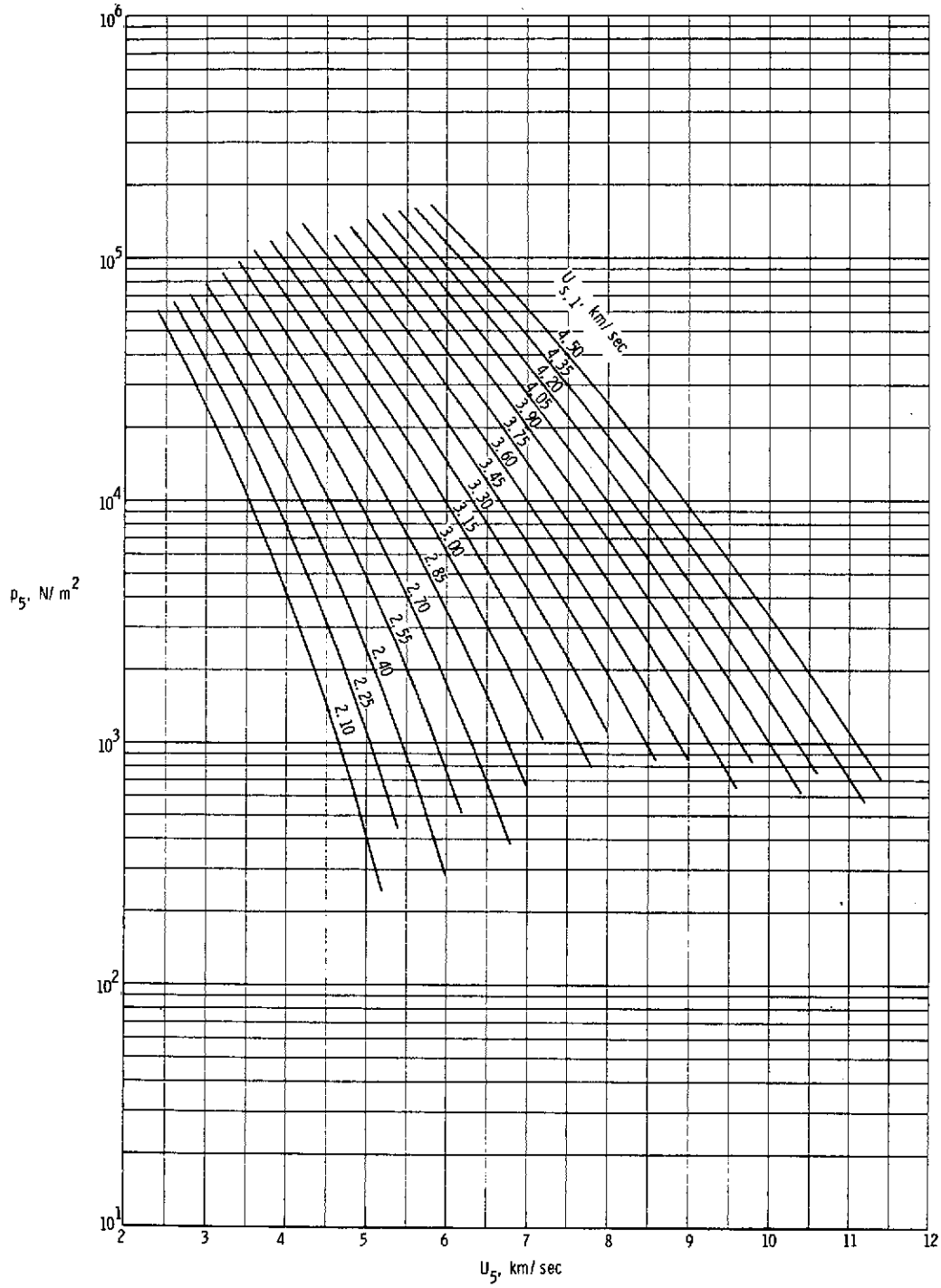
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 12.- Continued.



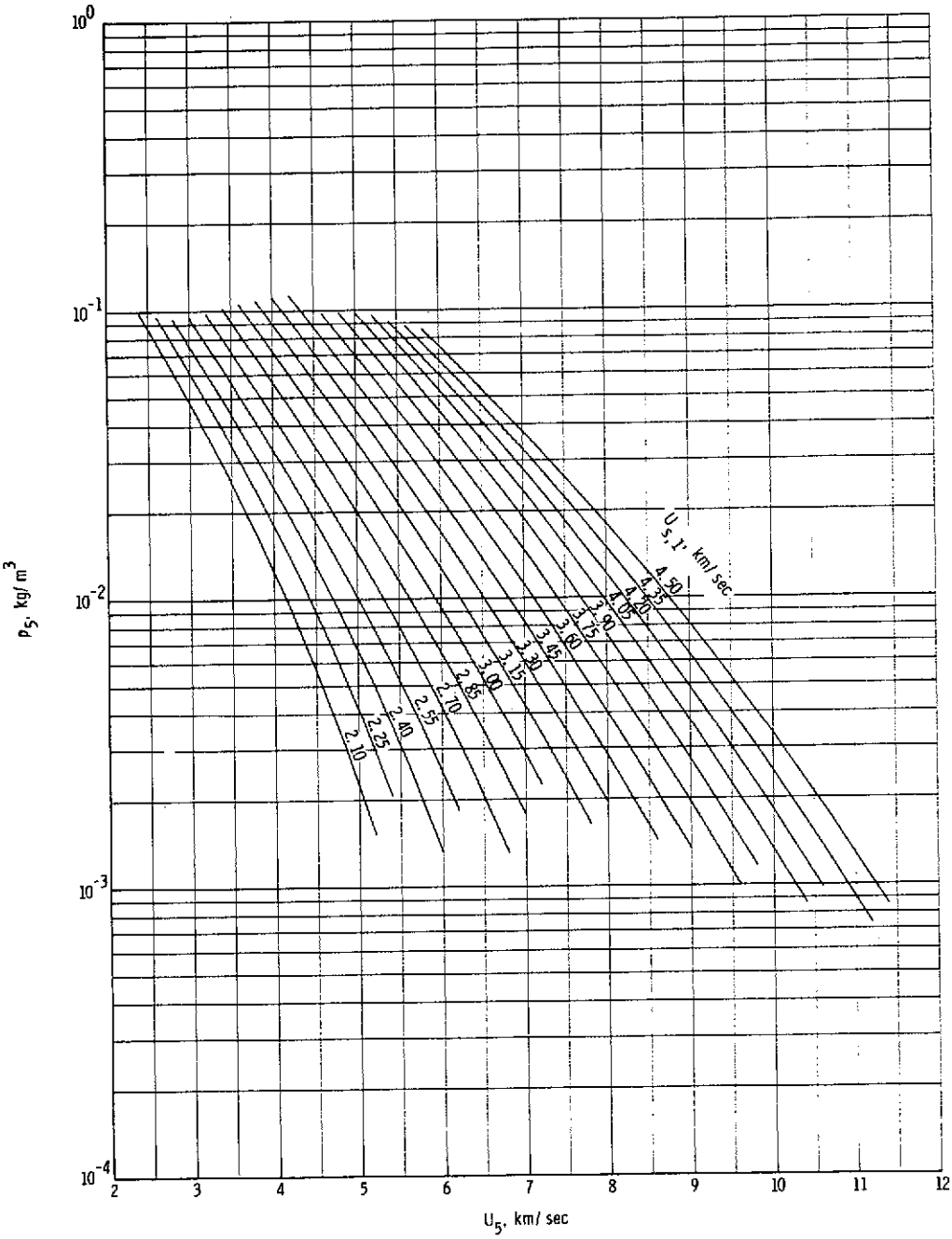
(l) Quiescent acceleration air pressure in region (10).

Figure 12.- Concluded.



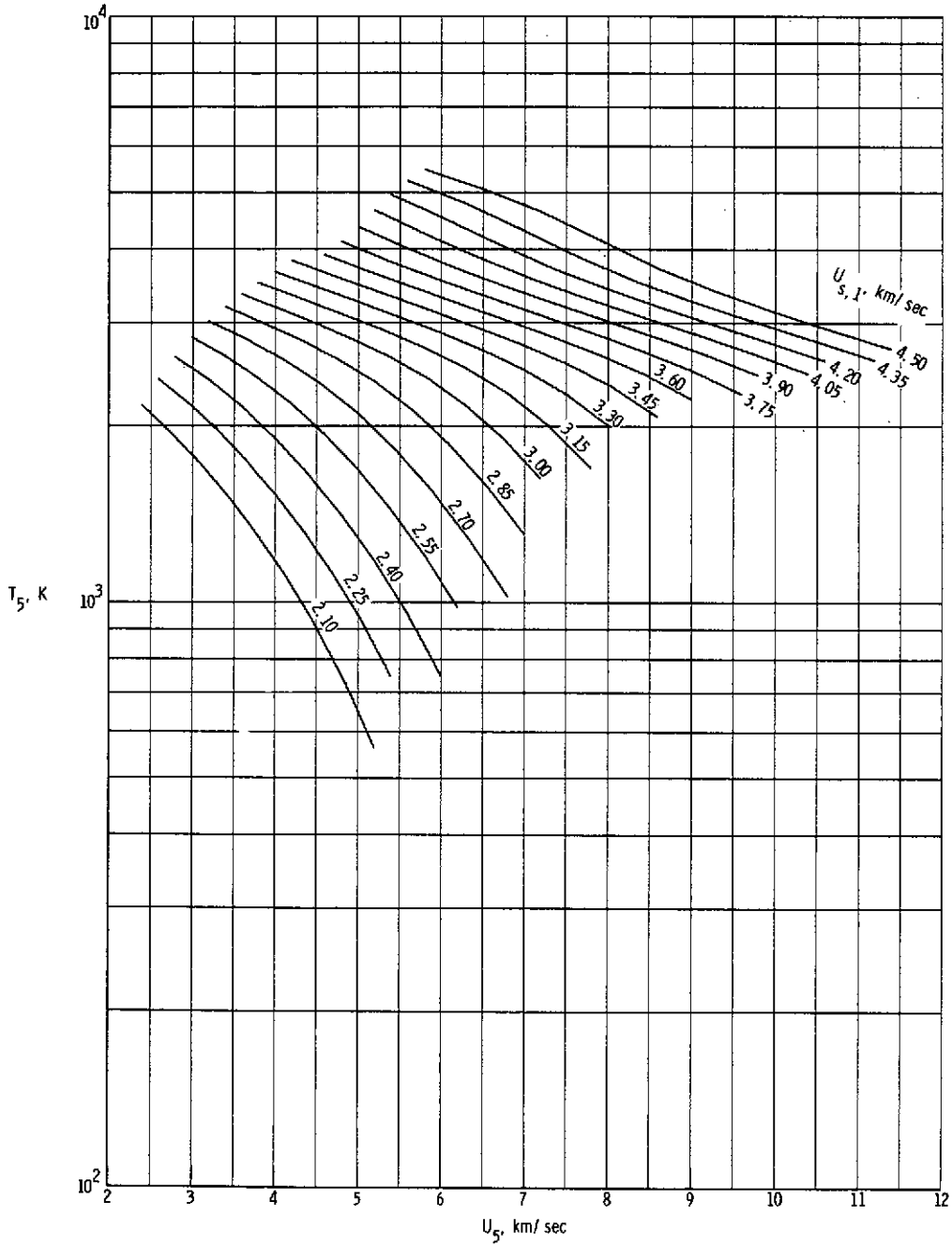
(a) Static pressure in region (5).

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. $p_1 = 3.45$ kN/m^2.



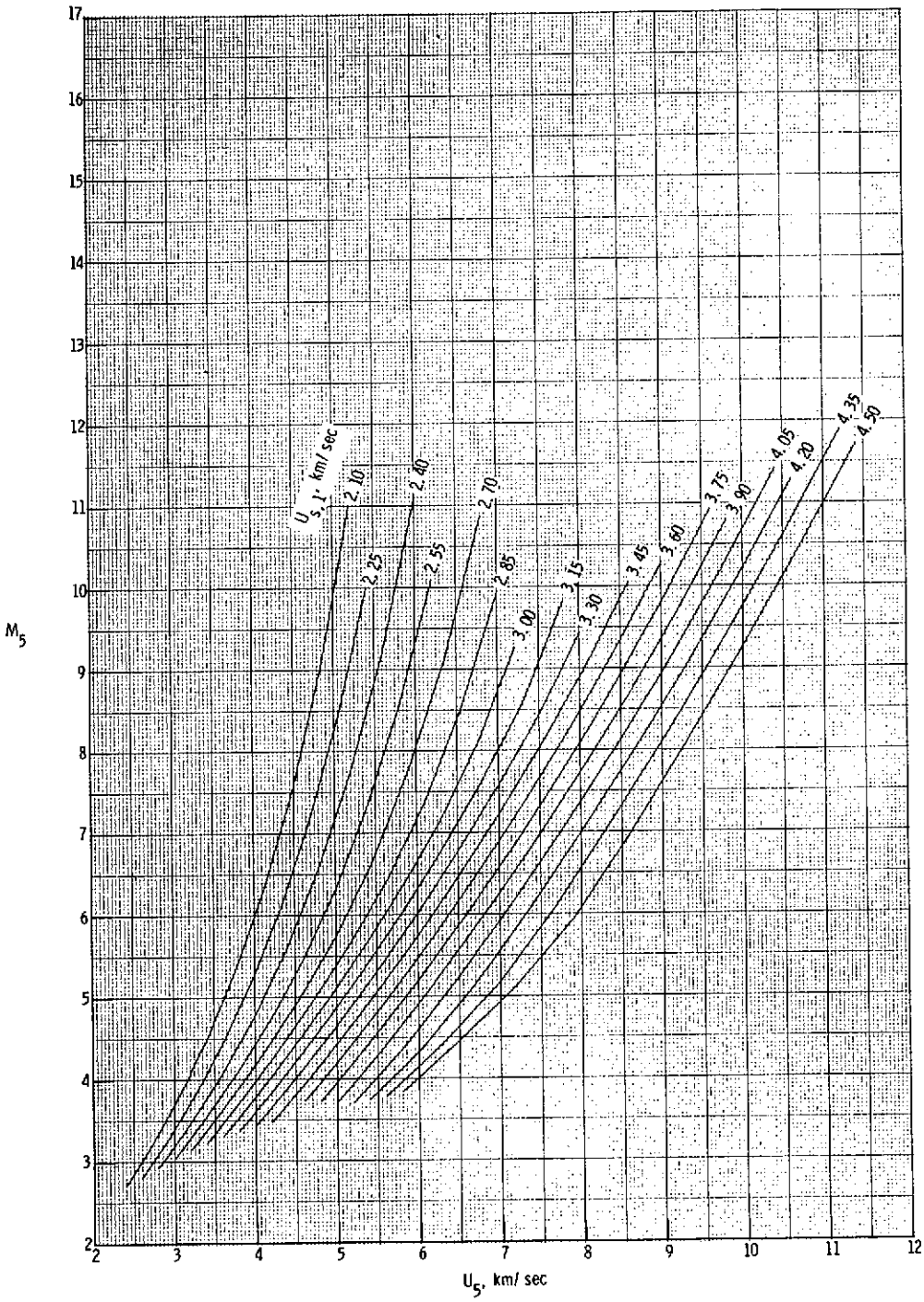
(b) Static density in region (5).

Figure 13.- Continued.



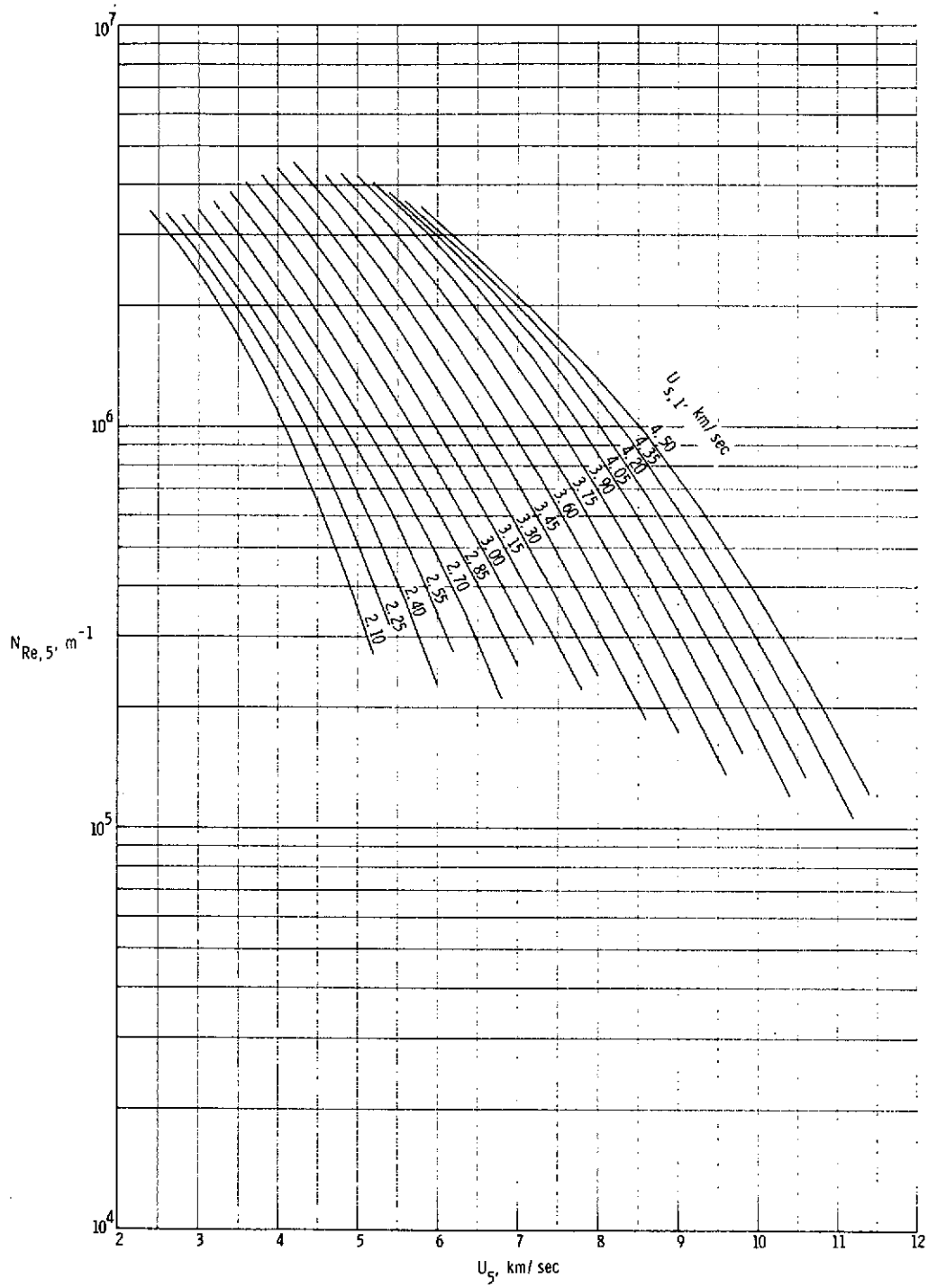
(c) Static temperature in region (5).

Figure 13.- Continued.



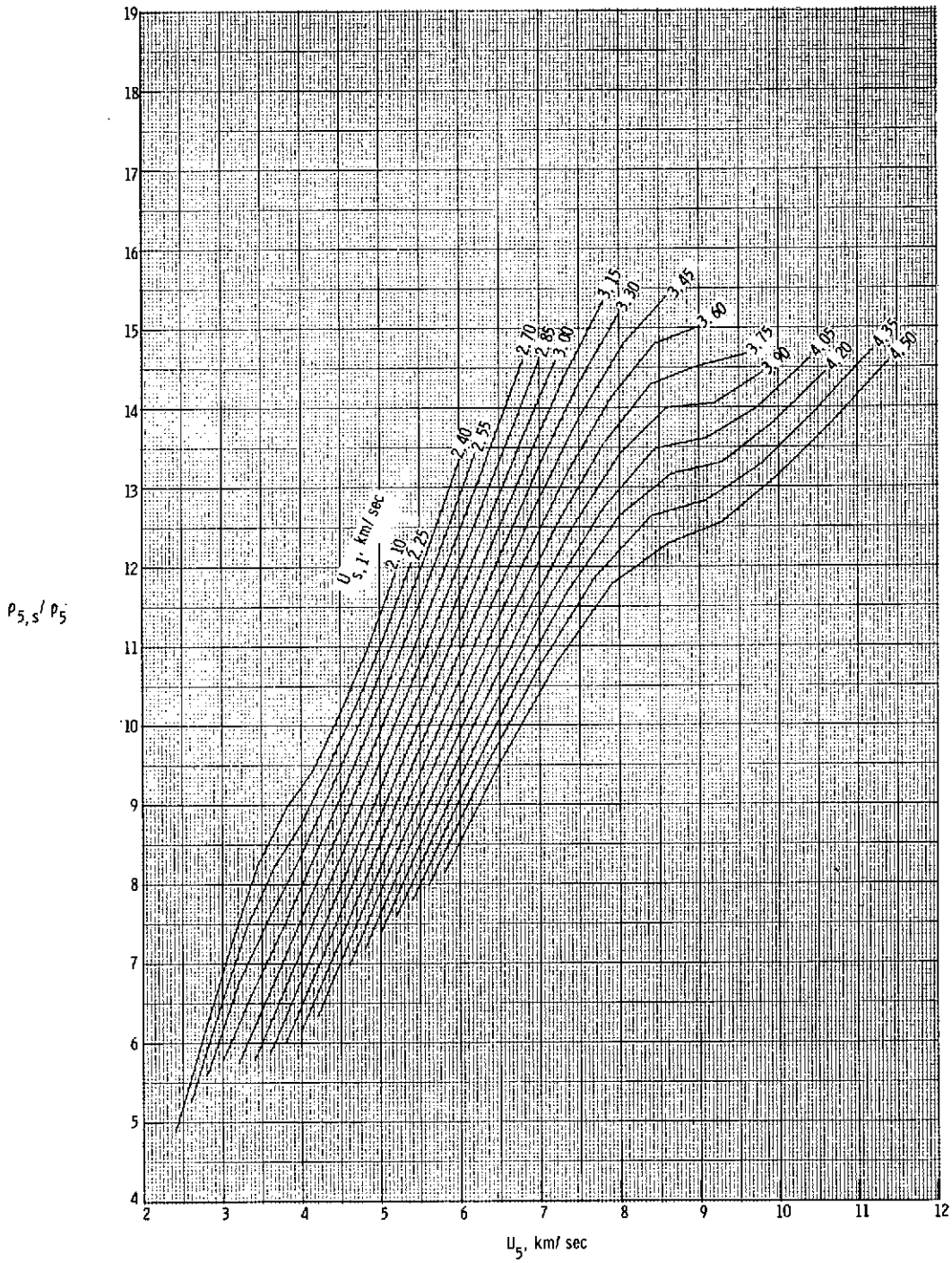
(d) Mach number in region (5).

Figure 13.- Continued.



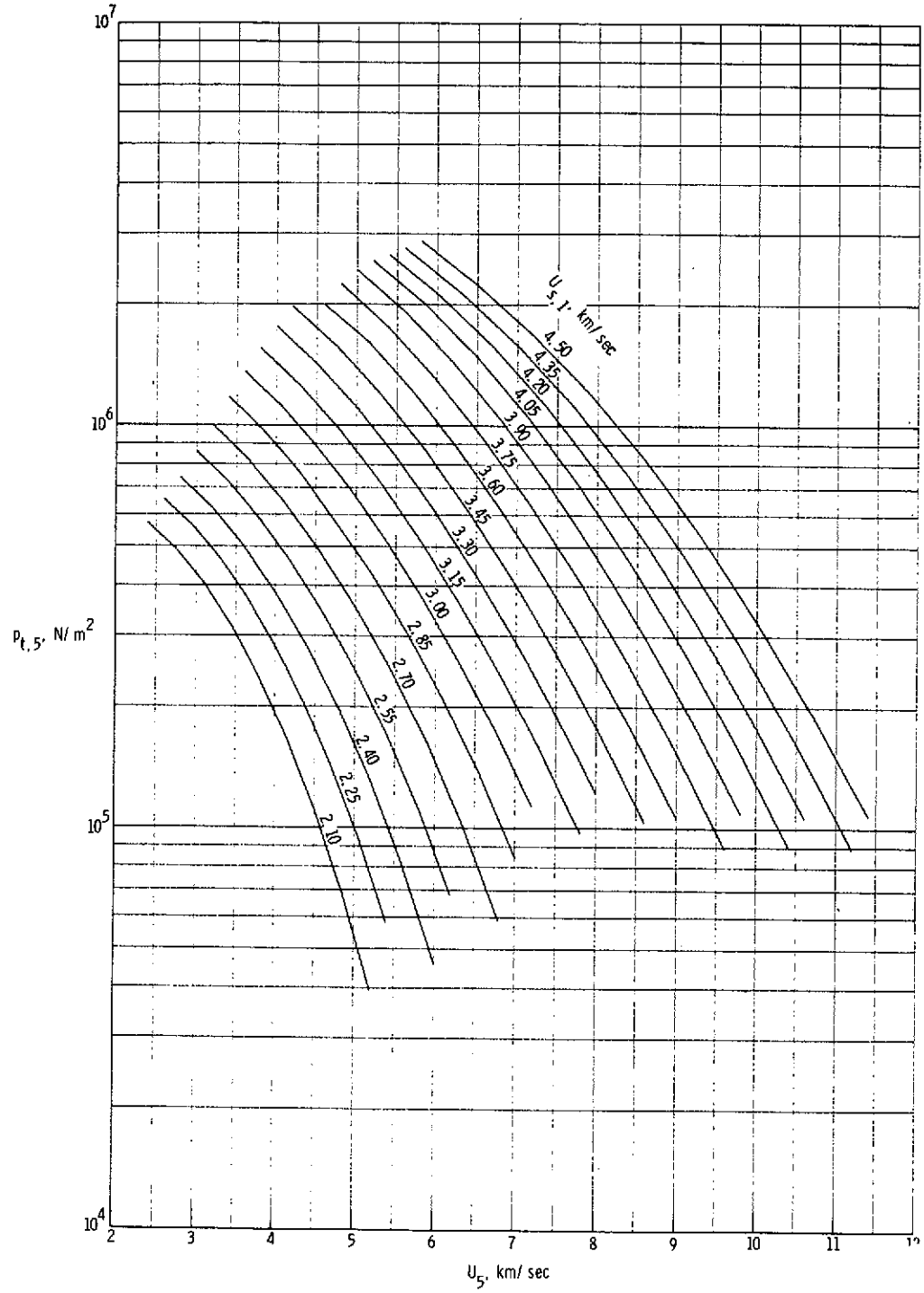
(e) Unit Reynolds number in region (5).

Figure 13.- Continued.



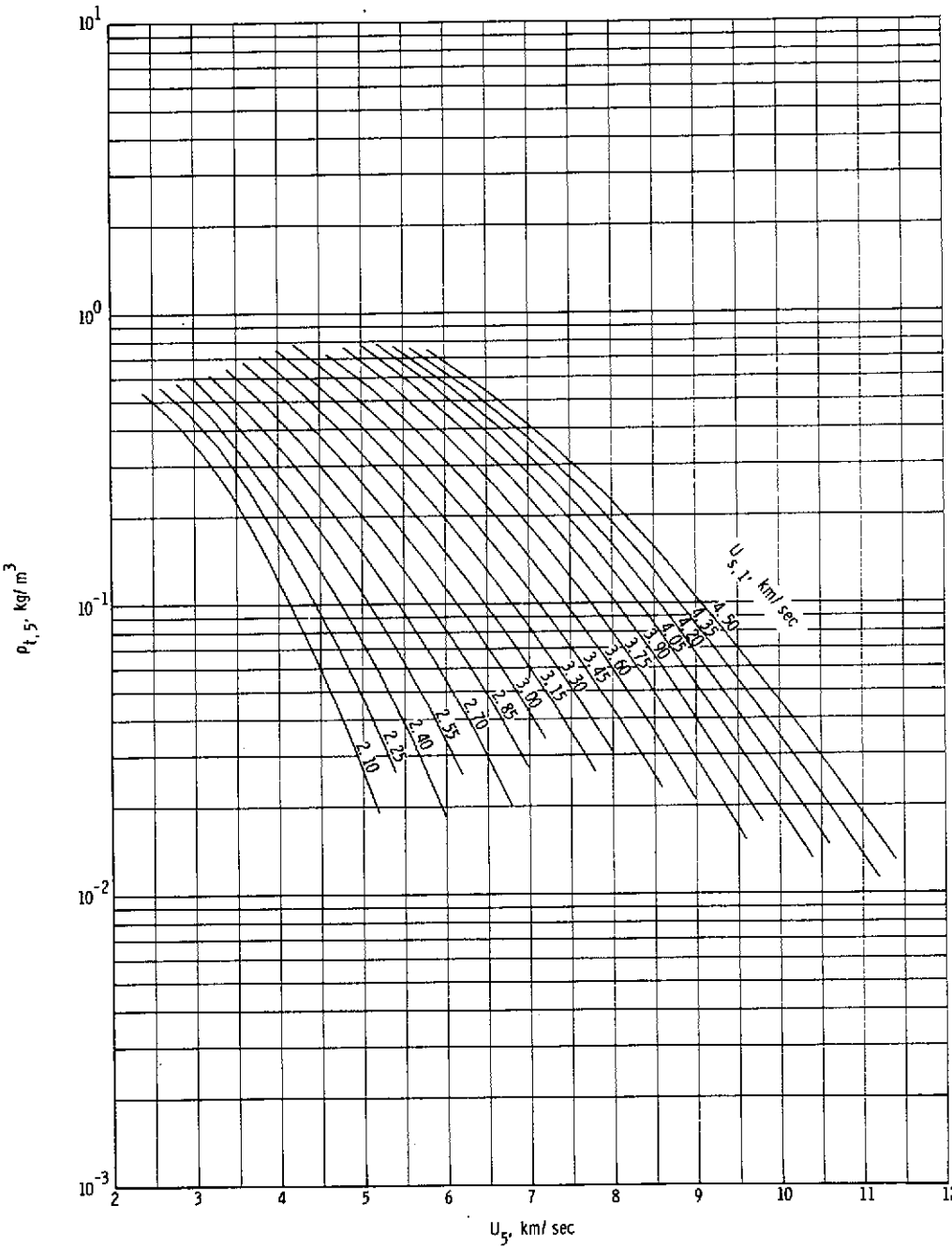
(f) Normal shock density ratio.

Figure 13.- Continued.



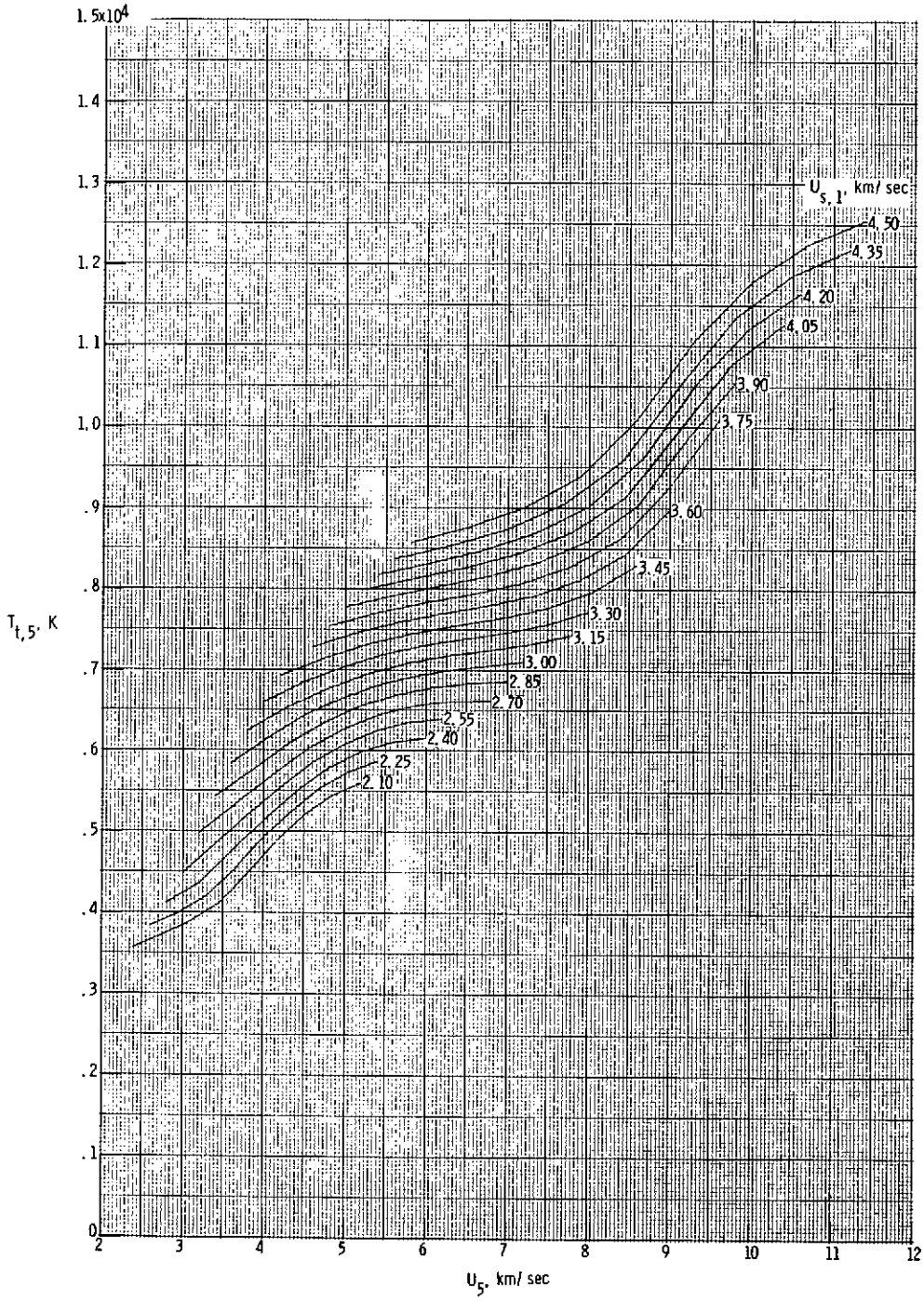
(g) Stagnation pressure behind normal bow shock.

Figure 13.- Continued.



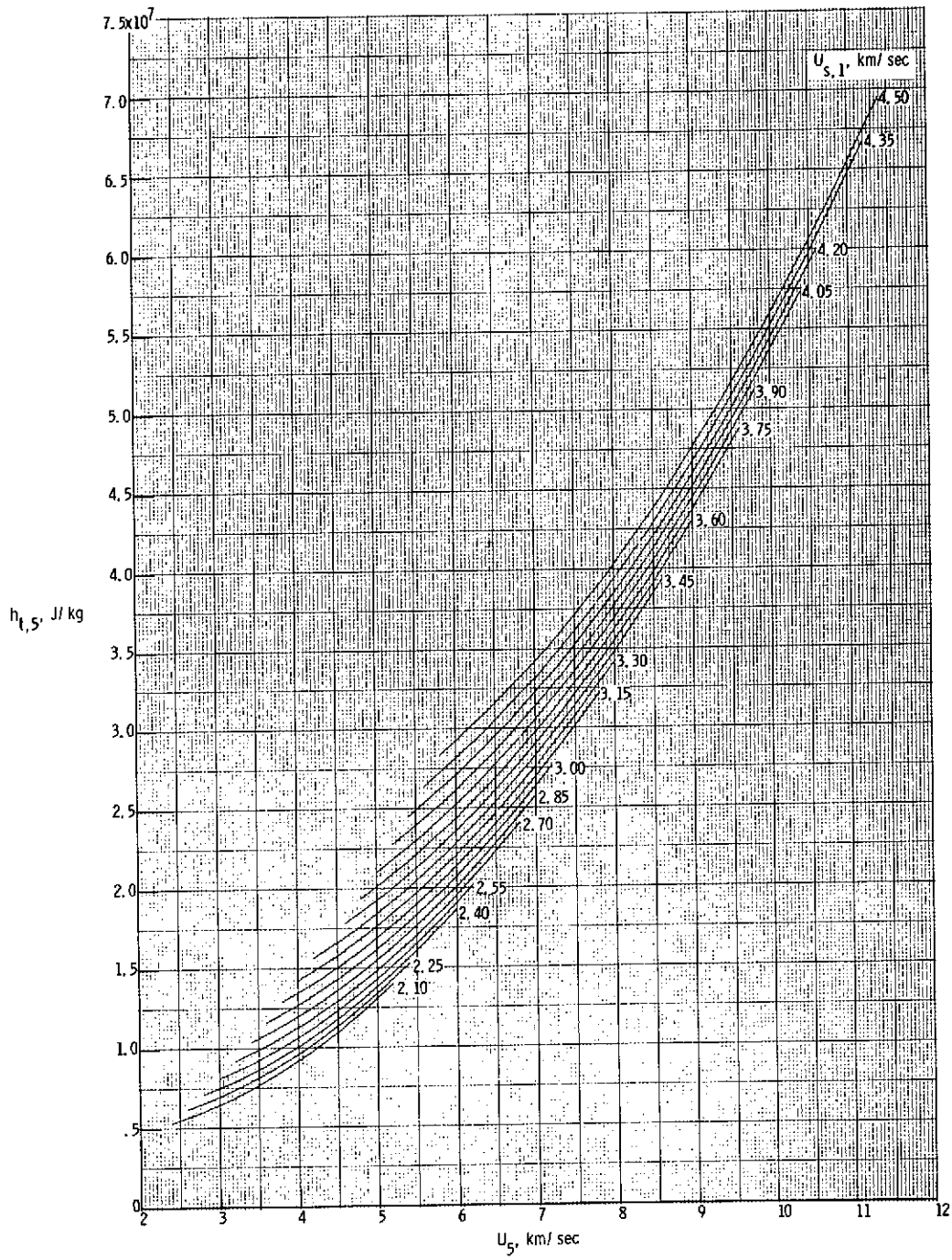
(h) Stagnation density behind normal bow shock.

