N65-28627
(ACCESSION NUMBER)
128
(PAGES)
(NASA CR OR TMX OR AD NUMBER)
(THRU)
1
(CODE)
01
(CATEGORY)
FACILITY FORM 602

NASA SP-3018

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SIMCOX AND PETERSON

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Hard copy (HC)
Microfiche (MF) 1.00

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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CHARTS FOR EQUILIBRIUM AND FROZEN FLOWS ACROSS PLANE SHOCK WAVES IN CARBON DIOXIDE

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Scientific and Technical Information Division 1965
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

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SUMMARY

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The properties across a number of types of shock waves common in engineering applications have been calculated. The shocks include the normal and oblique waves used for estimating aerodynamic performance of bodies in flight and the incident, standing, and reflected normal shock waves used for evaluating facility performance and for interpreting the results of experiments performed therein. In the present work, the flow was assumed to be in equilibrium and the chemistry to be frozen with molecular vibrations either not excited or fully excited. Results are presented in graphical form for ambient pressures ranging from 10^{-7} to 10 atmospheres and for speeds ranging from 1 to 16 km/sec.

author

INTRODUCTION

In studies of missions within the atmospheres of planets other than Earth, the flow of gases other than air must be considered. In particular, properties of flows across shock waves must be known for many applications, such as predicting aerodynamic and thermodynamic loads on atmosphere entry vehicles and evaluating experimental results from ground-based facilities. A number of gases have been suggested as possible constituents of the atmospheres of the near planets, Mars and Venus. Of these, carbon dioxide is the only one that has been positively identified and shown to exist in quantity. Therefore, it is deemed appropriate to document the shock-wave properties of carbon dioxide for wide ranges of speed and ambient pressure.

A number of types of shock waves are common in engineering applications. These include the normal and oblique waves for estimating characteristics of bodies in flight and the incident, standing, and reflected normal waves for evaluating facility performance and interpreting experimental data obtained therein. Technically, the flow properties across normal shock waves need to be calculated and presented only for one type of shock wave, since the characteristics across the various types are derivable from each other by simple mathematical transformations. In the interest of providing information requiring a minimum amount of interpretation, however, it is common practice to present charts of characteristics for each type of shock wave, and this practice will be followed herein.

In many applications the flows across shock waves are not in chemical and thermodynamic equilibrium. Treatment of the exact nonequilibrium situation is difficult, and in many instances the additional complexity is not warranted. It is instructive, however, to estimate possible differences between nonequilibrium and

equilibrium results as well as the equilibrium limit itself. This is done in the present work by calculating shock-wave properties with the assumption of chemical and thermodynamic equilibrium as one limit and the assumption of frozen chemistry with vibrations either not excited or fully excited at the classical value as the other limit.

NOTATION

a	sound speed
h	enthalpy
M	Mach number, V/a
p	pressure
R	gas constant of cold gas
s	entropy
T	temperature
U	flow speed relative to test facility
V	flow speed relative to shock wave
Z	compressibility factor, $p/\rho RT$
γ	ratio of specific heats
δ	semiwedge angle
θ	shock-wave angle
ρ	density

Subscripts

a	conditions upstream of shock wave
b	conditions downstream of shock wave
rs	reflected shock wave
s	incident shock wave
t	total conditions
o	standard Earth sea level conditions for carbon dioxide

1	conditions upstream of incident shock wave
2	conditions downstream of incident shock wave
3	conditions downstream of standing or reflected shock wave

Reference Constants

p_o	$1 \text{ atm} = 1.013 \times 10^5 \ \text{N/m}^2$
R	$189.2 \ \text{m}^2/\text{sec}^2 \ {}^{\circ}\text{K}$
T_o	300° K
ρ_o	$1.783 \ \text{kg/m}^3$

COMPUTATION PROCEDURE

Methods for calculating flow properties across shock waves in equilibrium flows and in flows with chemistry frozen and molecular vibrations either not excited or fully excited were programmed for solution on an electronic digital computer. Results were obtained for coordinate systems and shock waves of interest in both flight and experimental facilities. For flight applications, results for normal and oblique shock waves were obtained as functions of flight speed for flows in chemical and thermodynamic equilibrium and for flows with chemistry frozen in the ambient state ahead of the shock waves and molecular vibrations not excited. For facility applications, results for incident, standing, and reflected normal shock waves were obtained as functions of the incident shock speed for flows in chemical equilibrium and for flows with chemistry frozen in the ambient state ahead of the incident shock and molecular vibrations not excited. In addition, the situations of chemistry frozen and vibrations fully excited (classical value) across the incident shock wave followed by instantaneous return to complete equilibrium downstream of the reflected and standing shock waves were considered. The detailed procedures and some of the equations used in the calculations are presented in the following sections.

General Considerations

The changes in flow properties across shock waves in all of the flows considered herein are governed by the equations expressing conservation of mass, momentum, and energy, and by the equation of state.

$$\left.\begin{aligned} &\text{Mass} && \rho_a V_a = \rho_b V_b \\ &\text{Momentum} && p_a + \rho_a V_a^2 = p_b + \rho_b V_b^2 \\ &\text{Energy} && h_a + (1/2)V_a^2 = h_b + (1/2)V_b^2 \\ &\text{State} && \rho = \rho(p, h) \end{aligned}\right\} \qquad (1)$$

The method of solving equations (1) for the four unknowns p_b, ρ_b, h_b, and V_b, depends upon the explicit form of the equation of state which, in turn, depends upon the particular assumptions being made regarding flow chemistry and thermodynamics. The methods used herein are described below.

Equilibrium. - The equation of state cannot be expressed in closed analytical form when the gas is undergoing chemical changes across the shock wave. Under these circumstances, a closed-form analytic solution of equations (1) was not possible. Instead, a solution of the governing equations was obtained numerically by means of the equilibrium thermodynamic properties of carbon dioxide given in reference 1. The thermodynamic properties of reference 1 were obtained using a gas model composed of 10 species, each behaving as an ideal gas. The species considered were CO_2, O_2, CO, C, O, C^+, C^{++}, O^+, O^{++}, and e^-.

In order to obtain solutions for the flow properties it is advantageous to rewrite equations (1) in the following form:

$$\left.\begin{aligned} p_b &= p_a + \rho_a V_a^2 \left[1 - (V_b/V_a)\right] \\ h_b &= h_a + (1/2)V_a^2 \left[1 - (V_b/V_a)^2\right] \\ \rho_b &= \rho_b(p_b, h_b) \\ V_b/V_a &= \rho_a/\rho_b \end{aligned}\right\} \tag{2}$$

Choosing an initial value of V_b/V_a, say zero, allows first estimates of p_b and h_b to be calculated. These estimates are used in conjunction with the Mollier charts of reference 1 to obtain ρ_b which, in turn, is used in the last of equations (2) to obtain an improved estimate of the speed ratio V_b/V_a. The process is repeated until successive values of the speed ratio differ only by a negligible amount. Values of p_b and ρ_b obtained by this method are used with the results of reference 1 to solve for remaining quantities T_b, a_b, s_b, Z_b, and species concentrations.

For total conditions the gas was assumed to be brought to rest by an isentropic compression. In this case, $s_t \equiv s$ and $h_t \equiv h + (1/2)V^2$ are known. These two quantities are sufficient to define the thermodynamic state so that the remaining total conditions can be determined from the results of reference 1.

Chemistry frozen, vibrations not excited. - The equation of state can be expressed in closed analytical form when the flow chemistry and vibrational energy are fixed. In this case, the gas is frozen in the molecular state (pure CO_2 at 0° K) with no energy in the vibrational modes so that the ratio of specific heats is constant at the classical value of 7/5. Under these circumstances, the equation of state takes the form

$$\rho = [\gamma/(\gamma - 1)]\,(p/h)$$

and equations (1) can be solved analytically. Resulting equations for both static and stagnation properties for this case are the same as those given in reference 2.

Chemistry frozen, vibrations fully excited. - The equations for this case are the same as those previously discussed for unexcited vibrations. The similarity results from the fact that in both cases the flow chemistry and specific heat ratio are constant throughout the flow. The specific heat ratio is obtained if molecular vibrations are considered to behave like harmonic oscillators with no coupling between vibrations and rotation within the molecule. The undissociated carbon dioxide molecule has four degrees of vibrational freedom so that, for this case, the specific heat ratio has a classical value of 15/13.

Flight Applications

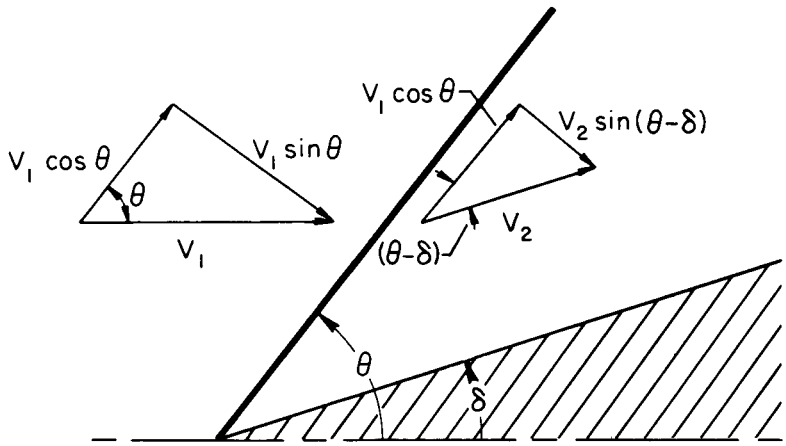
Values for three parameters must be specified in order to determine uniquely the properties of a flow across a shock wave in a real dissociating gas. In addition to flight speed, the ambient temperature and either pressure or density comprise the three specified quantities. In the event that the density and temperature profile of an atmosphere are known, such as for Earth, it is convenient to replace two of the three parameters with the single quantity, altitude. It is not possible to do this for the planets Mars and Venus, since the characteristics of their atmospheres are not known precisely. Therefore, the results presented herein are based on a single given ambient temperature and ranges of ambient pressures and flight speeds. All of the equilibrium results applicable to flight are for an ambient temperature of 200° K, a value near the mean of many estimates for the stratosphere temperatures of the atmospheres of Mars and Venus. The present results can be extended to other ambient temperatures, with only small loss in accuracy, by the methods described in the appendix.

Normal shock. - With the aid of equations (2), the equilibrium results were obtained by the previously described general procedure. The subscript a in equations (2) was replaced with the subscript 1 denoting upstream conditions and the subscript b was replaced with 2 denoting downstream conditions. The speed $V_a \equiv V_1$ is the flight speed and the speed $V_b \equiv V_2$ is the speed of the gas after the shock. With these substitutions, equations (2) for the equilibrium situation take the following form:

$$\left.\begin{aligned} p_2 &= p_1 + \rho_1 V_1^2 [1 - (V_2/V_1)] \\ h_2 &= h_1 + (V_1^2/2)[1 - (V_2/V_1)^2] \\ \rho_2 &= \rho_2(p_2, h_2) \\ V_2/V_1 &= \rho_1/\rho_2 \end{aligned}\right\} \tag{3}$$

To obtain the results for the frozen chemistry cases first the flight Mach number, $M_1 \equiv V_1/a_1$, was calculated and then the equations of reference 2 were used with $\gamma = 7/5$ for vibrations unexcited and $\gamma = 15/13$ for vibrations fully excited.

Oblique shock. - The flow geometry is illustrated in sketch (a). The equilibrium results were obtained from equations (2) with the subscript a replaced with the



Sketch (a)

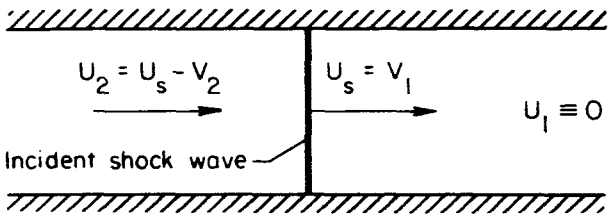
subscript 1 and the b replaced with 2. The speed V_a was set equal to the upstream speed normal to the wave $V_1 \sin\theta$ and the speed V_b was set equal to the downstream speed normal to the wave $V_2 \sin(\theta - \delta)$. An additional equation expressing conservation of momentum tangential to the shock wave was also introduced. With these substitutions and additions, equations (2) for the equilibrium situation take the following form:

$$\left.\begin{aligned}
p_2 &= p_1 + \rho_1 (V_1 \sin\theta)^2 \left[1 - \frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta}\right] \\
h_2 &= h_1 + \frac{1}{2}(V_1 \sin\theta)^2 \left\{1 - \left[\frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta}\right]^2\right\} \\
\rho_2 &= \rho_2(p_2, h_2) \\
\frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta} &= \frac{\rho_1}{\rho_2} \\
\tan\theta &= \frac{\left[1 - \frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta}\right] - \sqrt{\left[\frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta} - 1\right]^2 - 4 \tan\delta \frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta}}}{2 \tan\delta \frac{V_2 \sin(\theta - \delta)}{V_1 \sin\theta}}
\end{aligned}\right\} \tag{4}$$

The results for the frozen chemistry cases were obtained by using the equations of reference 2 with $\gamma = 7/5$ for vibrations unexcited and $\gamma = 15/13$ for vibrations fully excited.

Facility Applications

Three types of normal shock waves of interest in connection with experimental test facilities are the incident shock wave, the standing shock wave, and the reflected shock wave. The latter two types of shock waves occur behind or after an incident wave so that it is necessary to first solve for conditions downstream of the incident wave. These are the conditions upstream of the standing and reflected waves. An initial temperature of 300° K was used in all the equilibrium calculations.



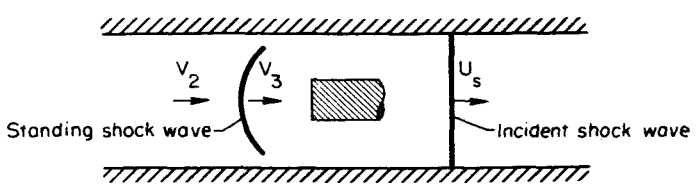
Sketch (b)

Incident shock wave. - The flow geometry is illustrated in sketch (b). The equilibrium results were obtained from equations (2) with the subscripts a and b replaced with 1 and 2, respectively. In addition, it was recognized that $V_1 = U_S$. With these substitutions, equations (2) take the following form:

$$\left.\begin{aligned} p_2 &= p_1 + \rho_1 U_S^2[1 - (V_2/U_S)] \\ h_2 &= h_1 + (U_S^2/2)[1 - (V_2/U_S)^2] \\ \rho_2 &= \rho_2(p_2, h_2) \\ V_2/U_S &= \rho_1/\rho_2 \end{aligned}\right\} \tag{5}$$

Downstream of the shock wave the flow speed relative to a laboratory fixed coordinate system is $U_2 = U_S - V_2$.

To obtain the results for the frozen chemistry cases the shock Mach number, $M_S \equiv U_S/a_1$, was calculated and the equations of reference 2 were used together with the respective values for specific heat ratios of 7/5 and 15/13.



Sketch (c)

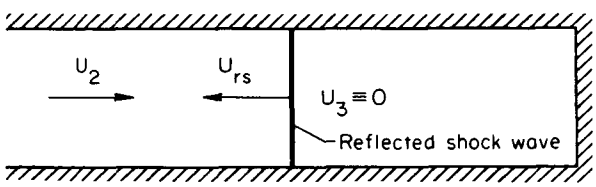
Standing shock wave. - The flow geometry is illustrated in sketch (c). It is clearly evident in sketch (c) that the conditions downstream of the incident shock wave are the upstream conditions for the standing shock wave. Therefore, the conditions with subscript 2 are known from the

incident shock-wave results and it is necessary to solve for the conditions downstream of the standing wave denoted by subscript 3. With these substitutions equations (2) take the following form:

$$\left.\begin{aligned} p_3 &= p_2 + \rho_2 V_2^2 [1 - (V_3/V_2)] \\ h_3 &= h_2 + (V_2^2/2)[1 - (V_3/V_2)^2] \\ \rho_3 &= \rho_3(p_3, h_3) \\ V_3/V_2 &= \rho_2/\rho_3 \end{aligned}\right\} \tag{6}$$

The flow speed relative to a laboratory fixed coordinate system is, of course, the same as that relative to the shock since the shock is not moving; $U_3 \equiv V_3$.

To obtain the results for the frozen chemistry the upstream Mach number, $M_2 = V_2/a_2$, was calculated and the equations of reference 2 were used together with the respective values for specific heat ratios of 7/5 and 15/13.



Sketch (d)

Reflected shock wave. - The flow geometry is illustrated in sketch (d). The conditions downstream of the incident shock wave are the upstream conditions for the reflected shock wave with the exception of the speed V_2; V_2 is the speed of the flow relative to the incident shock wave while the equations for the reflected shock properties require the speeds to be measured relative to the coordinates fixed to the reflected shock. In this case, the speed V_a is given by $U_2 + U_{rs}$ and V_b is equal to U_{rs}. With these substitutions, equations (2) take the following form:

$$\left.\begin{aligned} p_3 &= p_2 + \rho_2 U_2^2 [1 + (U_{rs}/U_2)] \\ h_3 &= h_2 + (1/2)U_2^2 [1 + (2U_{rs}/U_2)] \\ \rho_3 &= \rho_3(p_3, h_3) \\ U_{rs}/U_2 &= 1/[(\rho_3/\rho_2) - 1] \end{aligned}\right\} \tag{7}$$

The equations of reference 2 were used to obtain the results for the frozen chemistry cases. The upstream Mach number given by $(U_2 + U_{rs})/a_2$ is not known a priori in this case. Thus, a solution by trial is necessary. Successive values of

U_{rs}, were chosen until the computed speed V_3 downstream of the reflected shock wave equaled the speed U_{rs} of the shock wave.

RESULTS

All the results are presented in graphical form. Summary data which can be used to make quick estimates of total conditions behind normal shock waves in flight applications, and standing and reflected shock waves in facility applications are presented in figures 1, 2, and 3, respectively. All other results are presented in charts 1 through 63. Those pertinent to flight applications are presented in charts 1 through 31, and those pertinent to facility applications are given in charts 32 through 63. An index to all of the charted results is given in table I.

Most of the results are presented for speeds ranging from 1 to 16 km/sec and initial pressures ranging from 10^{-7} to 10 atmospheres. In some instances results could not be obtained over these complete ranges because values exceeded the ranges of thermodynamic properties presented in reference 1. The flight results for equilibrium flow were obtained for an ambient temperature of 200° K, and the facility results for equilibrium flow were calculated for an initial temperature of 300° K. Methods for adjusting the equilibrium normal shock results for different ambient temperatures are presented in the appendix.

APPENDIX A

METHODS FOR EXTENDING EQUILIBRIUM NORMAL SHOCK RESULTS TO OTHER VALUES OF AMBIENT TEMPERATURE

Ambient temperature is one of the quantities usually specified when properties of flows are calculated across shock waves. Shock-wave properties are often needed for various values of ambient temperature, but because of the voluminous nature of the data complete results are included for only one value. The purpose here is to present methods for extending some of the results given for one value of ambient temperature to other values of temperature. In particular, the quantities, p_2/p_1, h_2, ρ_2/ρ_1, V_2/V_1, and Z_2T_2 are considered.