Figure 13.- Continued.



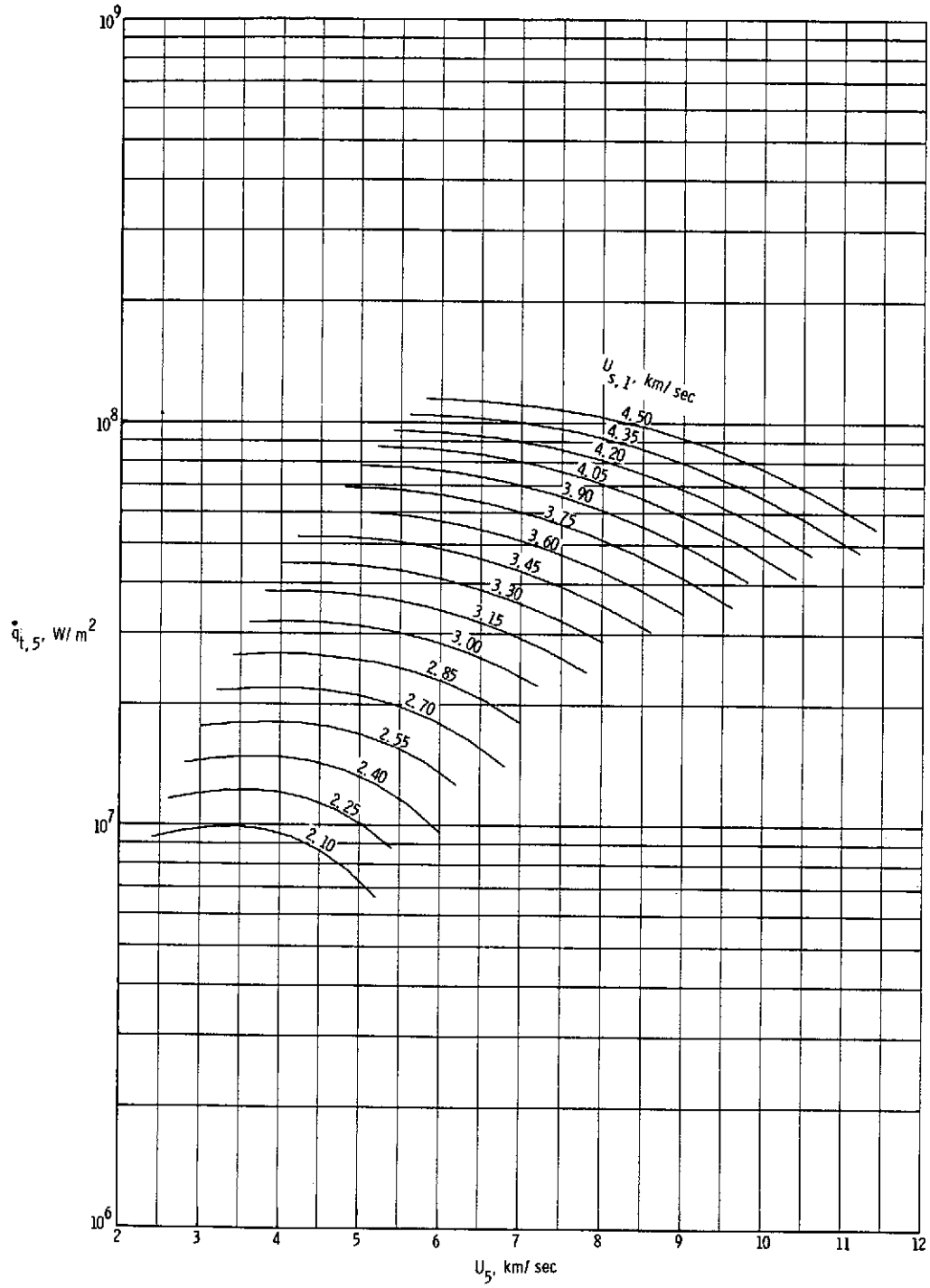
(i) Stagnation temperature behind normal bow shock.

Figure 13.- Continued.



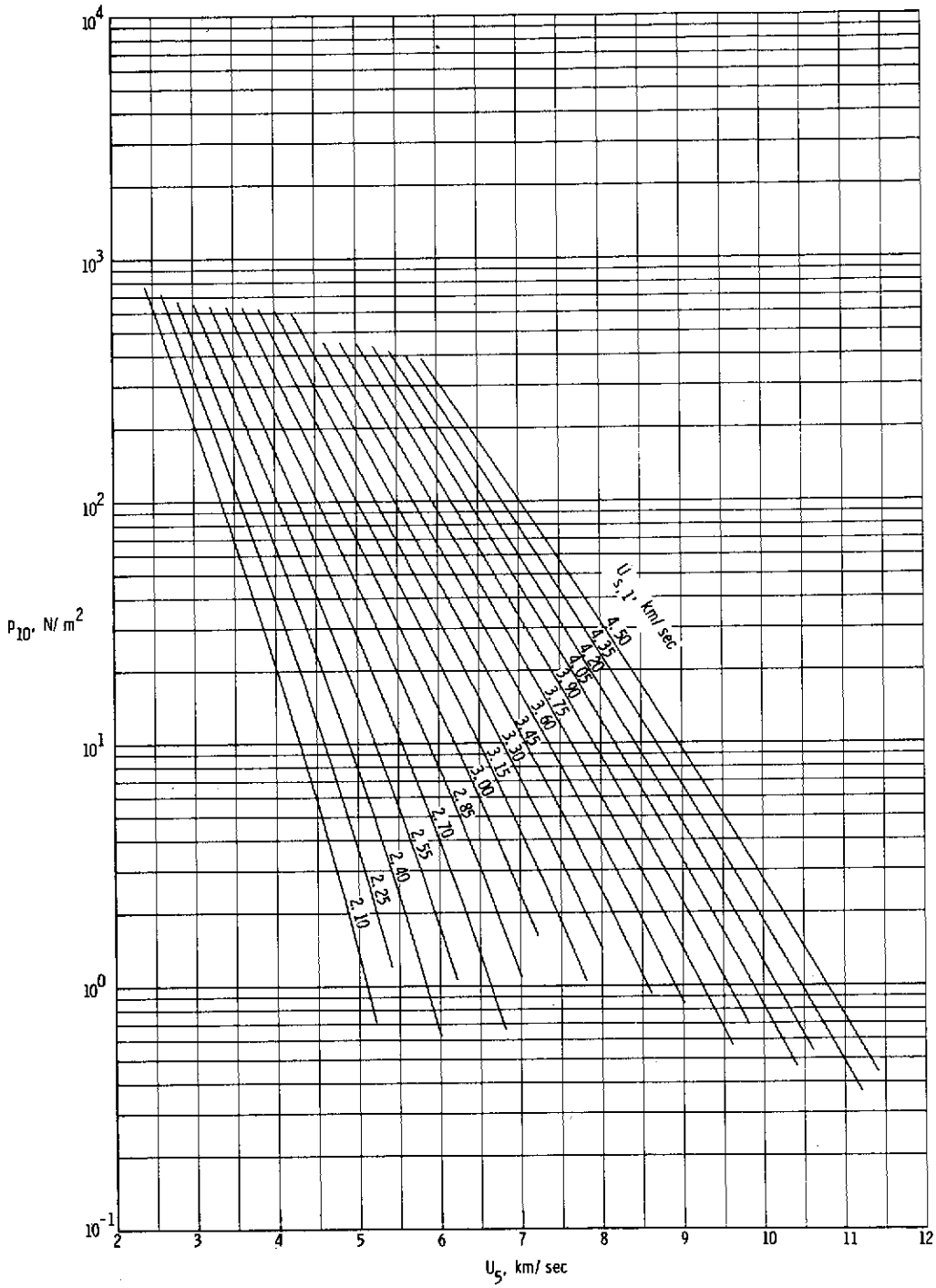
(j) Stagnation enthalpy behind normal bow shock.

Figure 13.- Continued.



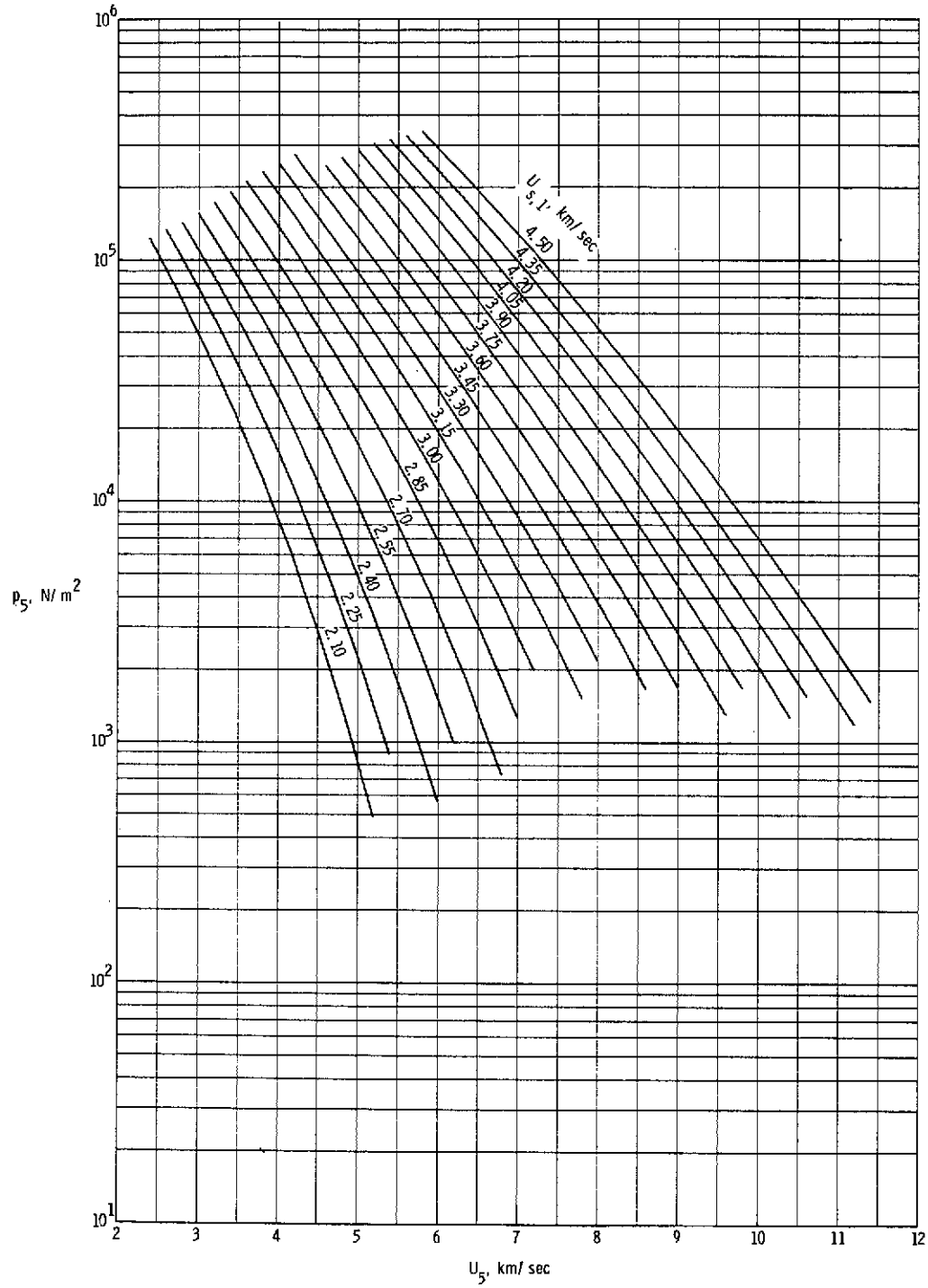
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 13.- Continued.



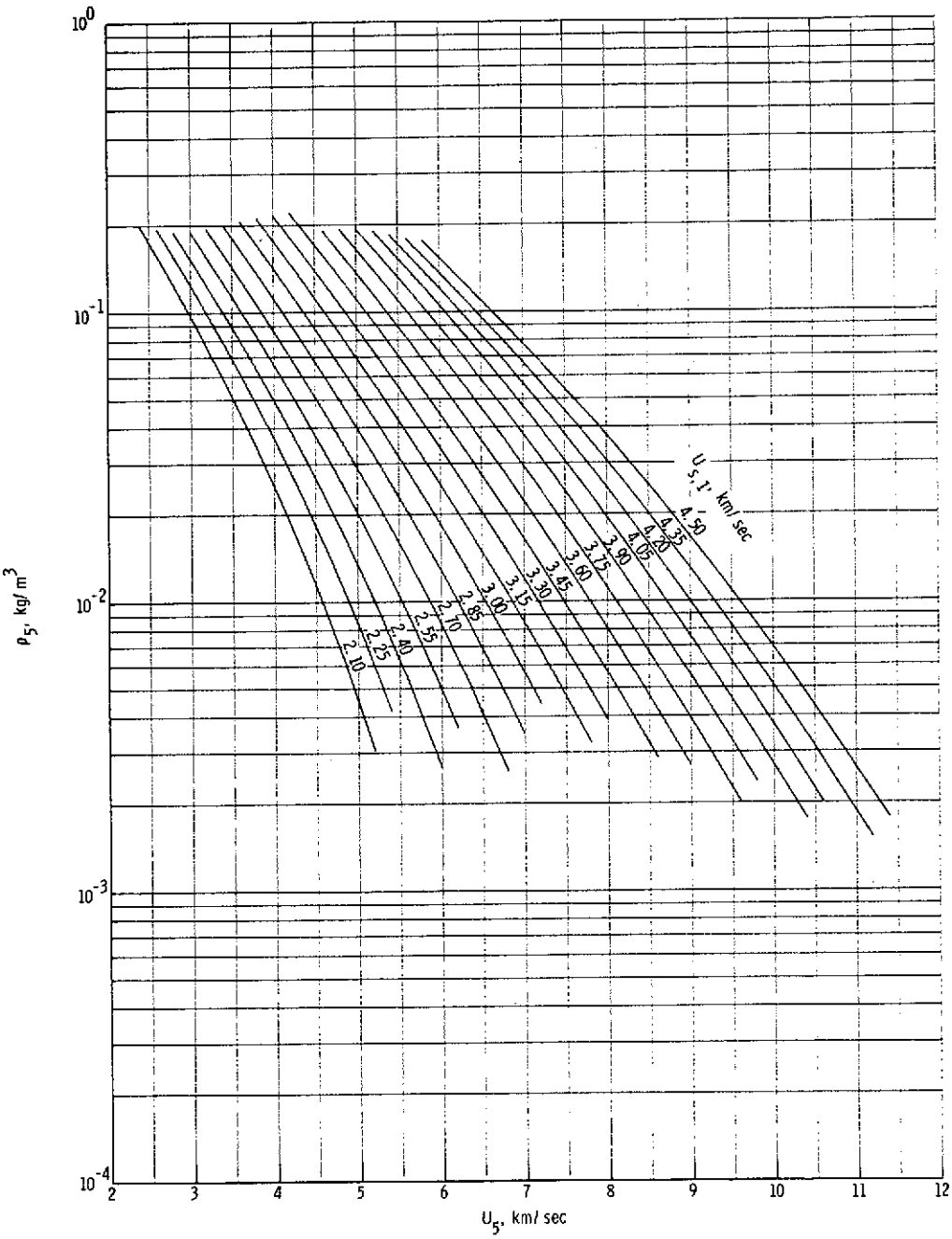
(l) Quiescent acceleration air pressure in region (10).

Figure 13.- Concluded.



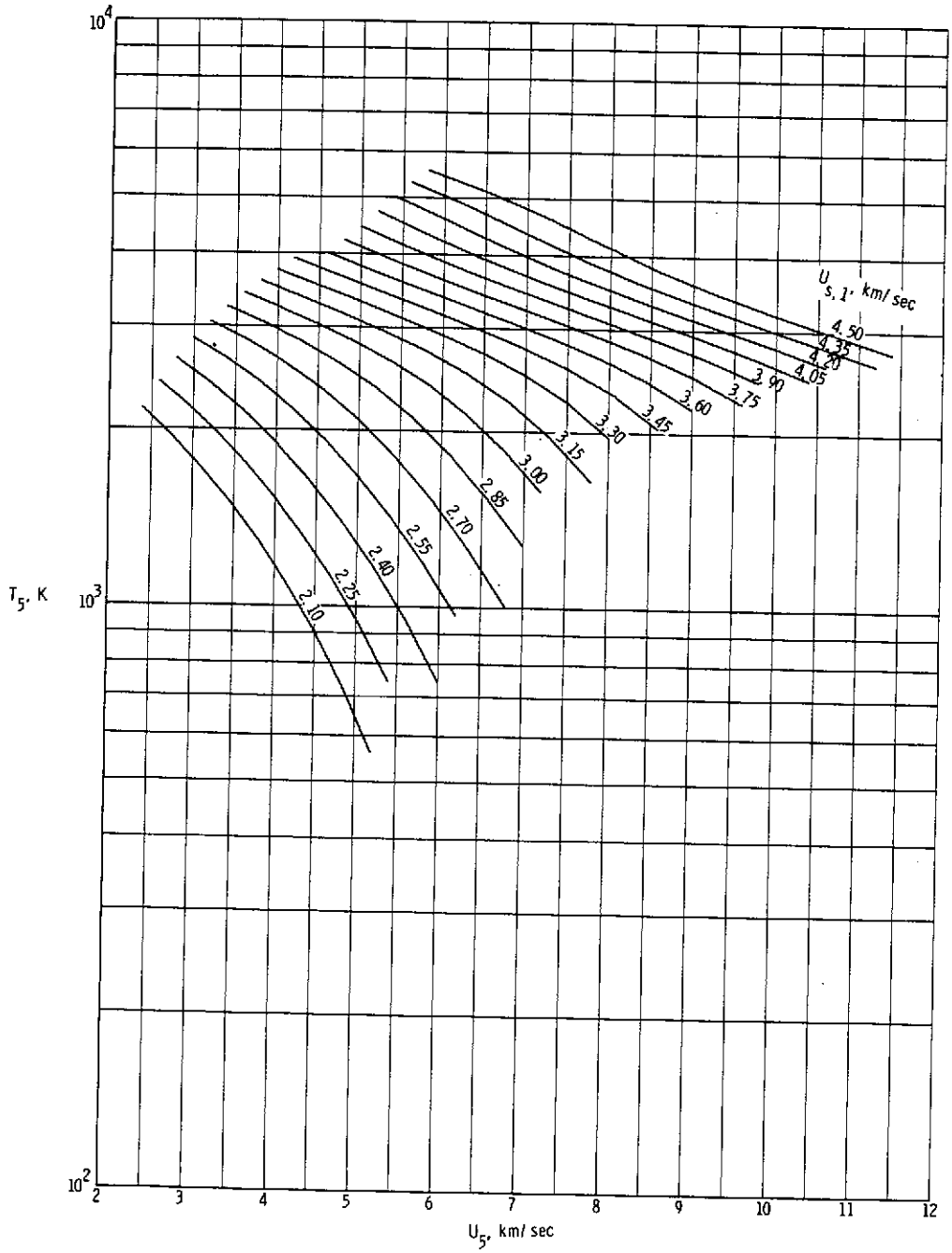
(a) Static pressure in region (5).

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 kN/m^2.



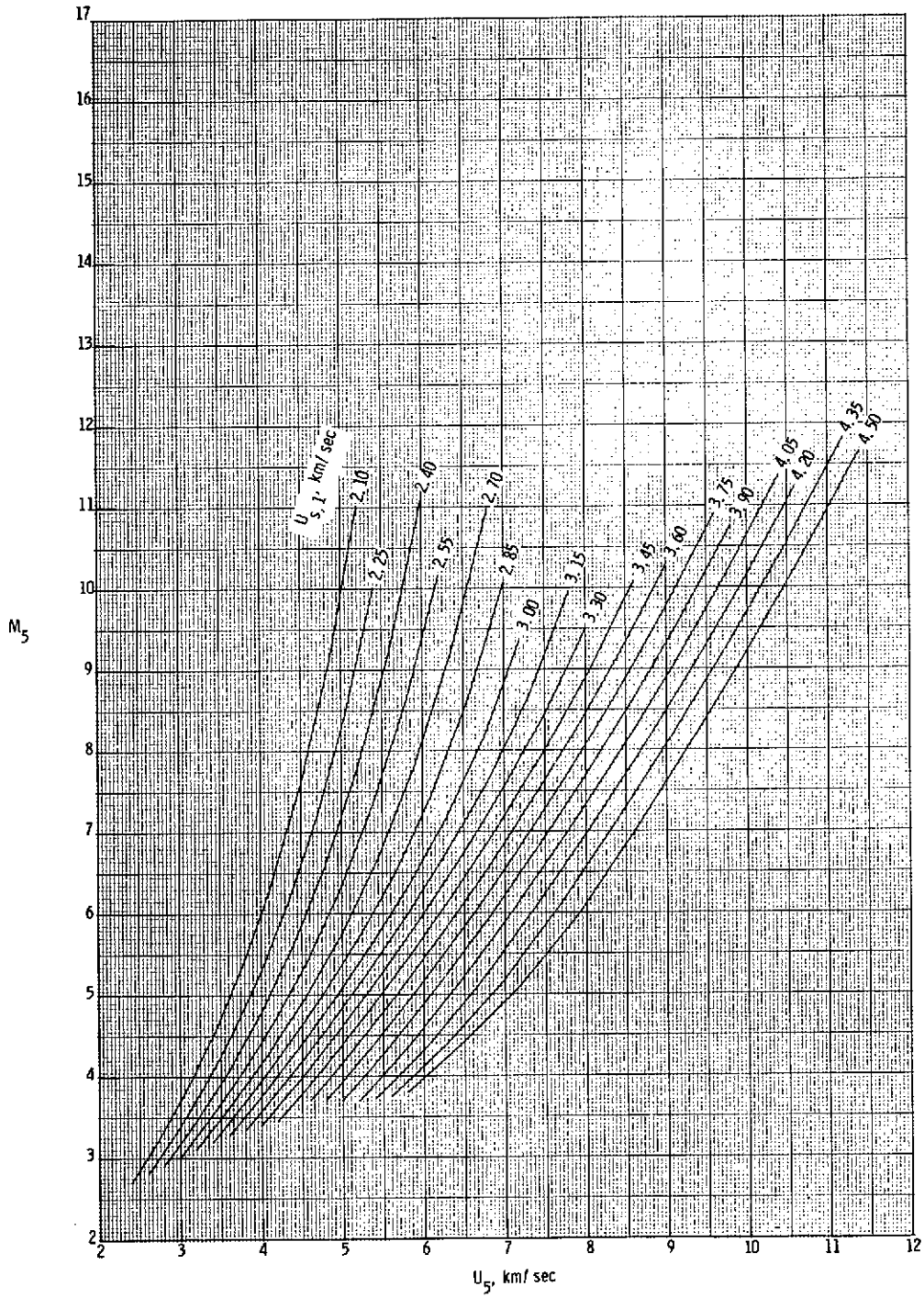
(b) Static density in region (5).

Figure 14.- Continued.



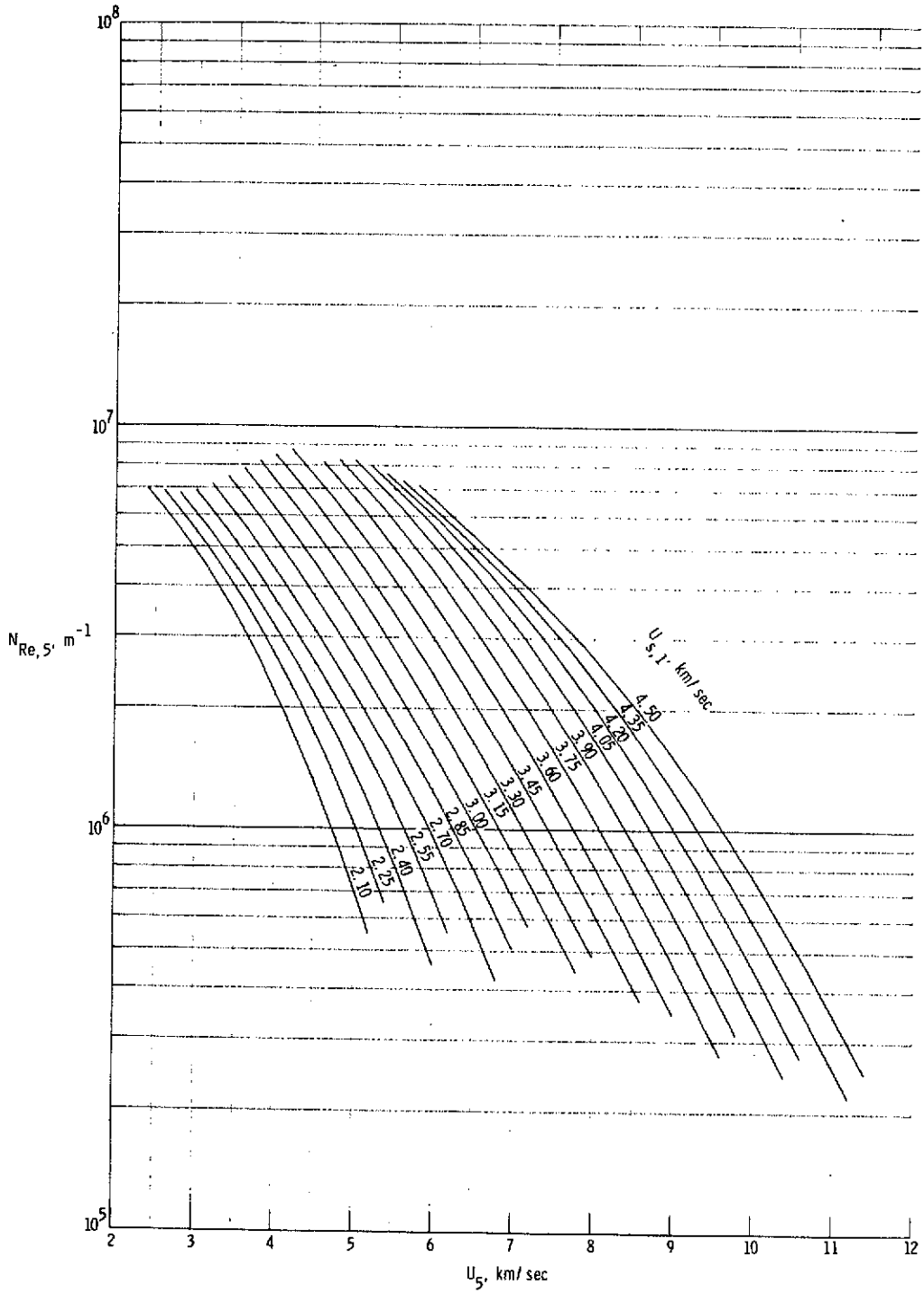
(c) Static temperature in region (5).

Figure 14.- Continued.



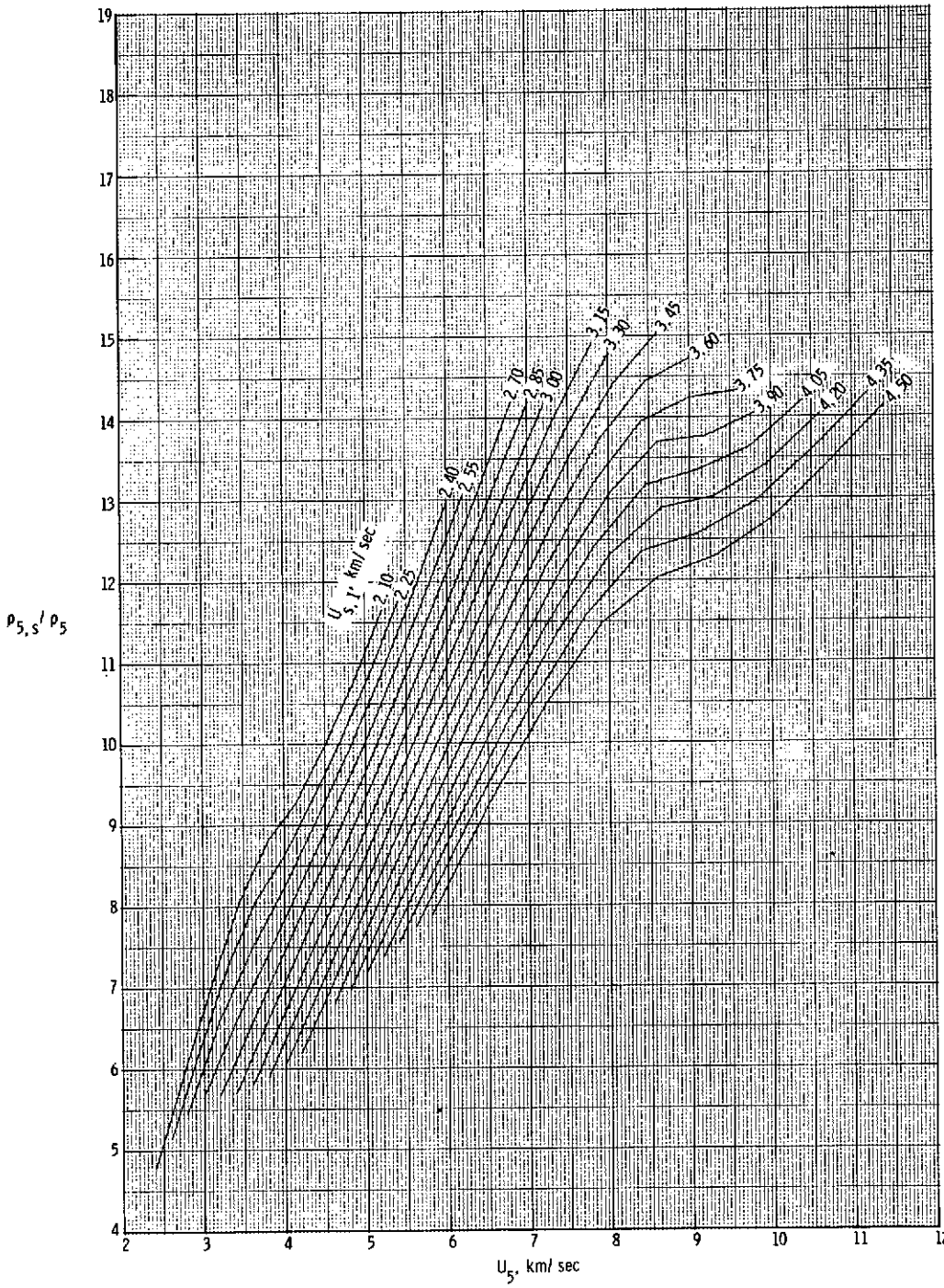
(d) Mach number in region (5).

Figure 14.- Continued.



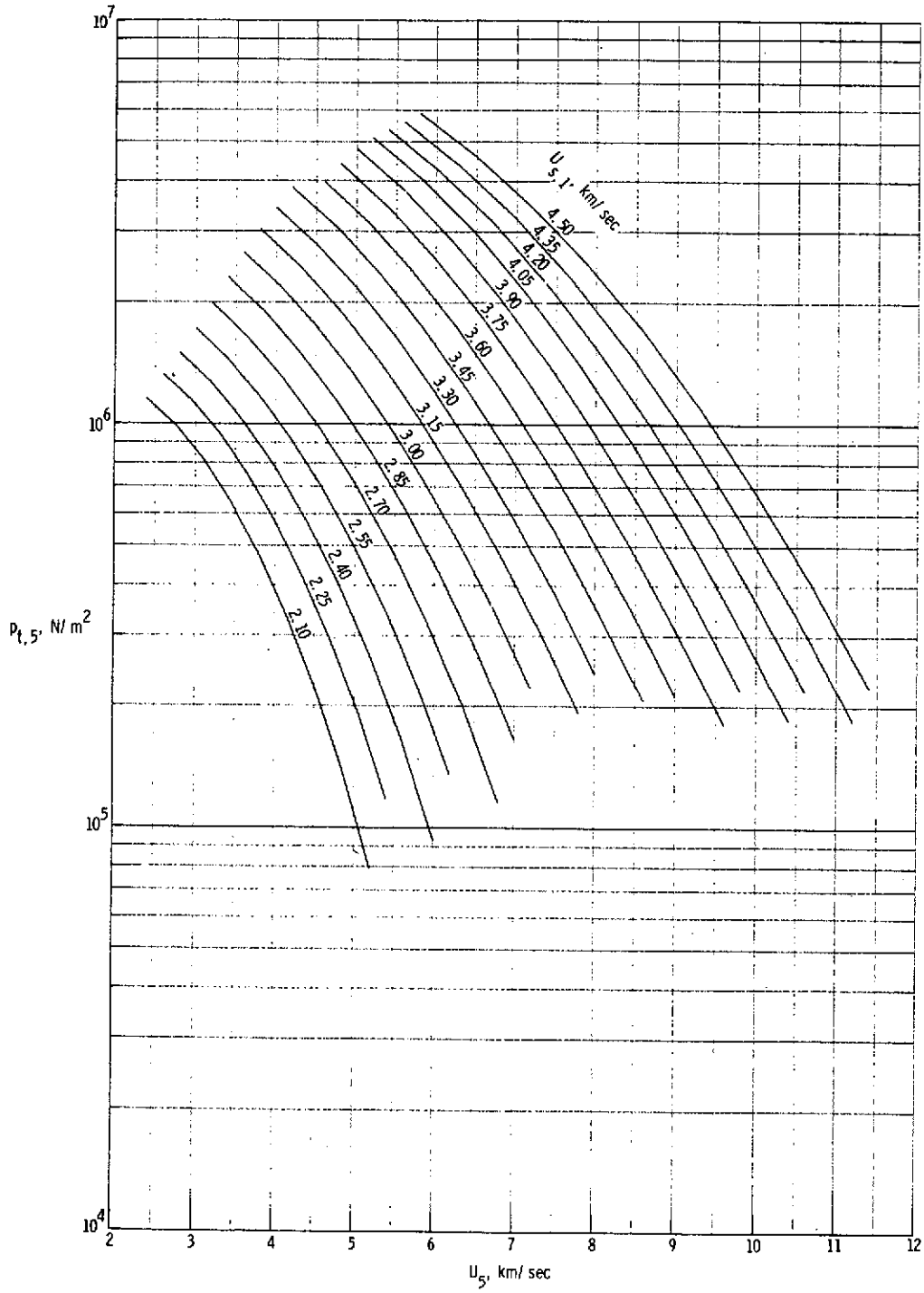
(e) Unit Reynolds number in region (5).

Figure 14.- Continued.



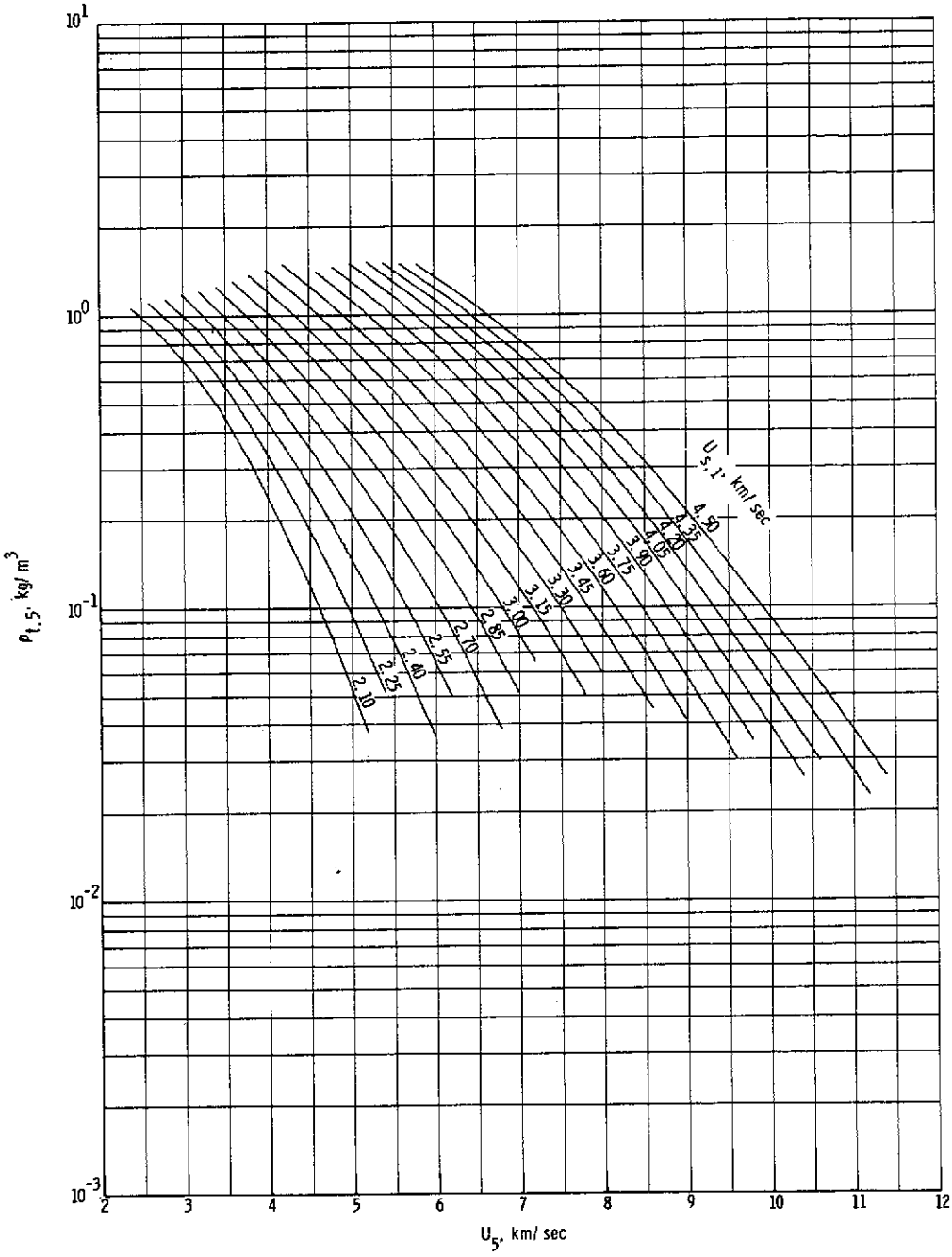
(f) Normal shock density ratio.