Extension of Results for p_2/p_1

The equation expressing conservation of momentum can be written as follows:

$$p_2 = p_1 + \rho_1 V_1^2 \left[1 - (V_2/V_1)\right]$$

This equation takes the following simple form when the strong shock approximations $p_1 \ll p_2$ and $V_2/V_1 \ll 1$ are made:

$$p_2 = \rho_1 V_1^2$$

Dividing by p_1, multiplying by T_1, and substituting for ρ_1 from the thermal equation of state ($\rho_1 = p_1/Z_1RT_1$) gives

$$(p_2/p_1)T_1 = V_1^2/Z_1R \tag{A1}$$

For given values of V_1 and R and for Z_1 constant, the right side of the above equation is a constant. The parameter given in equation (A1) has been calculated by means of exact data and the results of these calculations are presented in figure 4. These results provide numerical verification that the quantity $(p_2/p_1)T_1$ is nearly constant for a wide range of conditions. Thus, it has been shown analytically and confirmed numerically that the pressure ratio p_2/p_1 is inversely proportional to the ambient temperature T_1.

Extension of Results for h_2

The enthalpy downstream of a shock wave is nearly independent of upstream ambient temperature for given values of V_1, p_1, and R so long as the ambient temperature T_1 is low enough for Z_1 to be constant. This can be verified if one considers the energy equation

$$h_2 = h_1 + (1/2)V_1^2 \left[1 - (V_2/V_1)^2\right]$$

This equation takes the following simple form when the strong shock approximations $h_1 << V_1^2$ and $(V_2/V_1)^2 << 1$ are made:

$$h_2 = (1/2)V_1^2 = \text{constant} \tag{A2}$$

The result given by equation (A2) is verified by numerical data given in figure 5.

Extension of Results for ρ_2/ρ_1 and V_2/V_1

The mass, momentum, and energy conservation equations can be combined to give the following exact relation

$$\frac{\rho_1}{\rho_2} = \frac{2\rho_1(h_2 - h_1) - (p_2 - p_1)}{p_2 - p_1}$$

If the thermal equation of state is introduced along with the strong shock approximation that $h_1 << h_2$, the above equation becomes

$$\frac{\rho_1}{\rho_2} = \frac{\frac{2h_2}{Z_1R} - \frac{p_2}{p_1}T_1 + T_1}{\frac{p_2}{p_1}T_1 - 1}$$

It has been shown previously that for the strong shock assumption both $(p_2/p_1)T_1$ and $p_2/p_1 >> 1$, so that

$$\frac{\rho_1}{\rho_2} \approx \frac{2h_2/Z_1R}{(p_2/p_1)T_1} - 1 \tag{A3}$$

The numerator and the denominator of equation (A3) are each independent of upstream static temperature T_1 for given values of V_1, p_1, and R, and for Z_1 constant. Thus, the ratio of densities across strong normal shock waves is independent of T_1 as long as T_1 is low enough for Z_1 to be constant. This result is verified by numerical calculation, and the results are presented in figure 6.

It follows from mass conservation considerations that the speed ratio V_2/V_1 is also very nearly independent of T_1 for the same conditions since $V_2/V_1 = \rho_1/\rho_2$.

Extension of Results for Z_2T_2

The product of Z_2T_2 can be shown to be independent of upstream ambient temperature by manipulating the thermal equation of state and by using previously derived results. The following is obtained by forming the ratio of the thermal equations of state written for both sides of a shock wave

$$p_2/p_1 = Z_2\rho_2T_2/Z_1\rho_1T_1$$

The above equation can be rearranged to give

$$Z_2 T_2 = Z_1 \left[(p_2/p_1)T_1\right] (\rho_1/\rho_2) \tag{A4}$$

It is recognized that each of the factors on the right side of the above equation is nearly independent of T_1 so that their combination is also insensitive to variations in ambient temperature. This result is verified by the numerical data presented in figure 7.

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2. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rep. 1135, 1953.

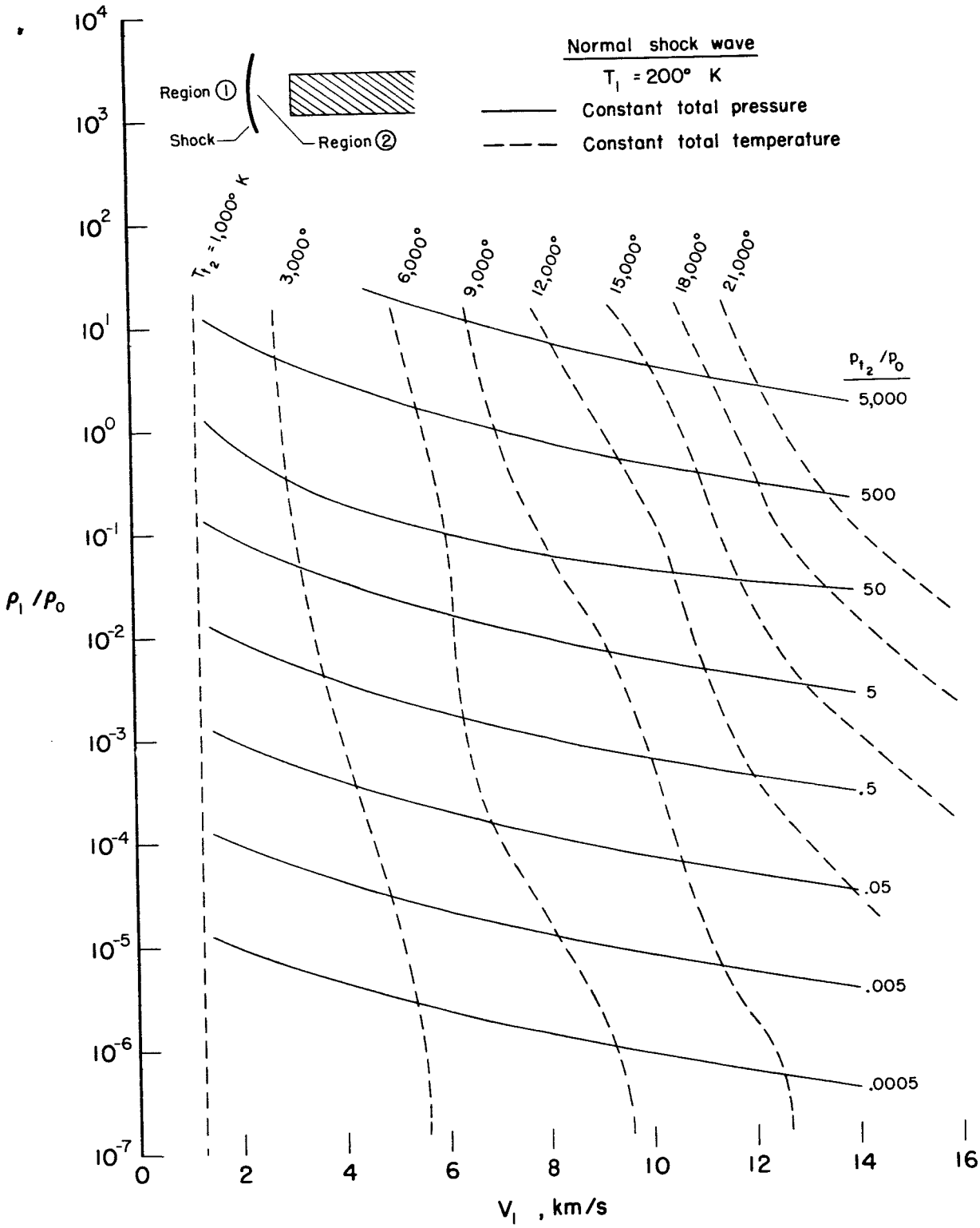


Figure 1. - Effects of flight speed and ambient density on total temperature and pressure downstream of a normal shock wave.

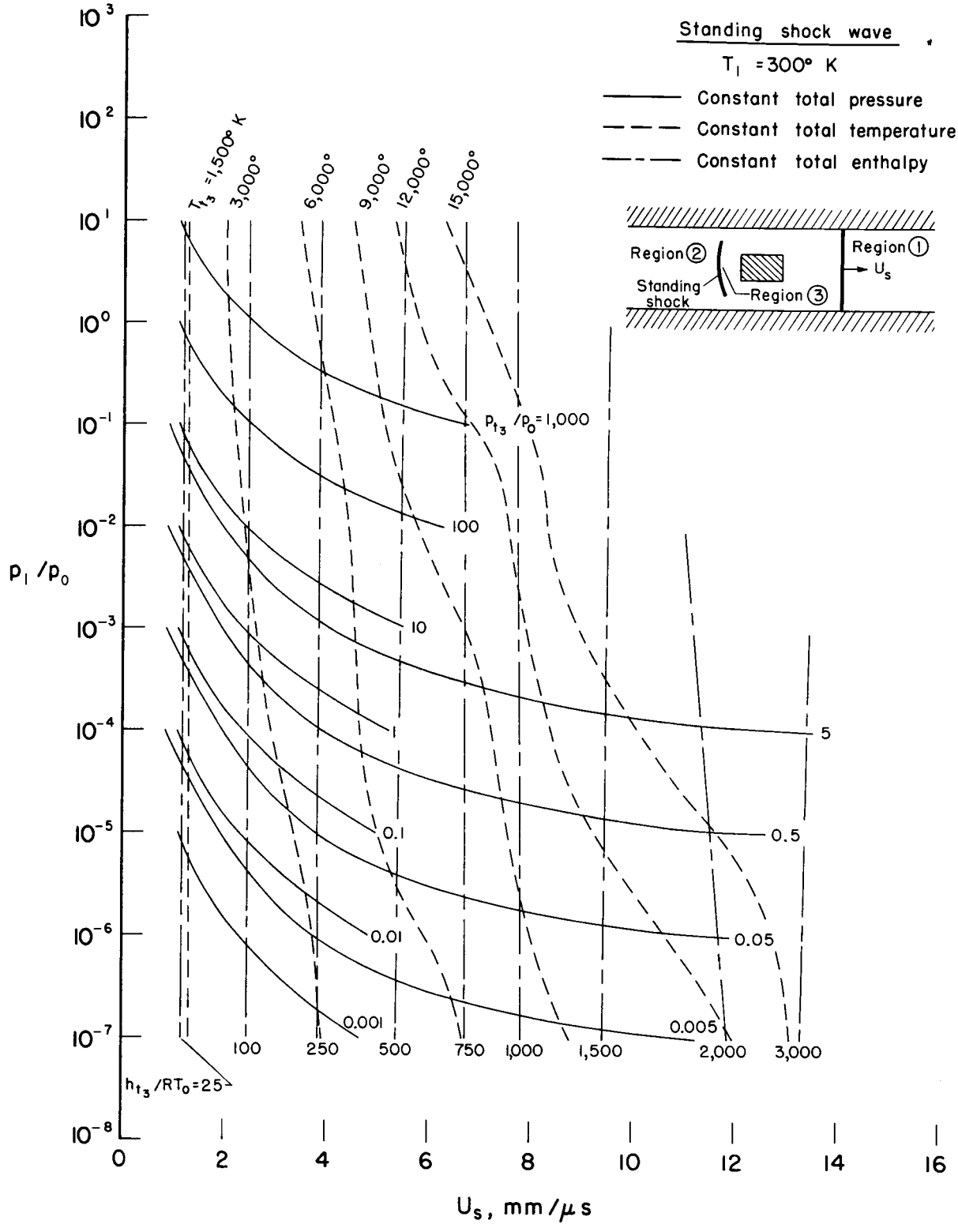


Figure 2. - Effects of incident shock wave speed and initial pressure on the total temperature and pressure behind a standing shock wave.

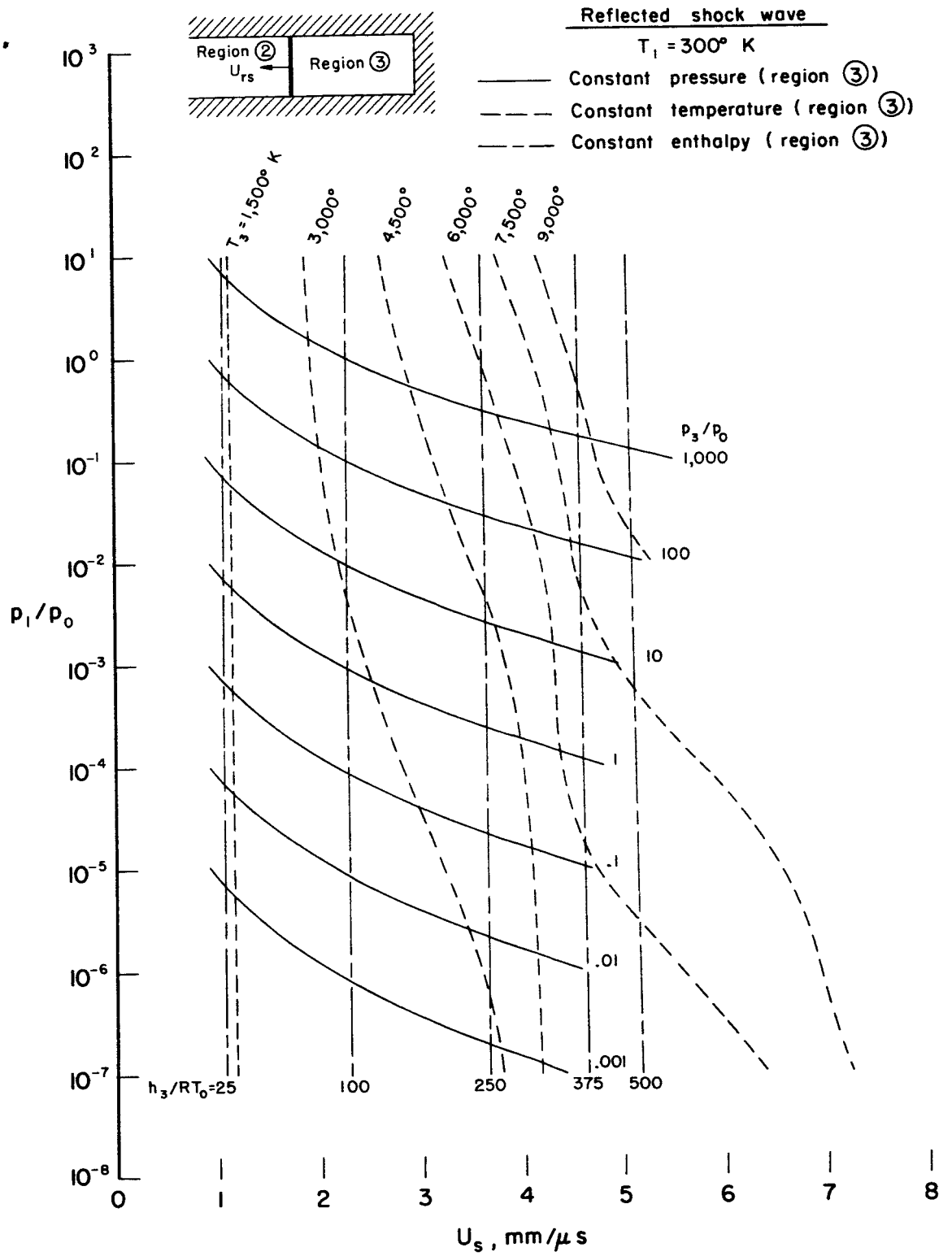


Figure 3. - Effects of incident shock wave speed and initial pressure on the total temperature and pressure behind a reflected shock wave.

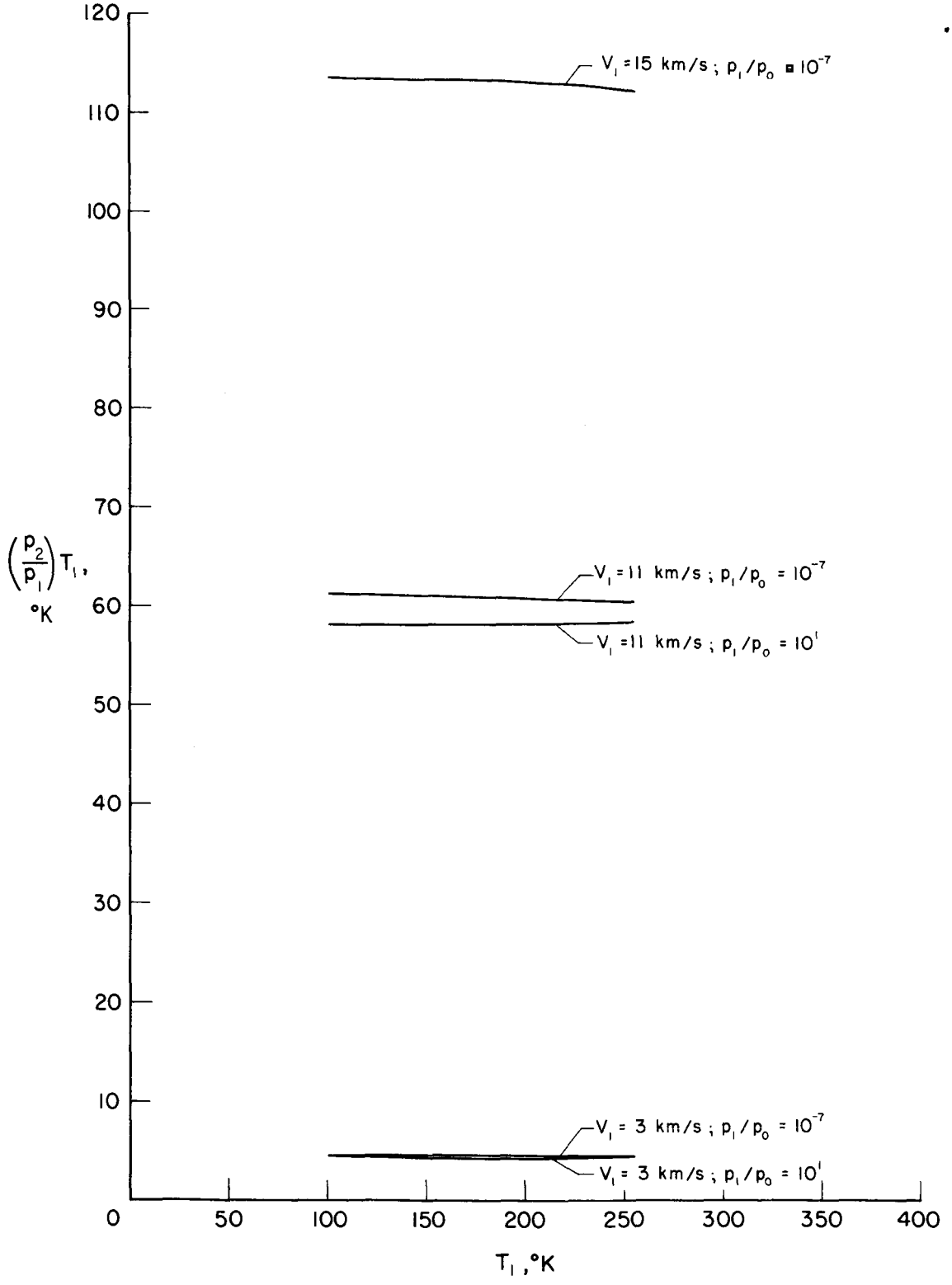


Figure 4. - Variation with ambient temperature of the product of ambient temperature and static pressure ratio across a normal shock wave.

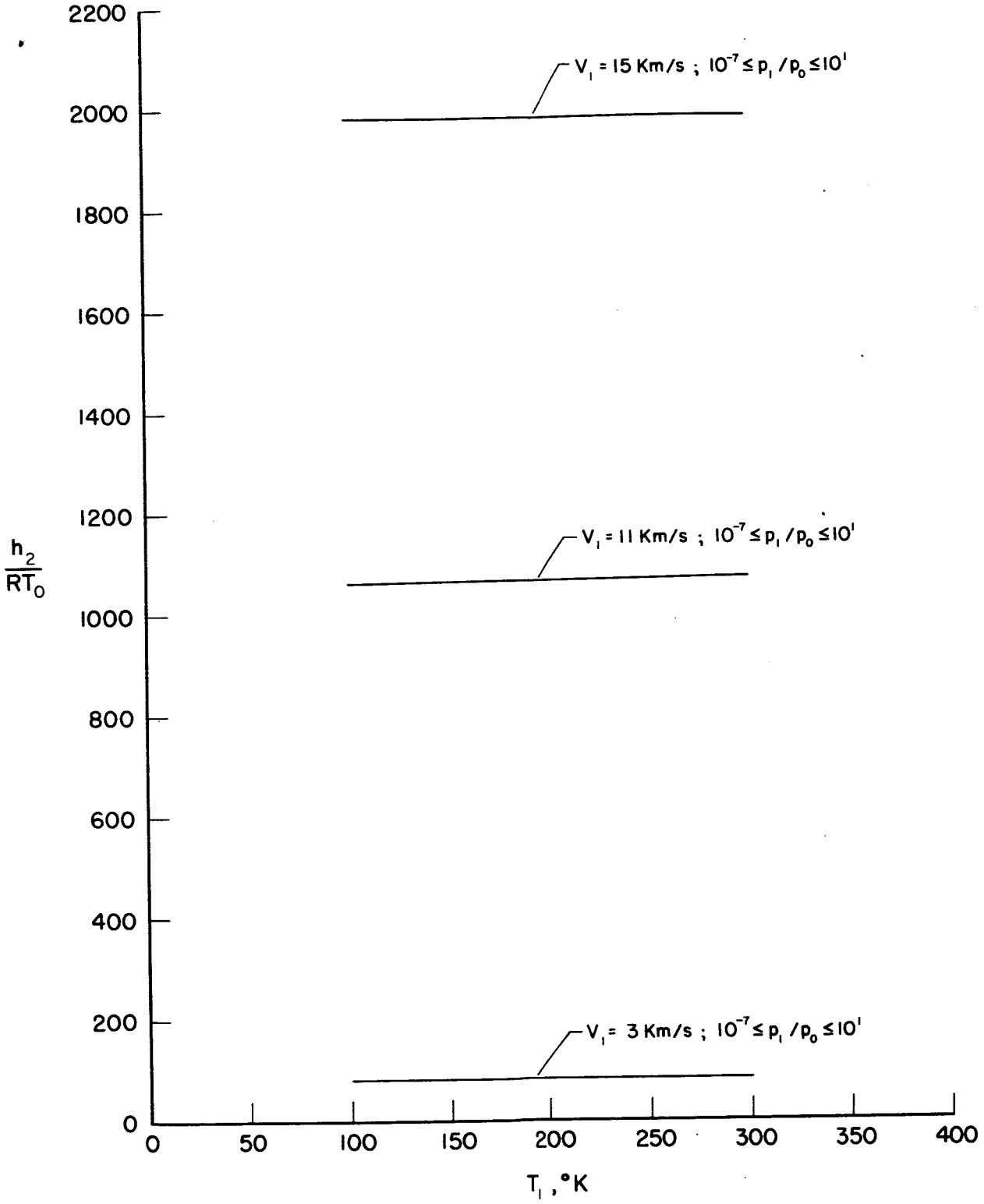


Figure 5. - Variation with ambient temperature of static enthalpy downstream of a normal shock wave.

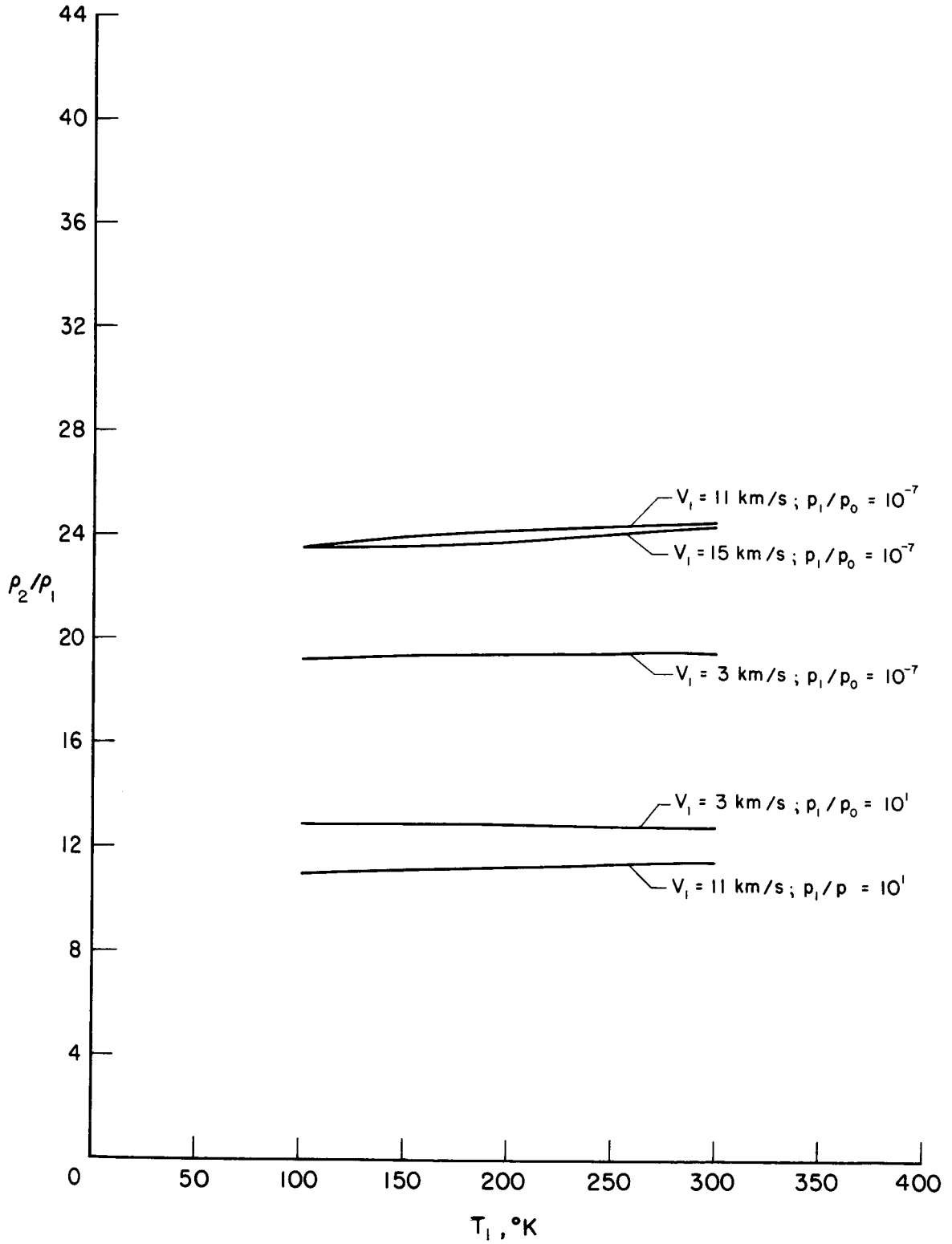


Figure 6. - Variation with ambient temperature of density ratio across a normal shock wave.

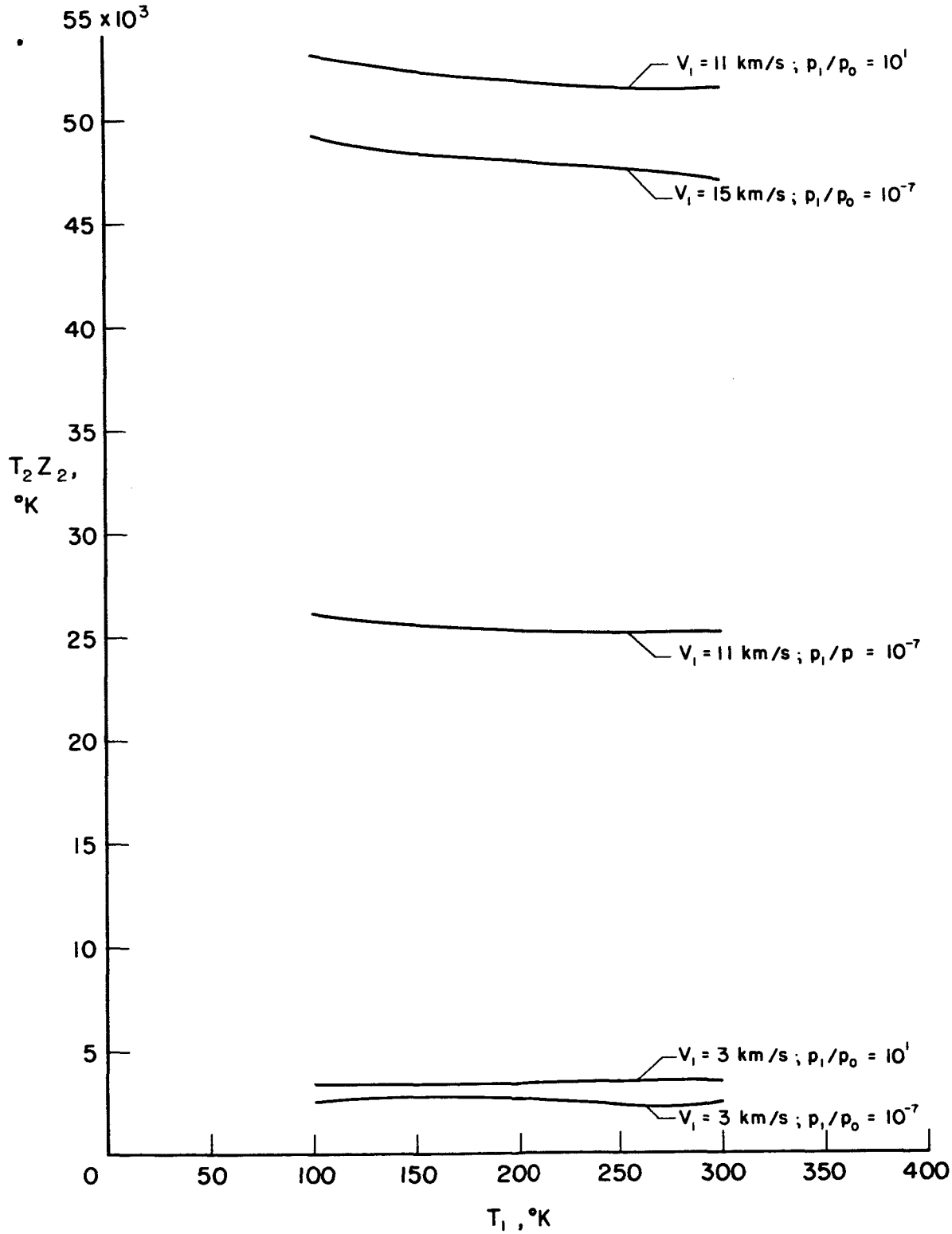


Figure 7. - Variation with ambient temperature of the product of compressibility factor and static temperature downstream of a normal shock wave.

TABLE I. - INDEX TO CHART NUMBERS

Quantities	Flight		Facility		
	Normal wave	Oblique wave	Incident wave	Standing wave	Reflected wave
Pressure ratio	1	17a, b, c, 18	32	41a, b	55a, b
Density ratio	2	19a, b, c, 20	33	42a, b	56a, b
Compressibility factor	3	21a, b, c	34	43a, b	57a, b
Temperature ratio	4	22a, b, c, 23	35	44a, b	58a, b
Enthalpy ratio	5	24a, b, c, 25	36	45a, b	59a, b
Flow speed ratio	6	26a, b, c, 27	37	46a, b	60a, b
Sound speed ratio	7	28a, b, c, 29	38	47a, b	61a, b
Entropy change	8	30a, b, c, 31	39	48a, b	62a, b
Wave angle		15a, b, c, 16			
Mole fraction	9a, b, c		40a, b, c	49a, b, c	63a, b, c
Downstream total pressure	10			50	
Downstream total density	11			51	
Downstream total compressibility factor	12			52	
Downstream total temperature	13			53	
Downstream total enthalpy	14			54	

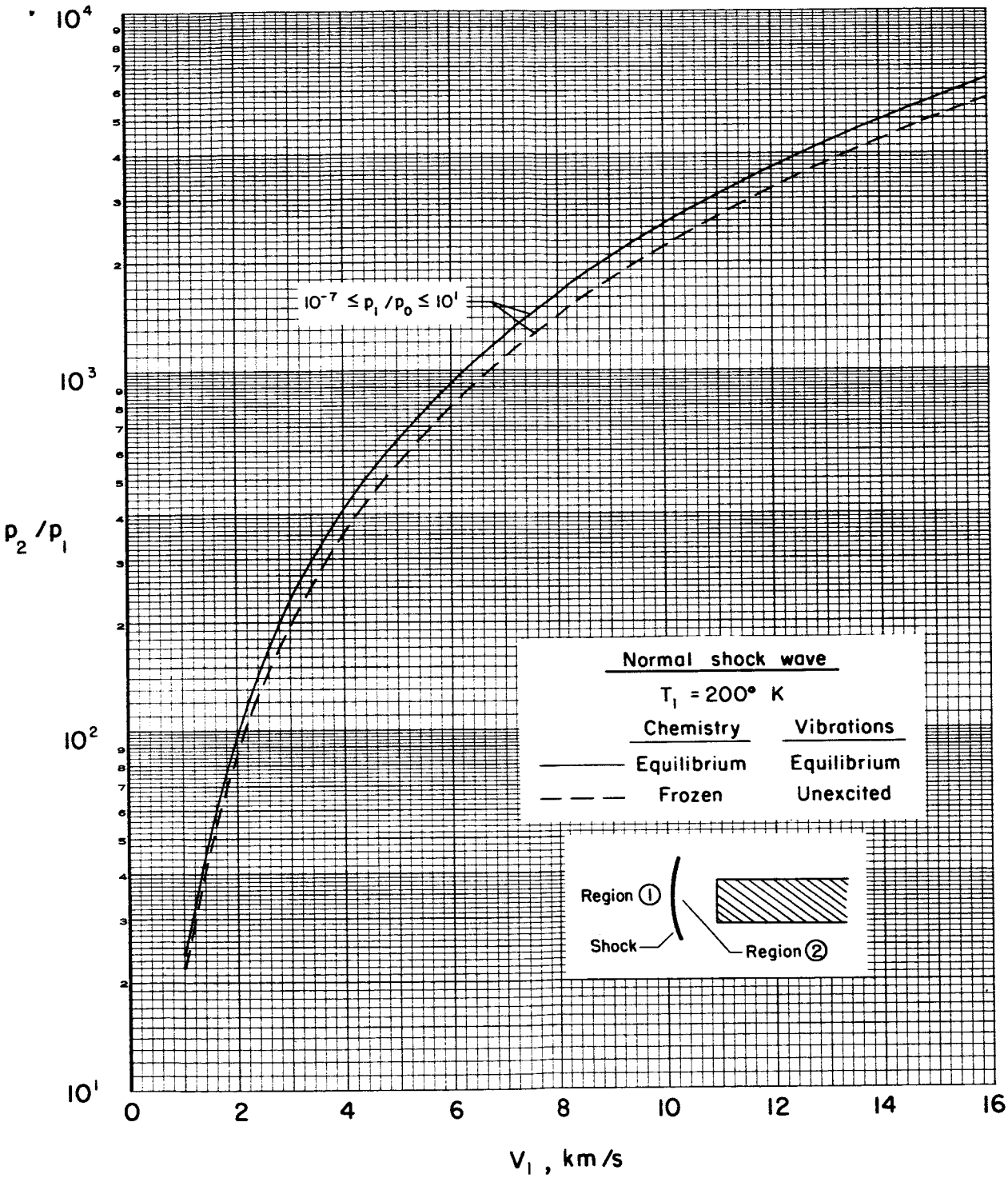


Chart 1. - Variation with flight speed of static pressure ratio across a normal shock wave.

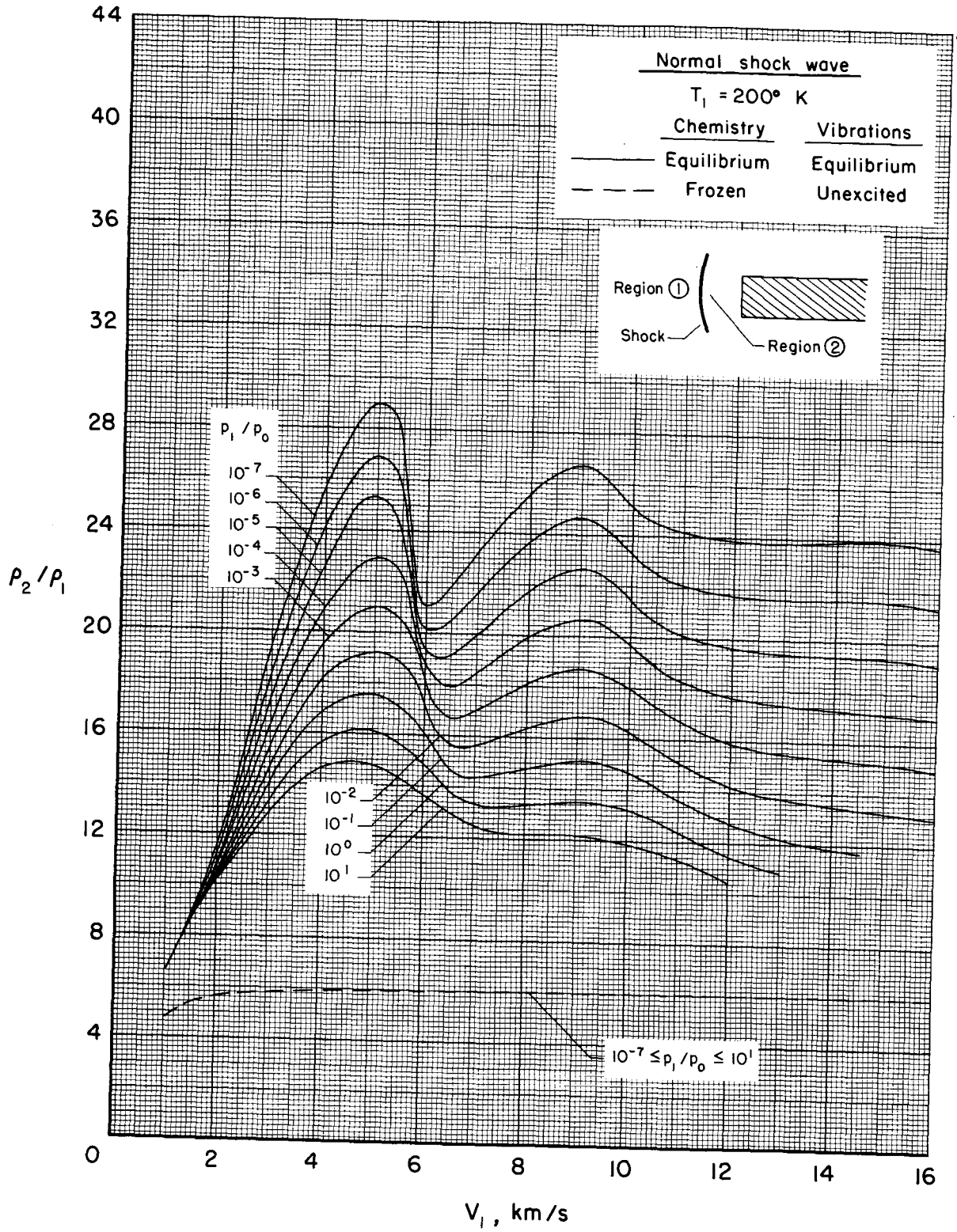


Chart 2. - Variation with flight speed of static density ratio across a normal shock wave.