Figure 14.- Continued.



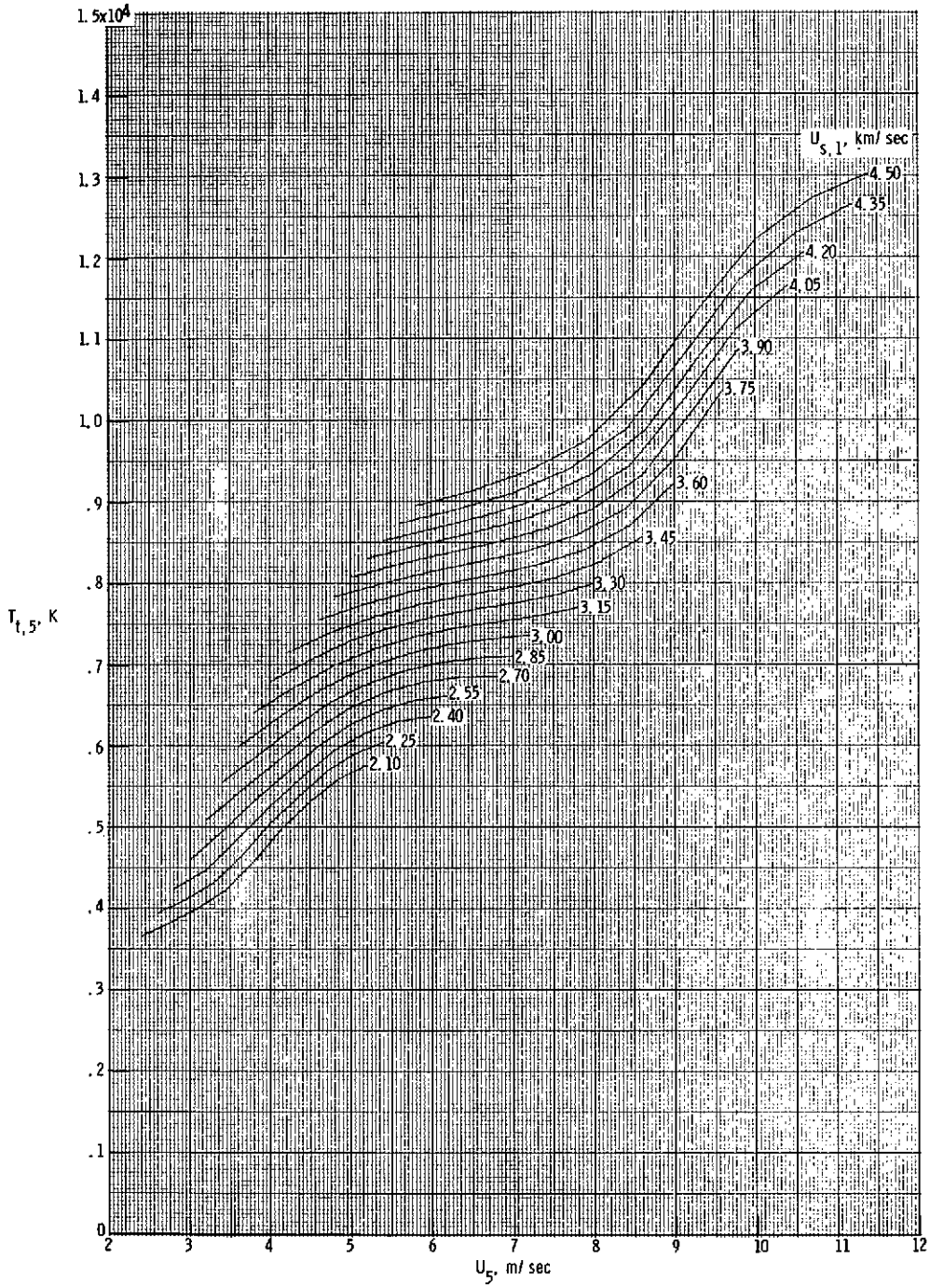
(g) Stagnation pressure behind normal bow shock.

Figure 14.- Continued.



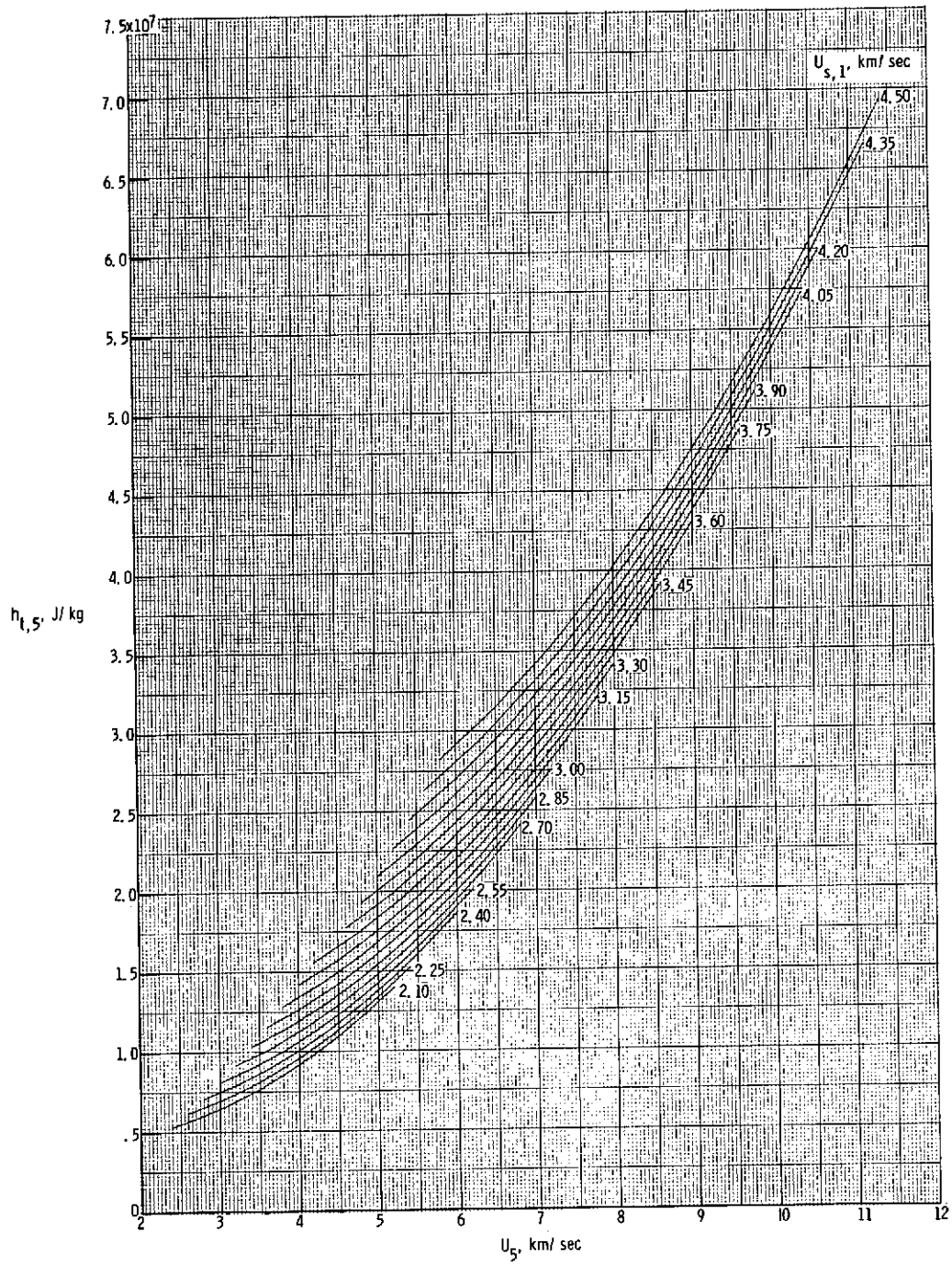
(h) Stagnation density behind normal bow shock.

Figure 14.- Continued.



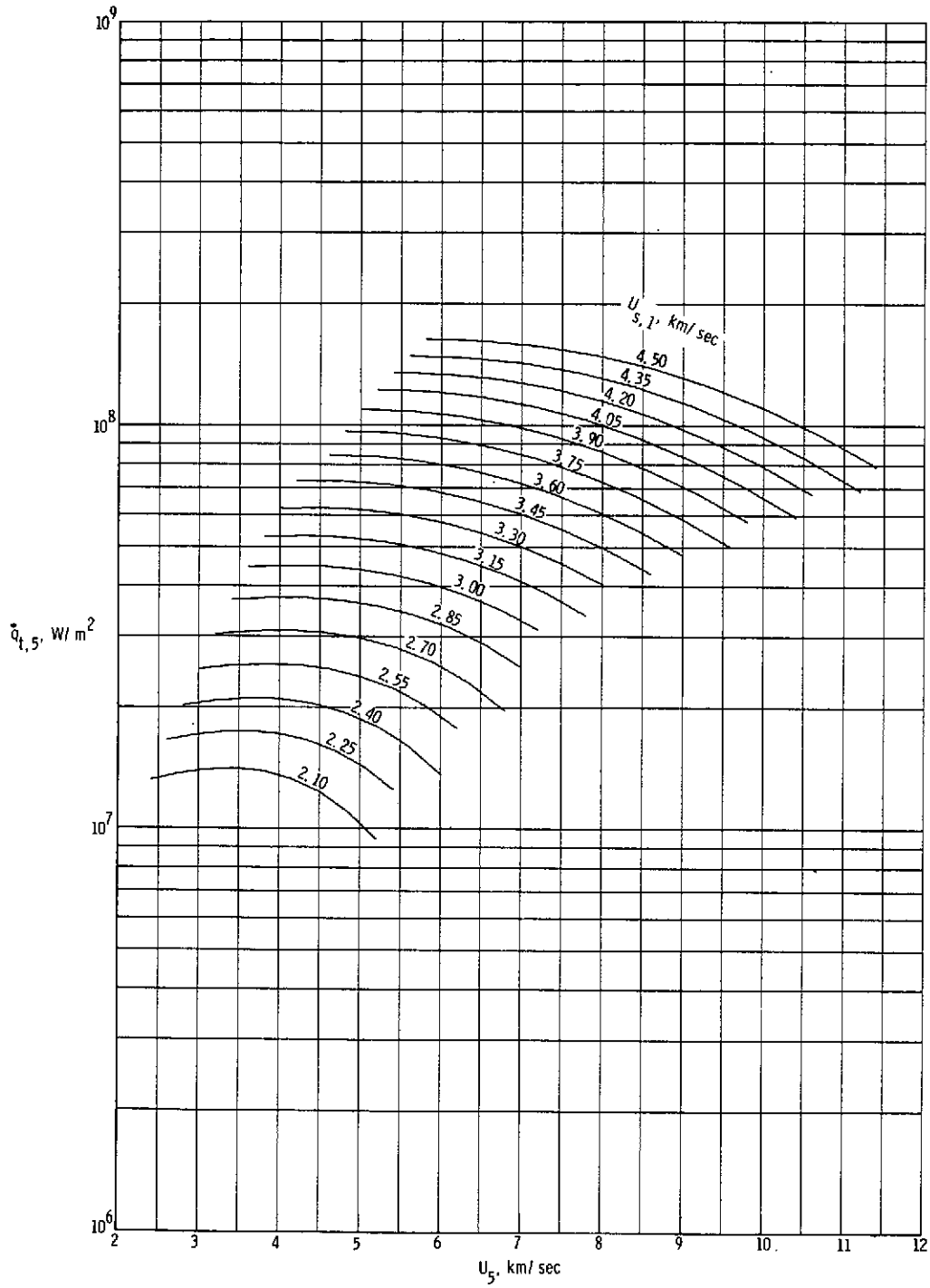
(i) Stagnation temperature behind normal bow shock.

Figure 14.- Continued.



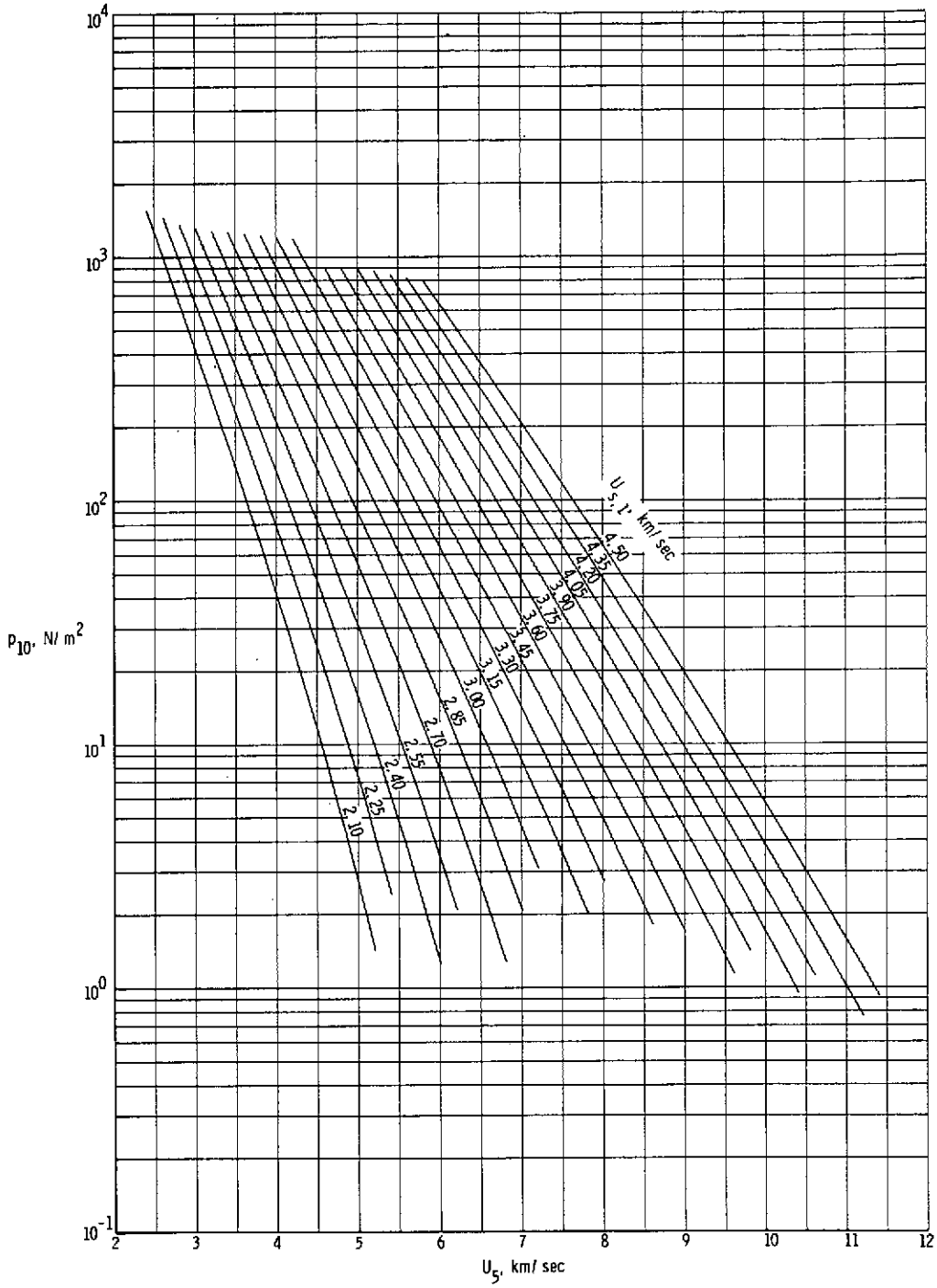
(j) Stagnation enthalpy behind normal bow shock.

Figure 14.- Continued.



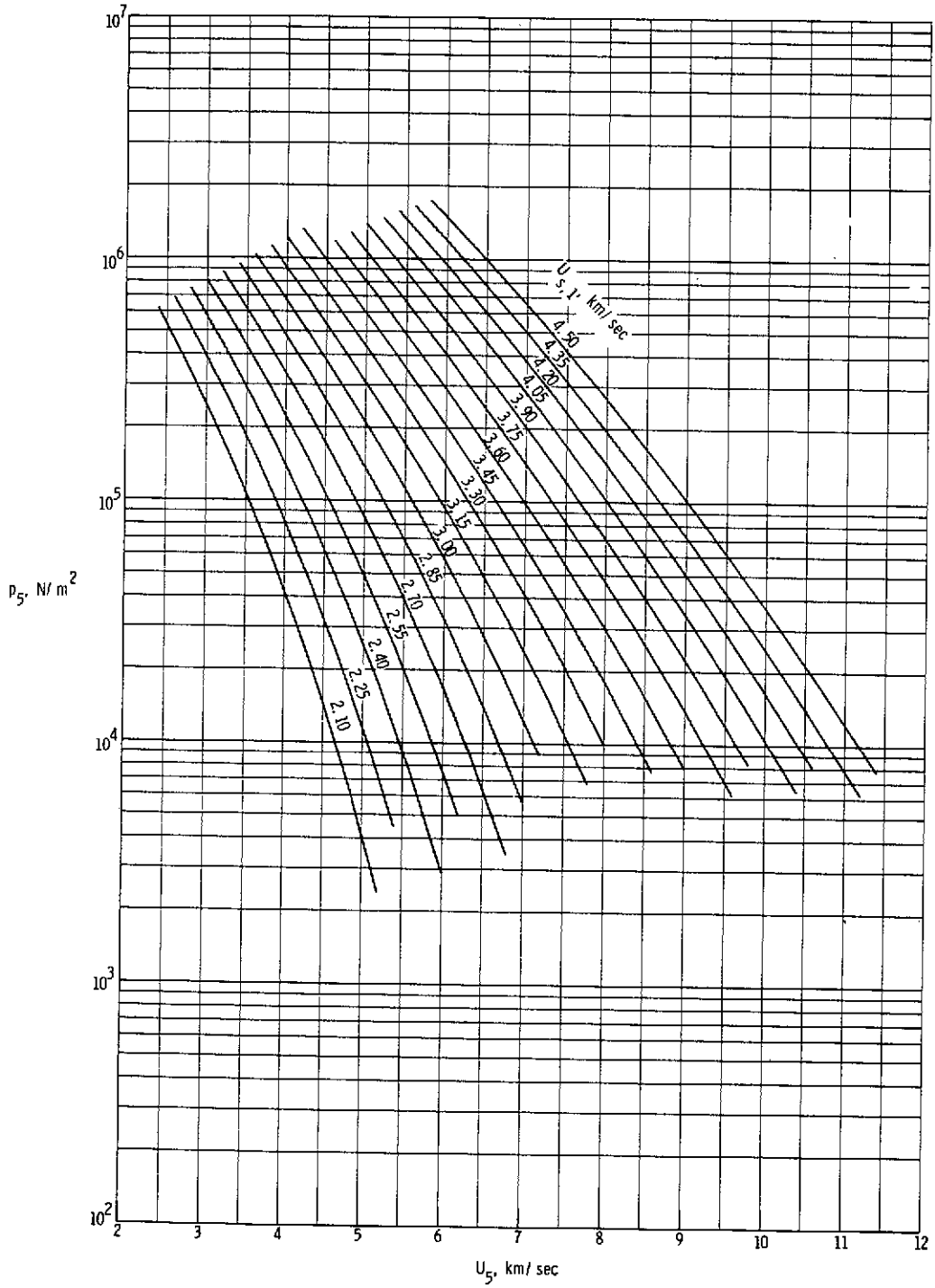
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 14.- Continued.



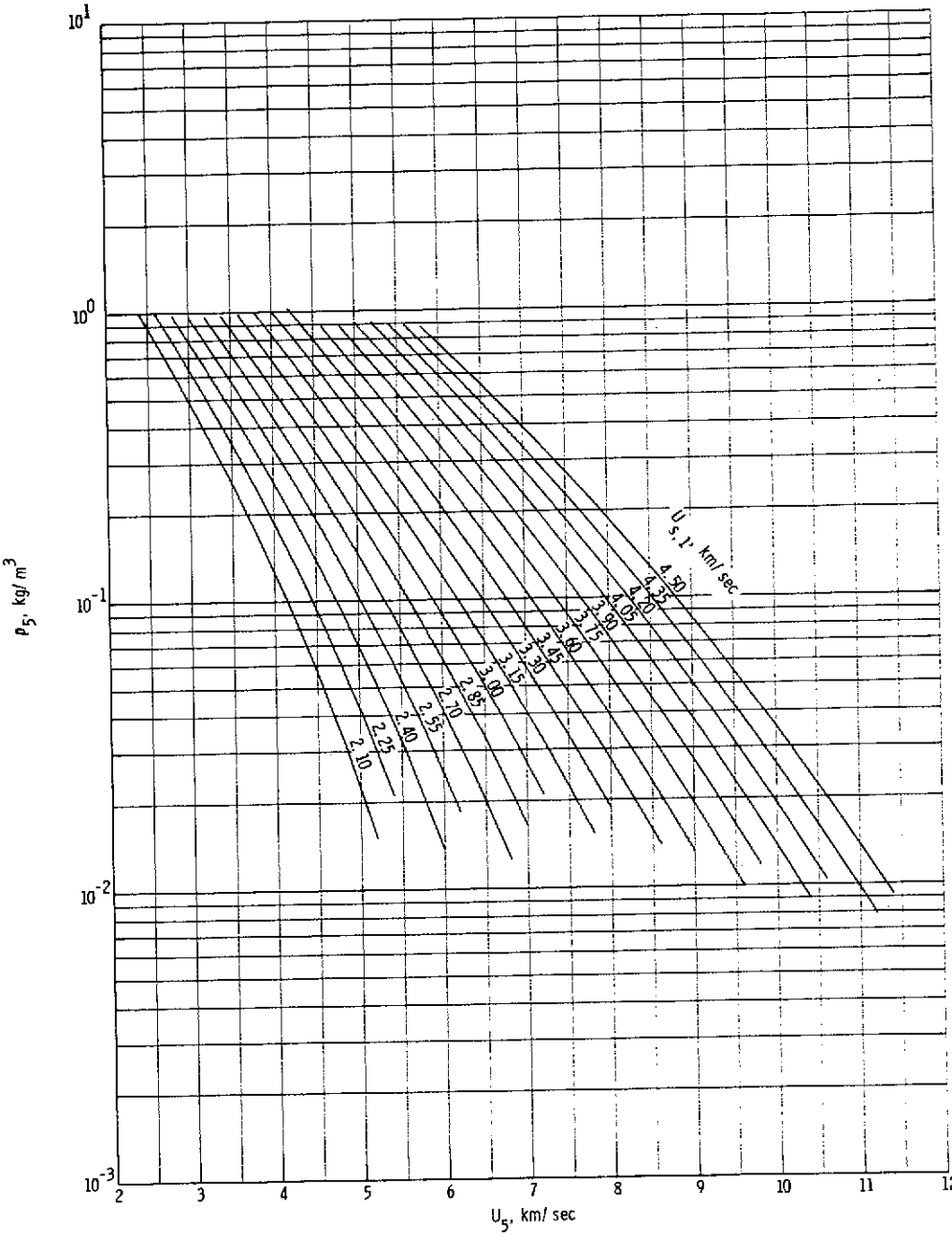
(l) Quiescent acceleration air pressure in region (10).

Figure 14.- Concluded.



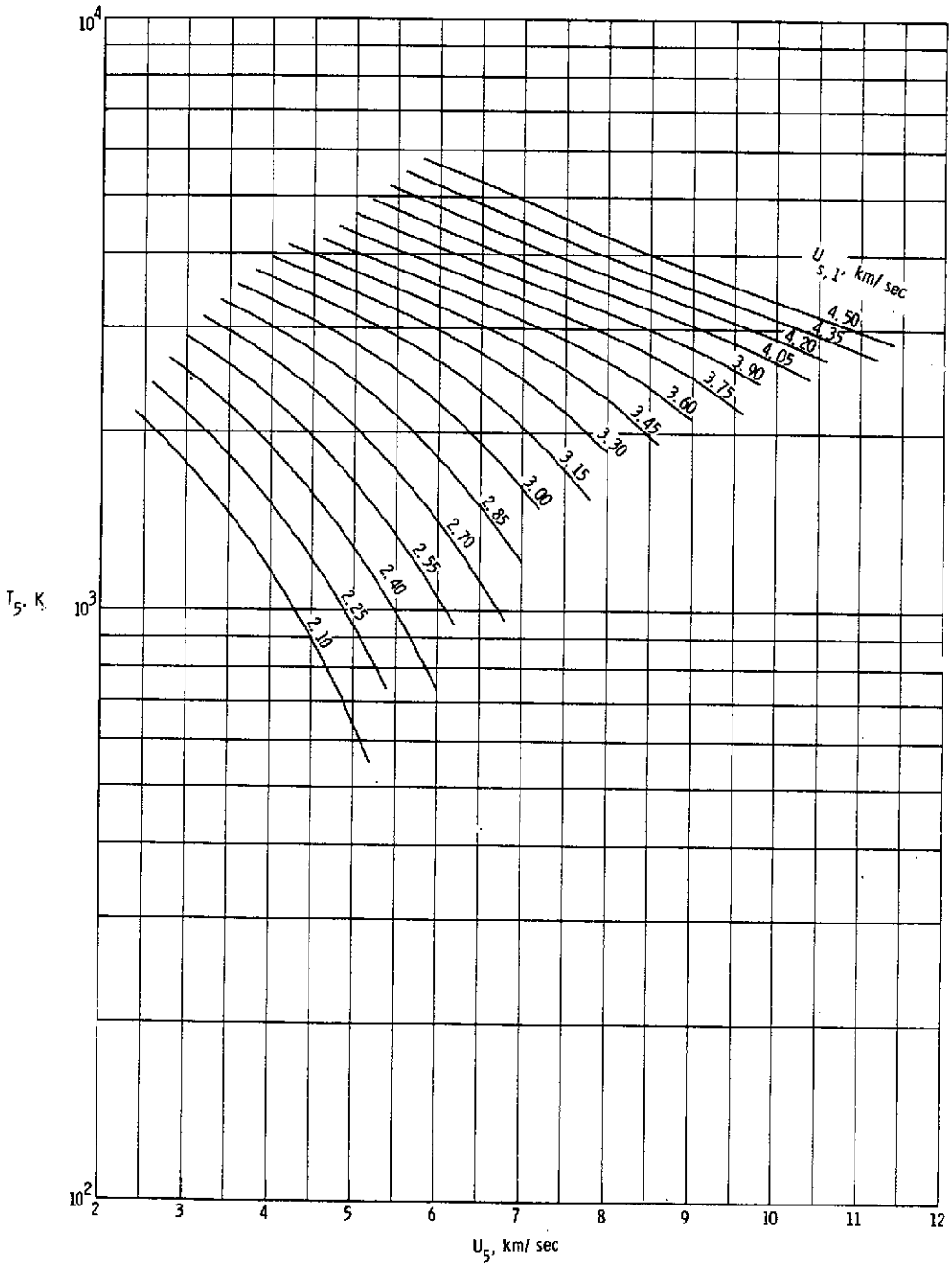
(a) Static pressure in region (5).

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. $p_1 = 34.47$ kN/m^2.



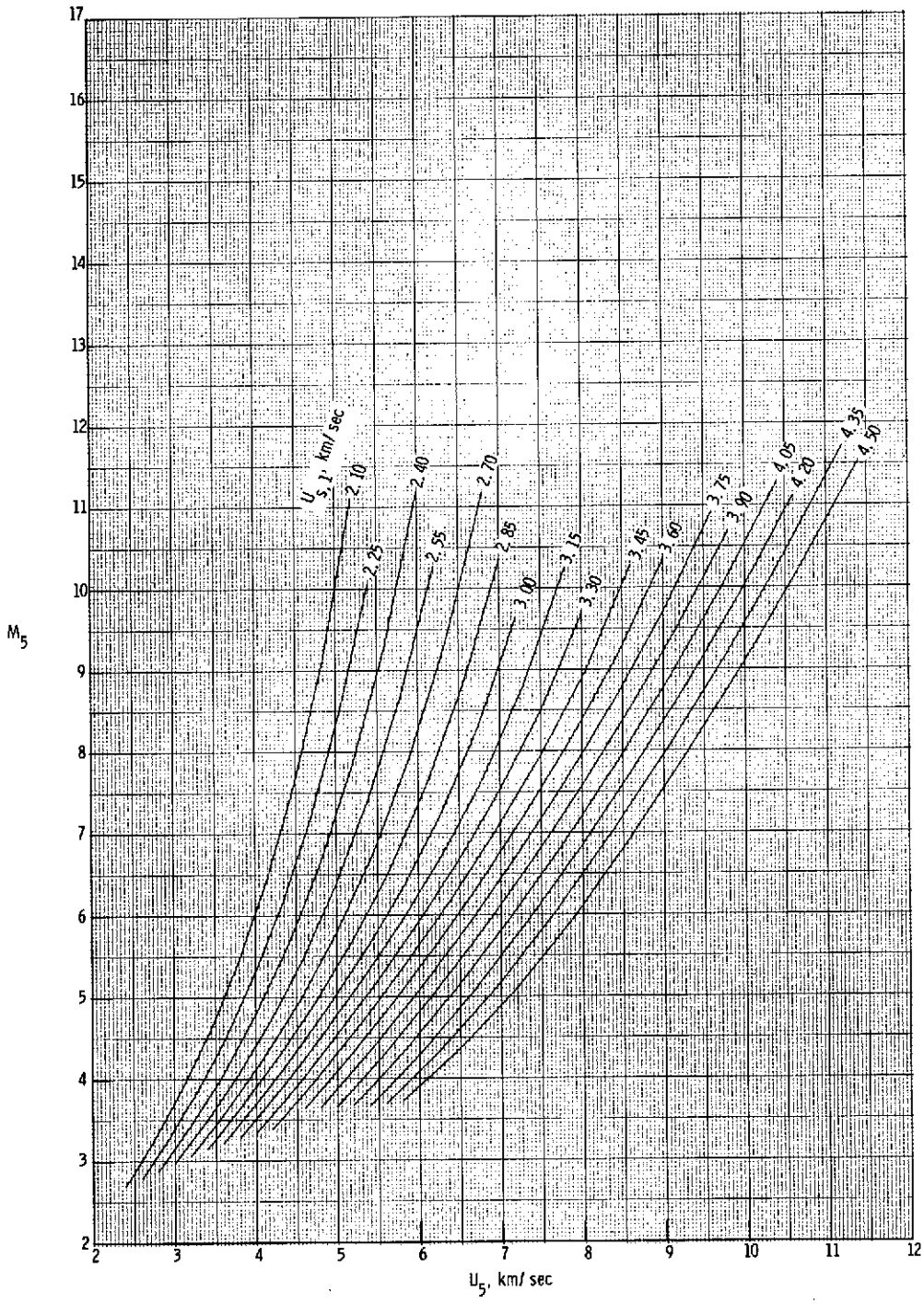
(b) Static density in region (5).

Figure 15.- Continued.



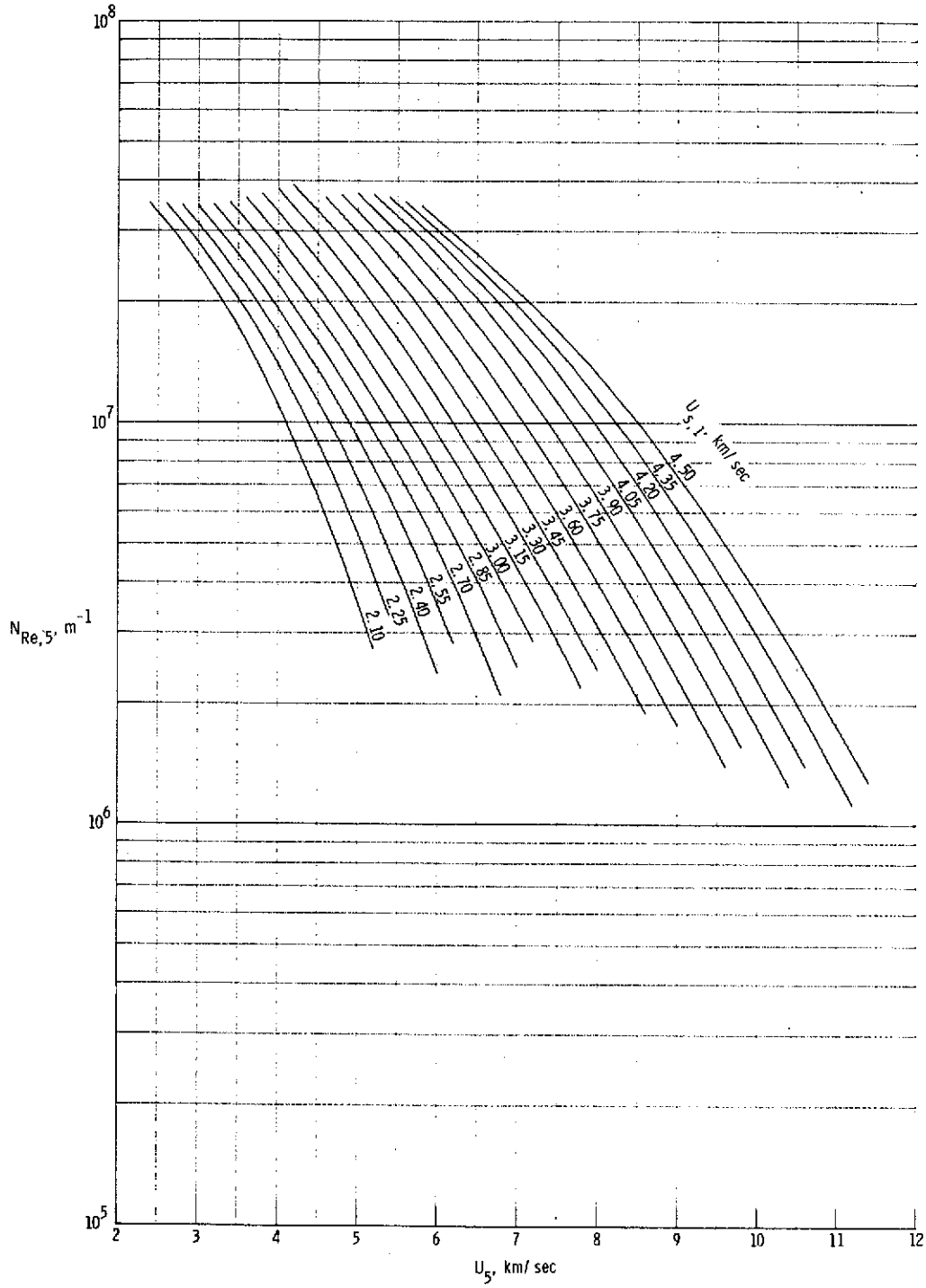
(c) Static temperature in region (5).

Figure 15.- Continued.



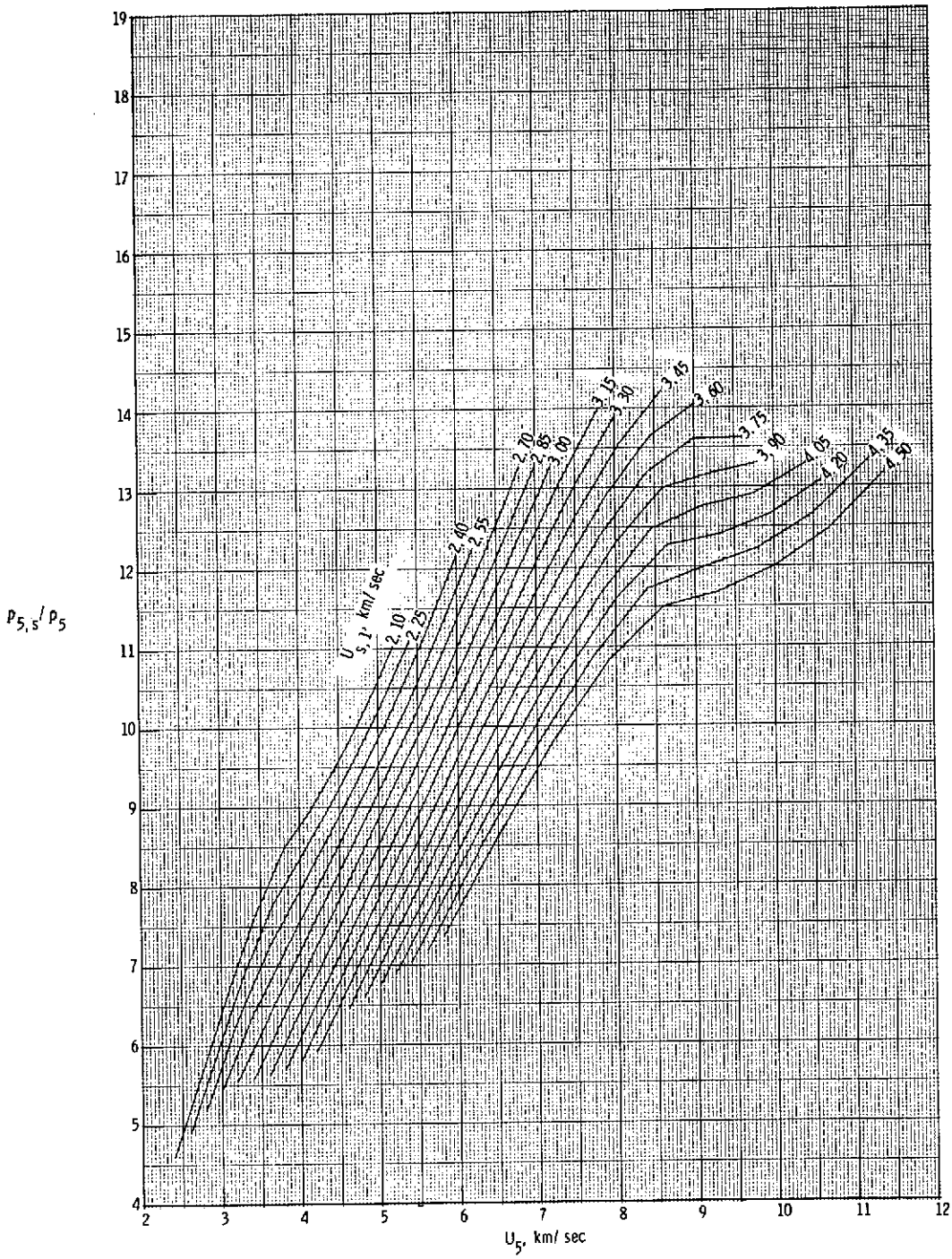
(d) Mach number in region (5).