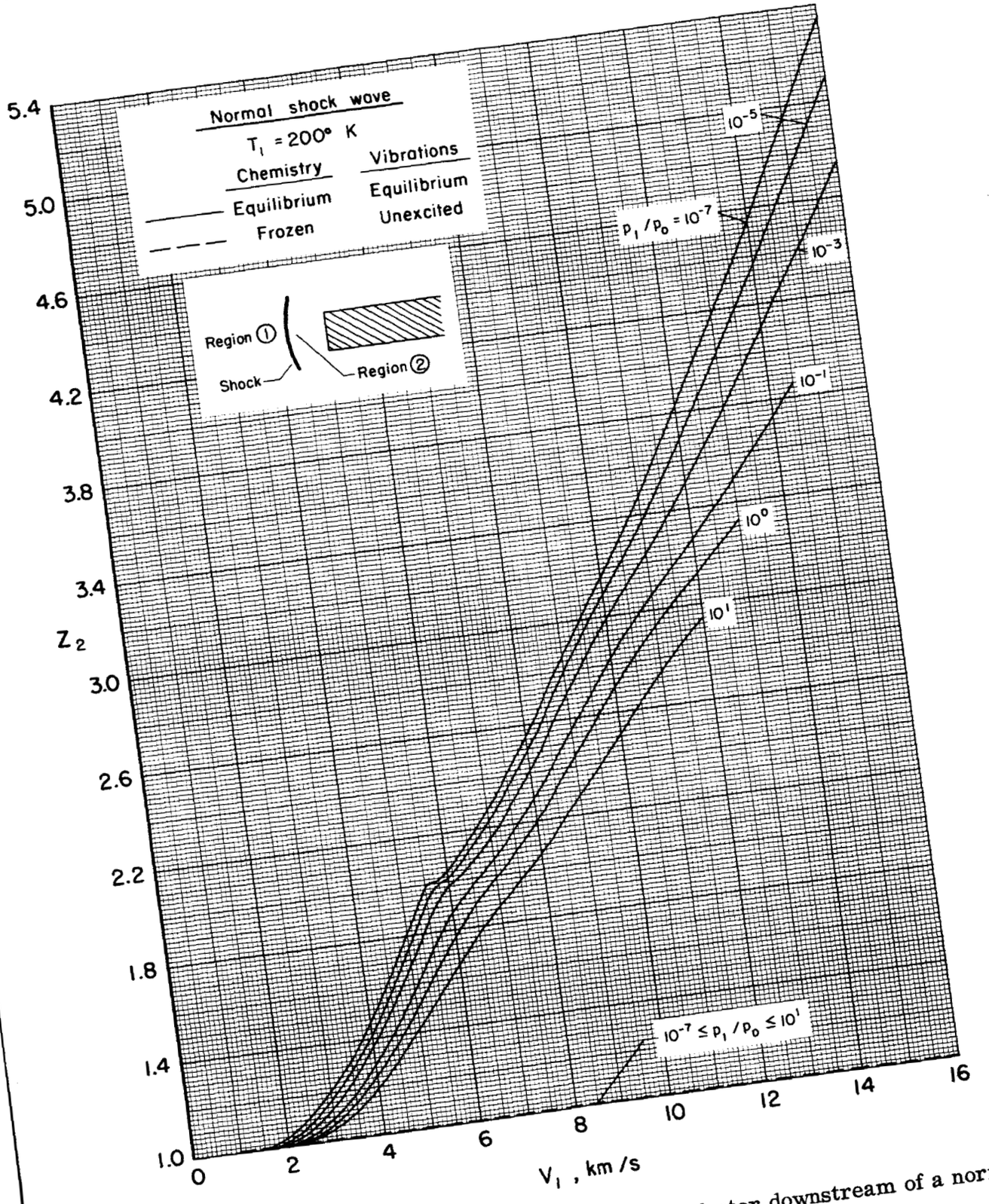


Chart 3. - Variation with flight speed of compressibility factor downstream of a normal shock wave.

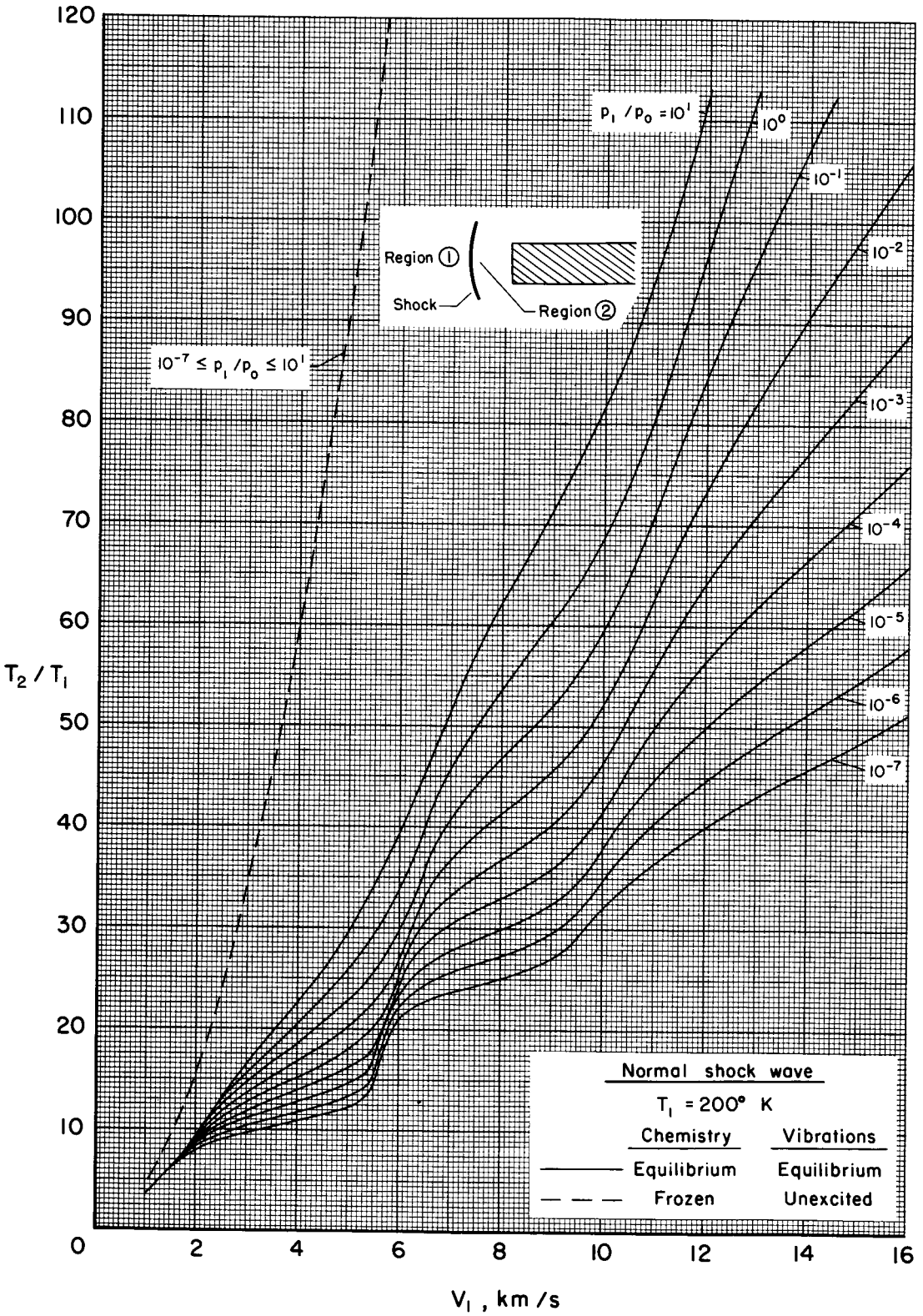


Chart 4. - Variation with flight speed of temperature ratio across a normal shock wave.

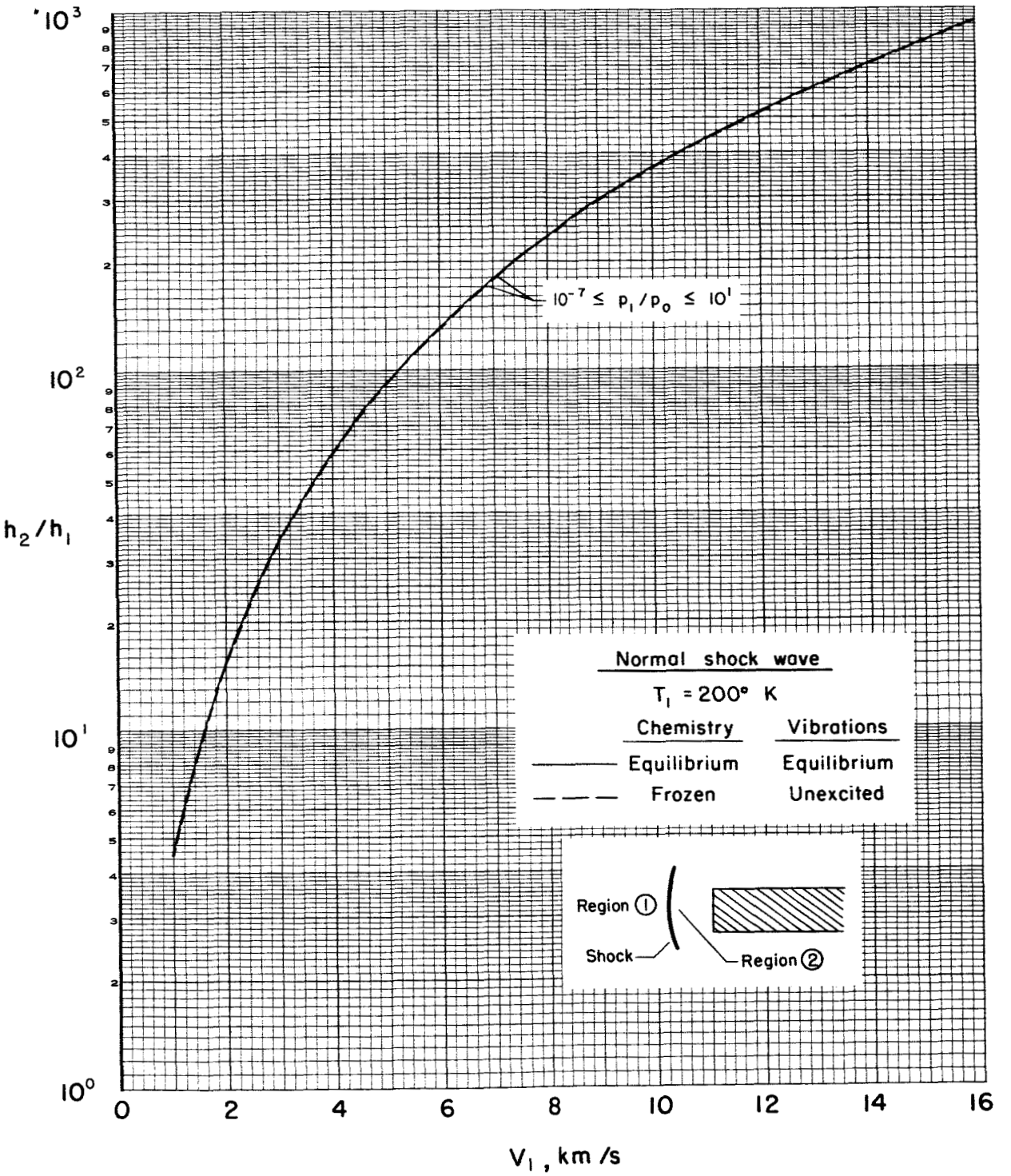


Chart 5. - Variation with flight speed of enthalpy ratio across a normal shock wave.

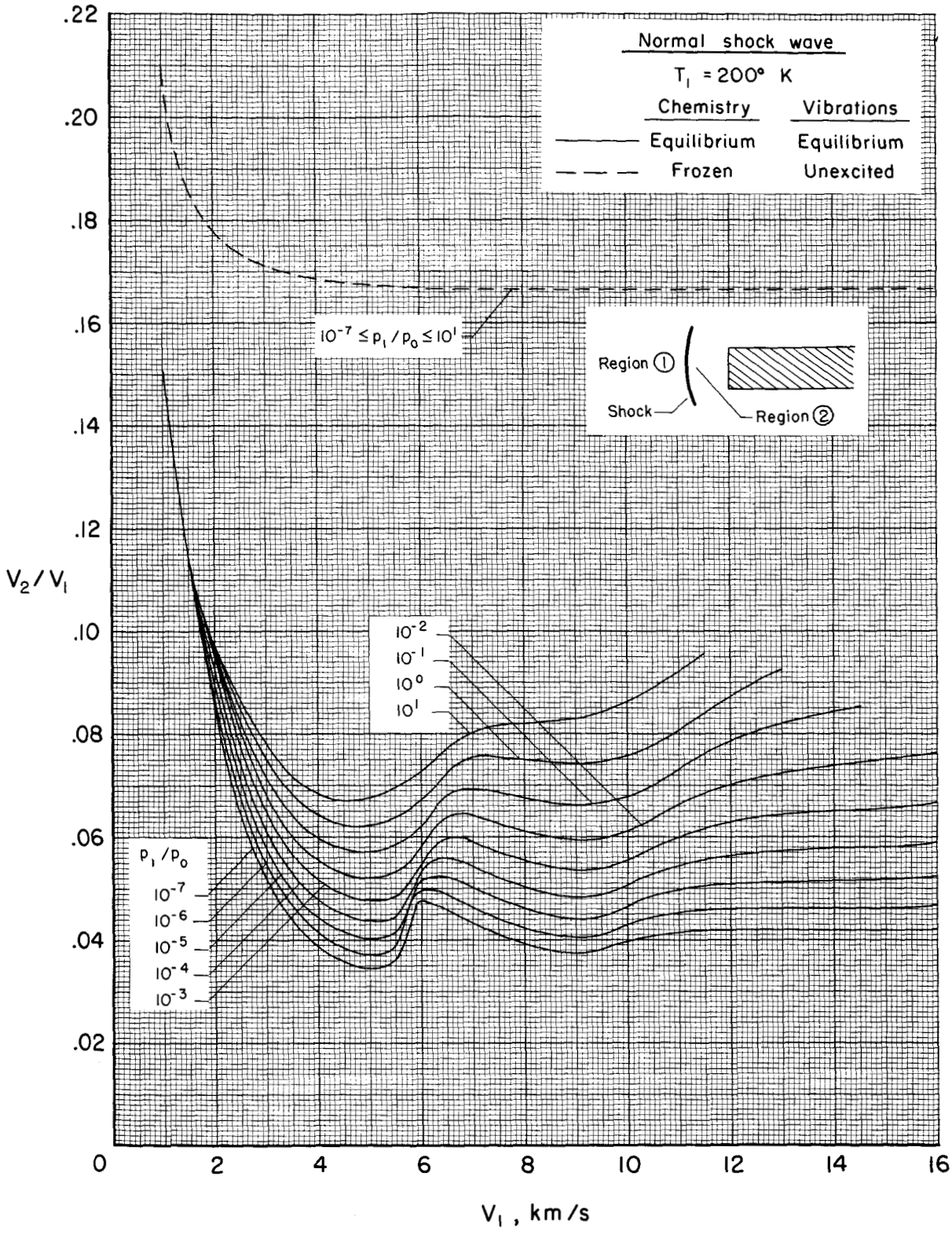


Chart 6. - Variation with flight speed of flow speed ratio across a normal shock wave.

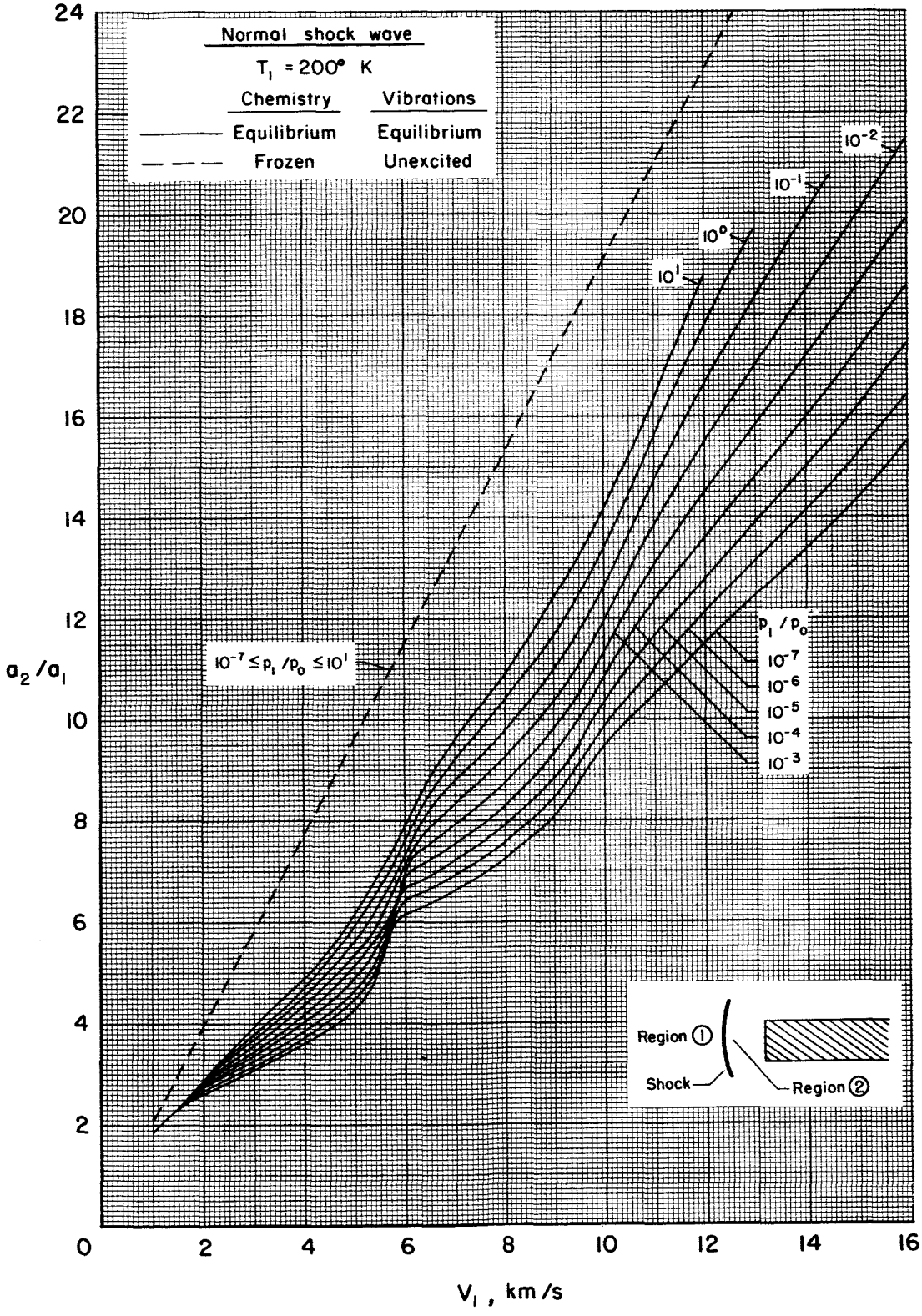


Chart 7. - Variation with flight speed of sound speed ratio across a normal shock wave.