Figure 15.- Continued.



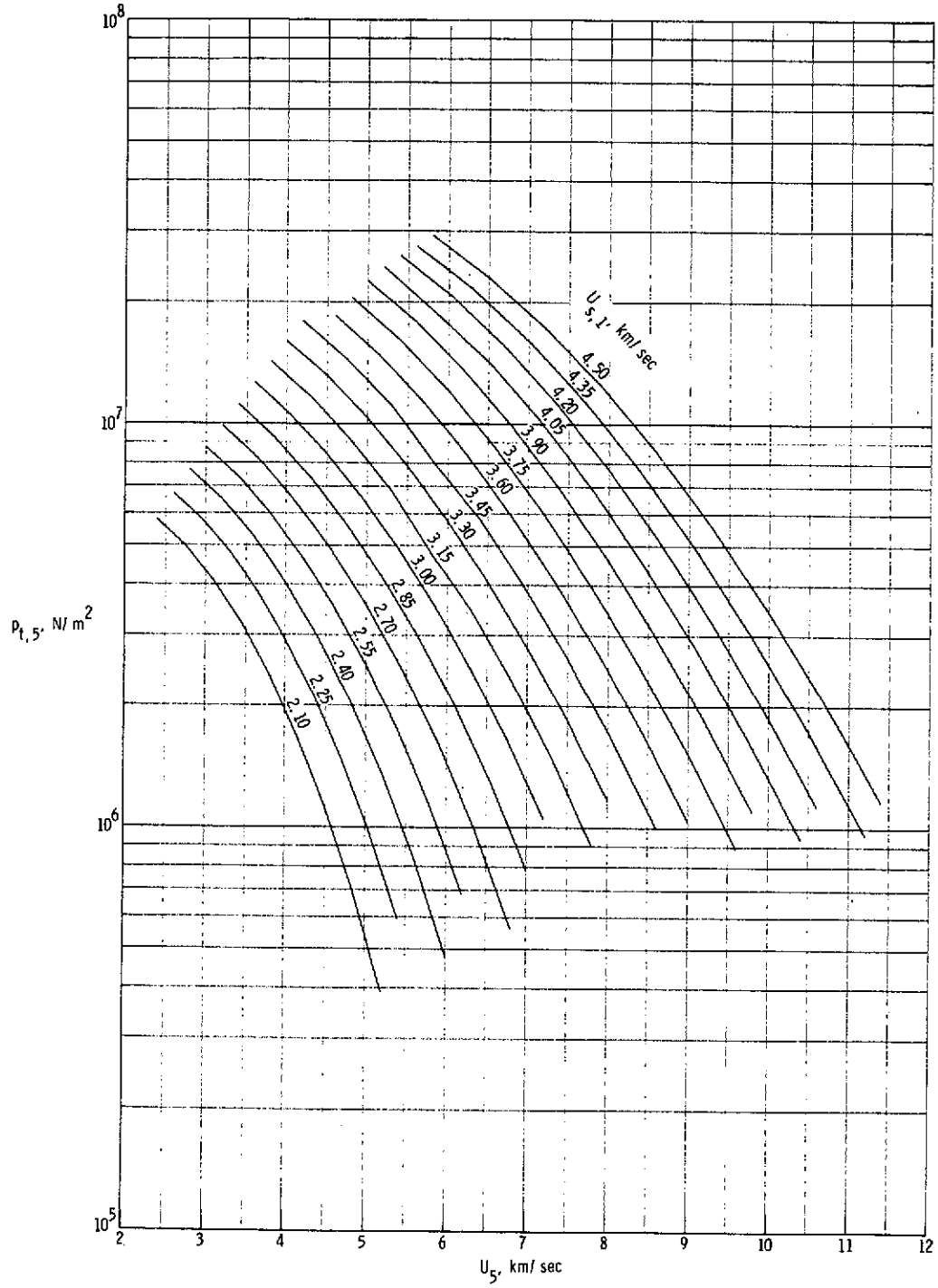
(e) Unit Reynolds number in region (5).

Figure 15.- Continued.



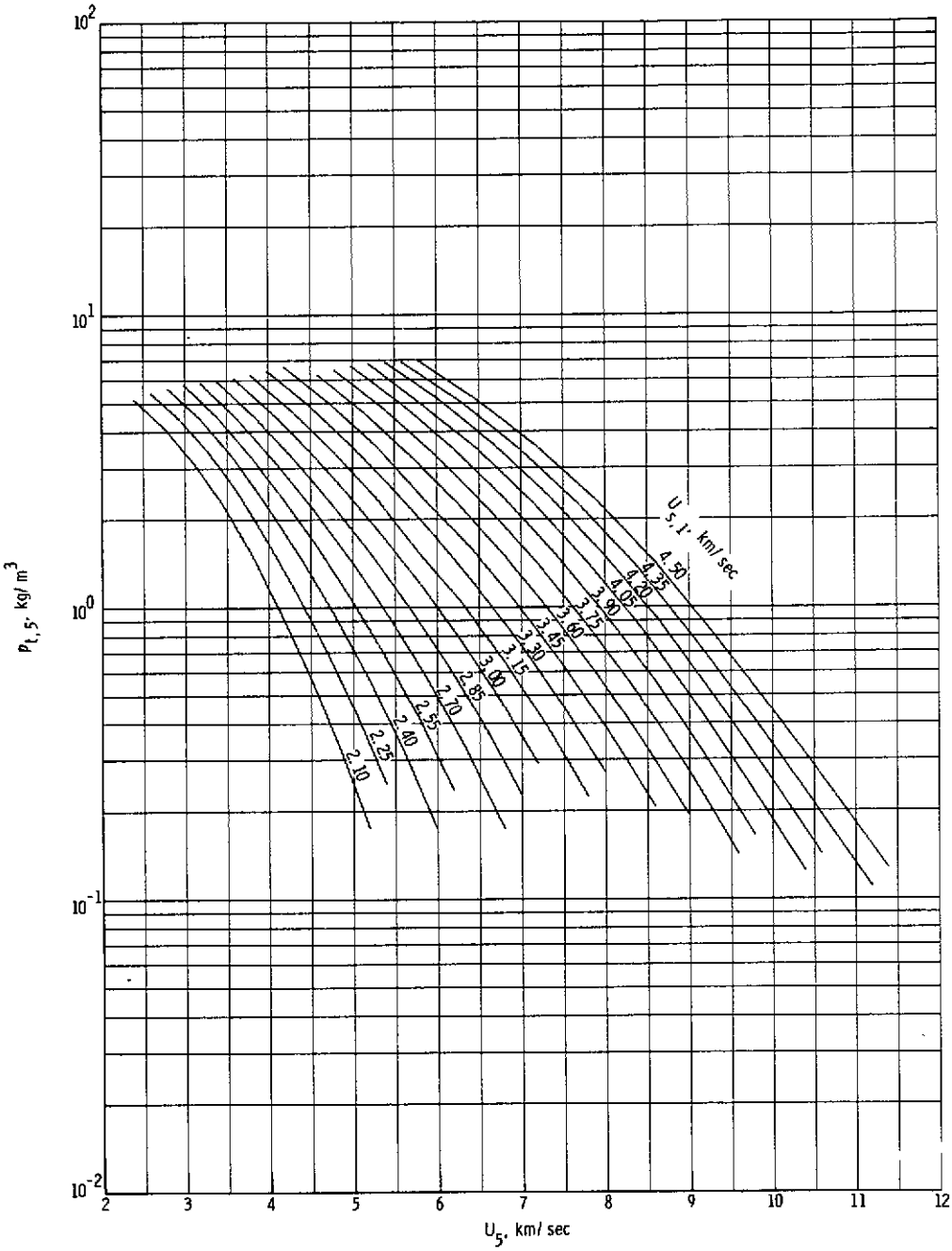
(f) Normal shock density ratio.

Figure 15.- Continued.



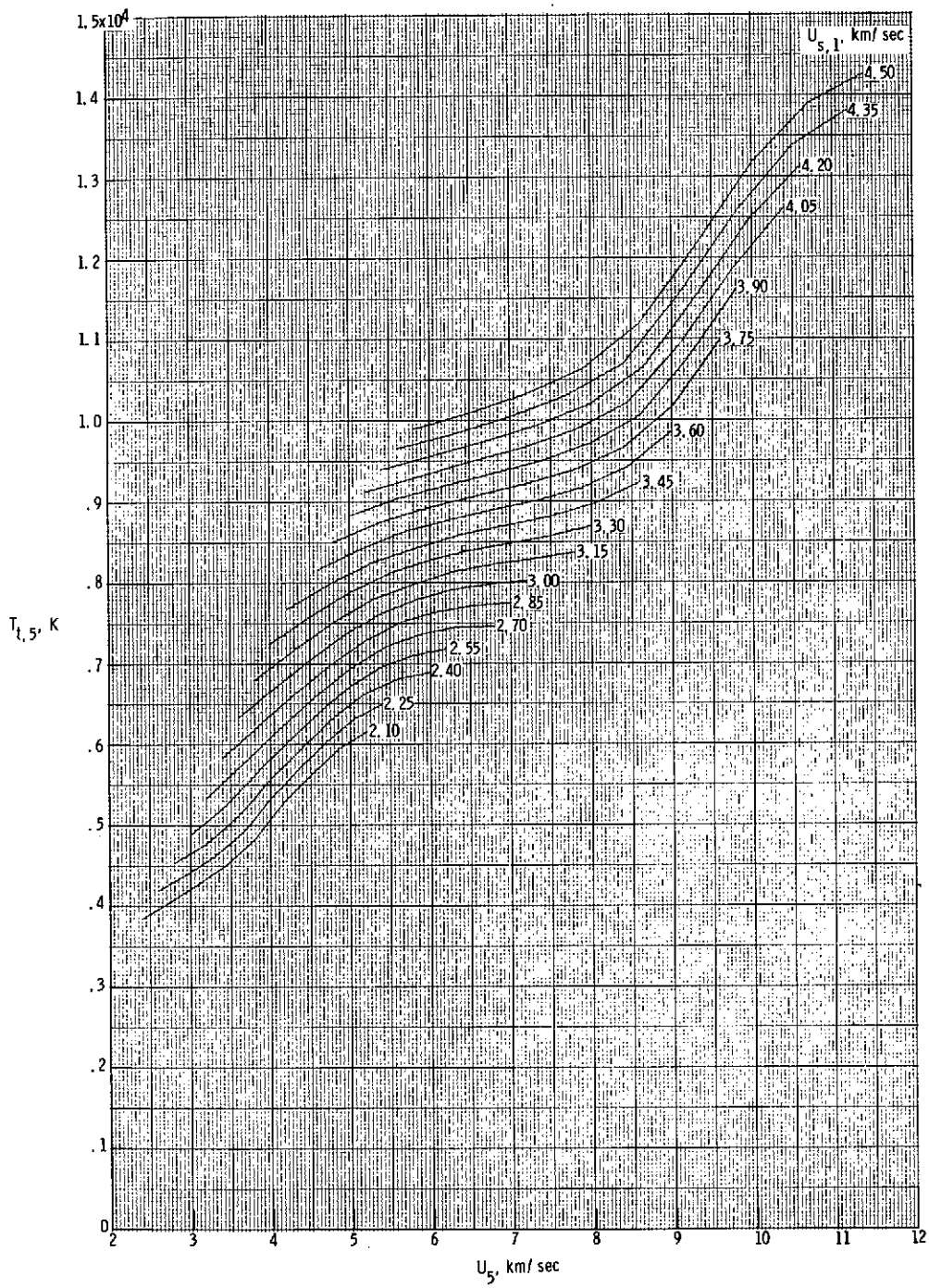
(g) Stagnation pressure behind normal bow shock.

Figure 15.- Continued.



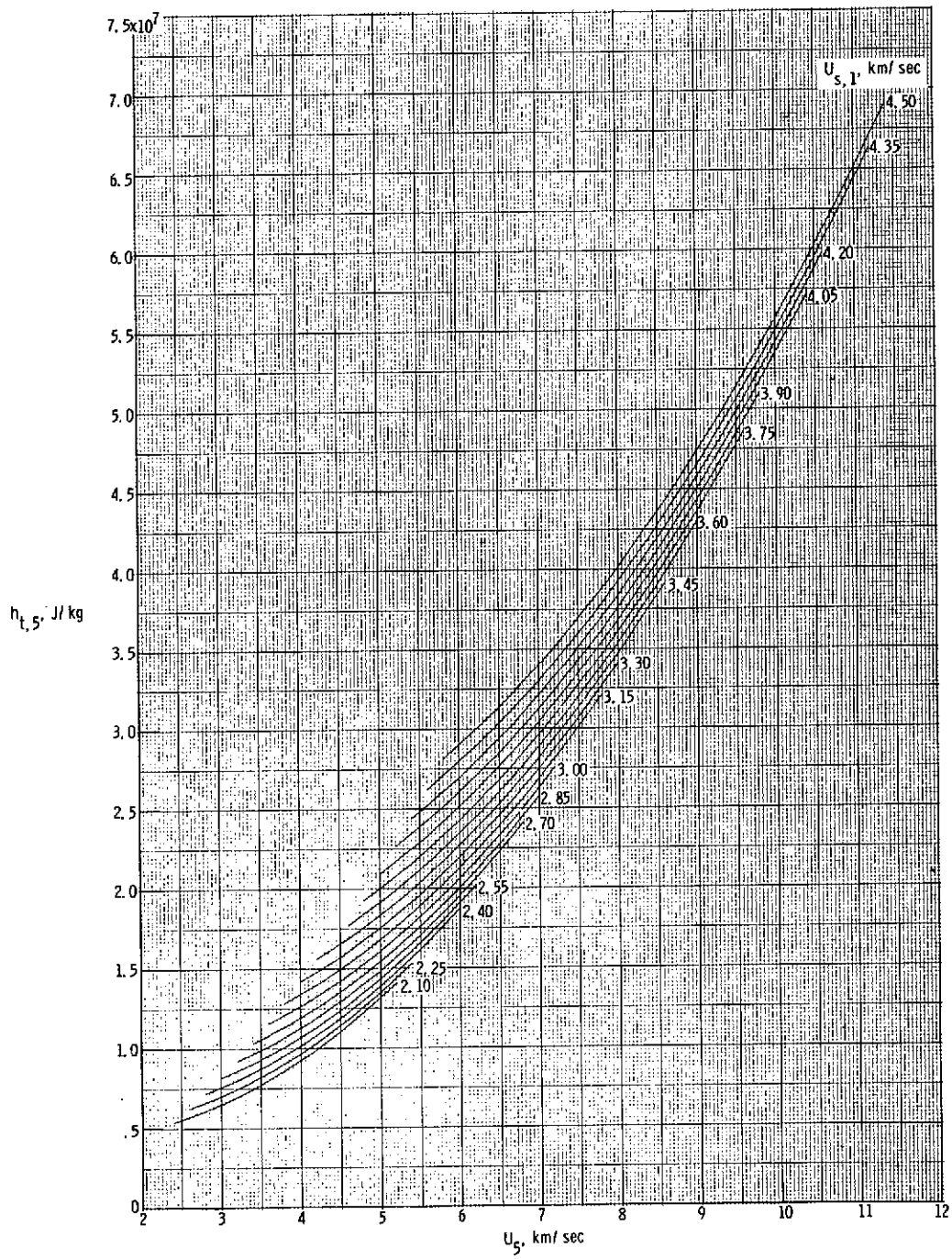
(h) Stagnation density behind normal bow shock.

Figure 15.- Continued.



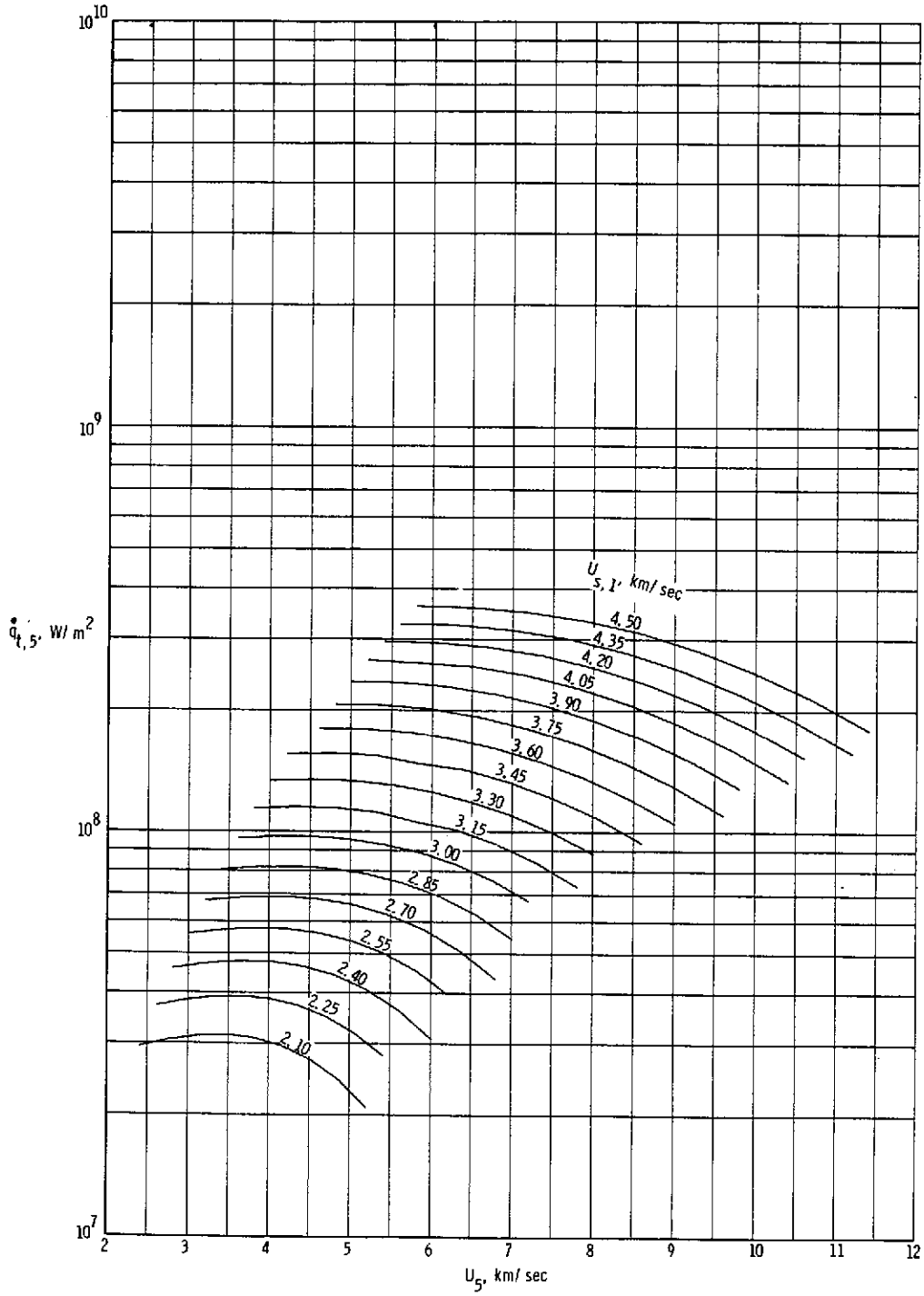
(i) Stagnation temperature behind normal bow shock.

Figure 15.- Continued.



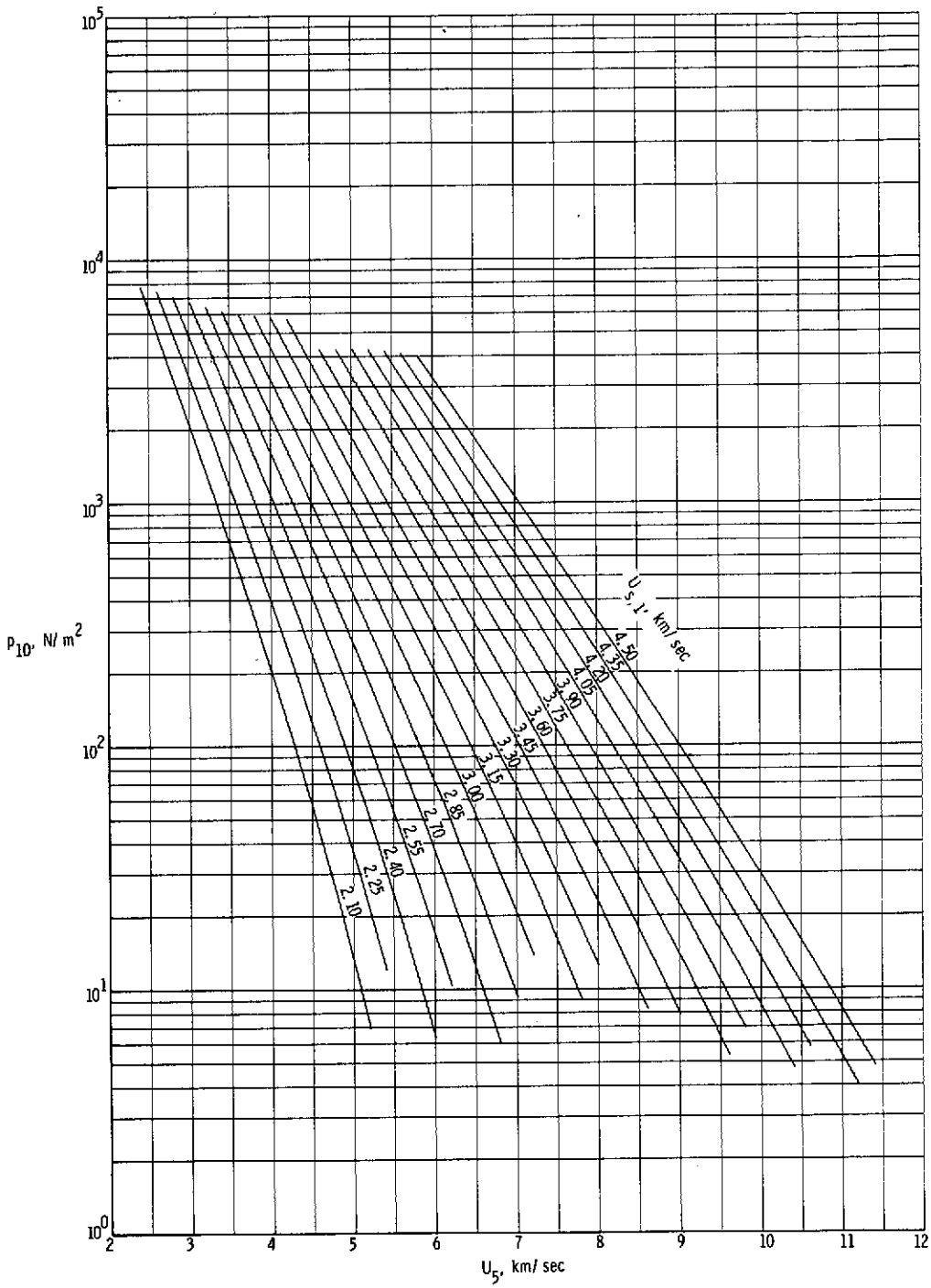
(j) Stagnation enthalpy behind normal bow shock.

Figure 15.- Continued.



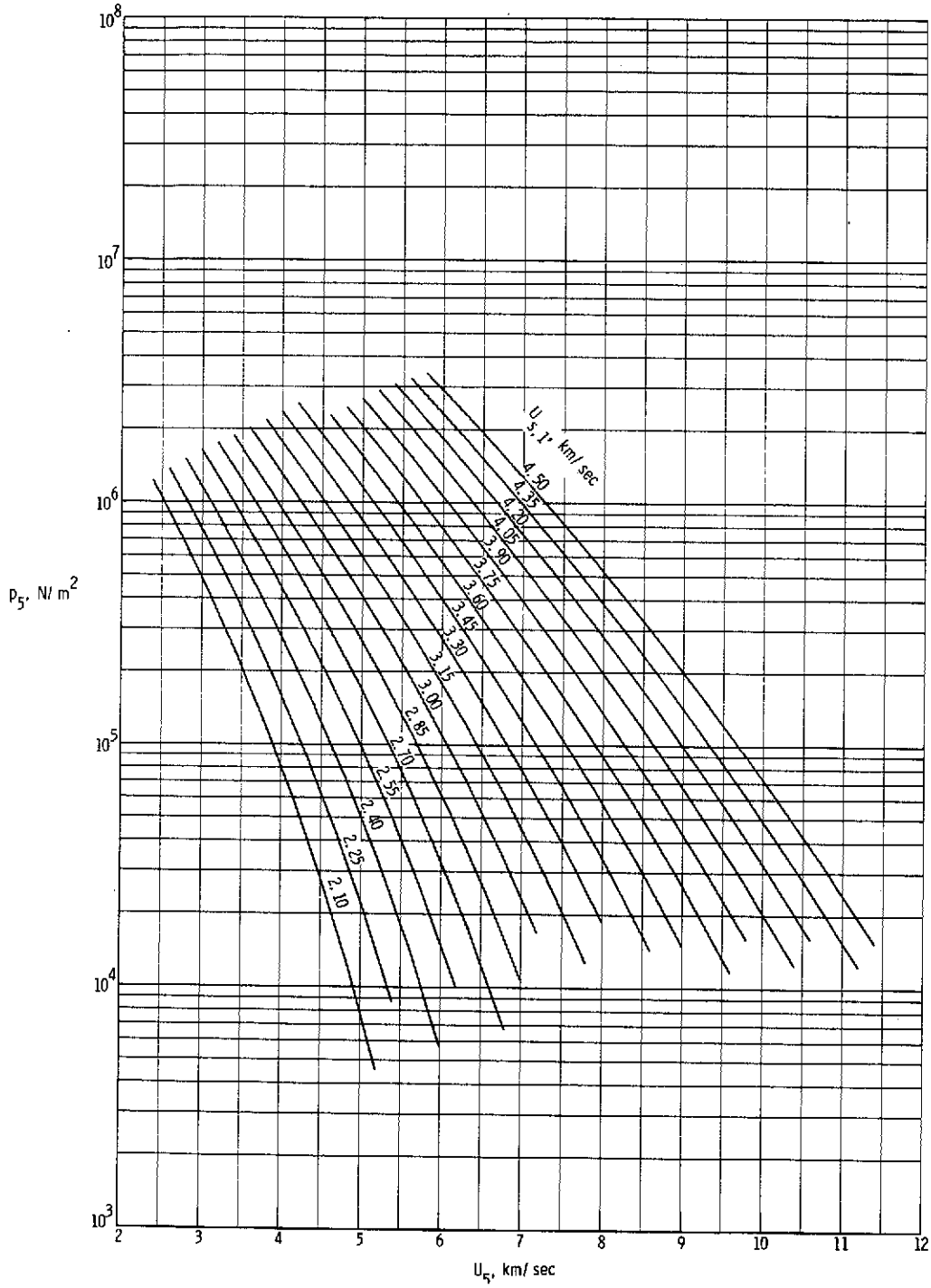
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 15.- Continued.



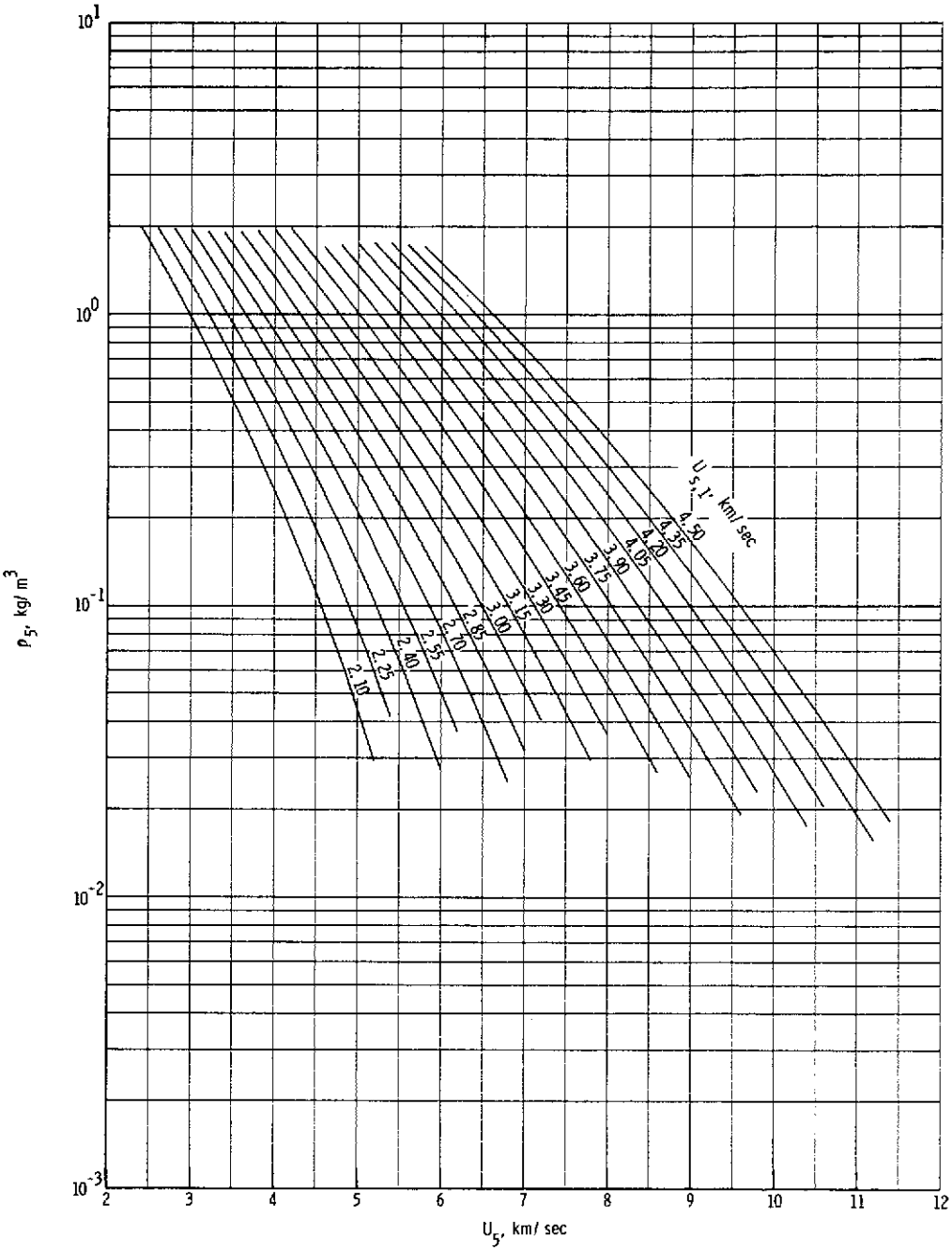
(l) Quiescent acceleration air pressure in region (10).

Figure 15.- Concluded.



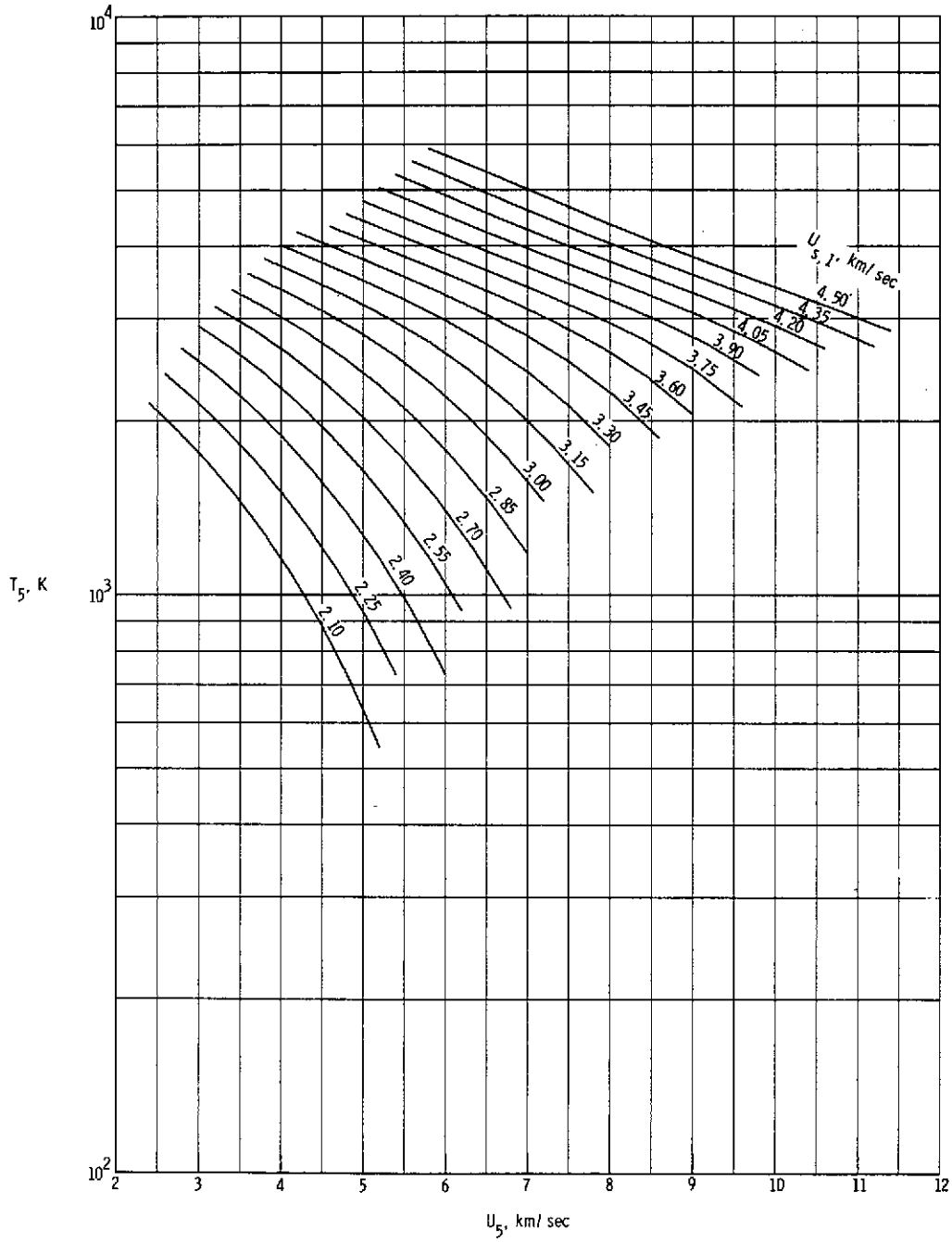
(a) Static pressure in region (5).

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. $p_1 = 68.95\ kN/m^2$.



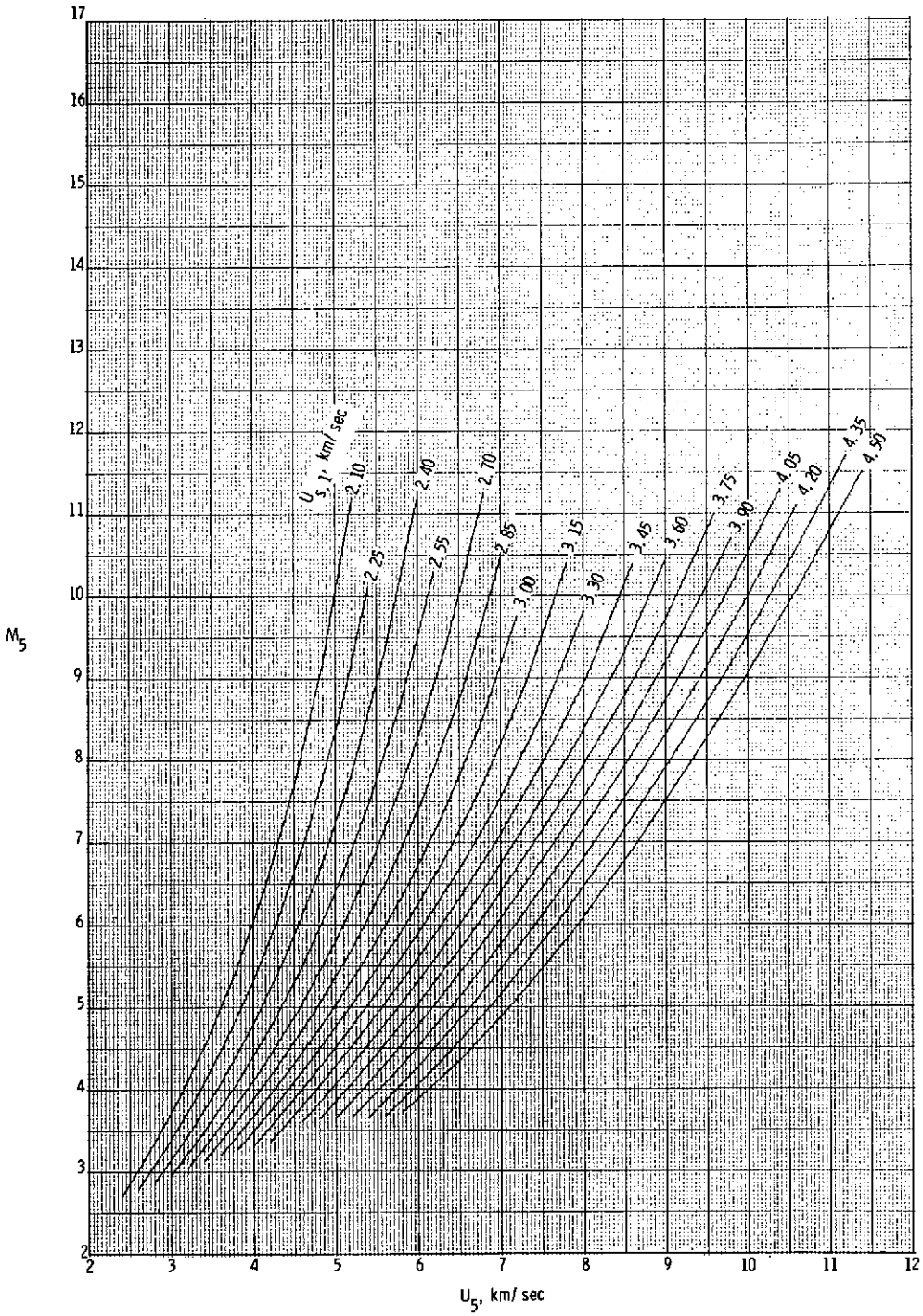
(b) Static density in region (5).