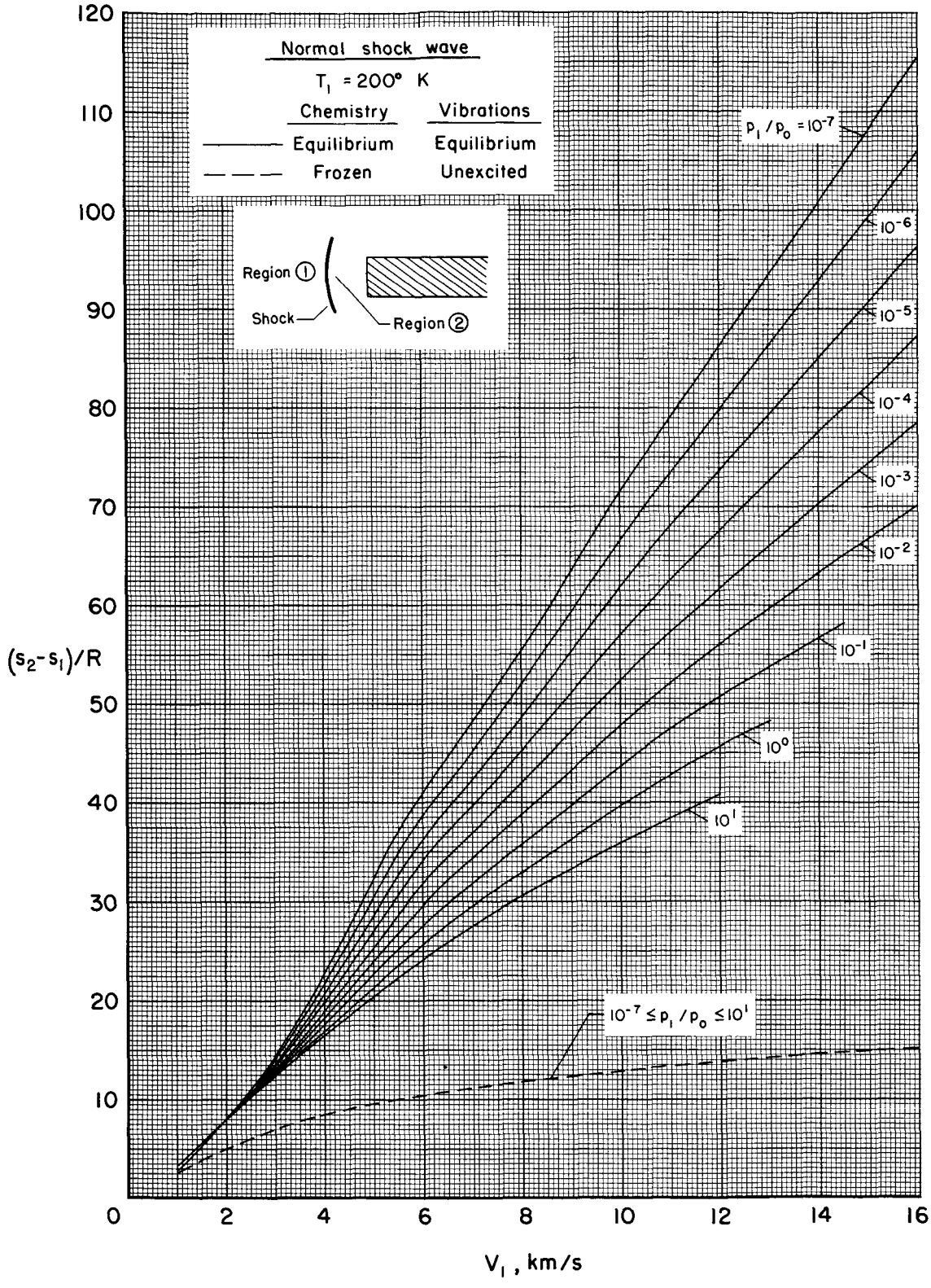
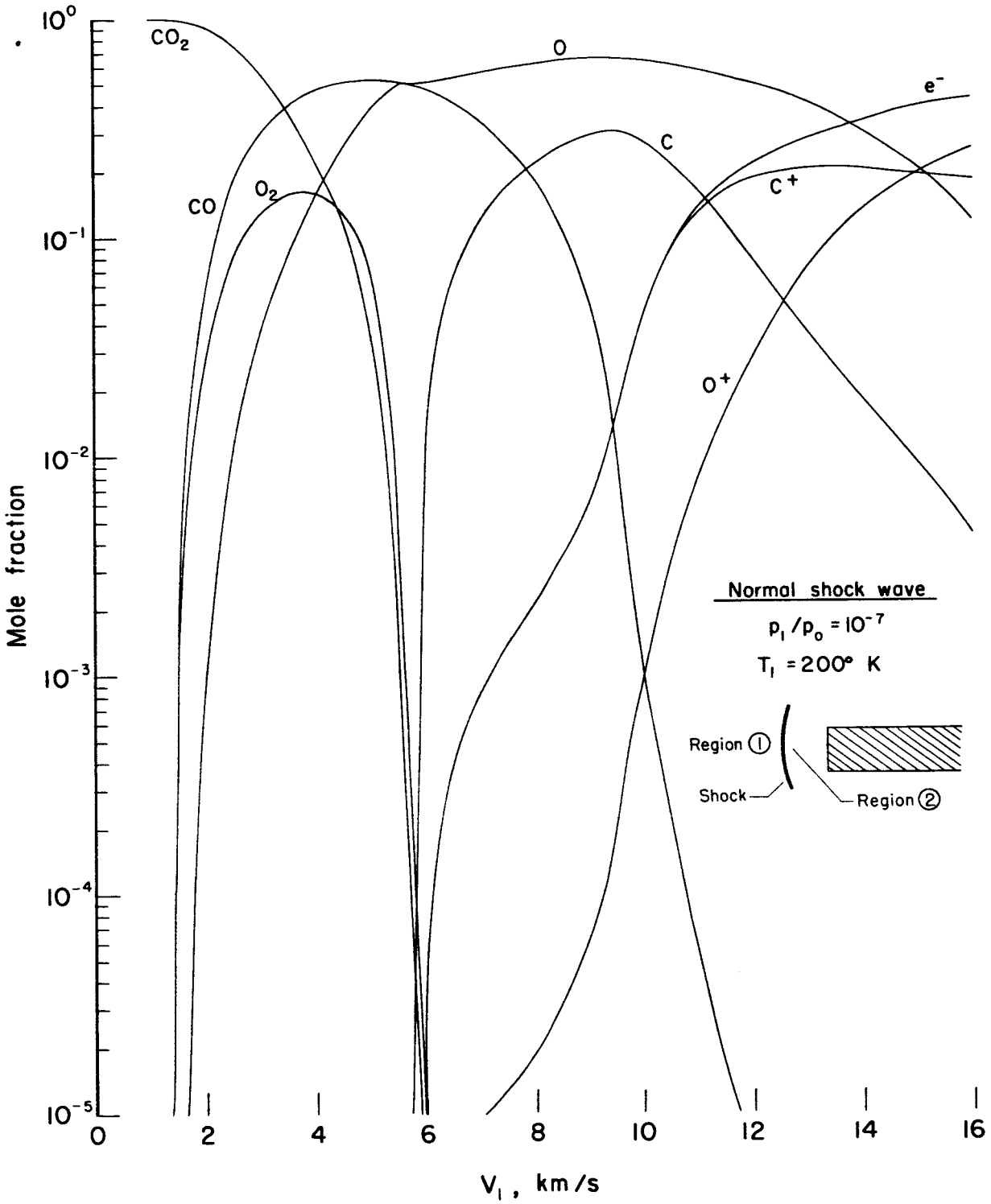
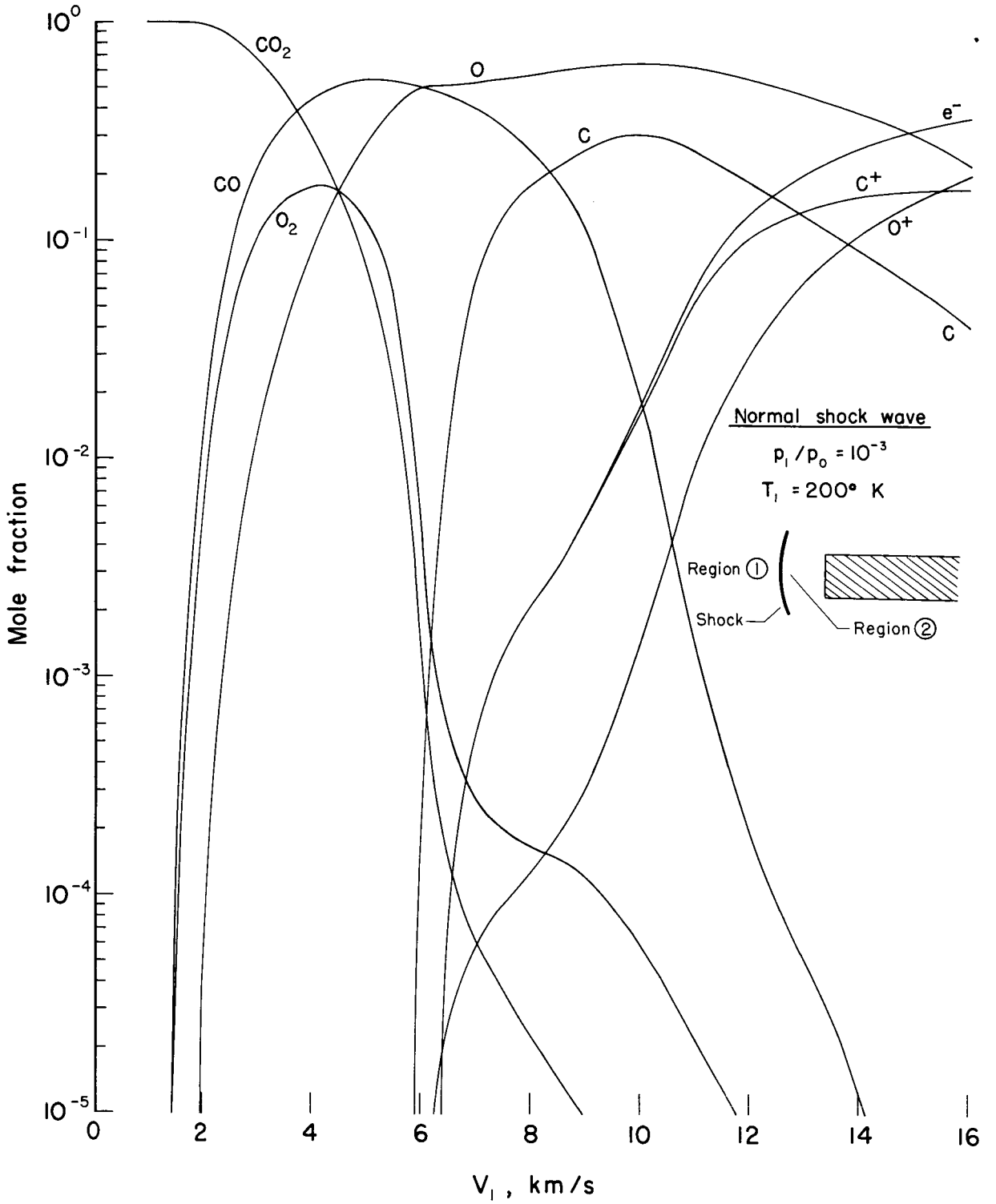


Chart 8. - Variation with flight speed of entropy change across a normal shock wave.



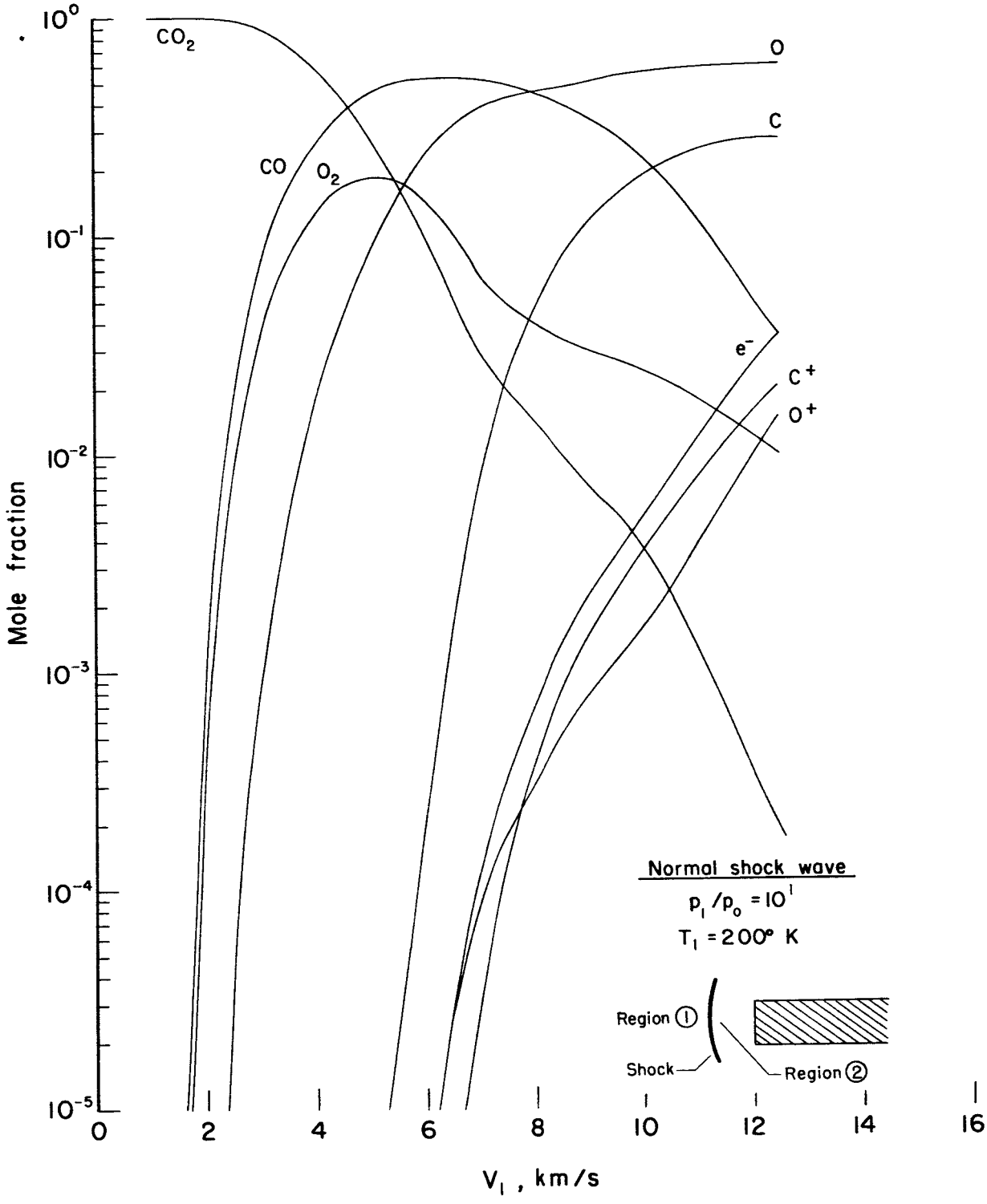
(a) $p_1/p_0 = 10^{-7}$

Chart 9. - Variation with flight speed of equilibrium flow chemistry downstream of a normal shock wave.



(b) $p_1/p_0 = 10^{-3}$

Chart 9. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 9. - Concluded.

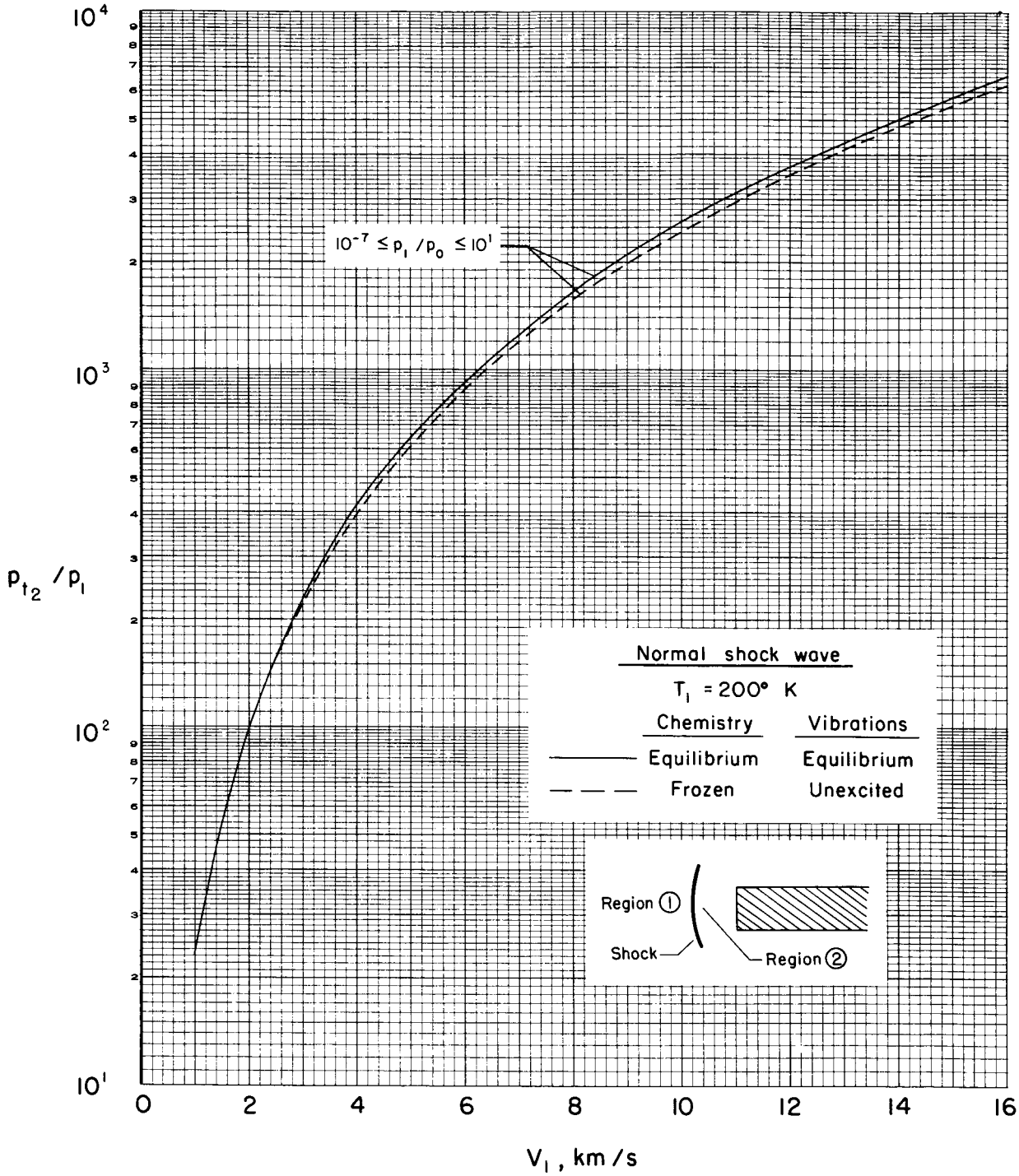


Chart 10. - Variation with flight speed of total pressure downstream of a normal shock wave.

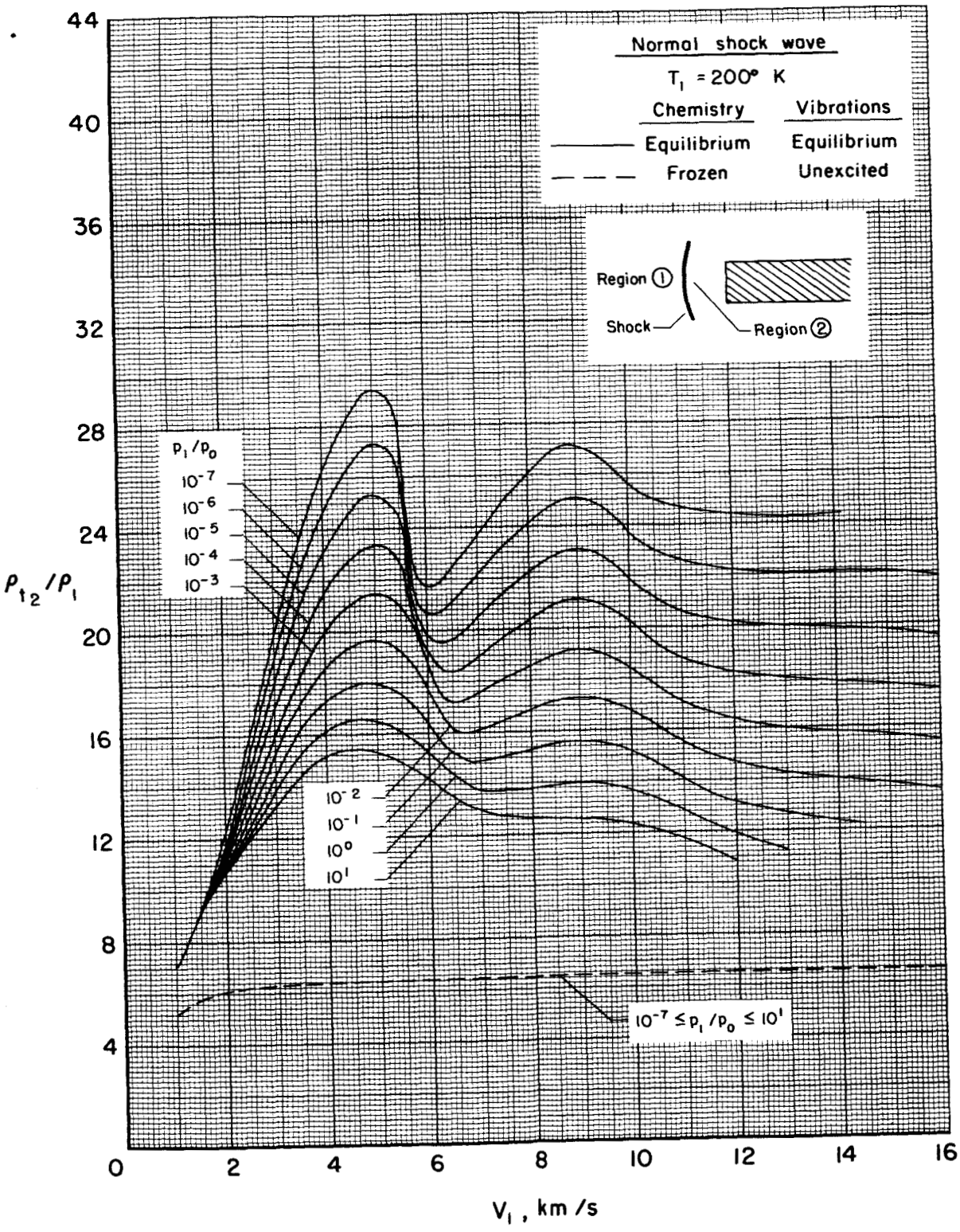


Chart 11. - Variation with flight speed of total density downstream of a normal shock wave.

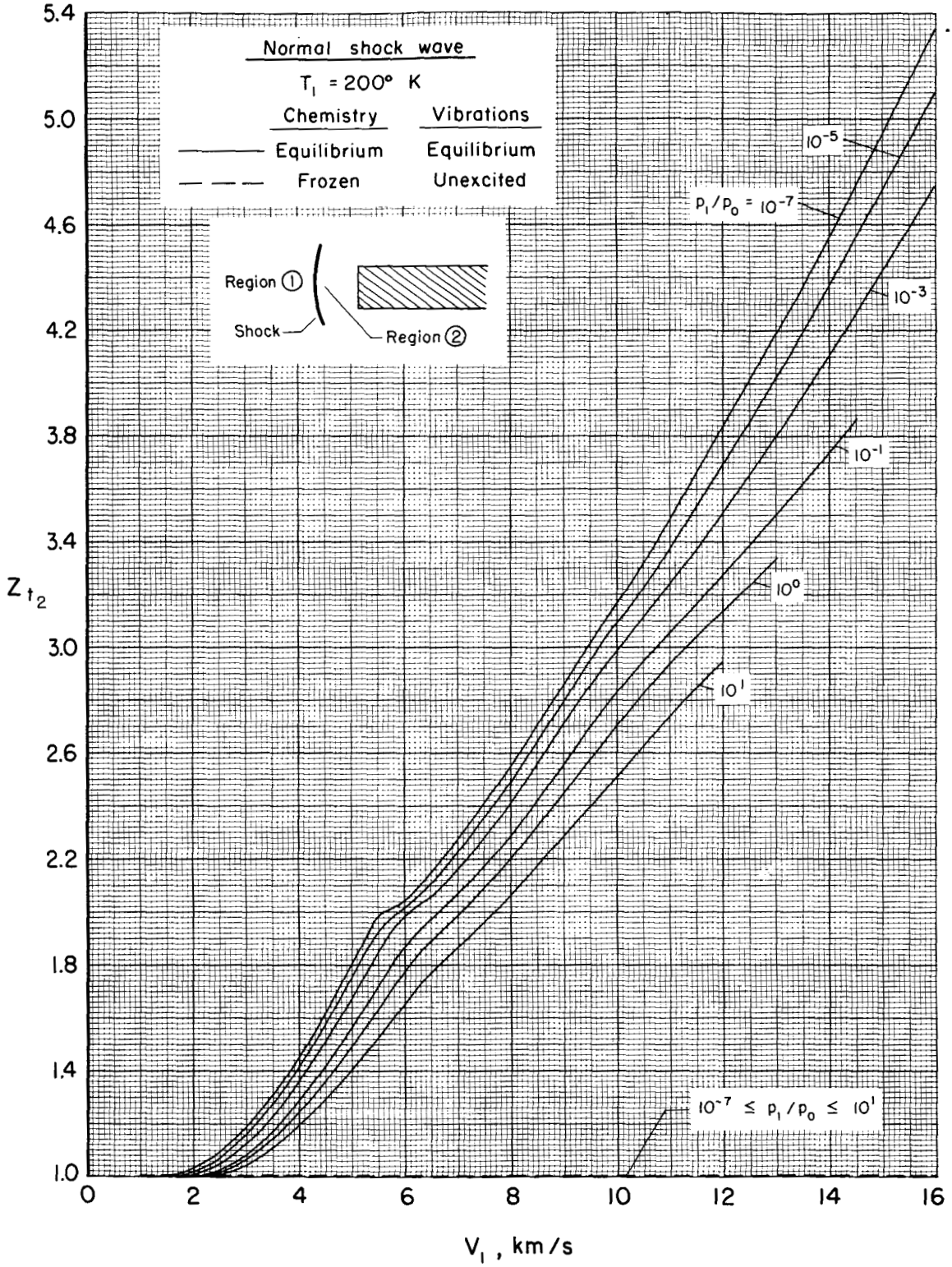


Chart 12. - Variation with flight speed of total compressibility factor downstream of a normal shock wave.

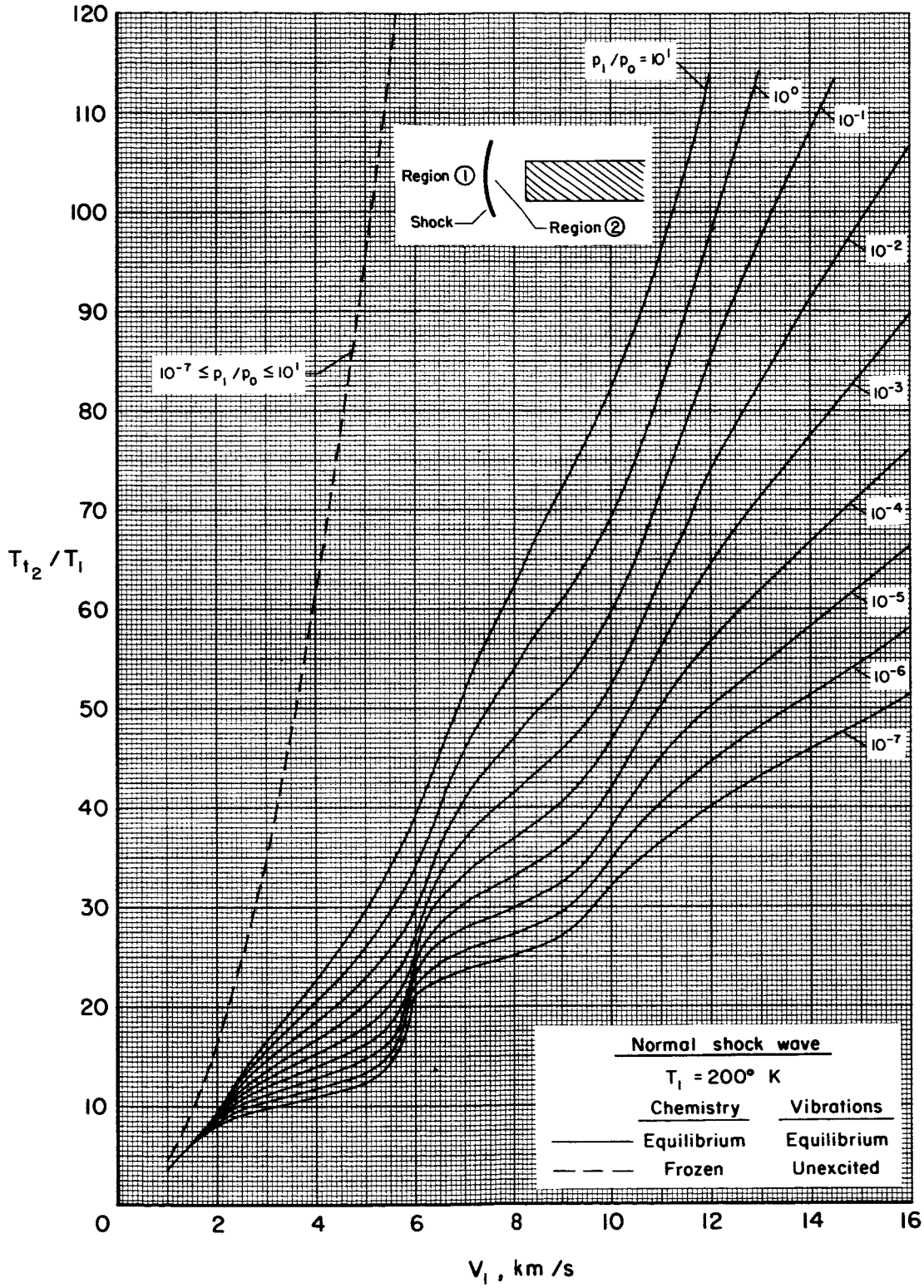


Chart 13. - Variation with flight speed of total temperature downstream of a normal shock wave.

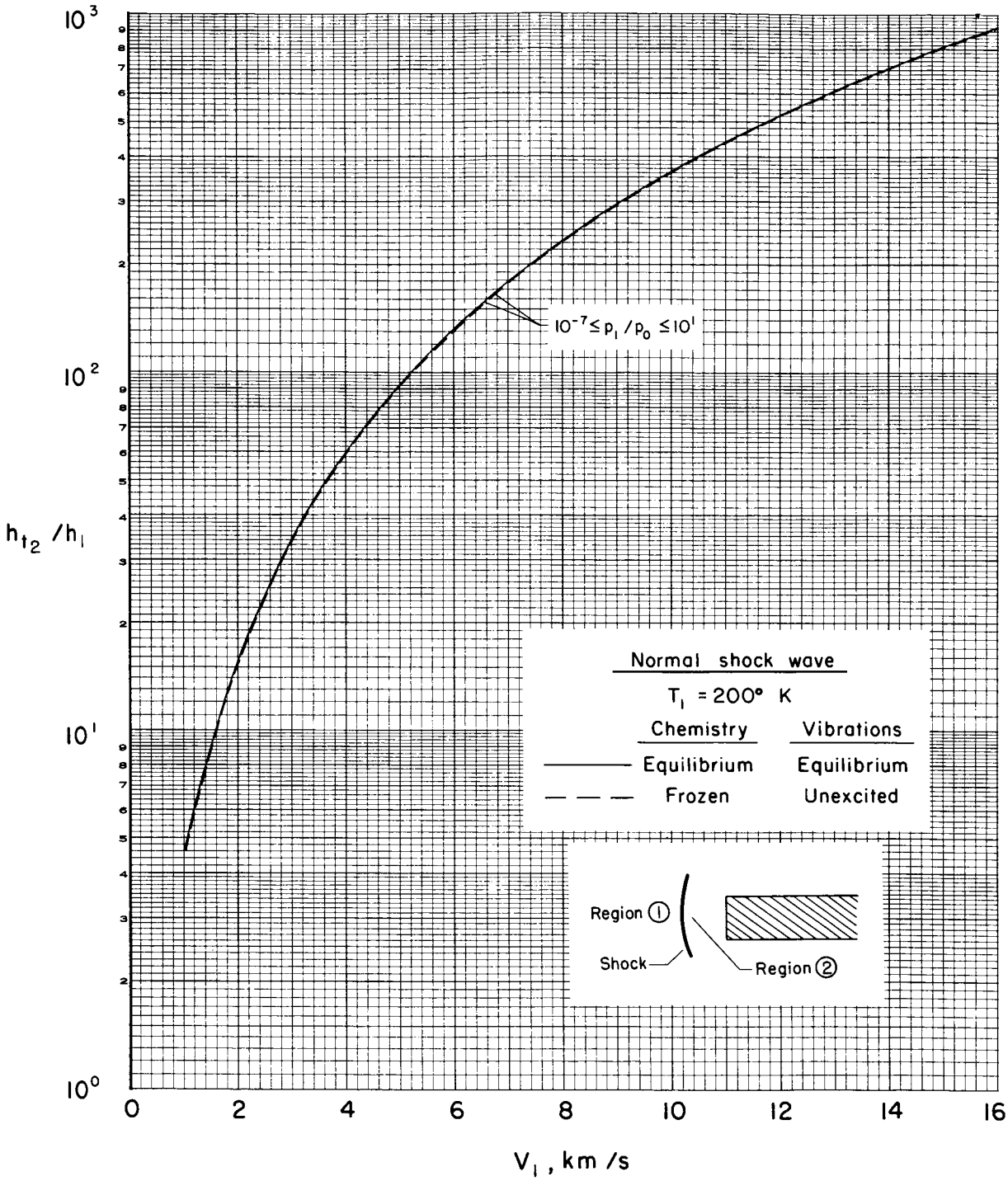
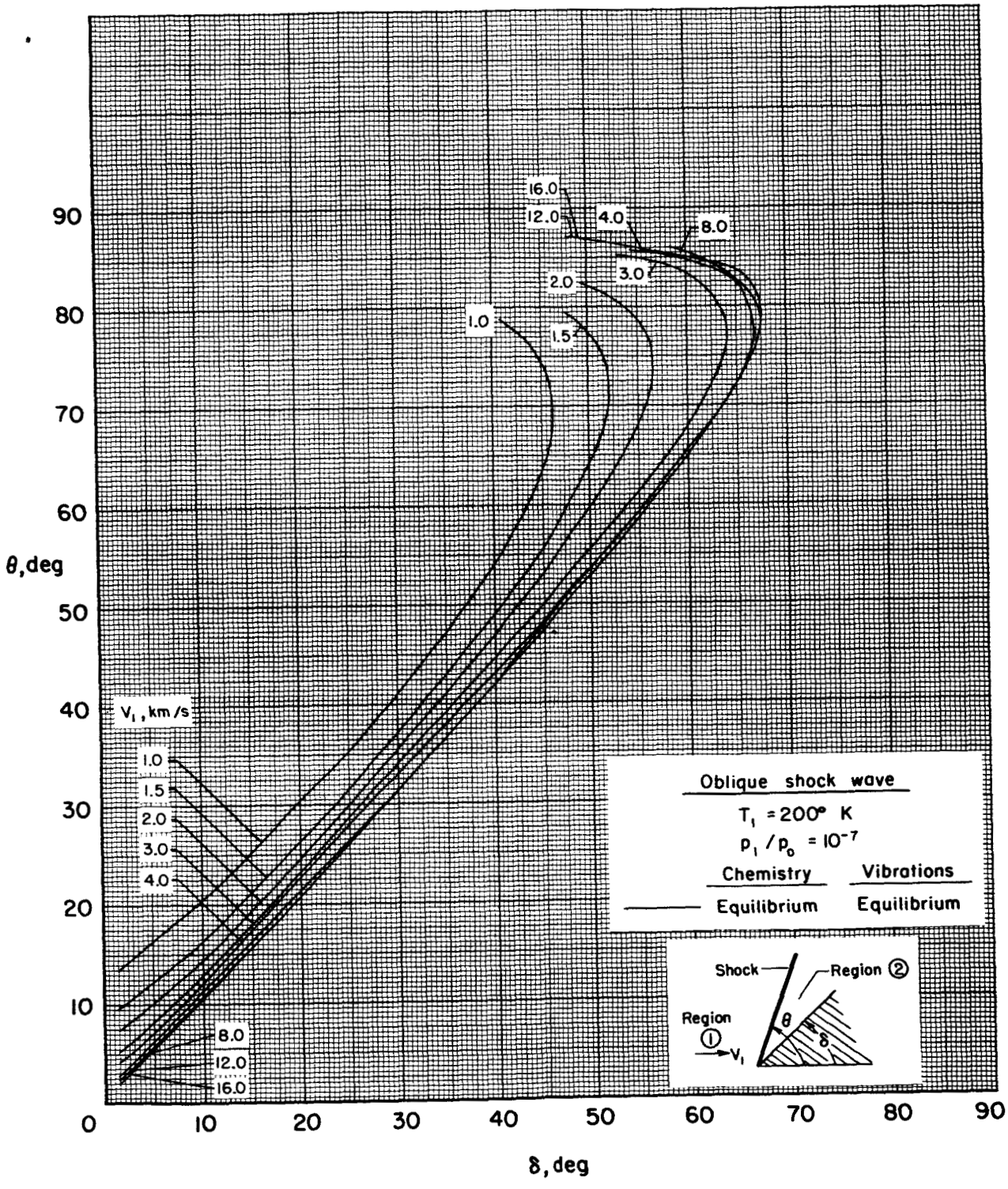
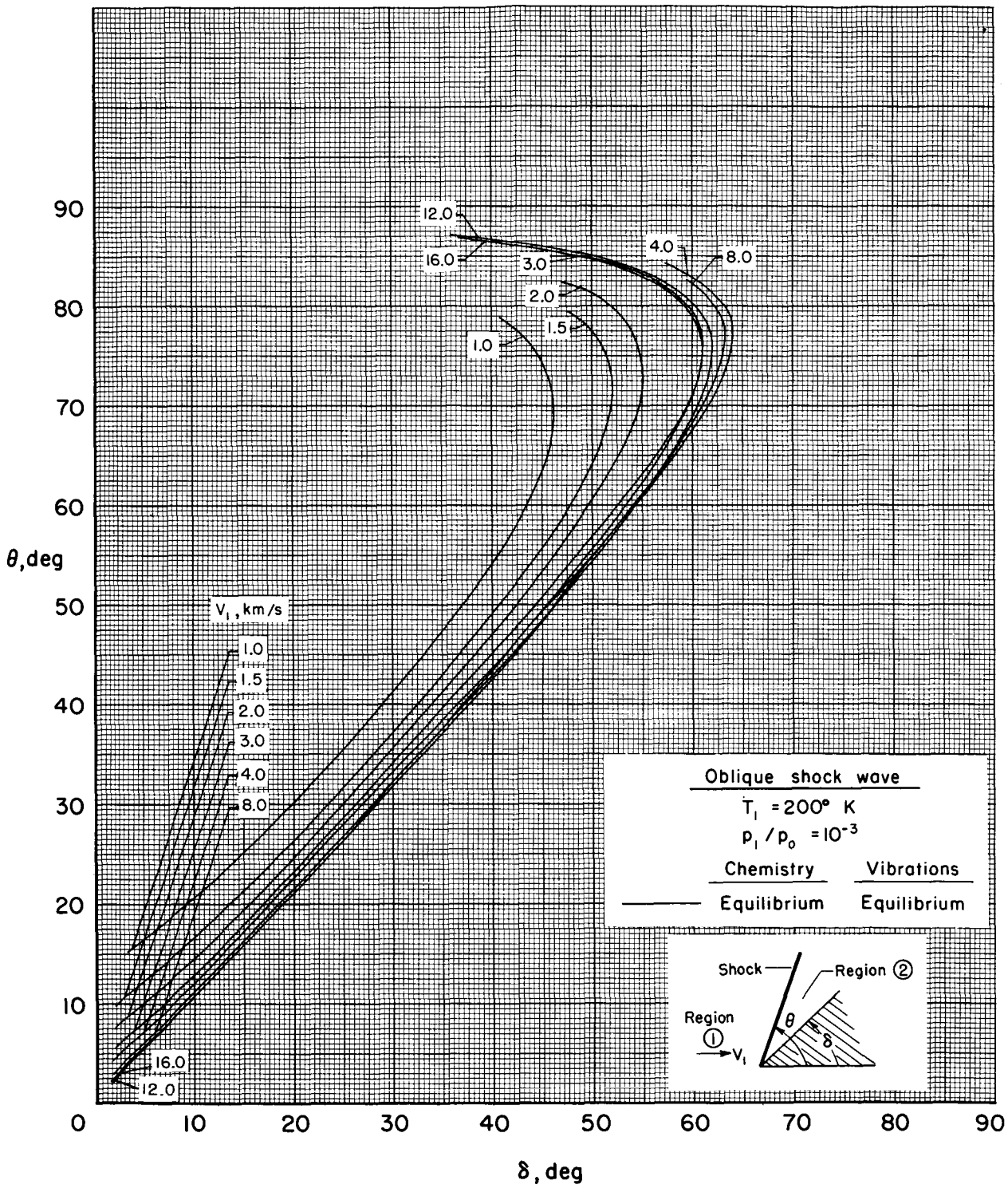