Figure 16.- Continued.



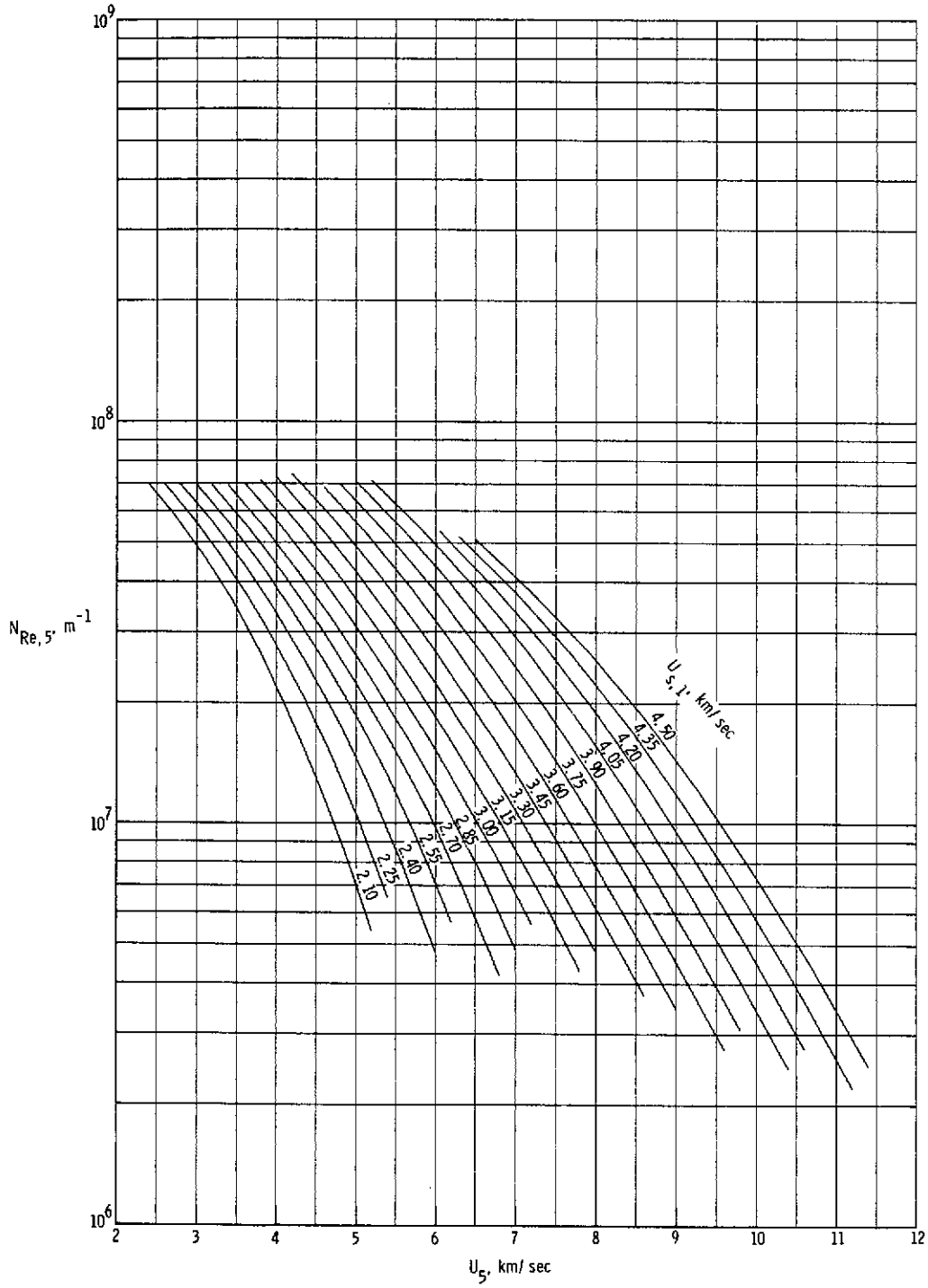
(c) Static temperature in region (5).

Figure 16.- Continued.



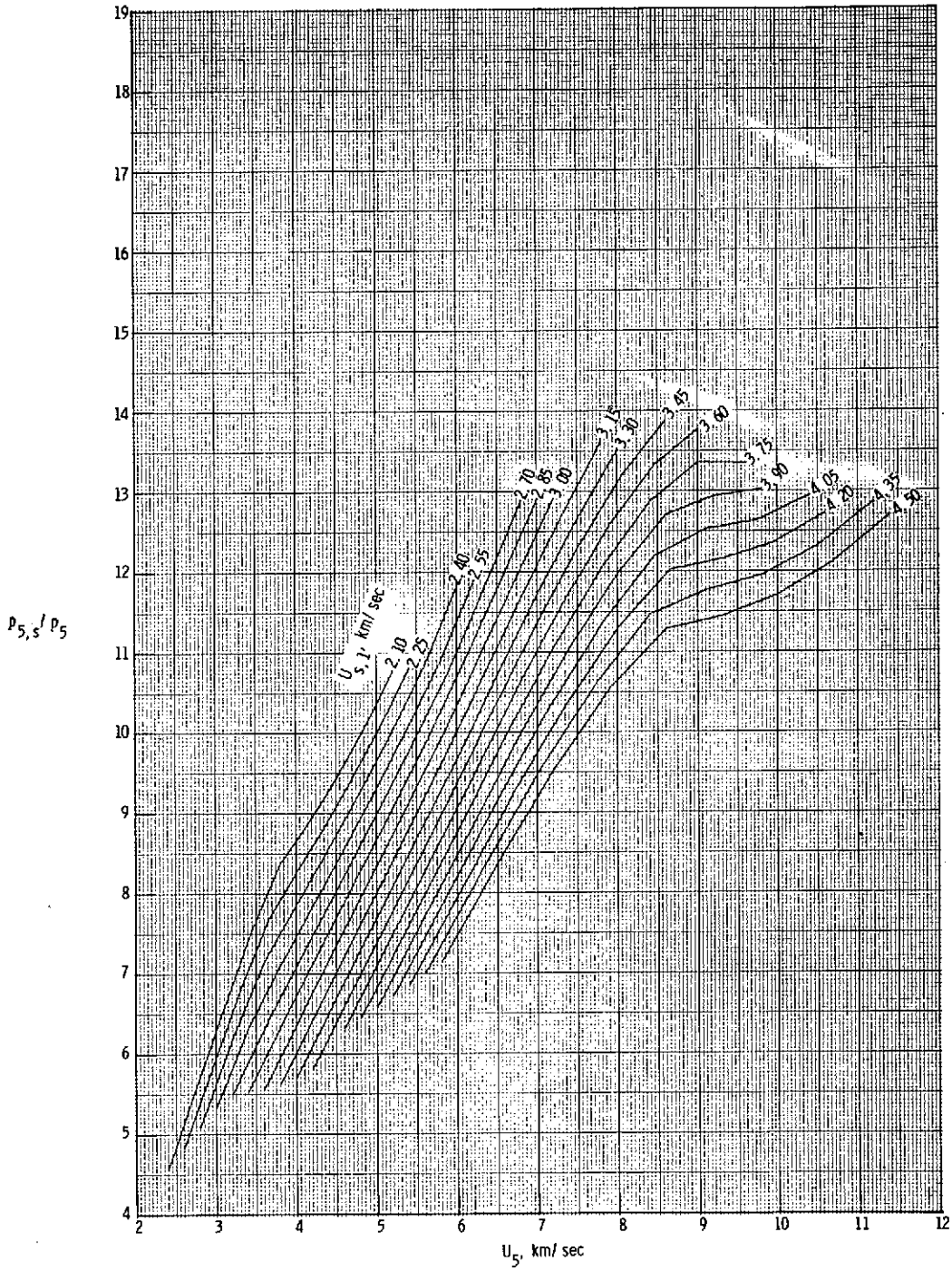
(d) Mach number in region (5).

Figure 16.- Continued.



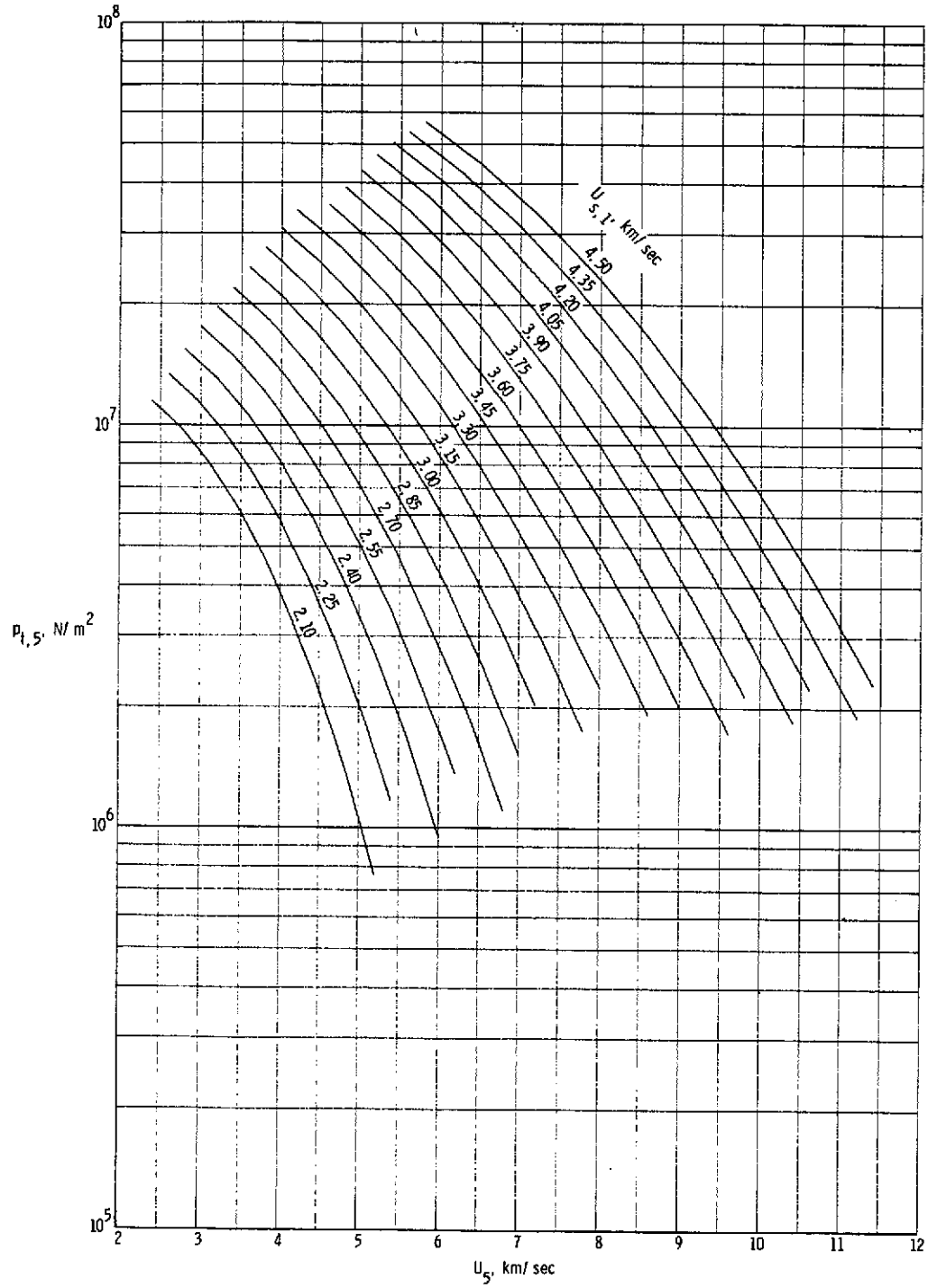
(e) Unit Reynolds number in region (5).

Figure 16.- Continued.



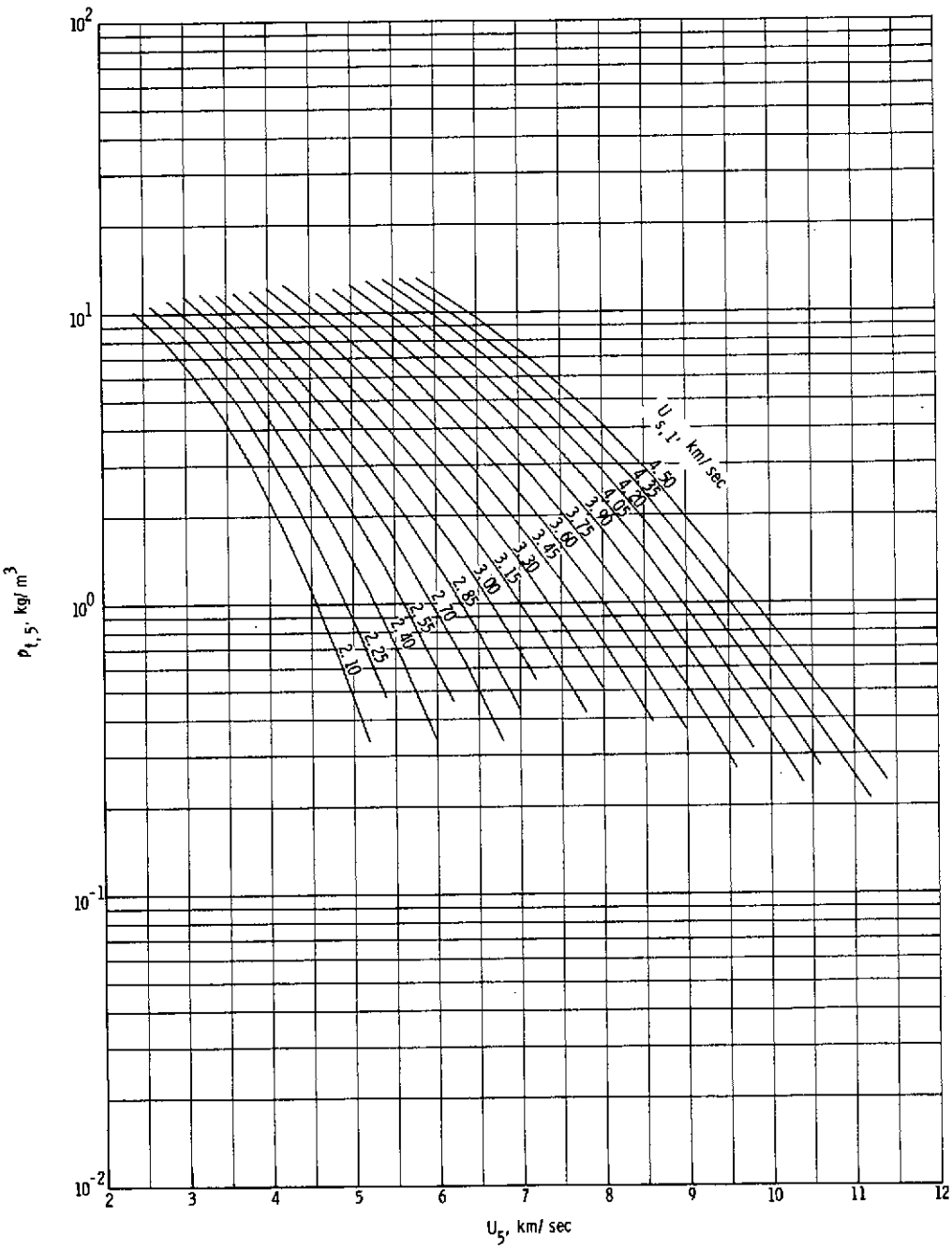
(f) Normal shock density ratio.

Figure 16.- Continued.



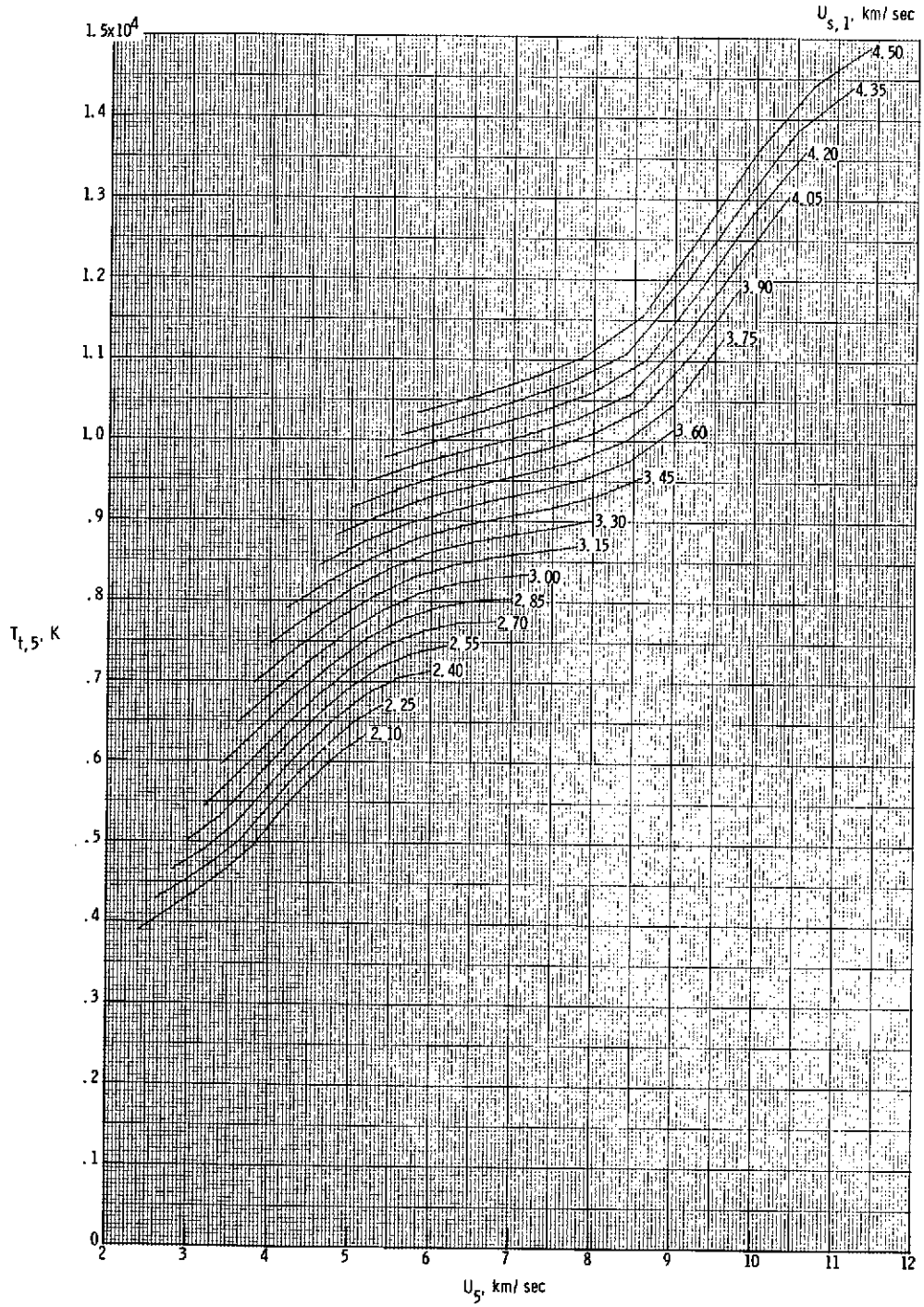
(g) Stagnation pressure behind normal bow shock.

Figure 16.- Continued.



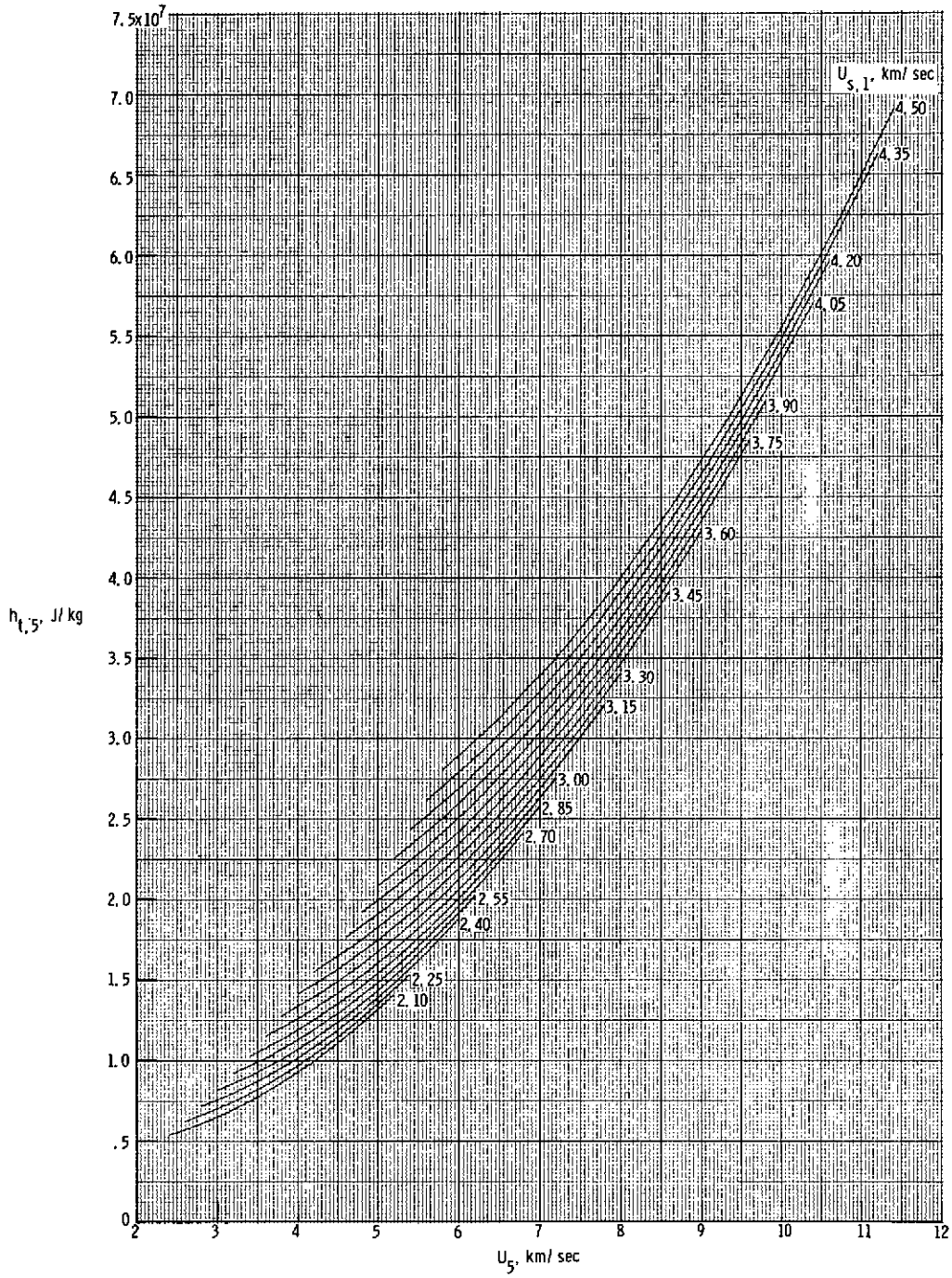
(h) Stagnation density behind normal bow shock.

Figure 16.- Continued.



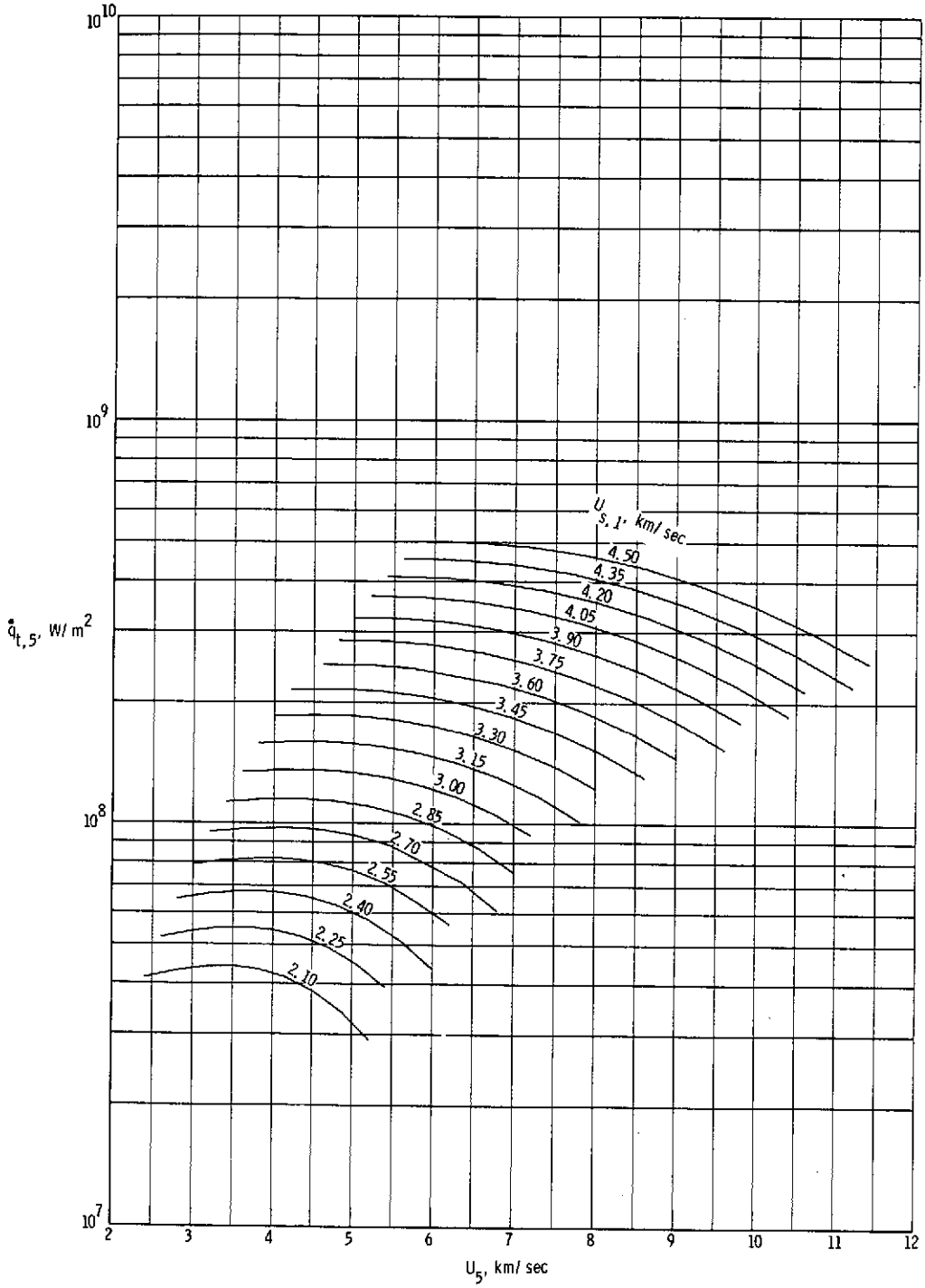
(i) Stagnation temperature behind normal bow shock.

Figure 16.- Continued.



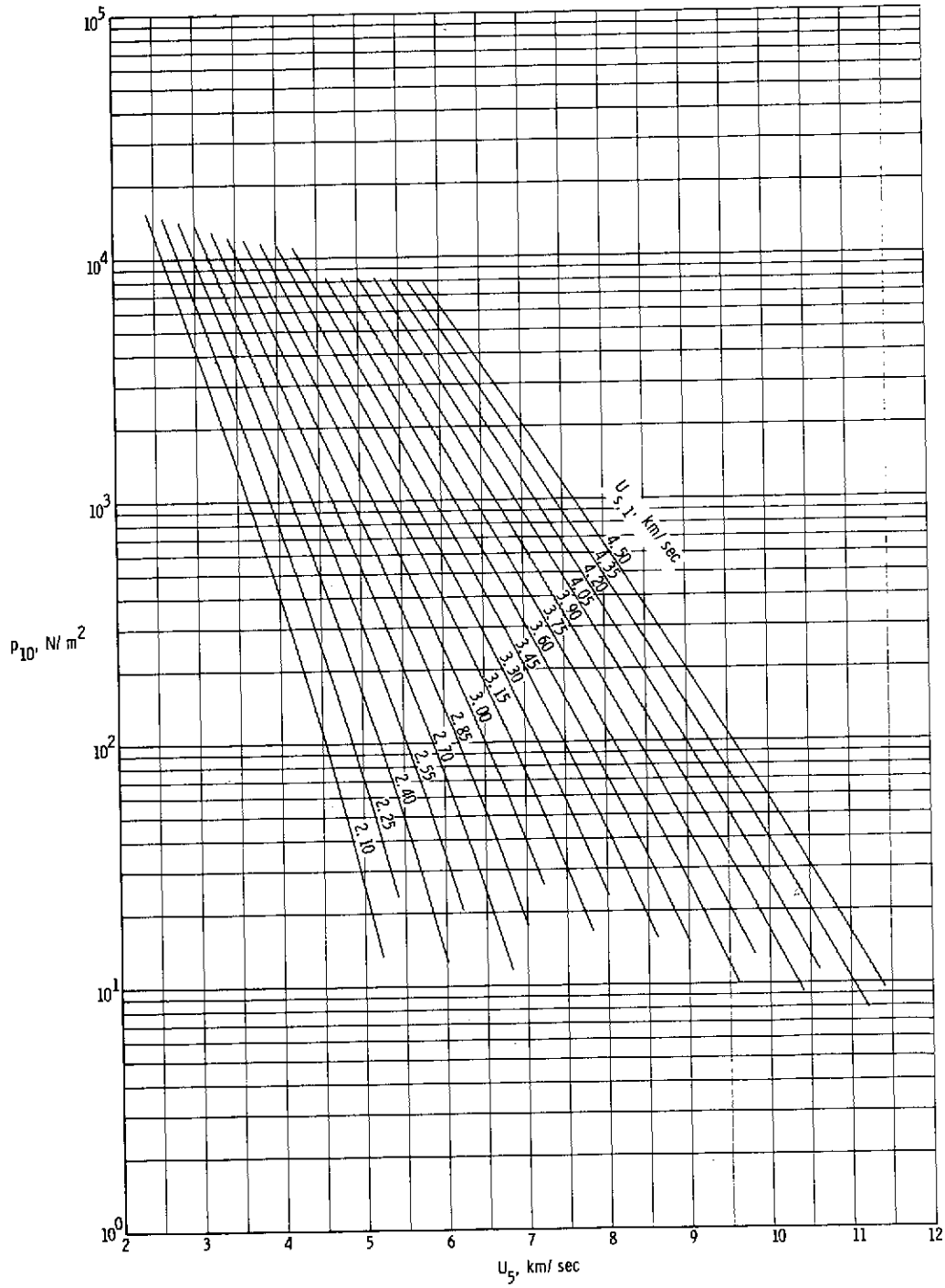
(j) Stagnation enthalpy behind normal bow shock.

Figure 16.- Continued.



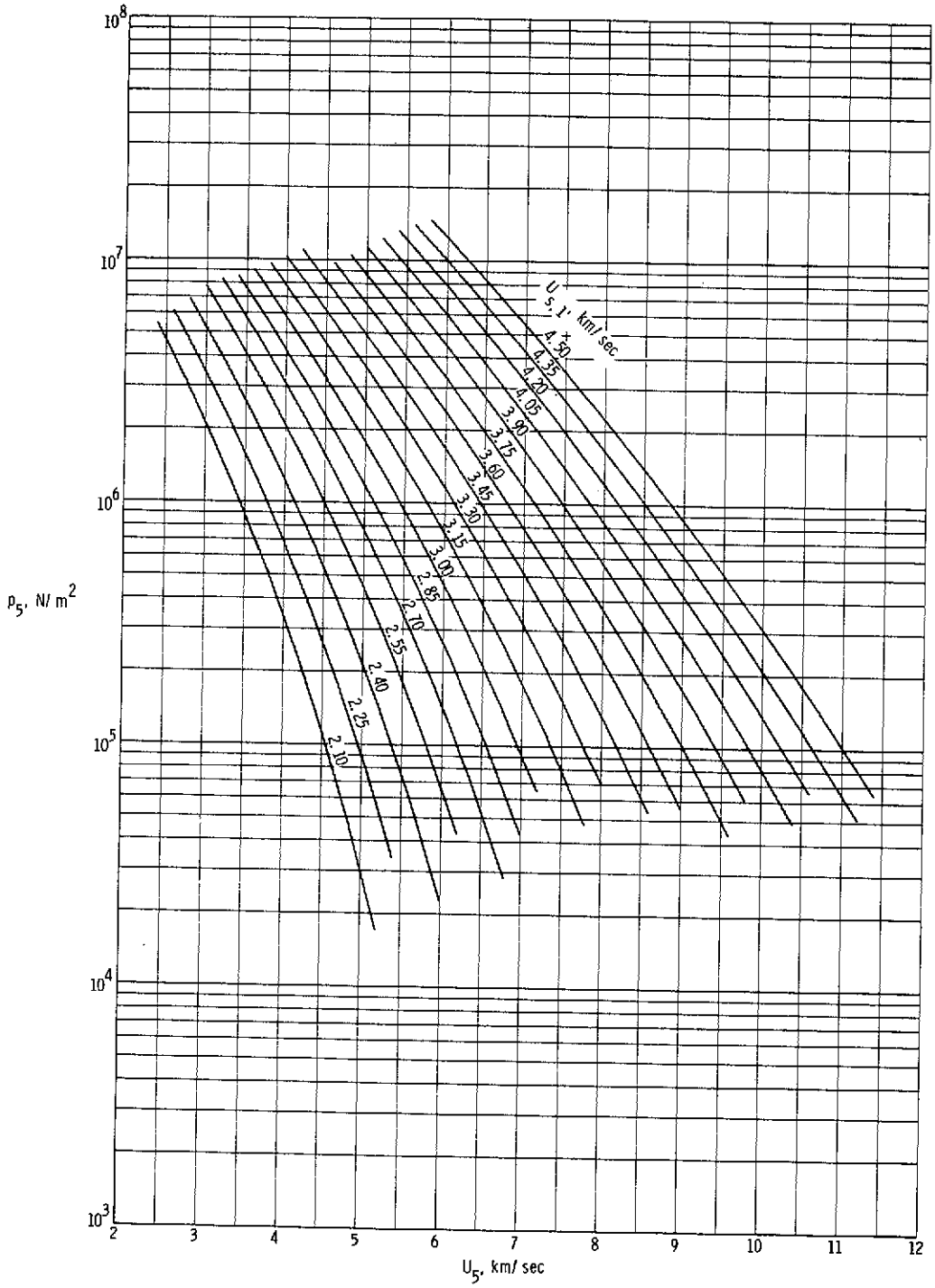
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 16.- Continued.



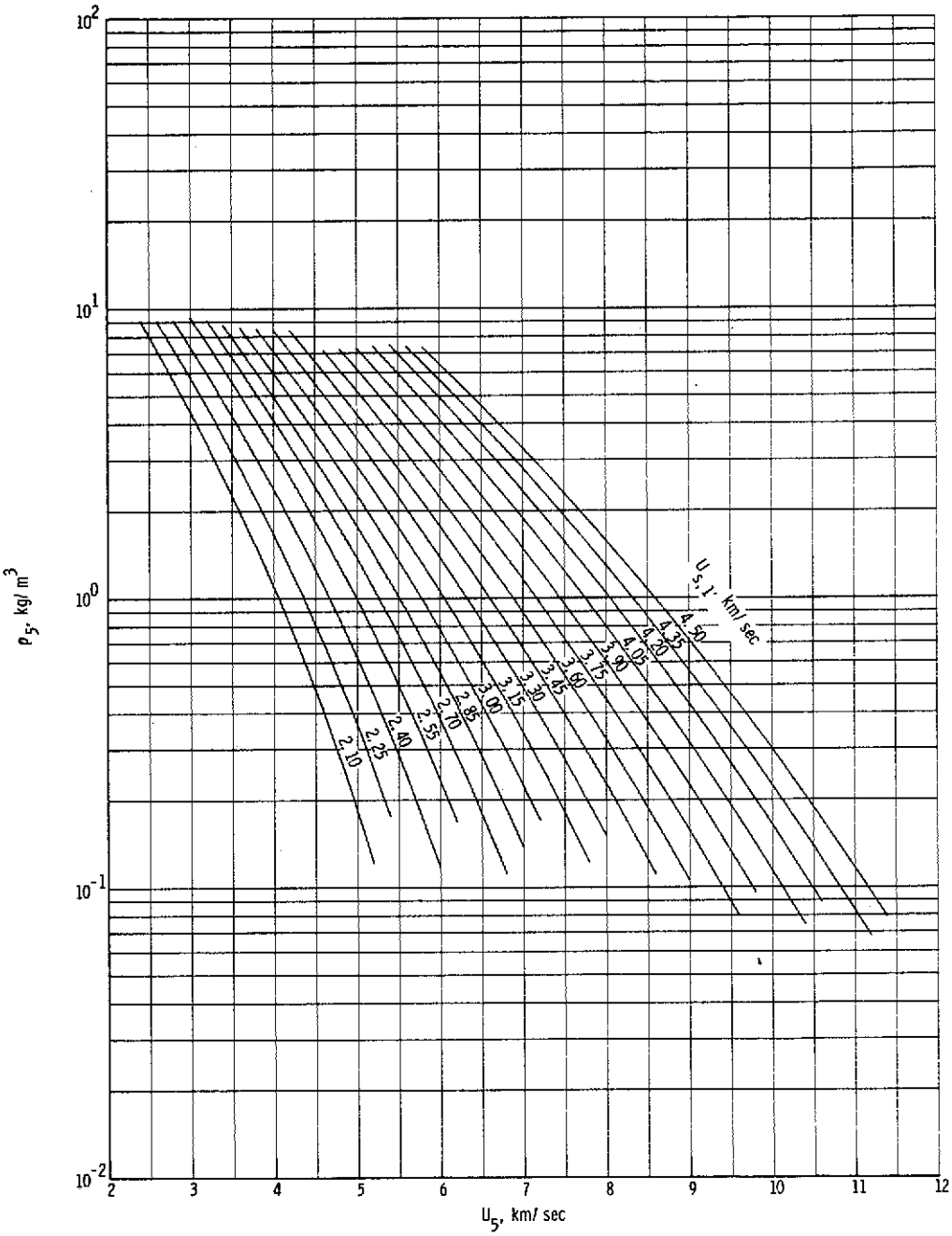
(l) Quiescent acceleration air pressure in region (10).