Chart 14. - Variation with flight speed of total enthalpy downstream of a normal shock wave.



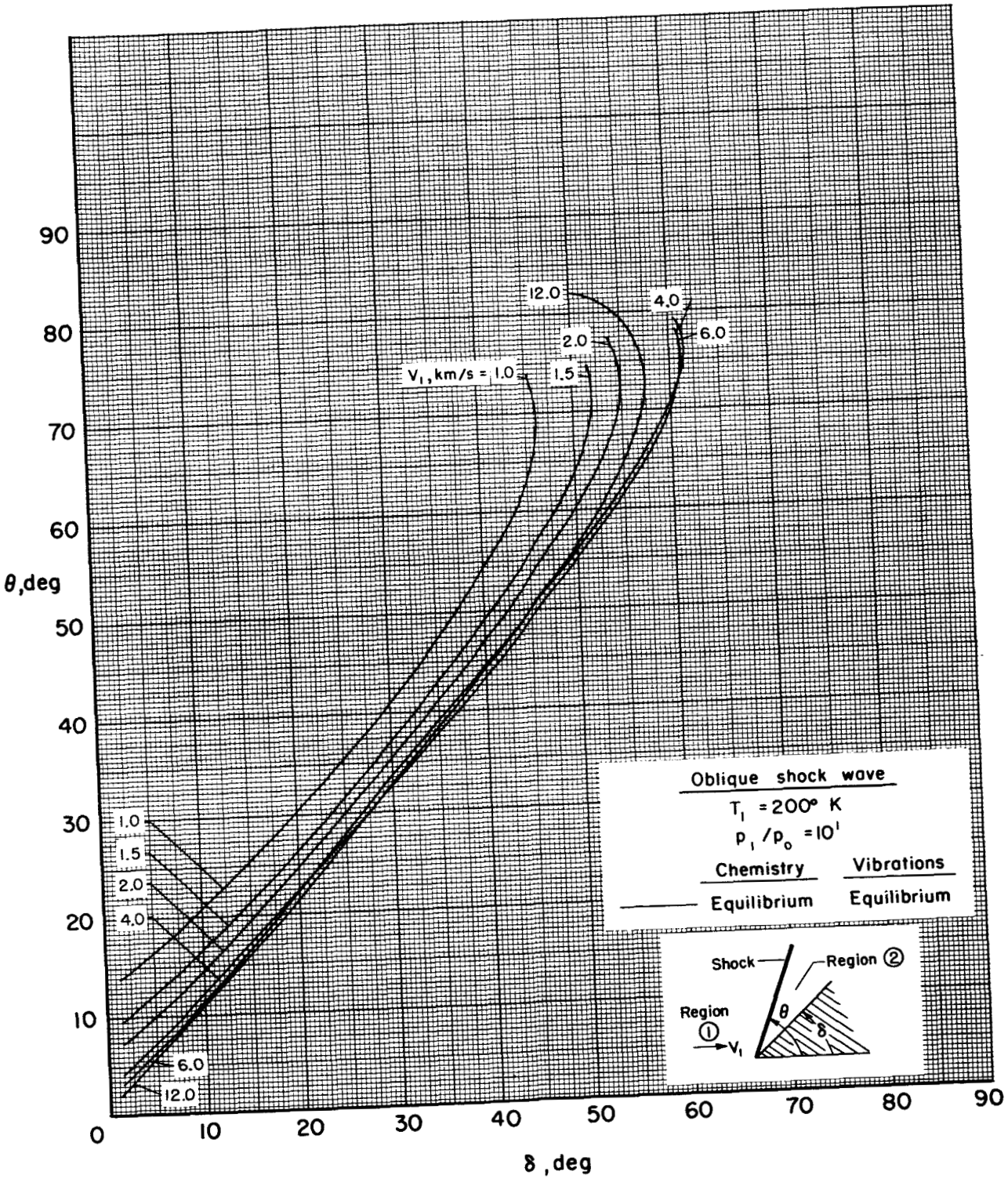
(a) $p_1/p_0 = 10^{-7}$

Chart 15. - Variation with wedge angle of the angle of an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_o = 10^{-3}$

Chart 15. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 15. - Concluded.

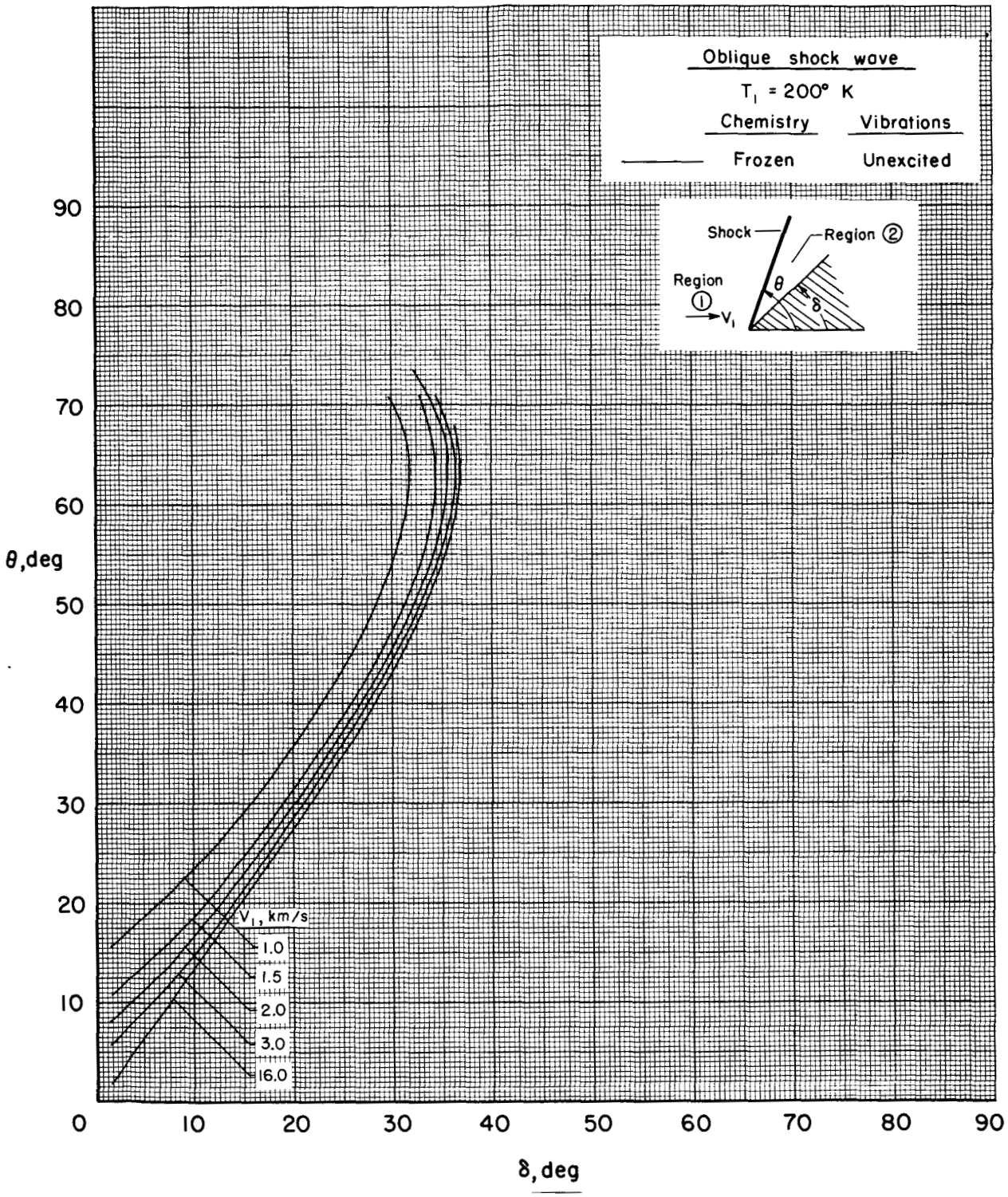
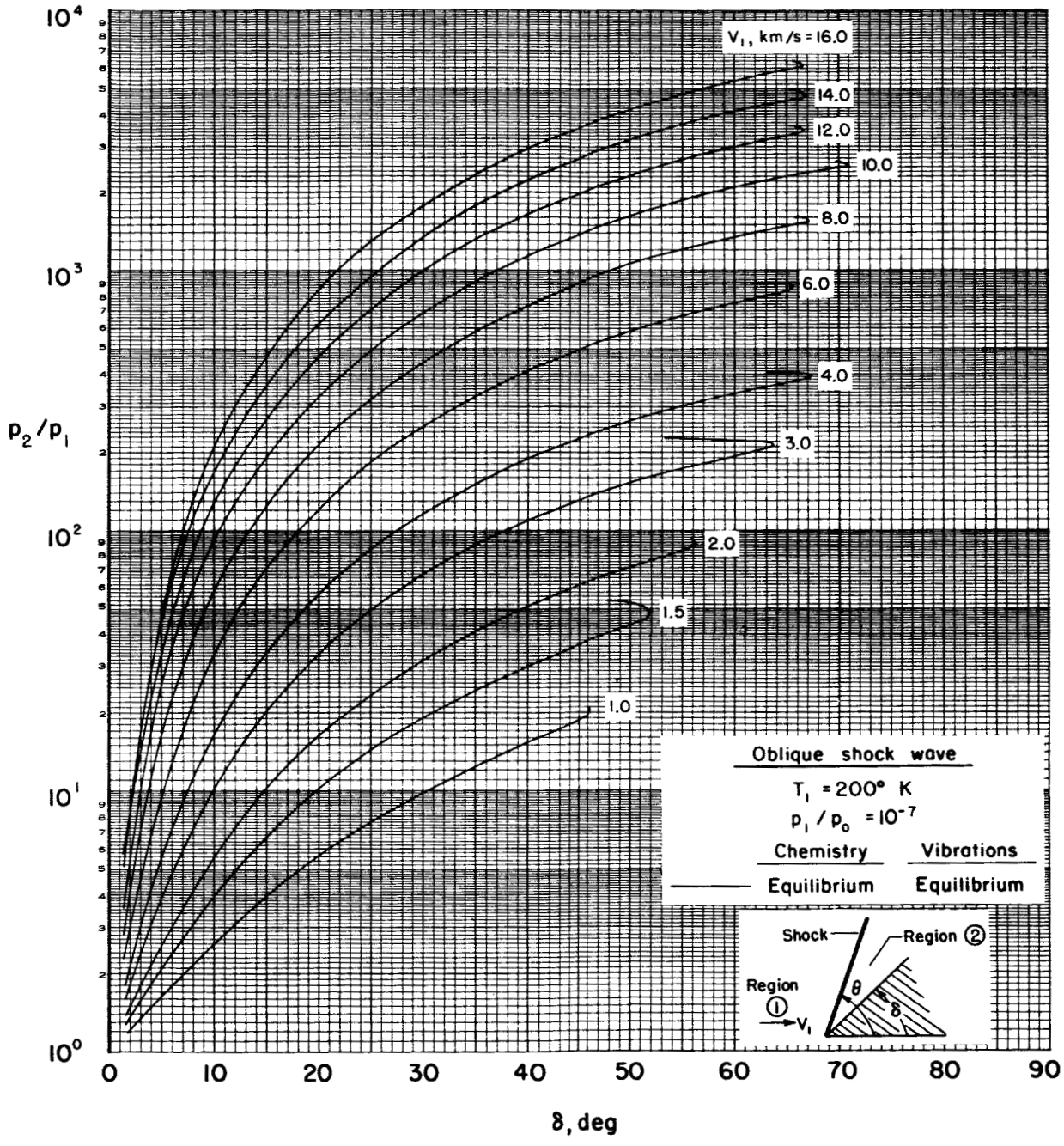
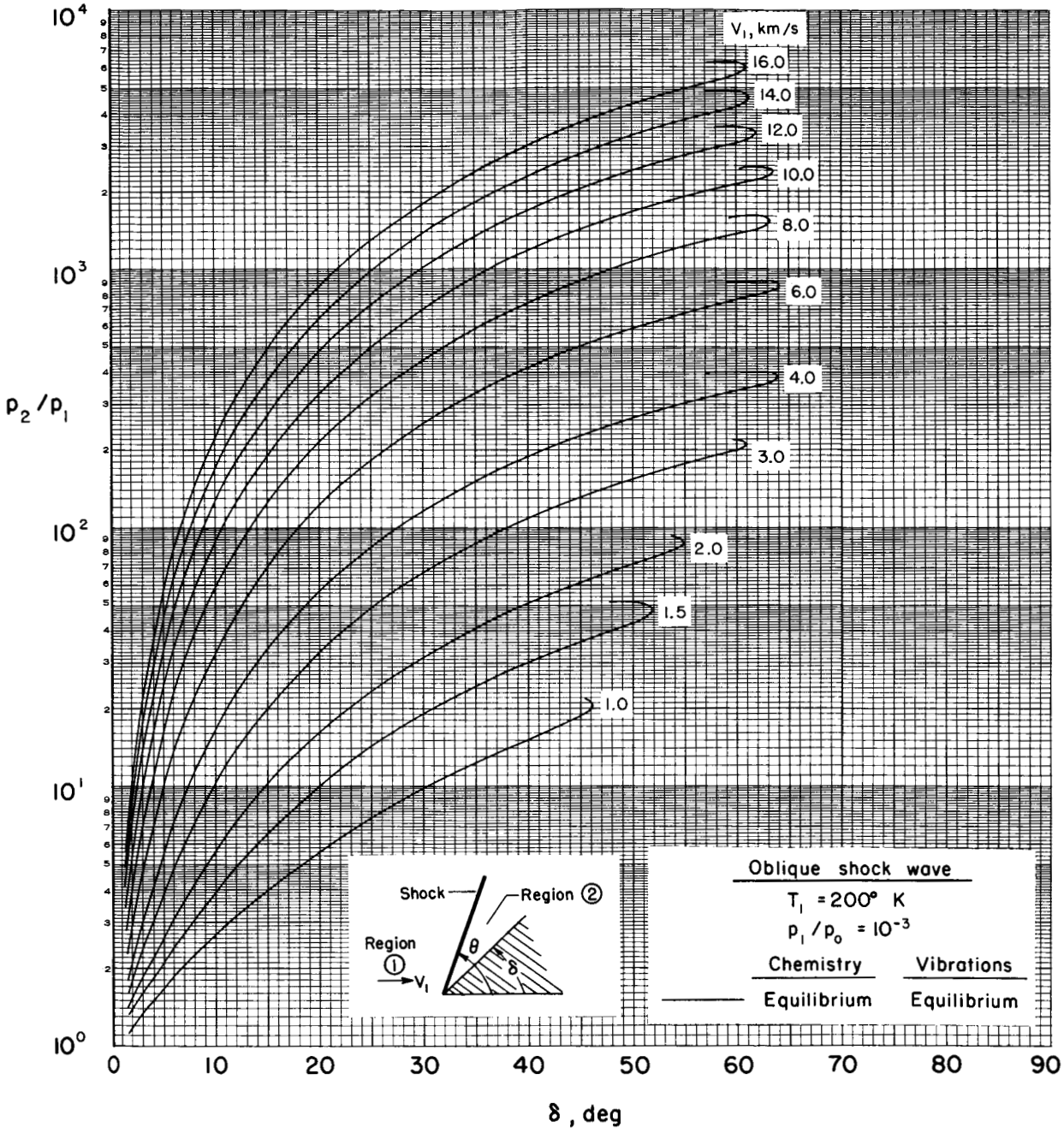


Chart 16. - Variation with wedge angle of the angle of an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