Figure 16.- Concluded.



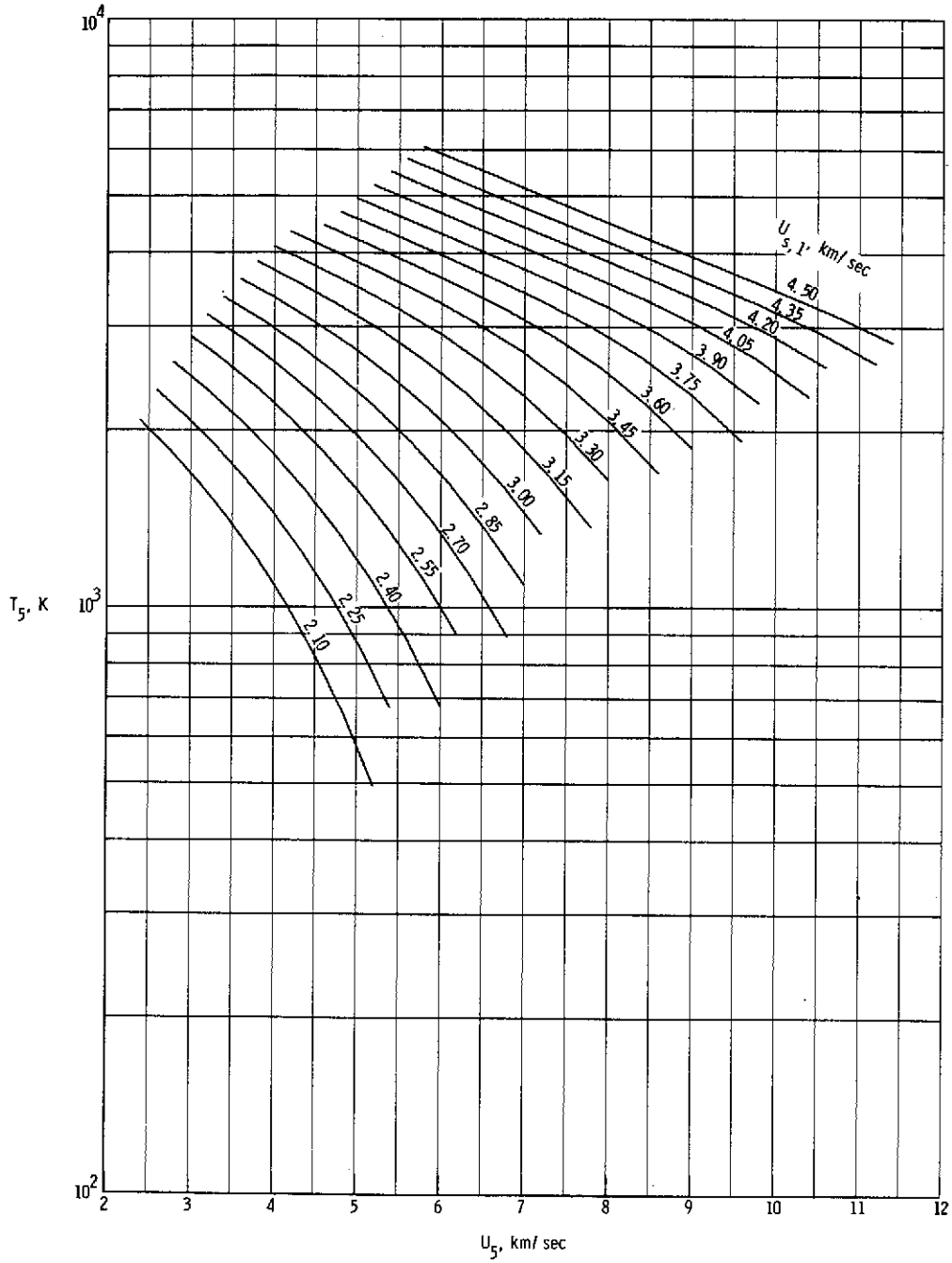
(a) Static pressure in region (5).

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 kN/m2.



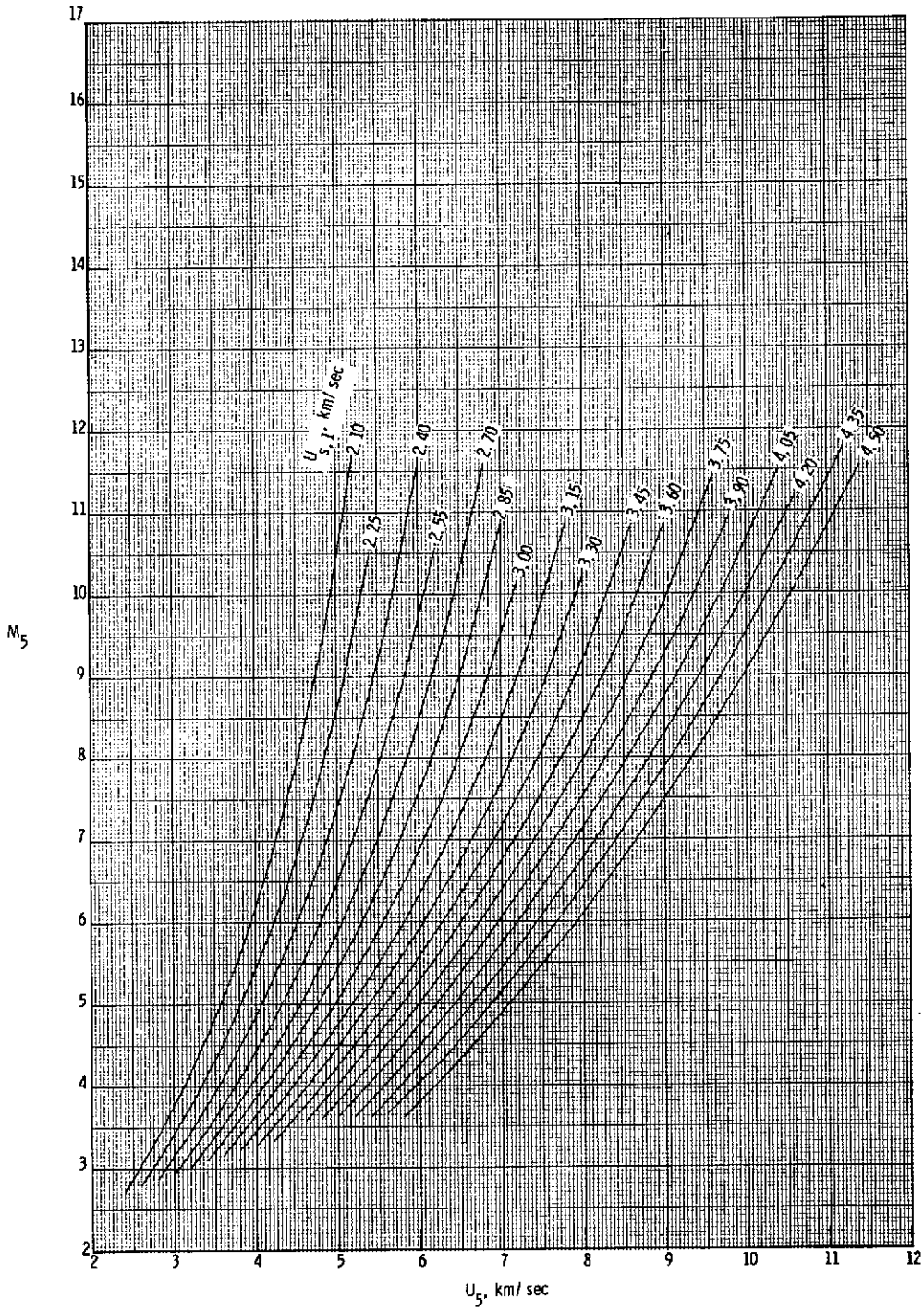
(b) Static density in region (5).

Figure 17.- Continued.



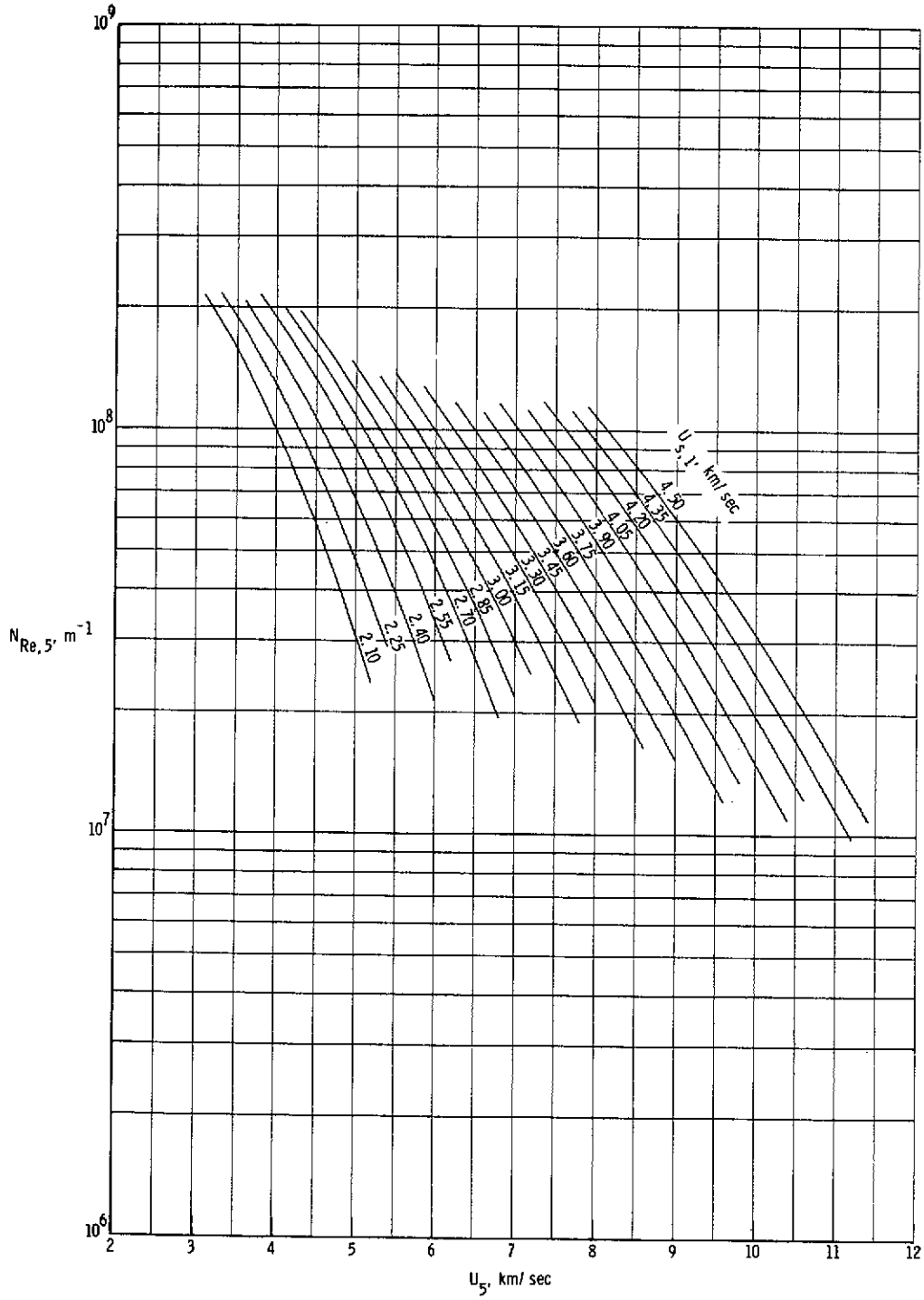
(c) Static temperature in region (5).

Figure 17.- Continued.



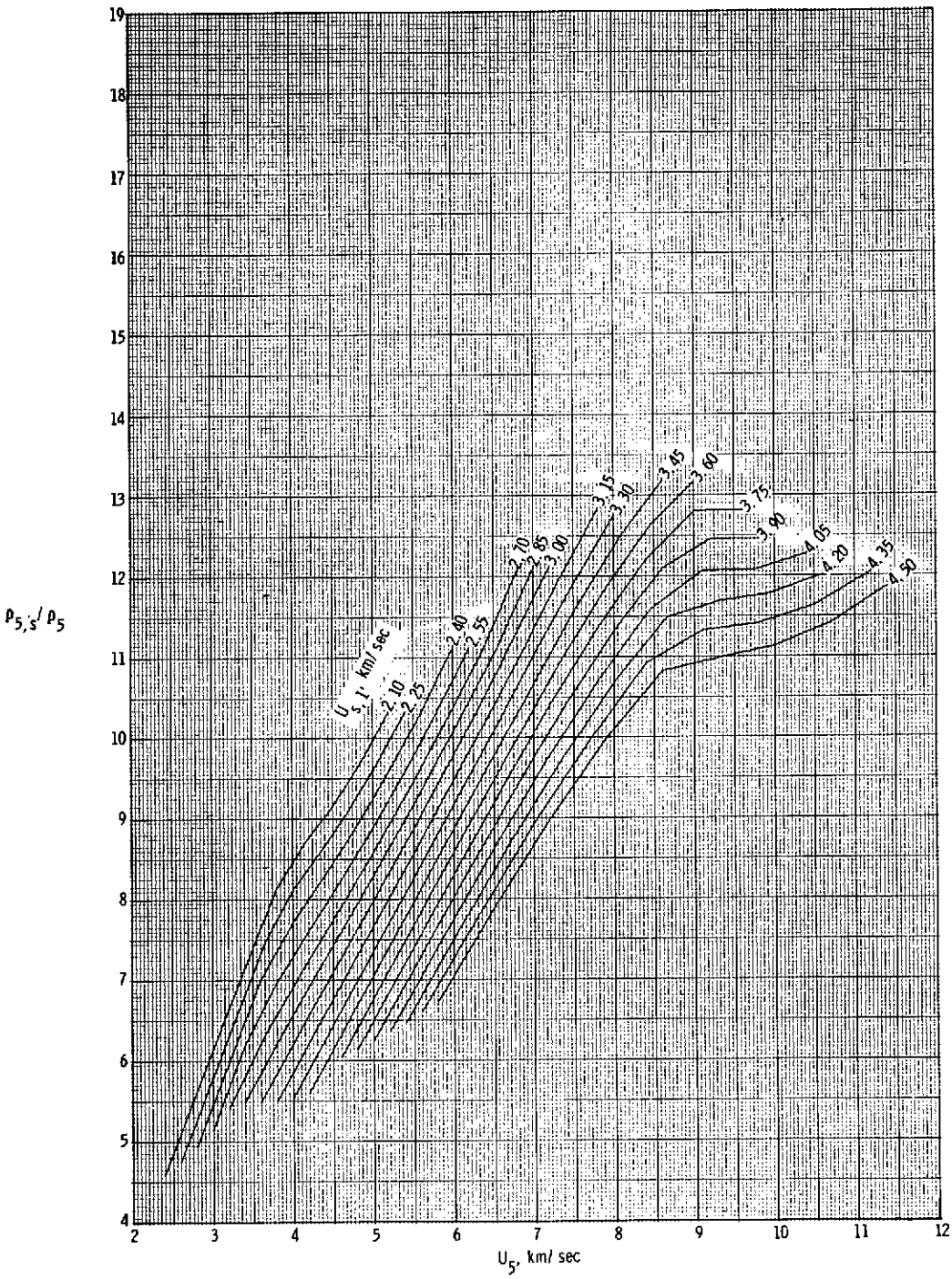
(d) Mach number in region (5).

Figure 17.- Continued.



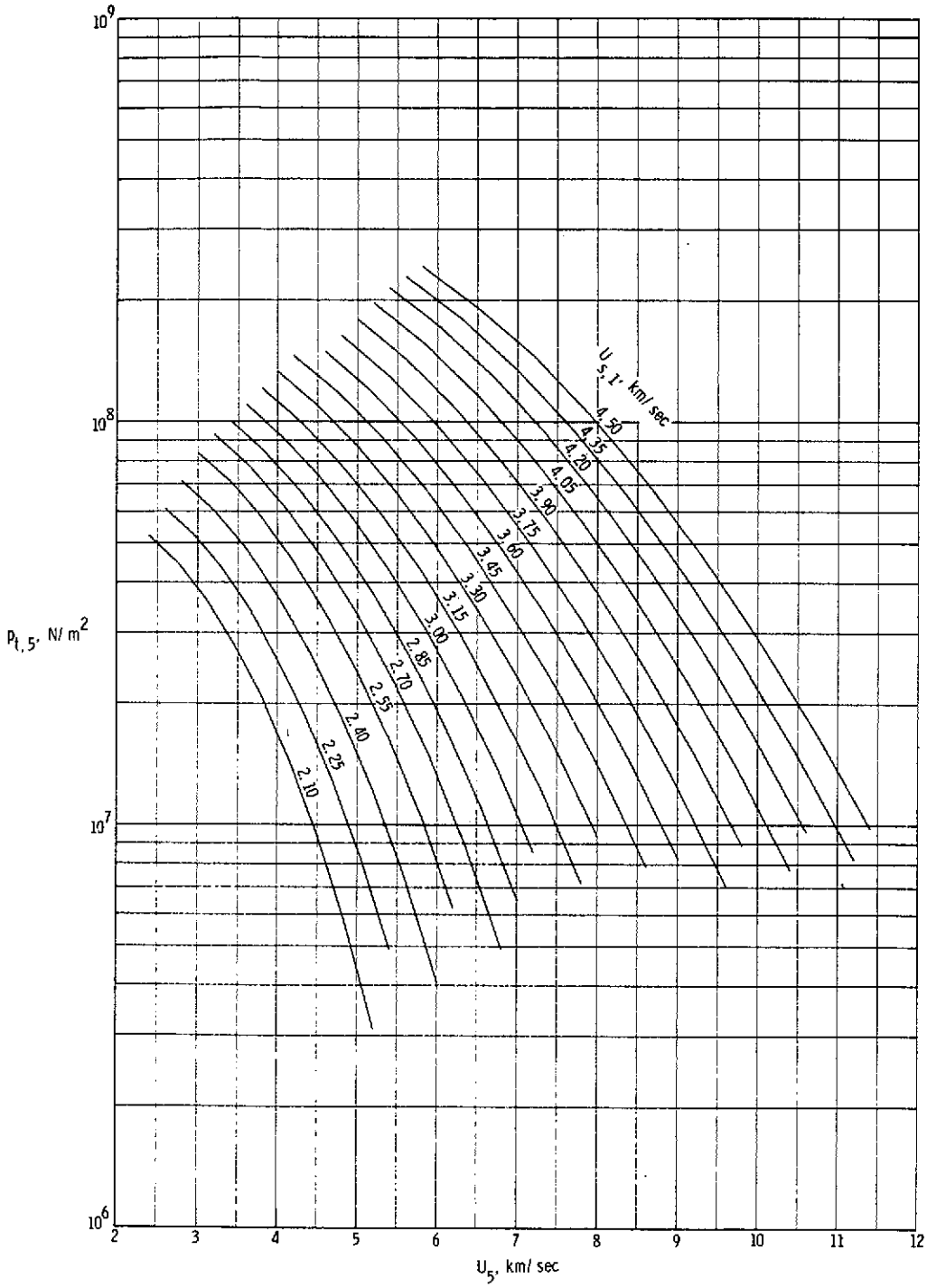
(e) Unit Reynolds number in region (5).

Figure 17.- Continued.



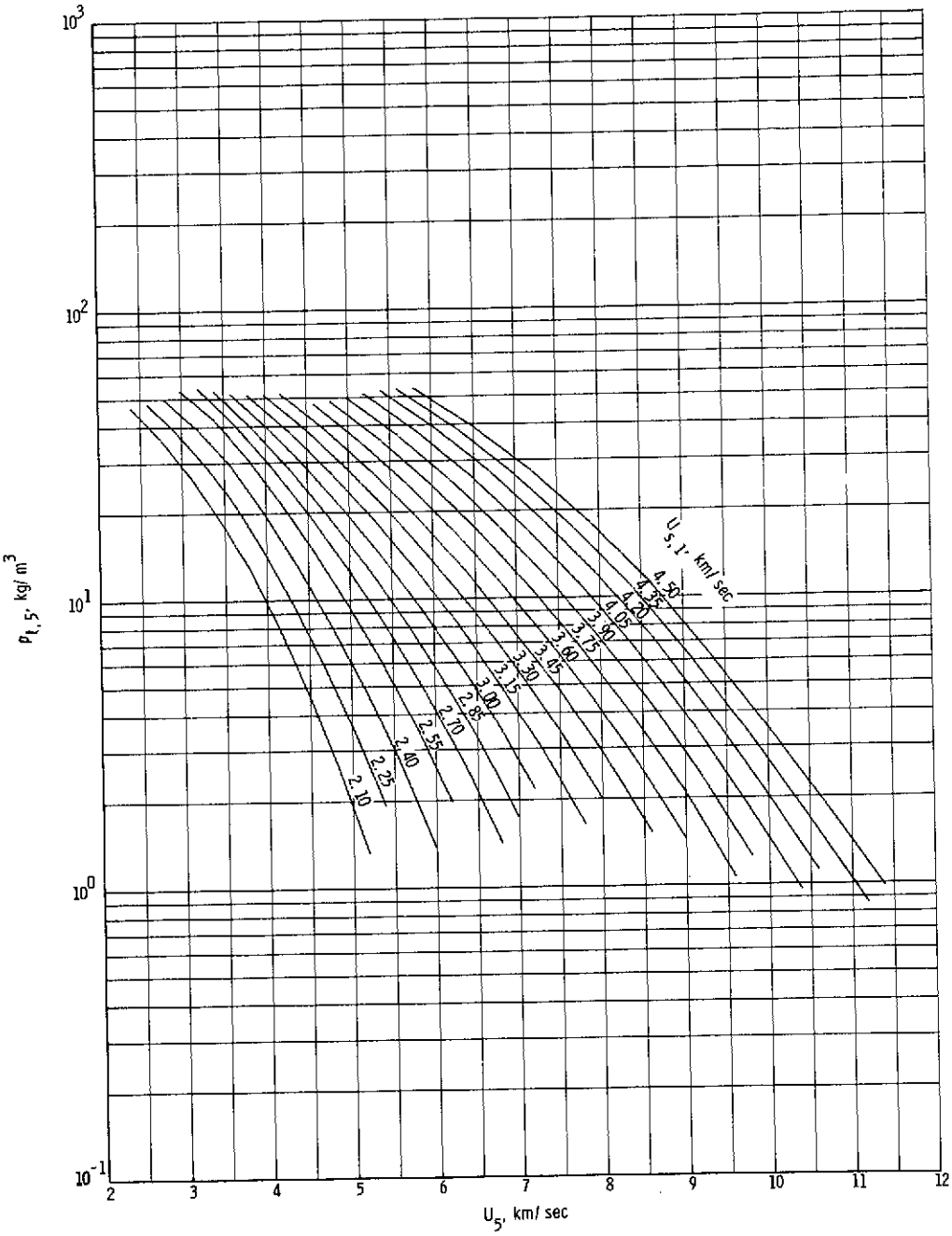
(f) Normal shock density ratio.

Figure 17.- Continued.



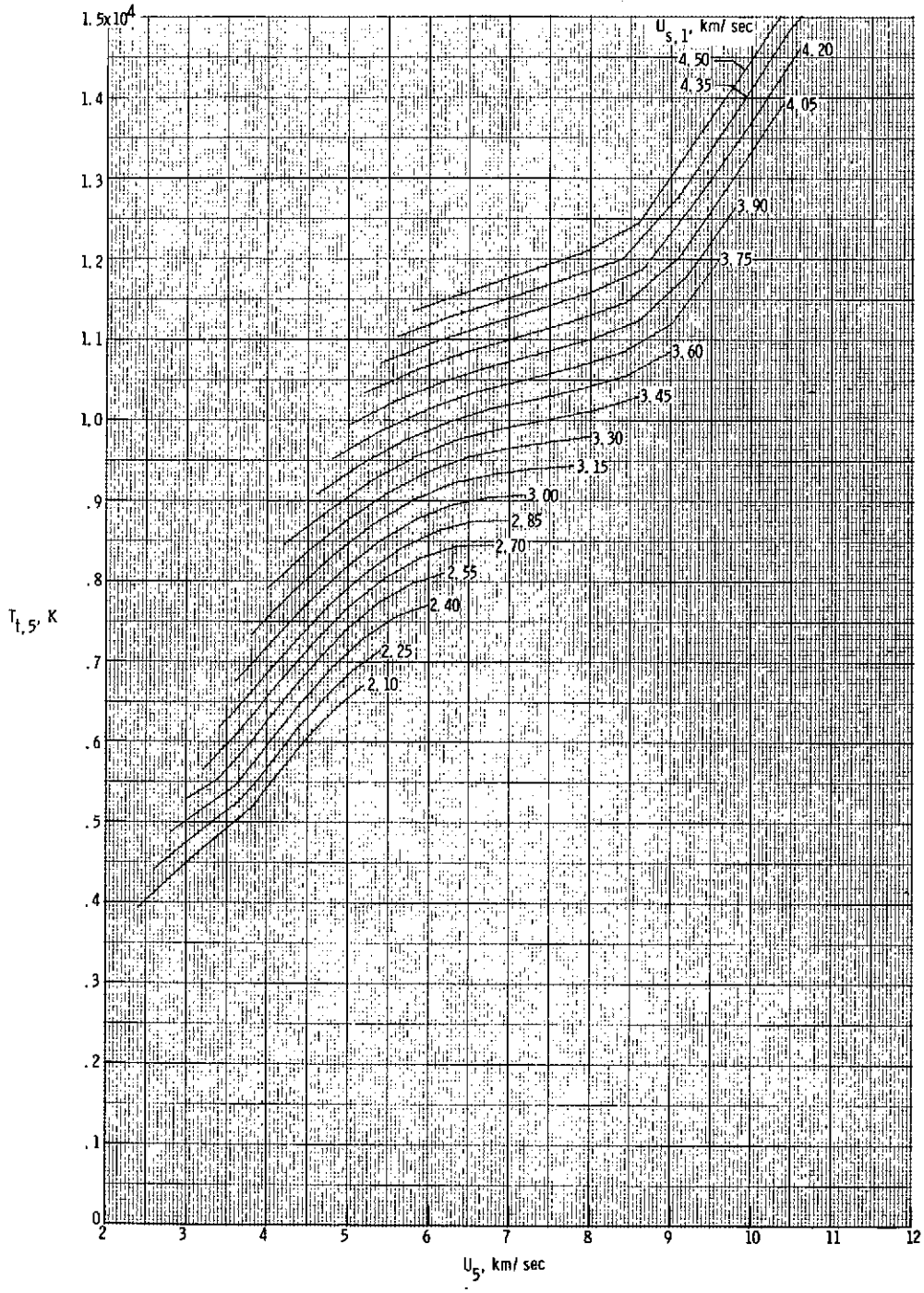
(g) Stagnation pressure behind normal bow shock.

Figure 17.- Continued.



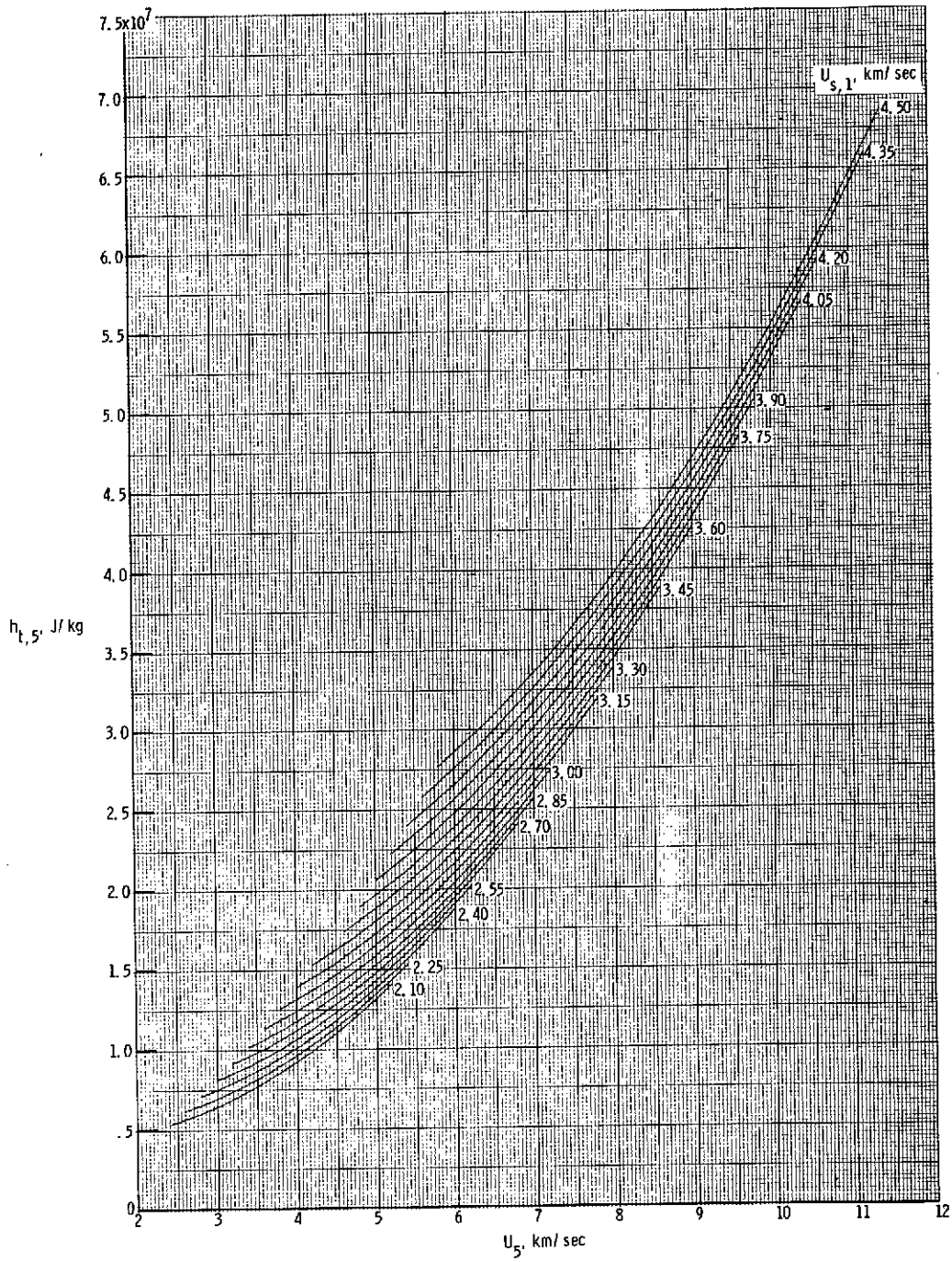
(h) Stagnation density behind normal bow shock.

Figure 17.- Continued.



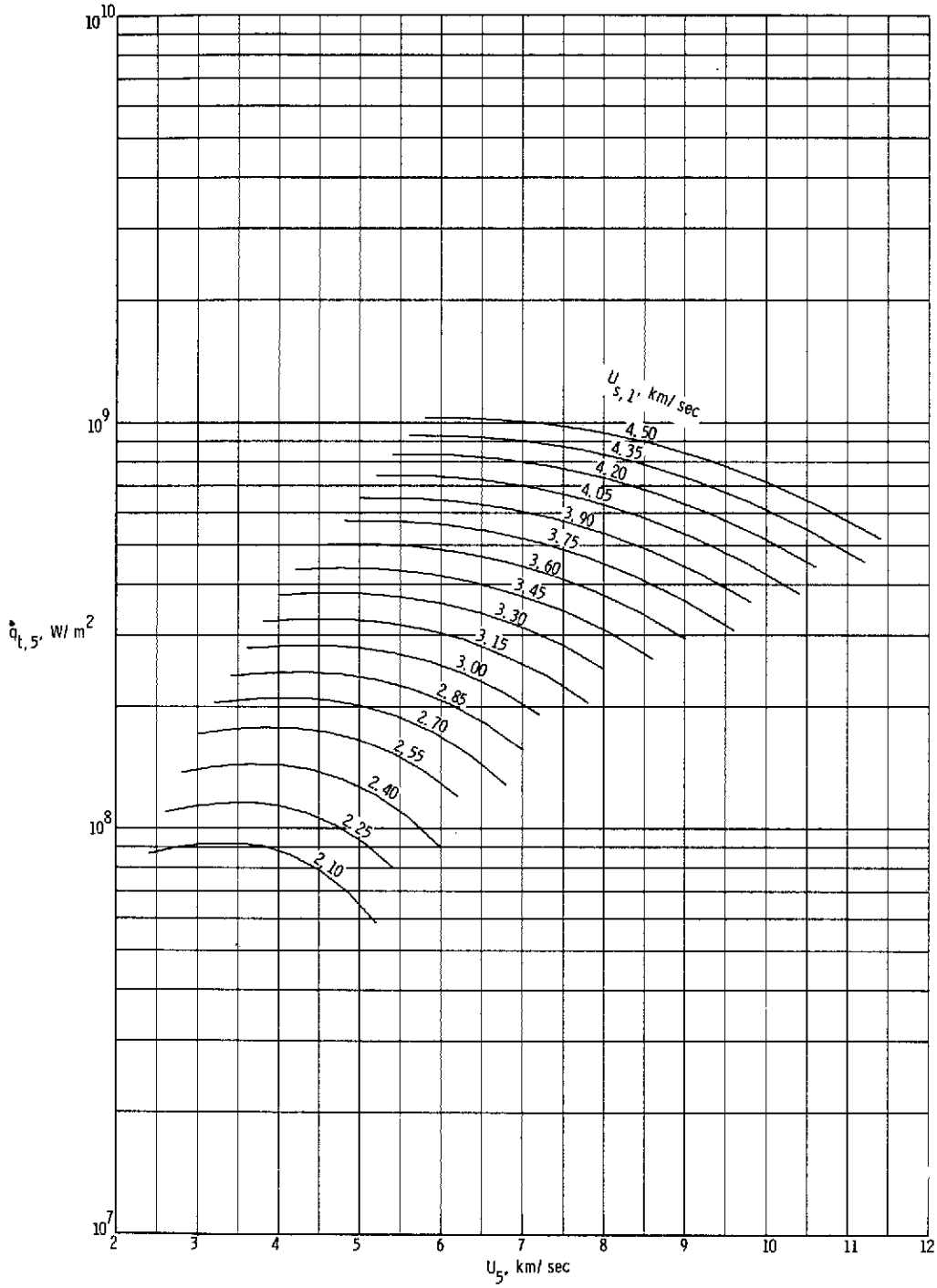
(i) Stagnation temperature behind normal bow shock.

Figure 17.- Continued.



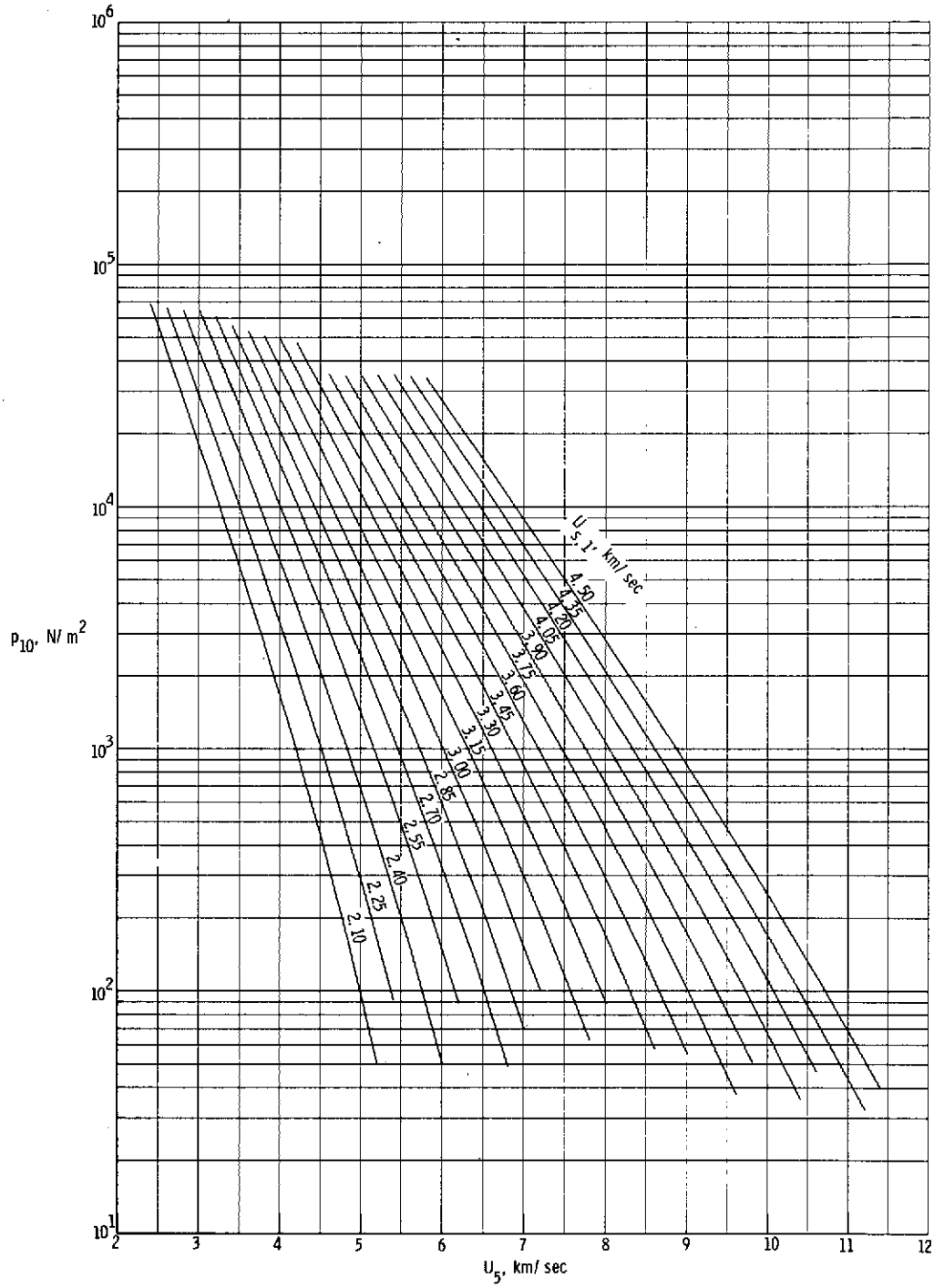
(j) Stagnation enthalpy behind normal bow shock.

Figure 17.- Continued.



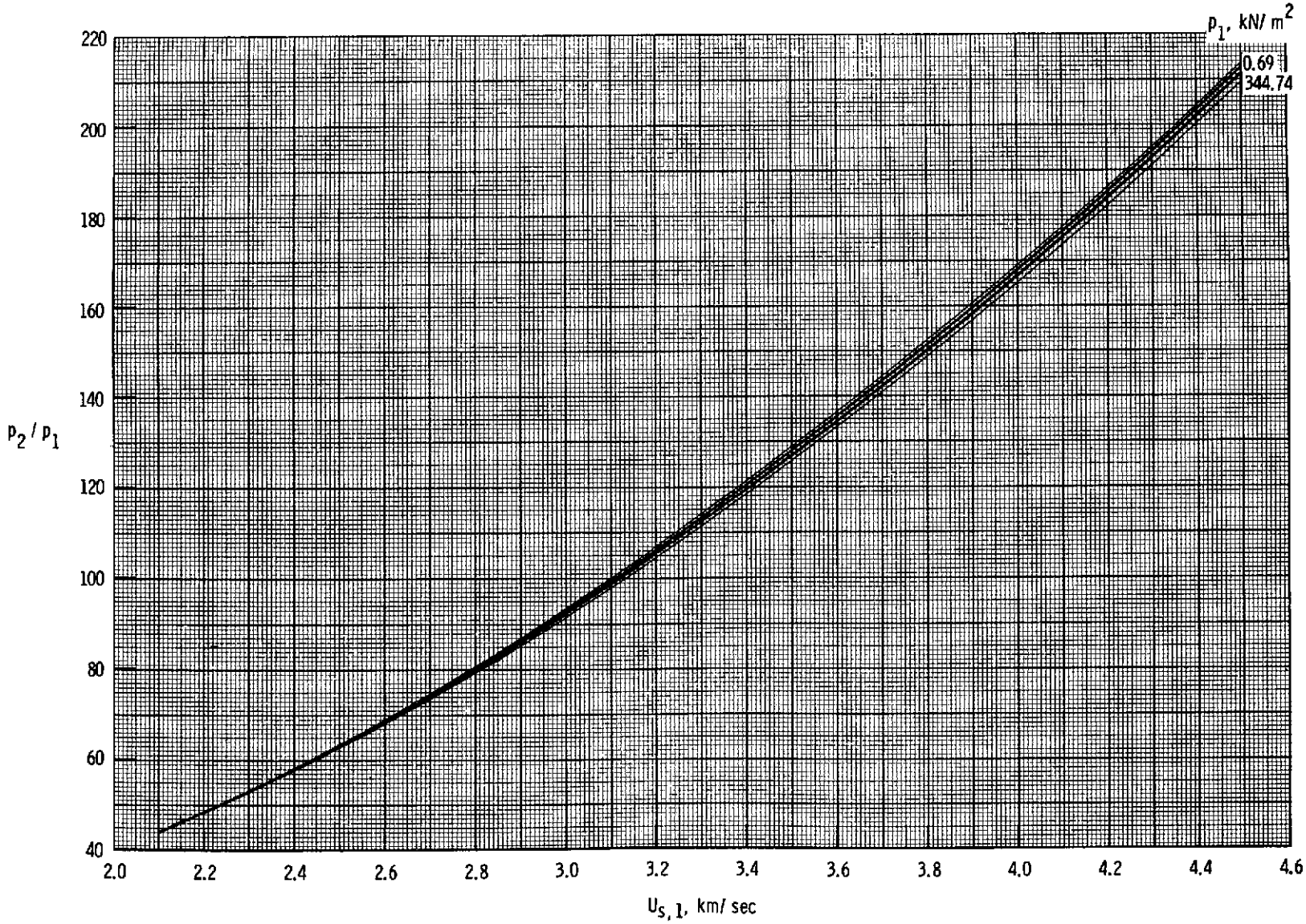
(k) Stagnation-point convective heat-transfer rate to sphere having radius of 2.54 cm.

Figure 17.- Continued.



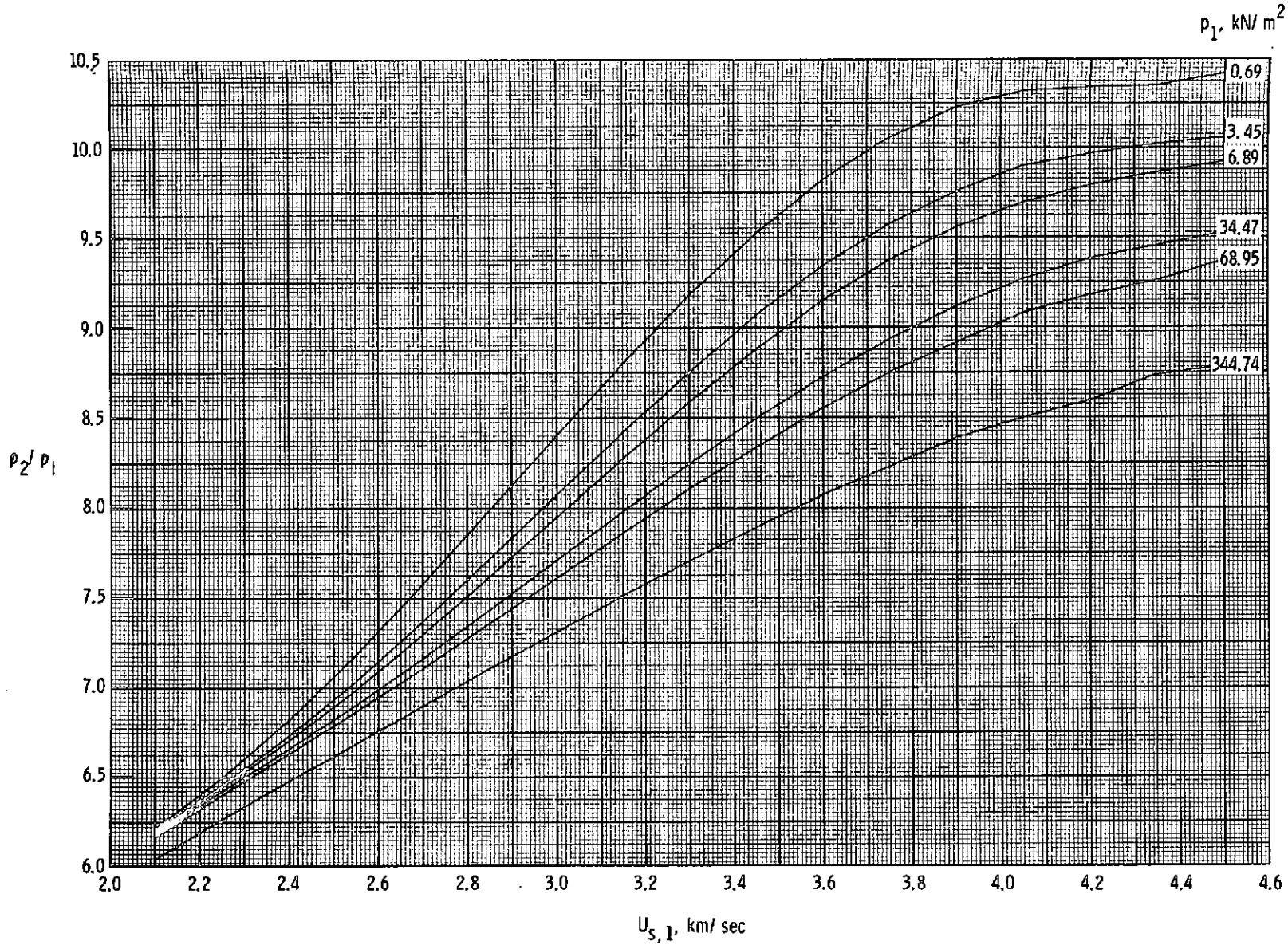
(l) Quiescent acceleration air pressure in region (10).

Figure 17.- Concluded.



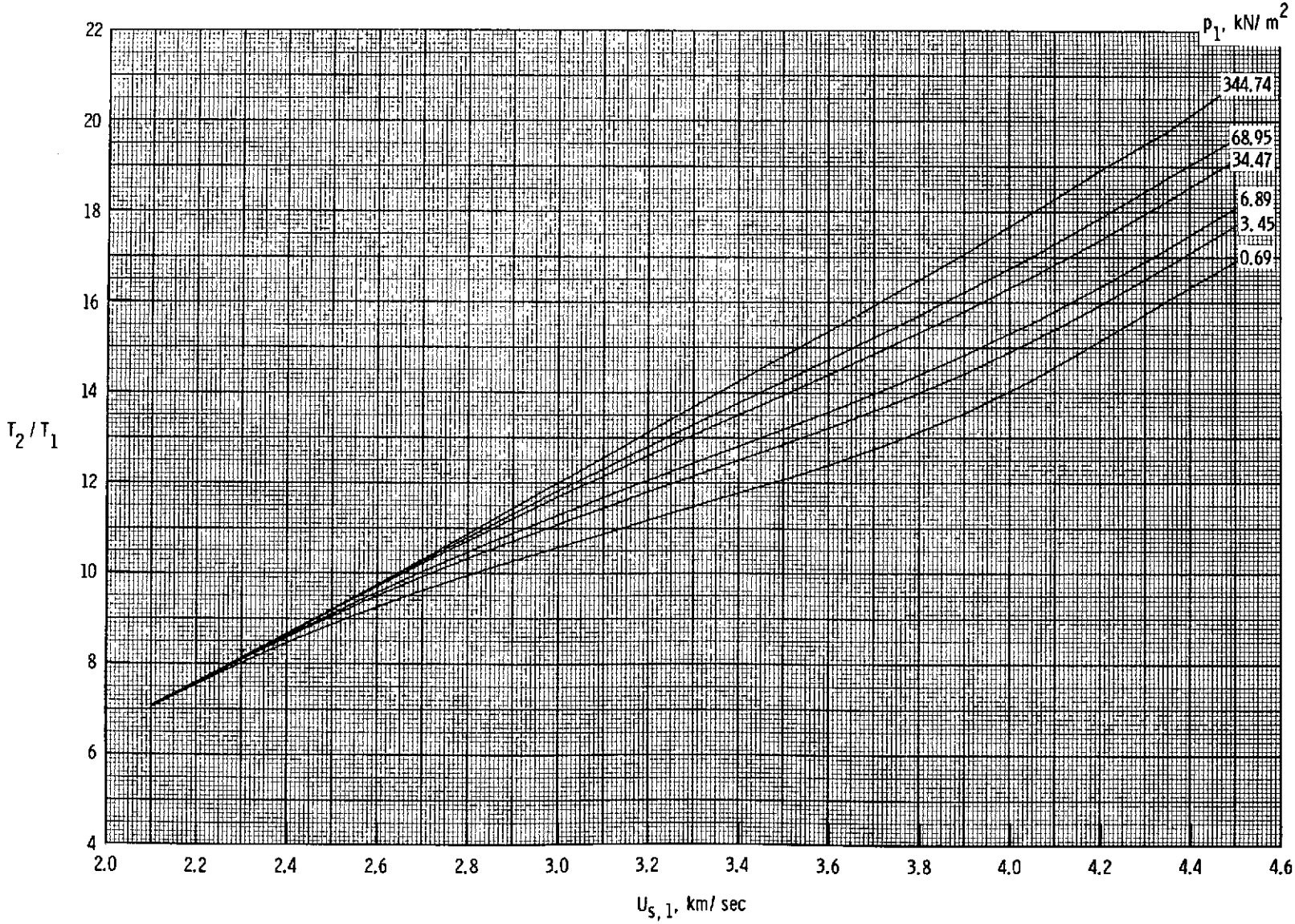
(a) Static pressure, p_2/p_1.

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



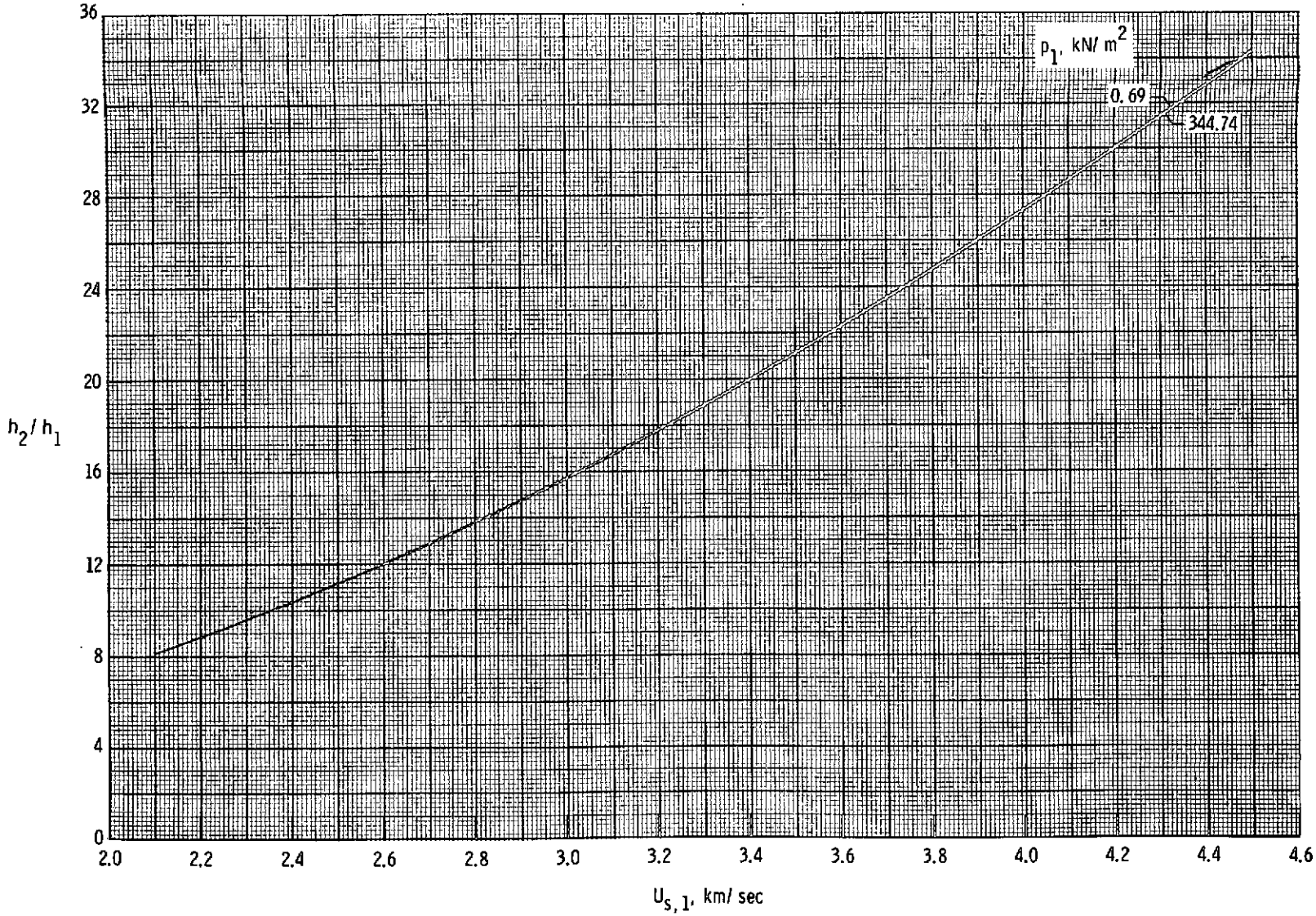
(b) Static density, ρ_2/ρ_1.

Figure 18.- Continued.



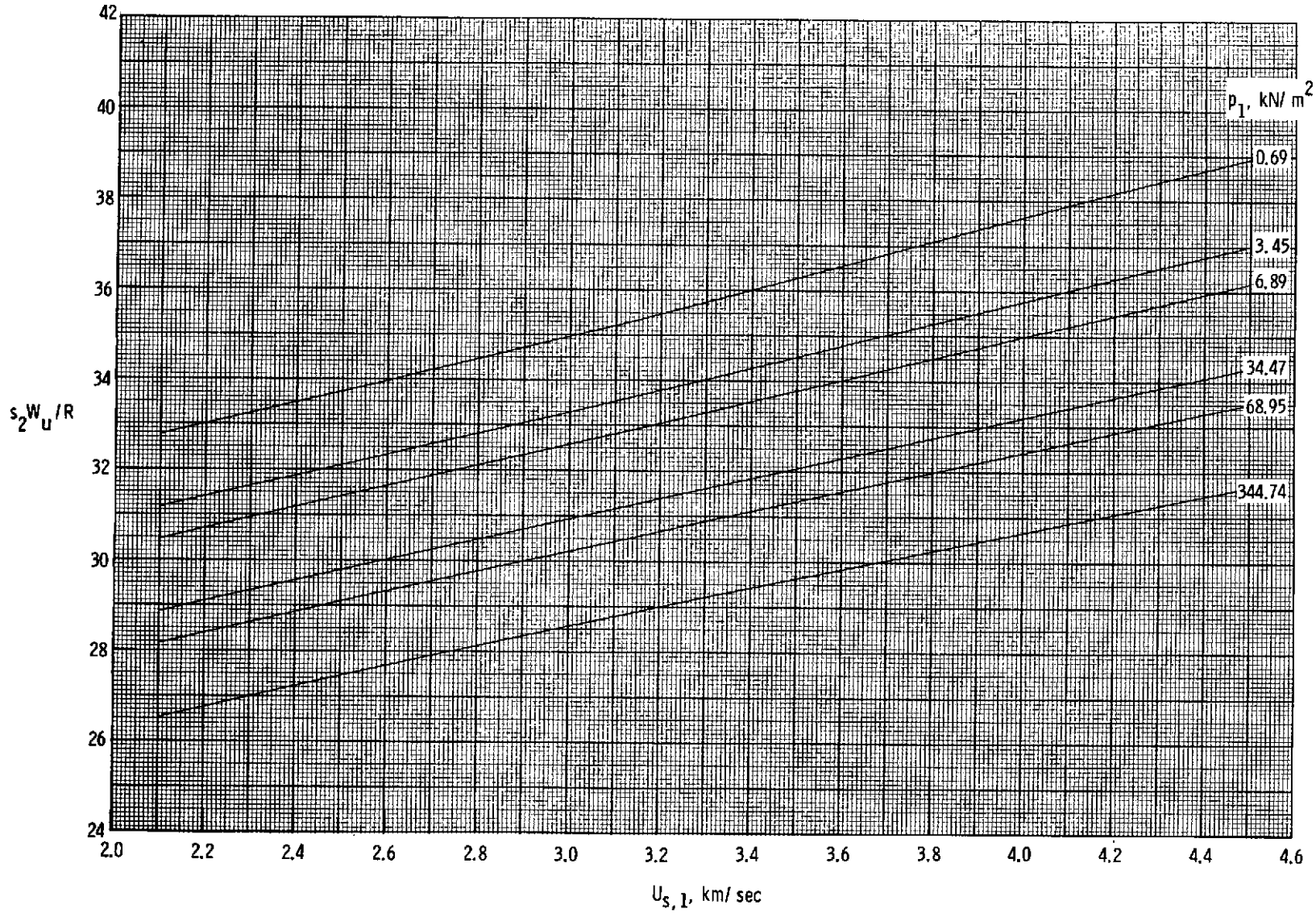
(c) Static temperature, T_2/T_1.

Figure 18.- Continued.



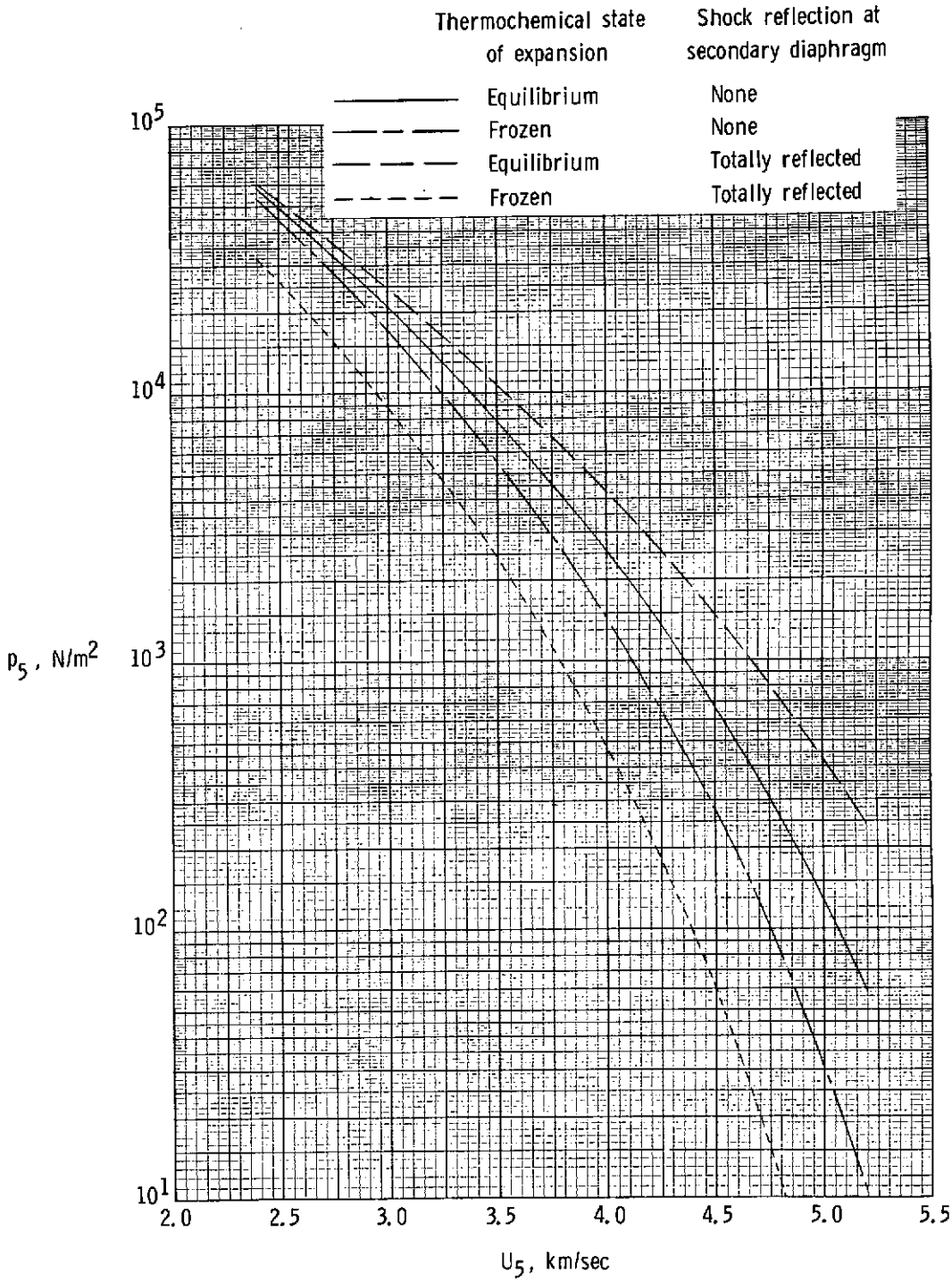
(d) Static enthalpy, h_2/h_1.

Figure 18.- Continued.



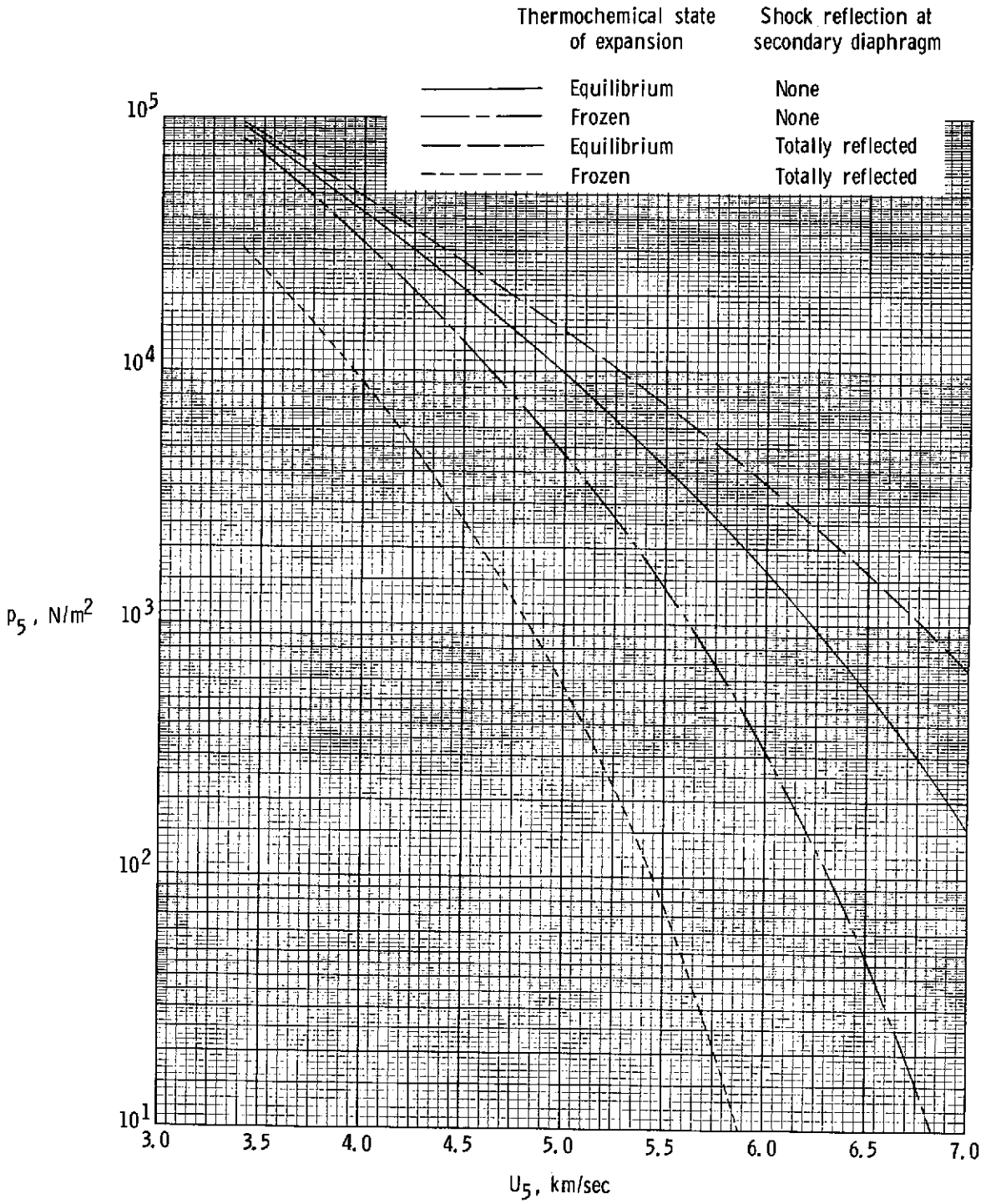
(e) Entropy, s_2W_u/R.

Figure 18.- Concluded.



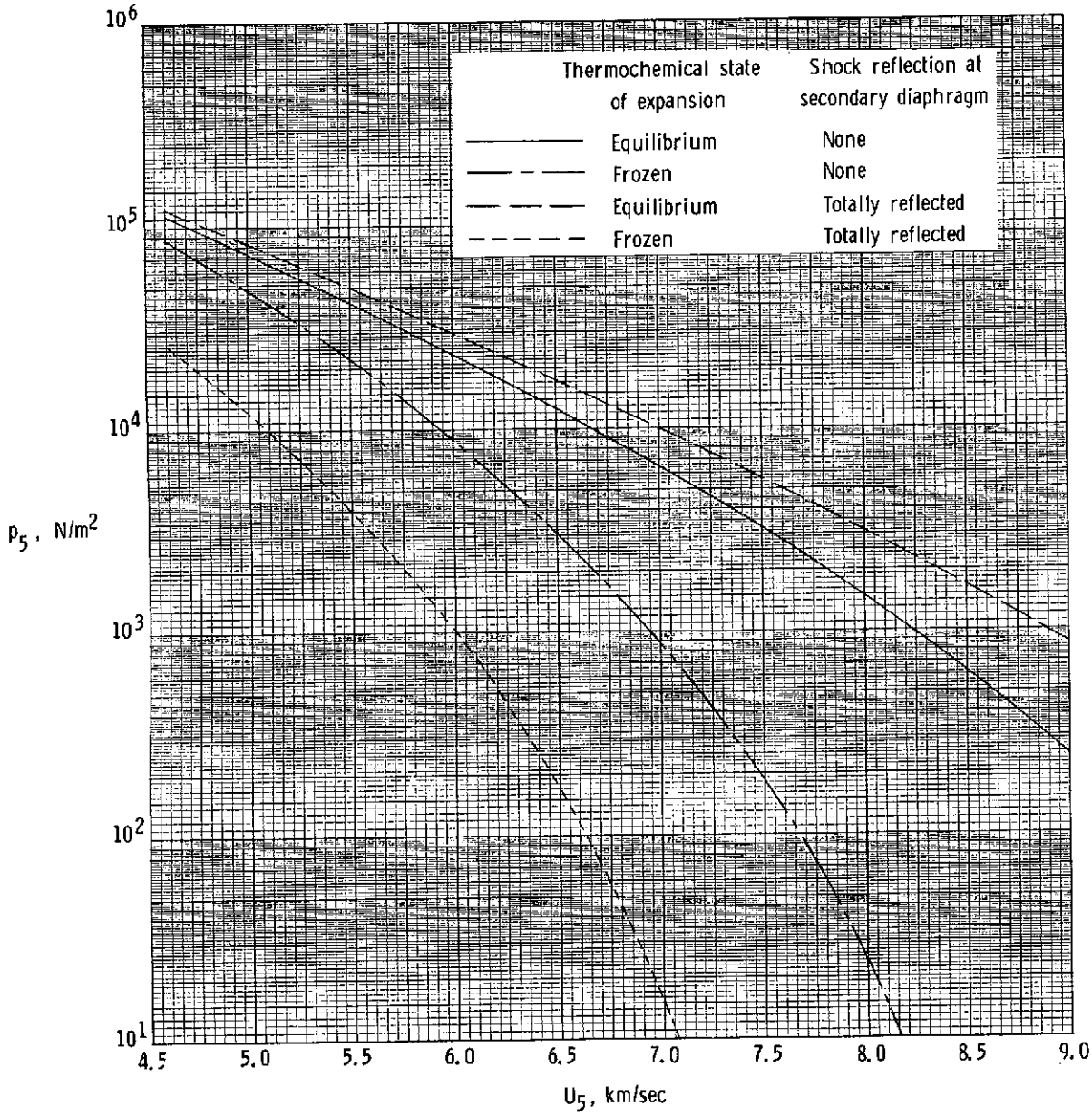
(a) $U_{s,1} = 2.1$ km/sec.

Figure 19.- Static pressure in region (5) as a function of air flow velocity for $p_1 = 3.45$ kN/m^2 and various incident normal-shock velocities.



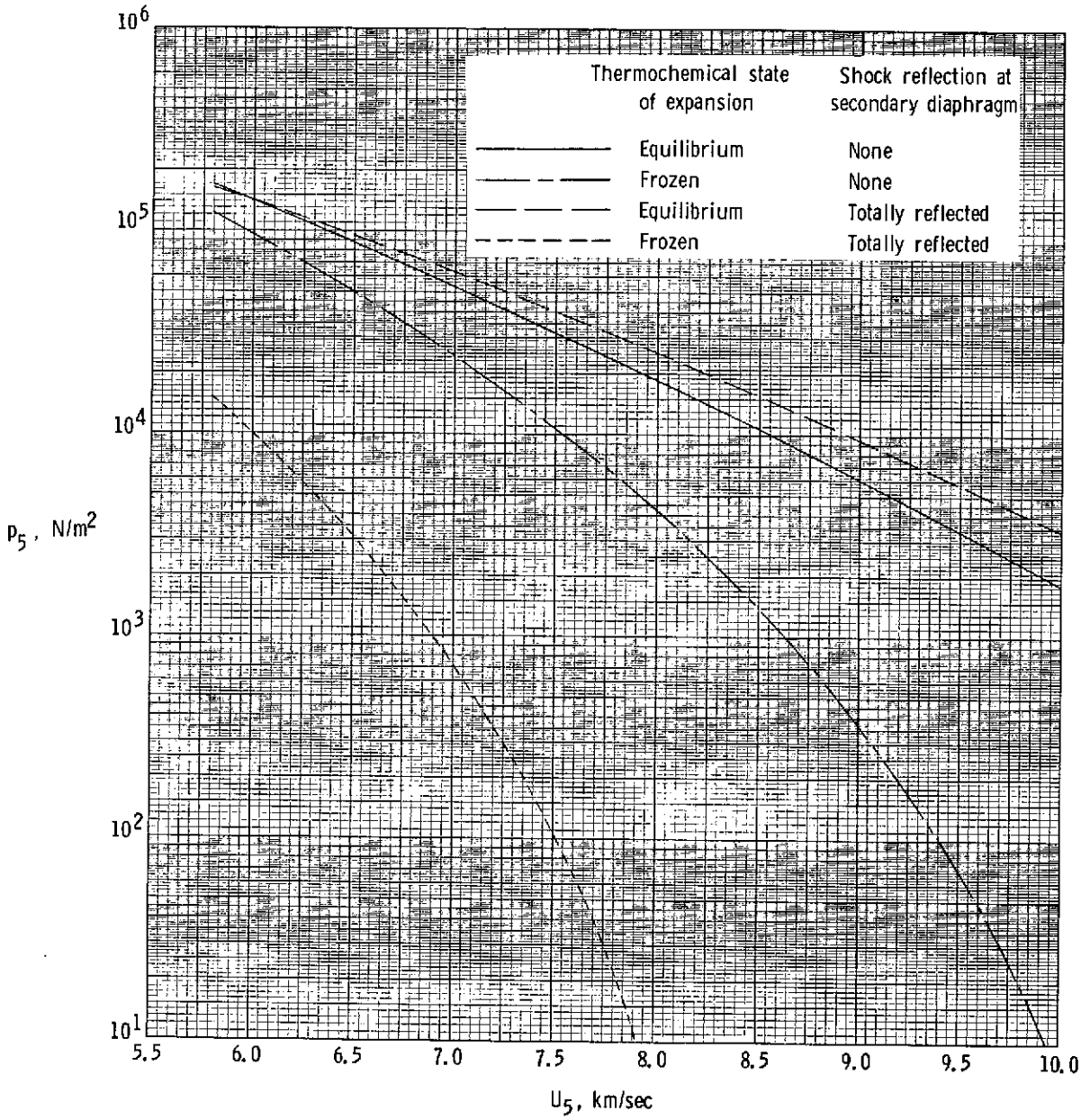
(b) $U_{s,1}$ = 2.85 km/sec.

Figure 19.- Continued.



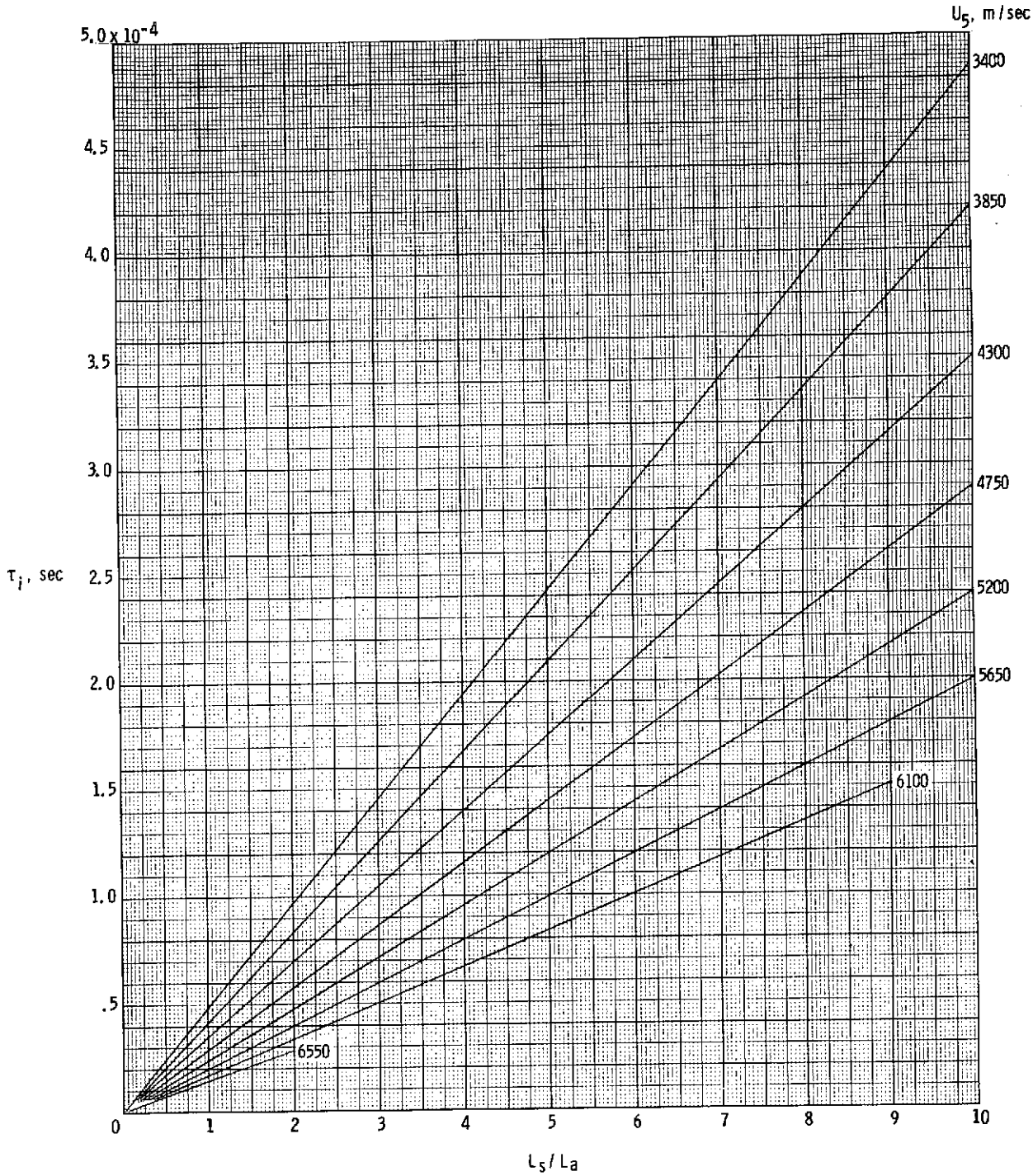
(c) $U_{s,1}$ = 3.6 km/sec.

Figure 19.- Continued.



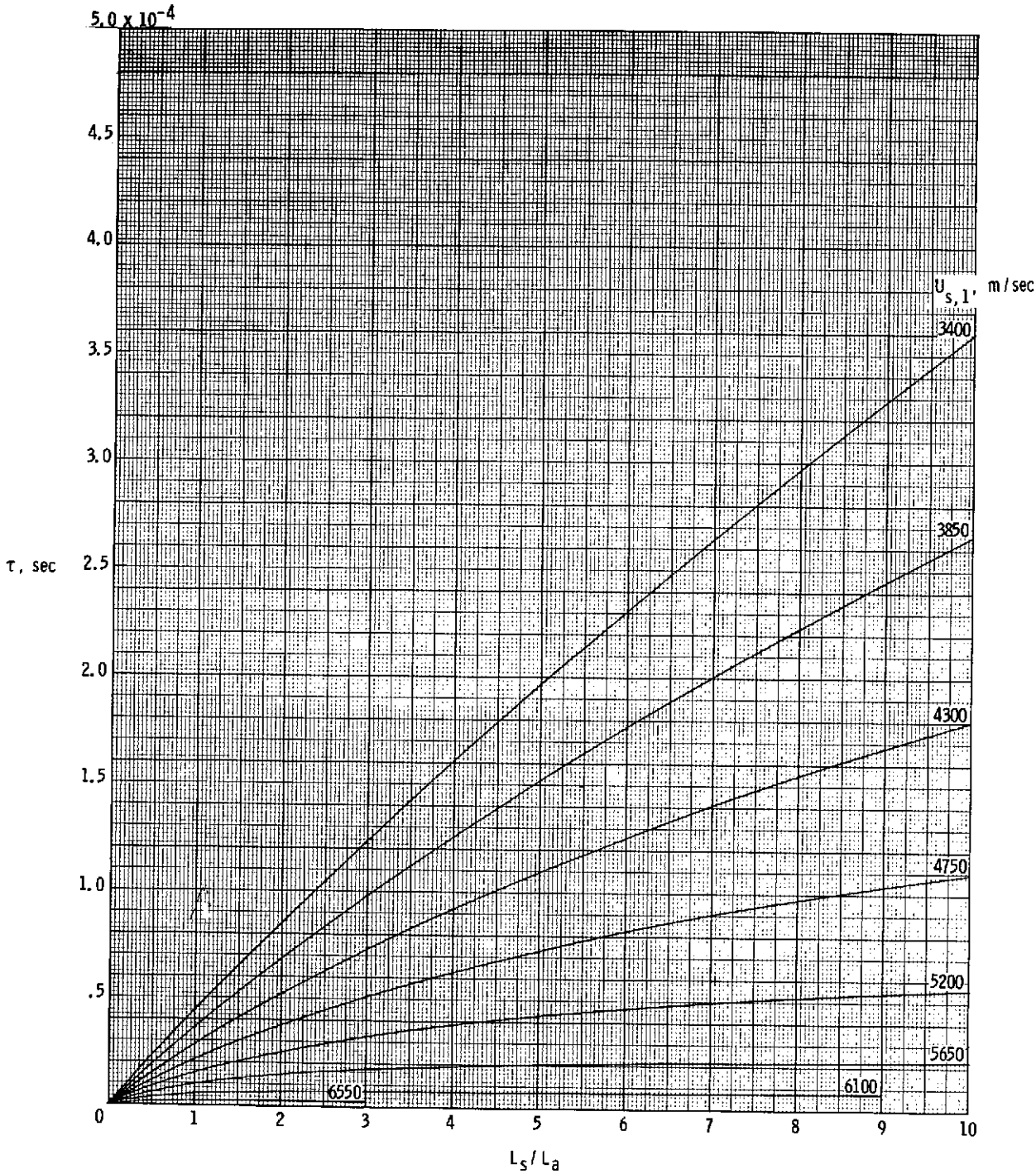
(d) $U_{s,1} = 4.5$ km/sec.

Figure 19.- Concluded.



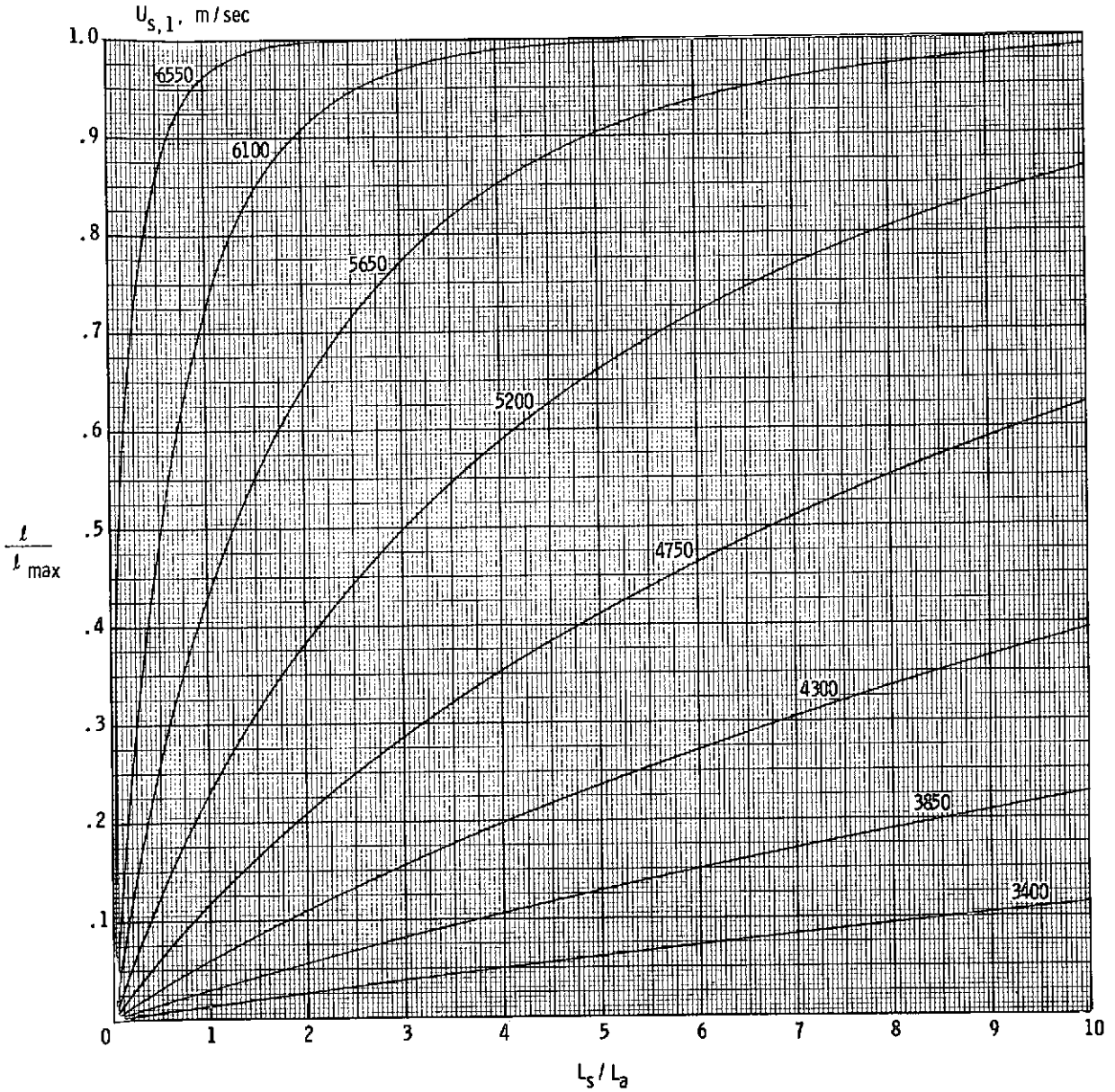
(a) Ideal time interval between arrival of incident normal shock into region (10) and acceleration-air—test-air interface.

Figure 20.- Acceleration air flow quantities as a function of distance downstream from secondary diaphragm for $p_1 = 3.45$ kN/m^2 and $U_{s,1} = 2.85$ km/sec.



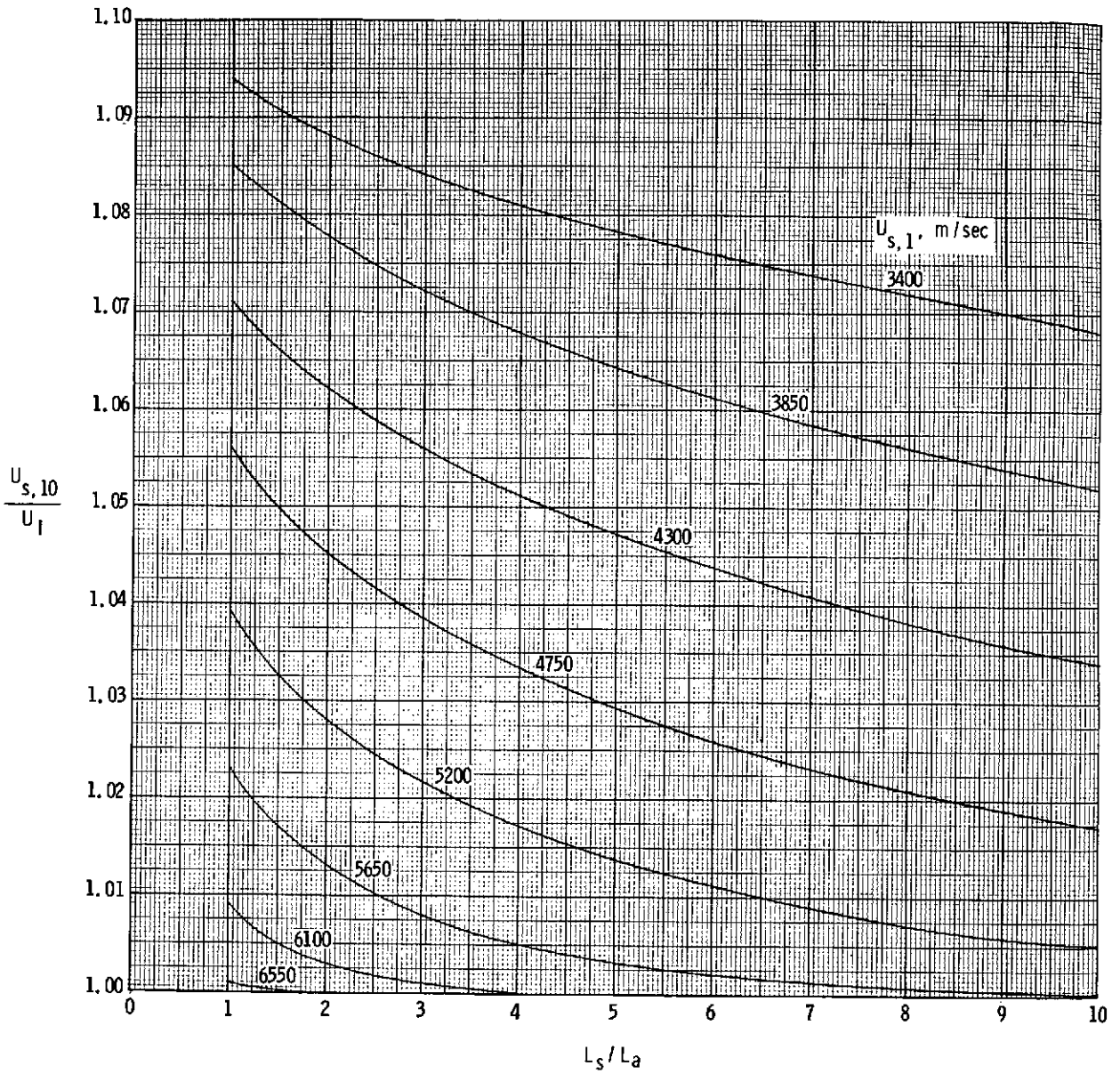
(b) Time interval between arrival of incident normal shock into region (10) and acceleration-air—test-air interface.

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.

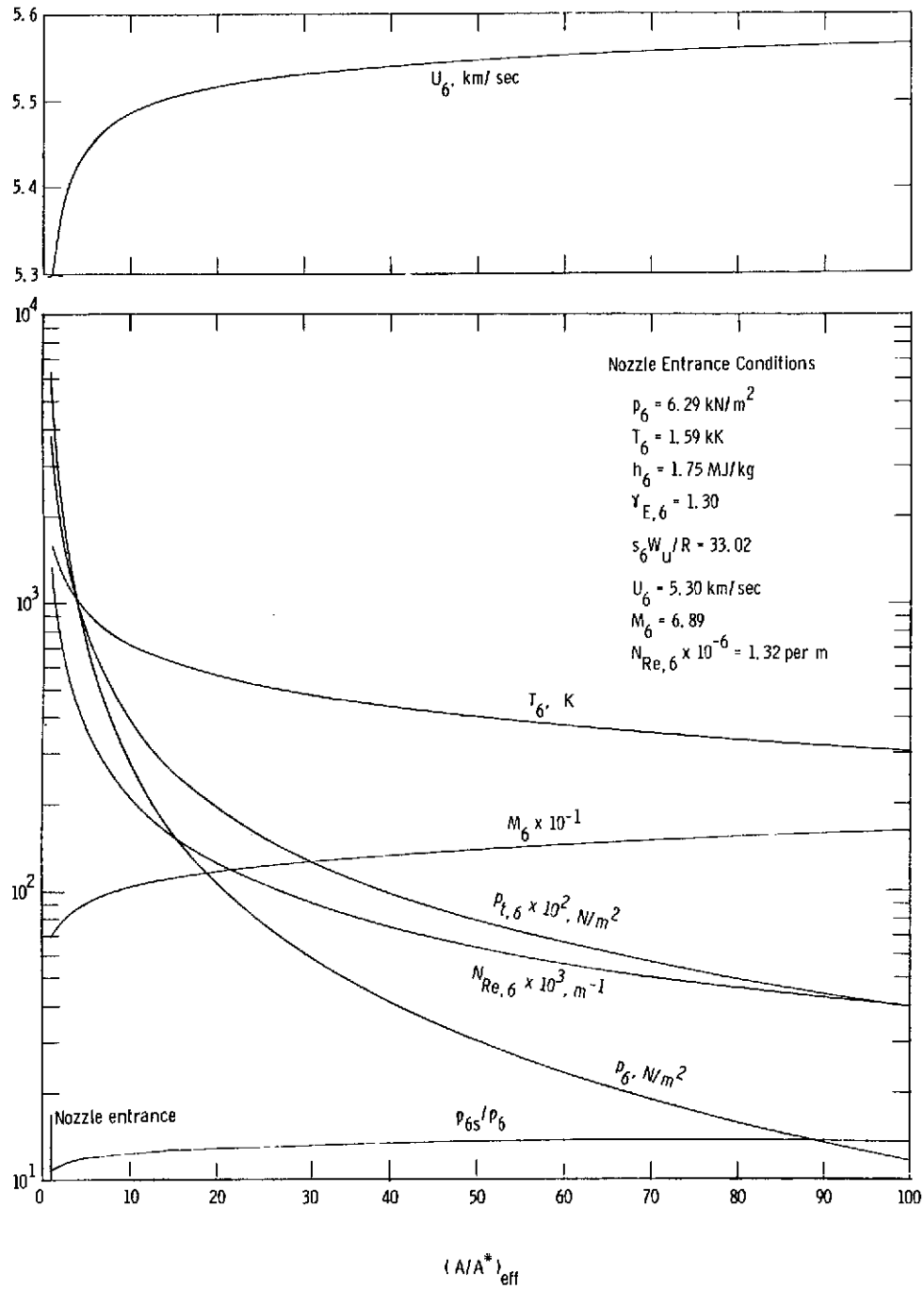
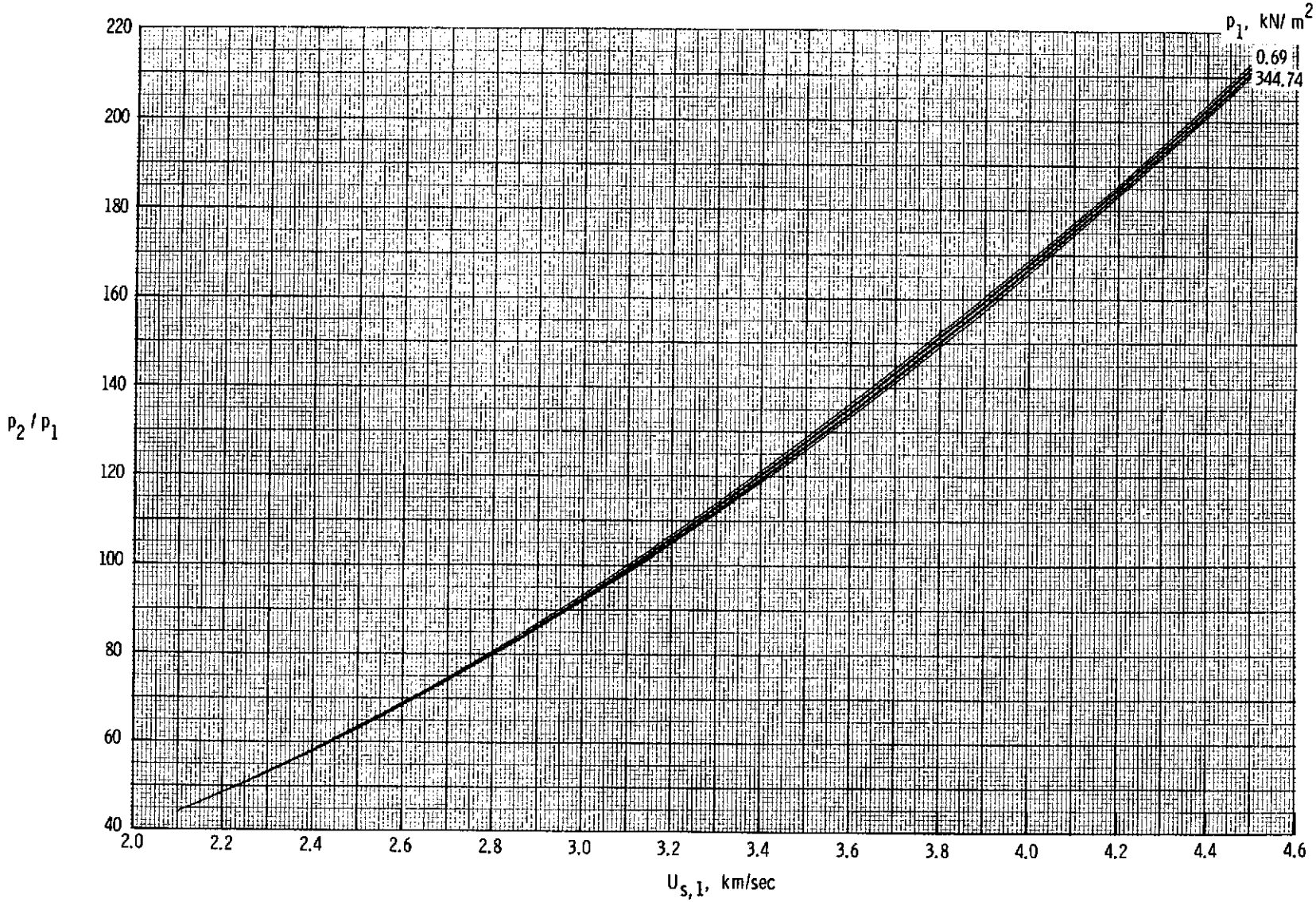
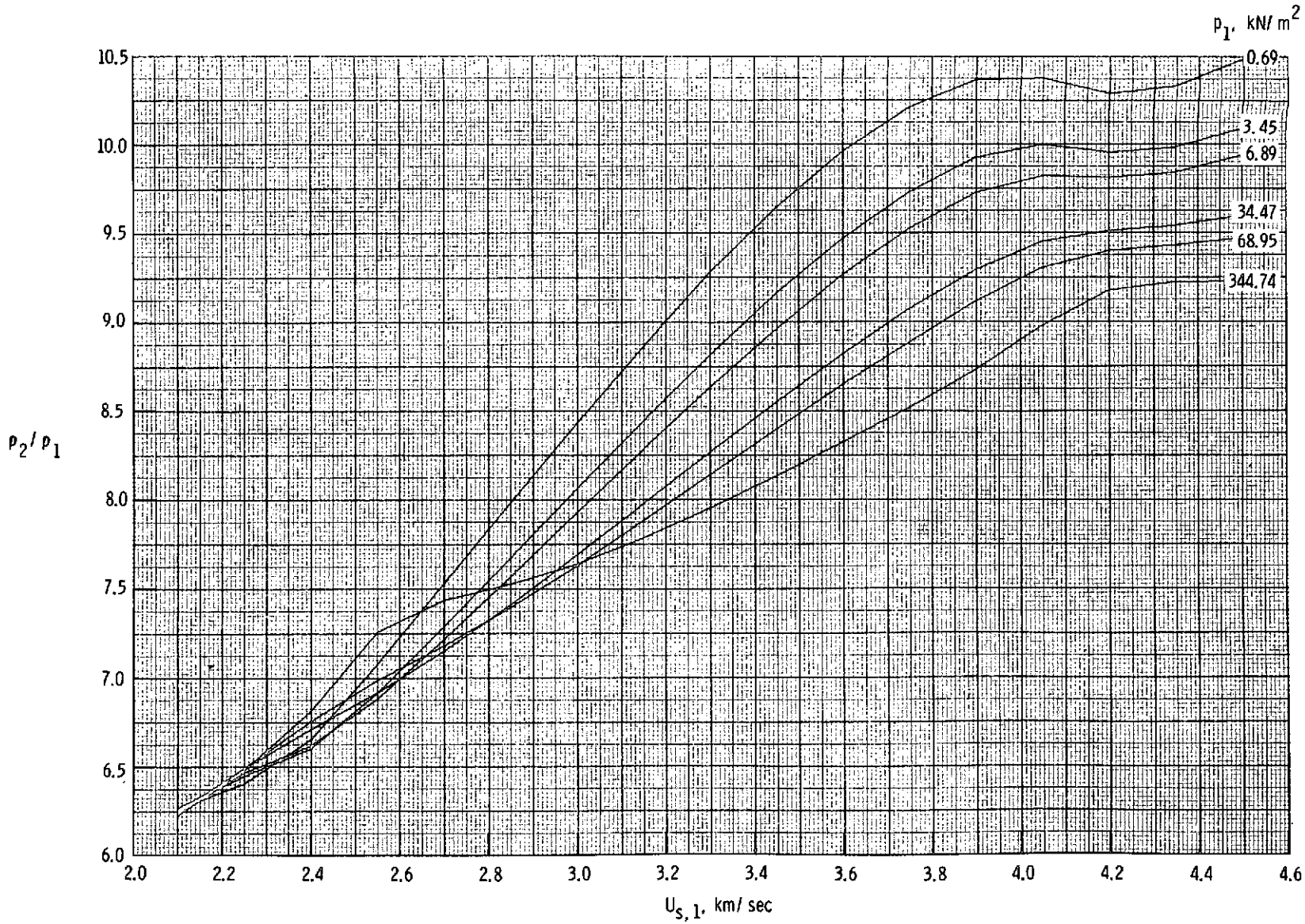


Figure 21.- Various expansion tunnel flow quantities as a function of effective area ratio.



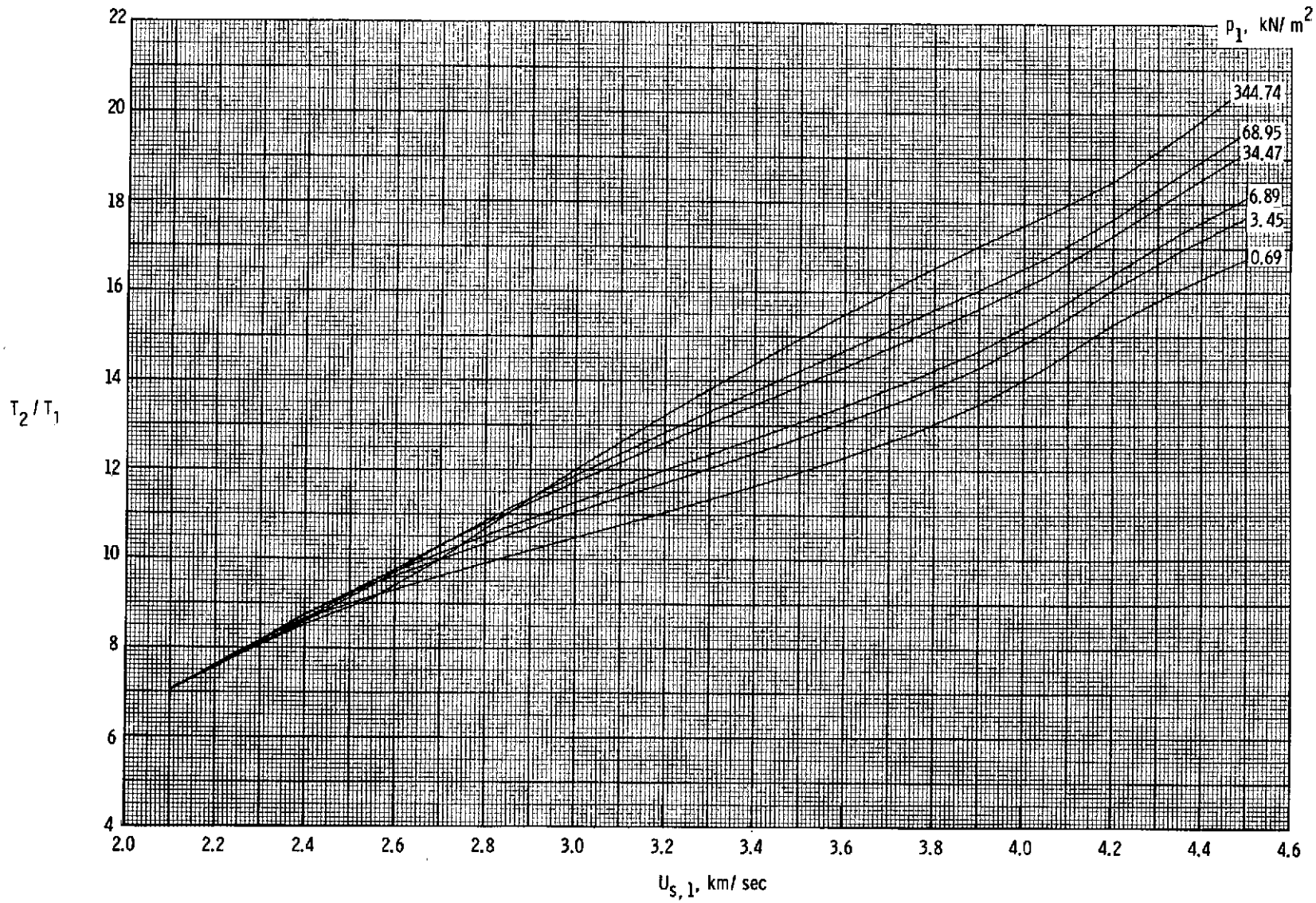
(a) Static pressure, p_2/p_1.

Figure 22.- Various nondimensional flow parameters in region (2) as a function of incident normal-shock velocity. (Predicted by using curve-fit expressions of ref. 11.)



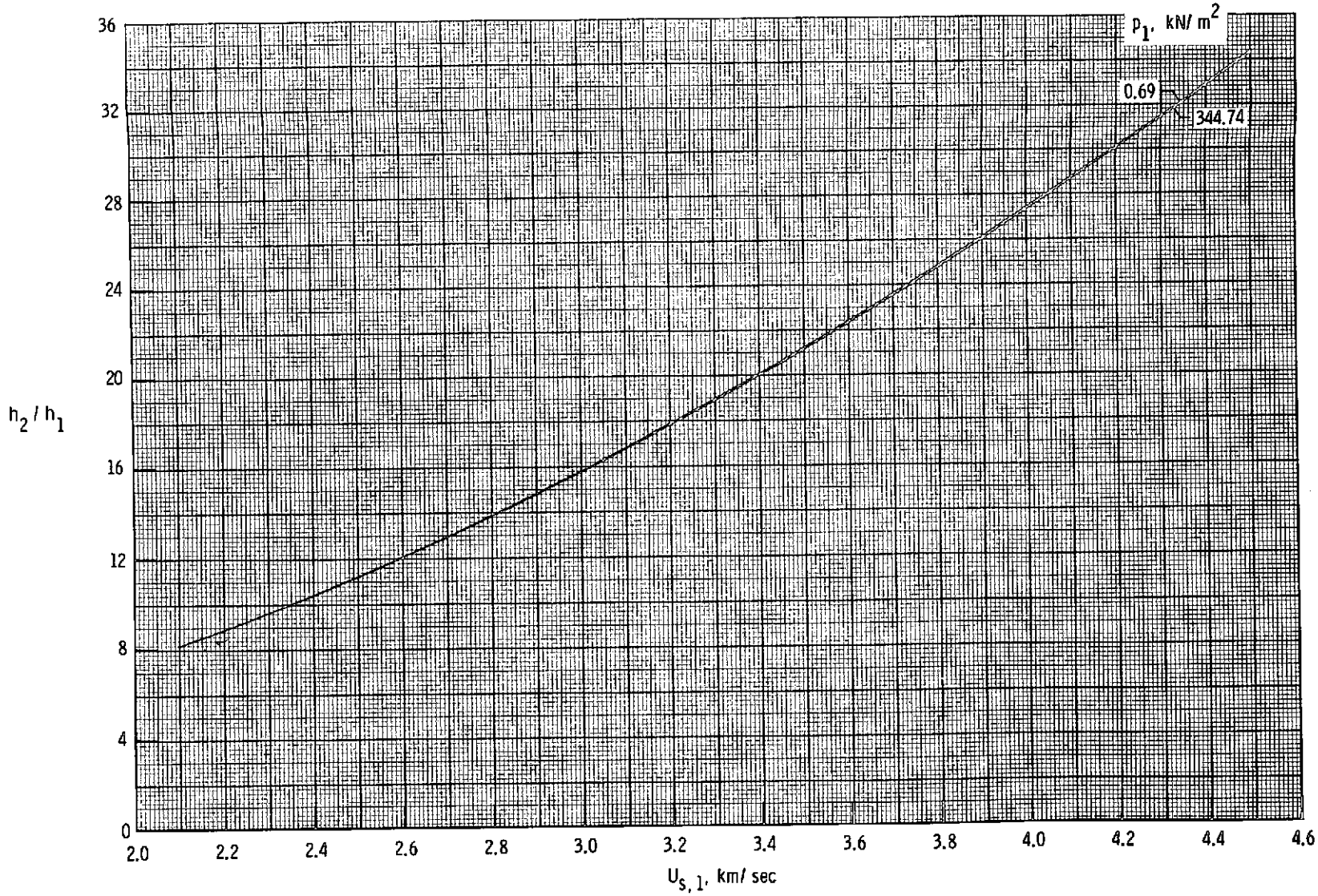
(b) Static density, ρ_2/ρ_1.

Figure 22.- Continued.



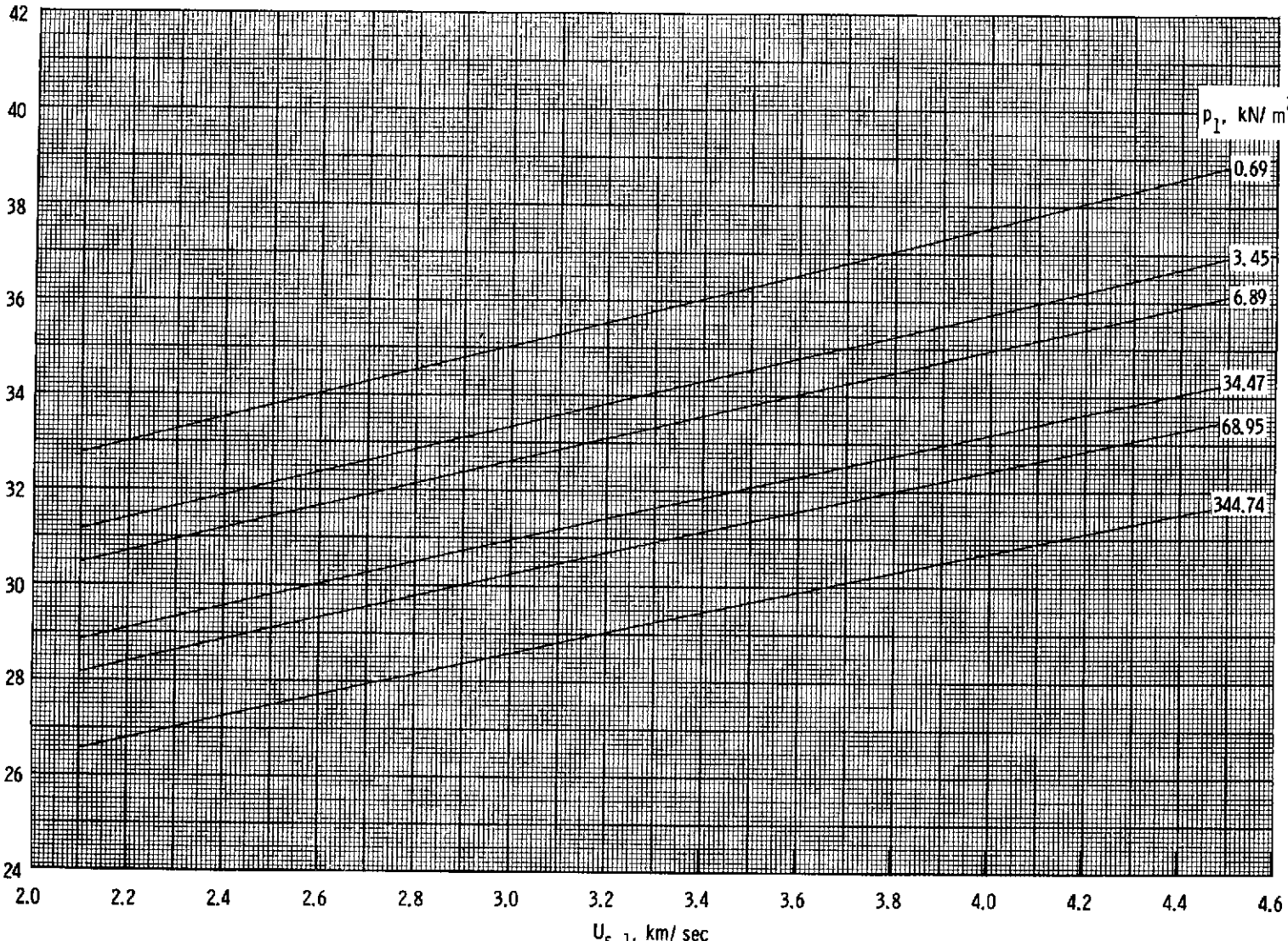
(c) Static temperature, T_2/T_1.

Figure 22.- Continued.



(d) Static enthalpy, h_2/h_1.

Figure 22.- Continued.



(e) Entropy, s_2W_u/R.

Figure 22.- Concluded.