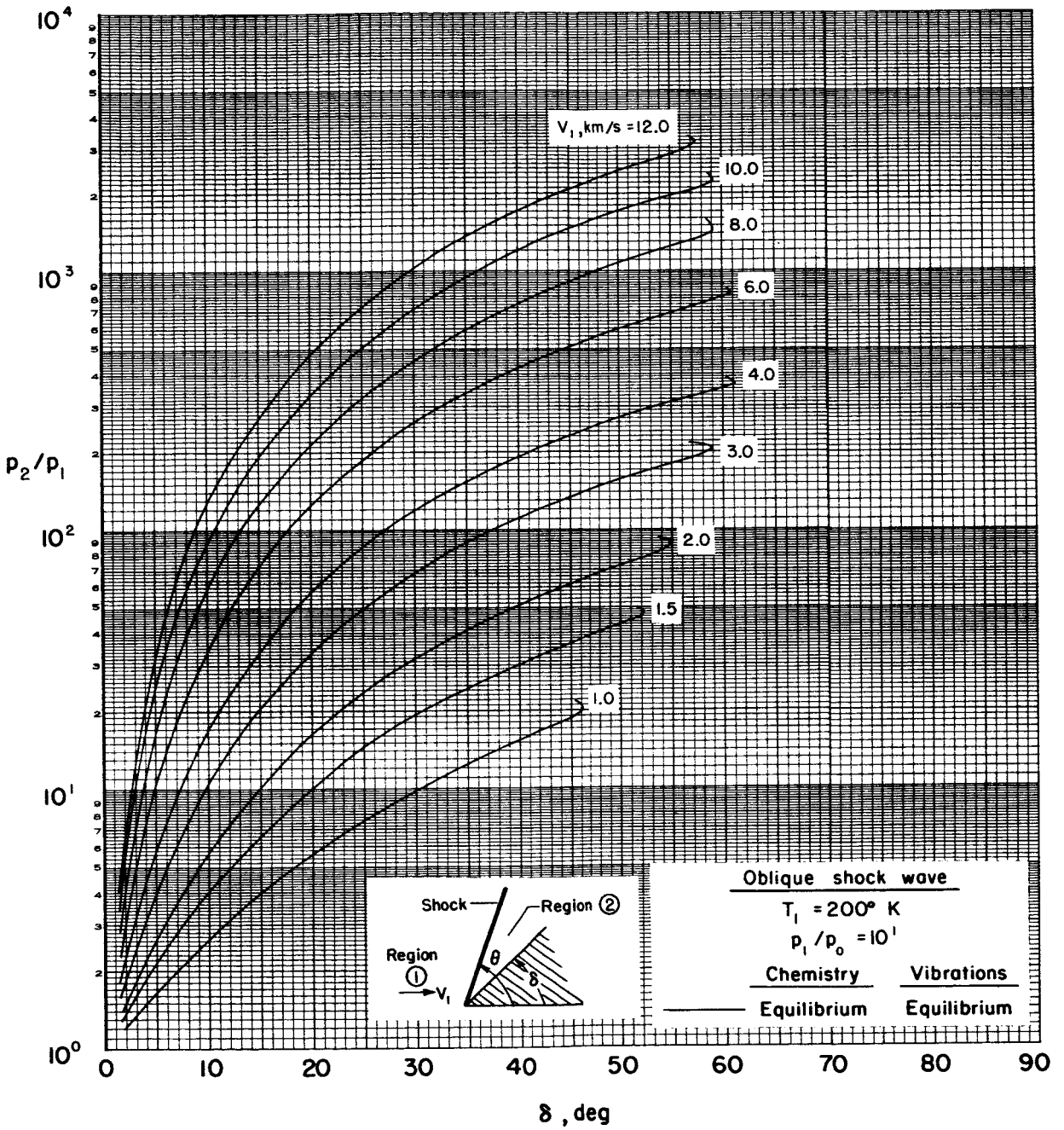
(a) $p_1/p_0 = 10^{-7}$

Chart 17. - Variation with wedge angle of the static pressure ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_0 = 10^{-3}$

Chart 17. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 17. - Concluded.

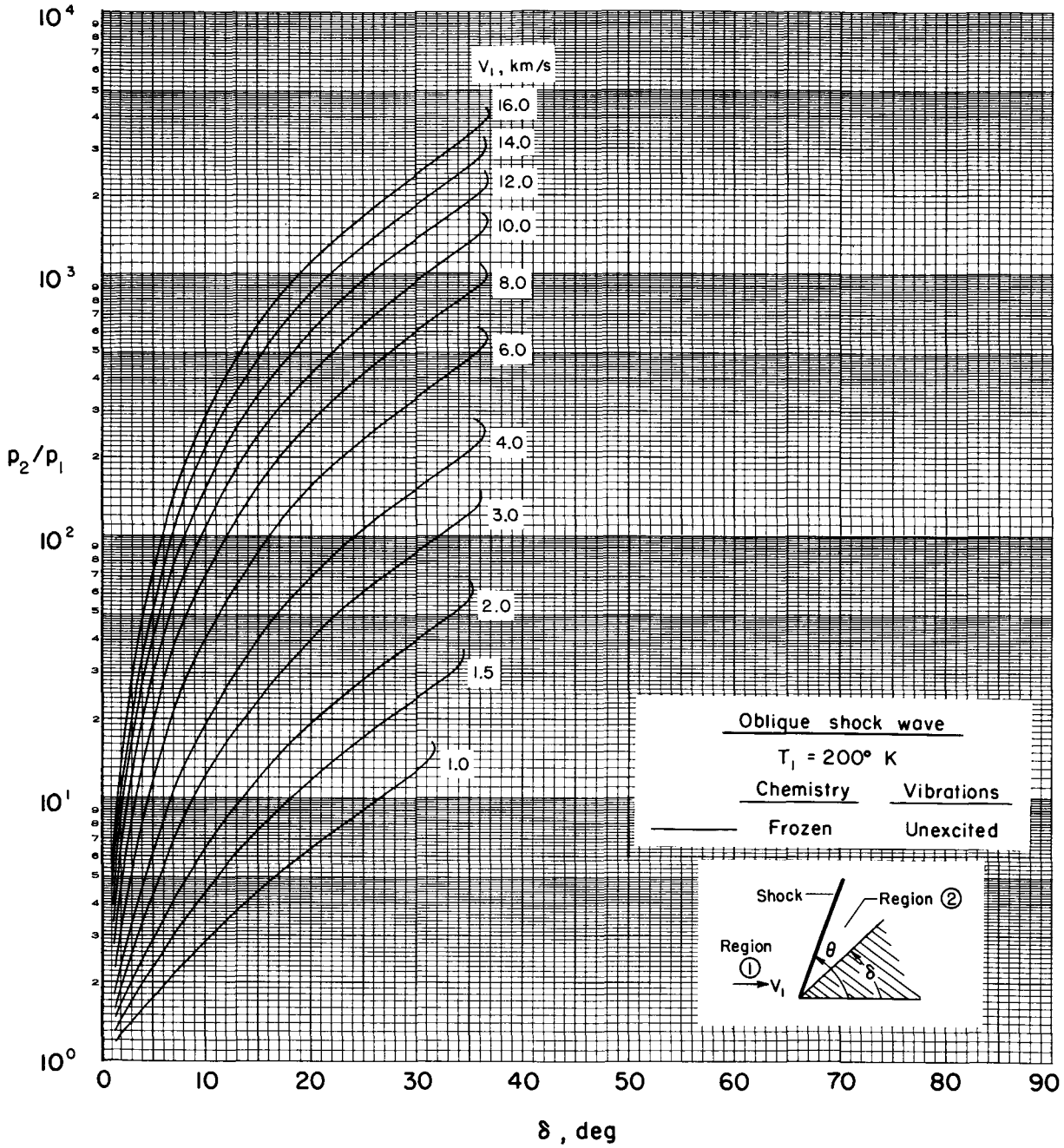
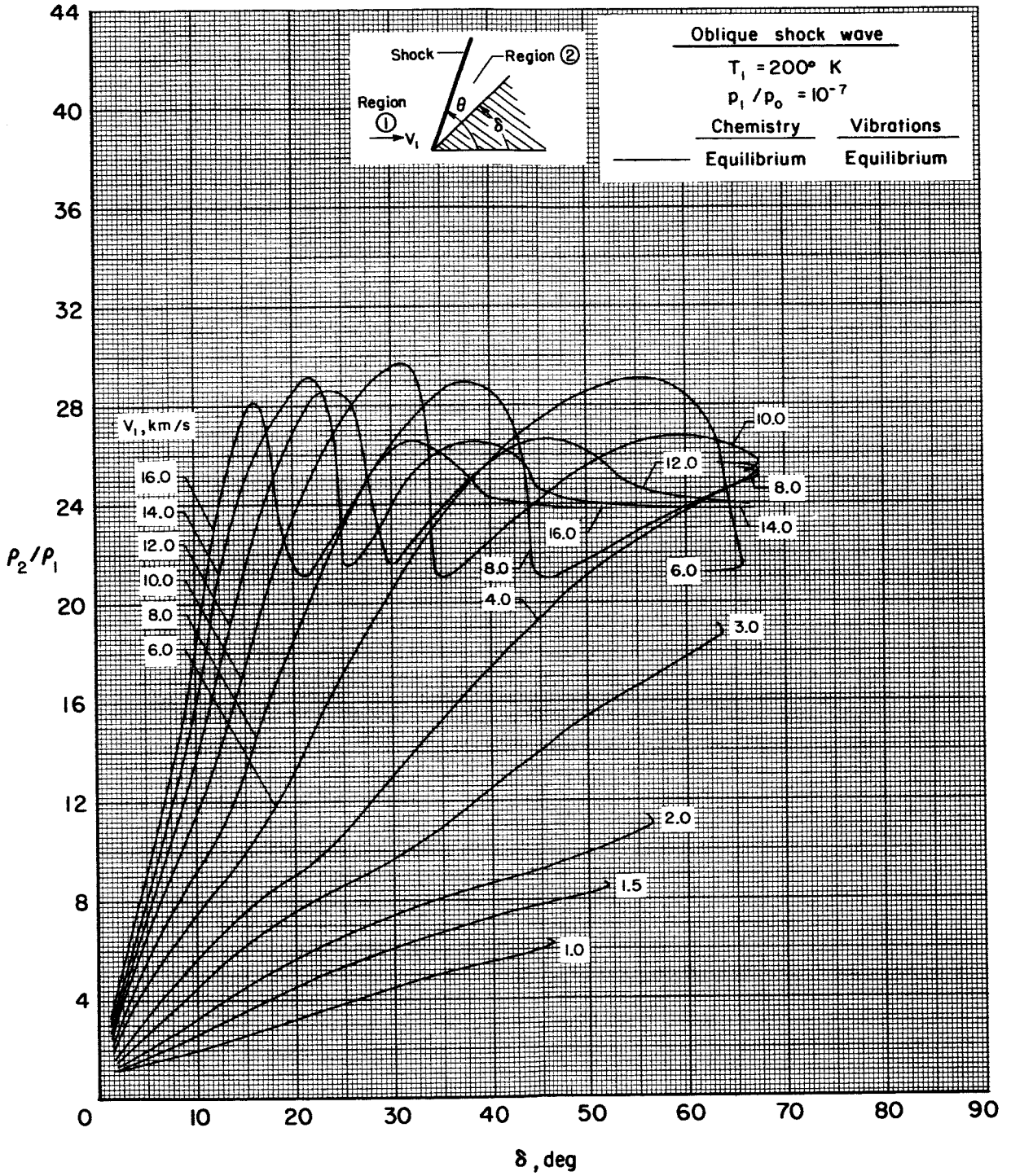
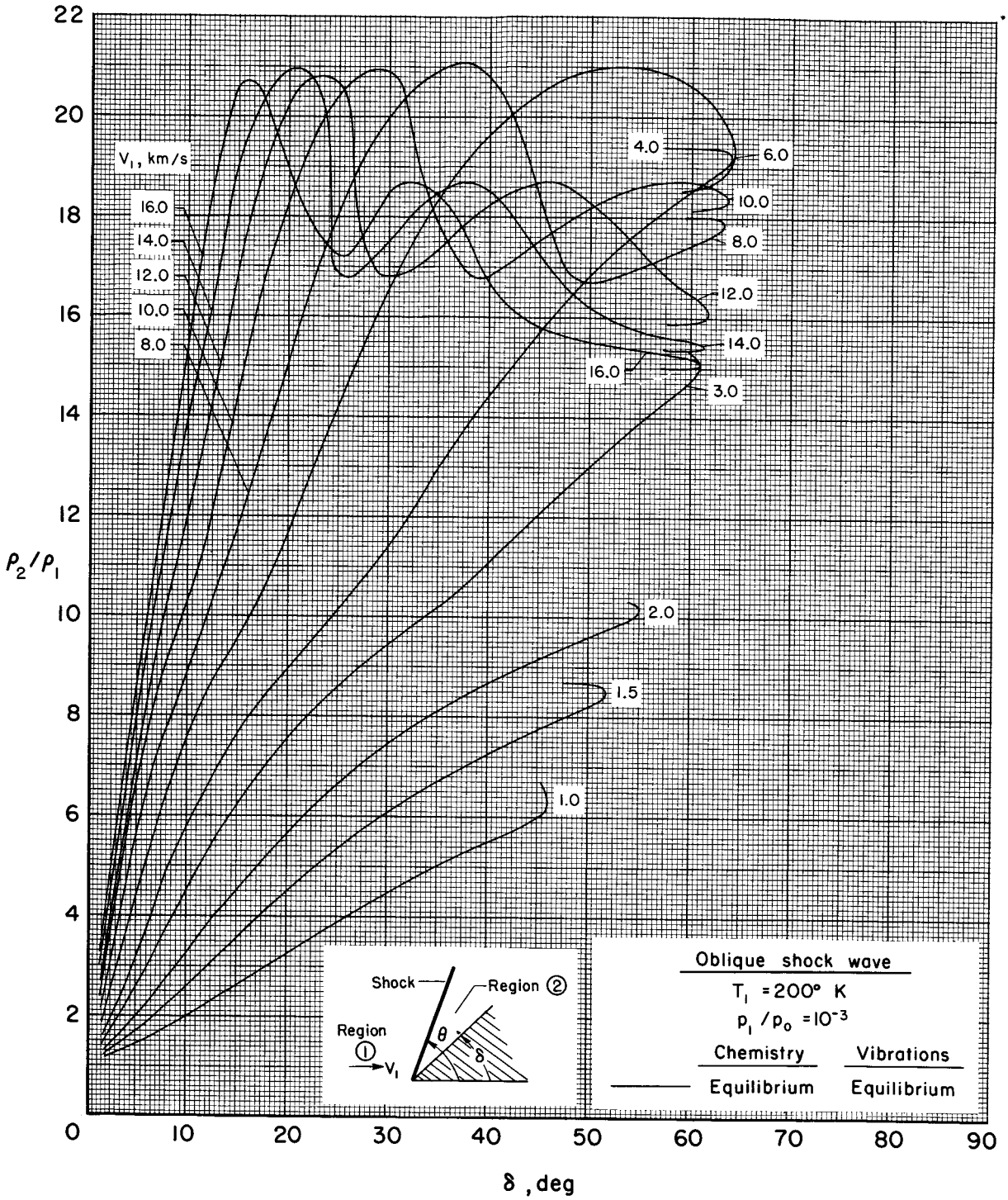


Chart 18.- Variation with wedge angle of the static pressure ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



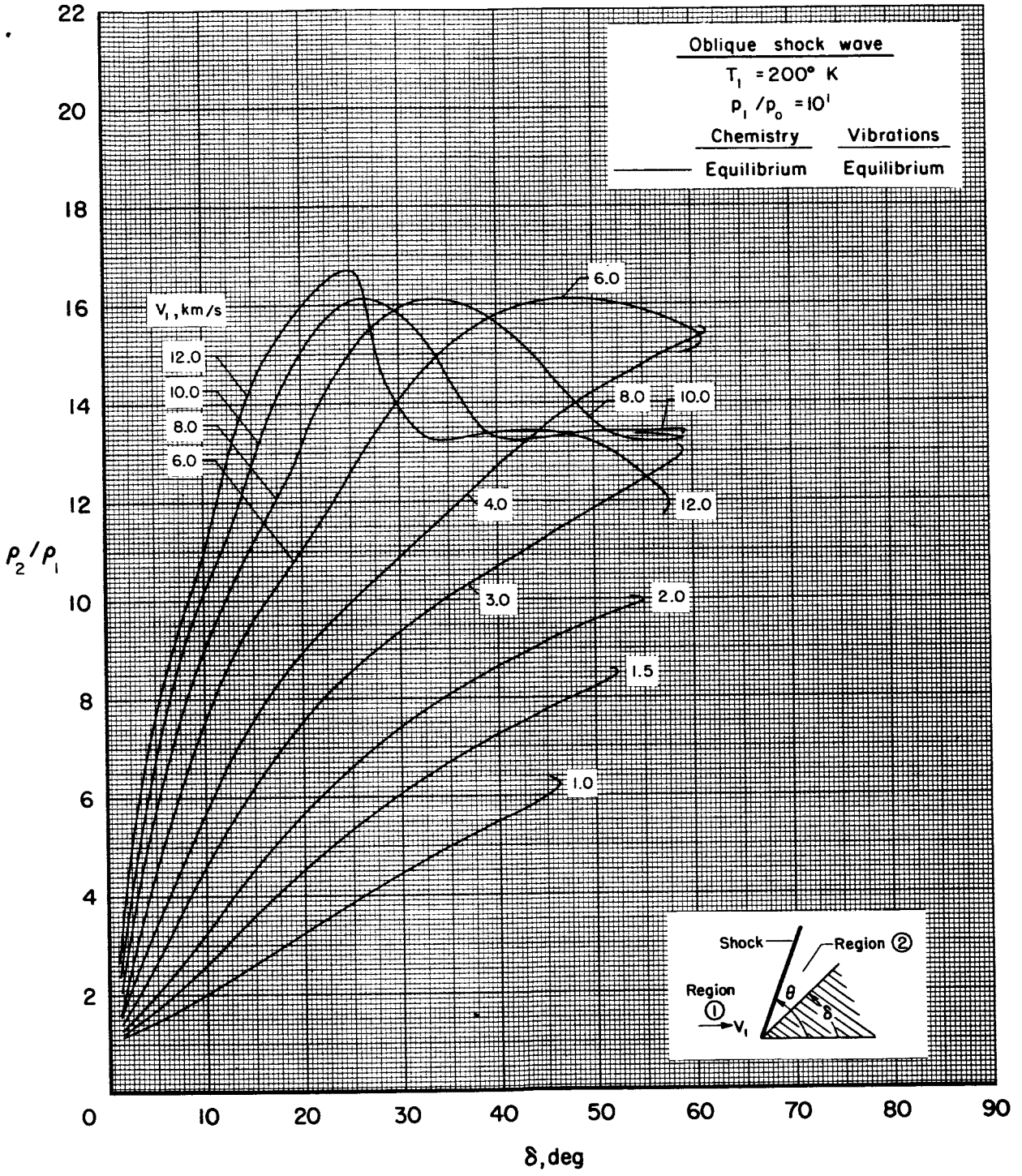
(a) $p_1/p_o = 10^{-7}$

Chart 19. - Variation with wedge angle of the static density ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_o = 10^{-3}$

Chart 19. - Continued.



(c) $p_1/p_o = 10^1$

Chart 19. - Concluded.

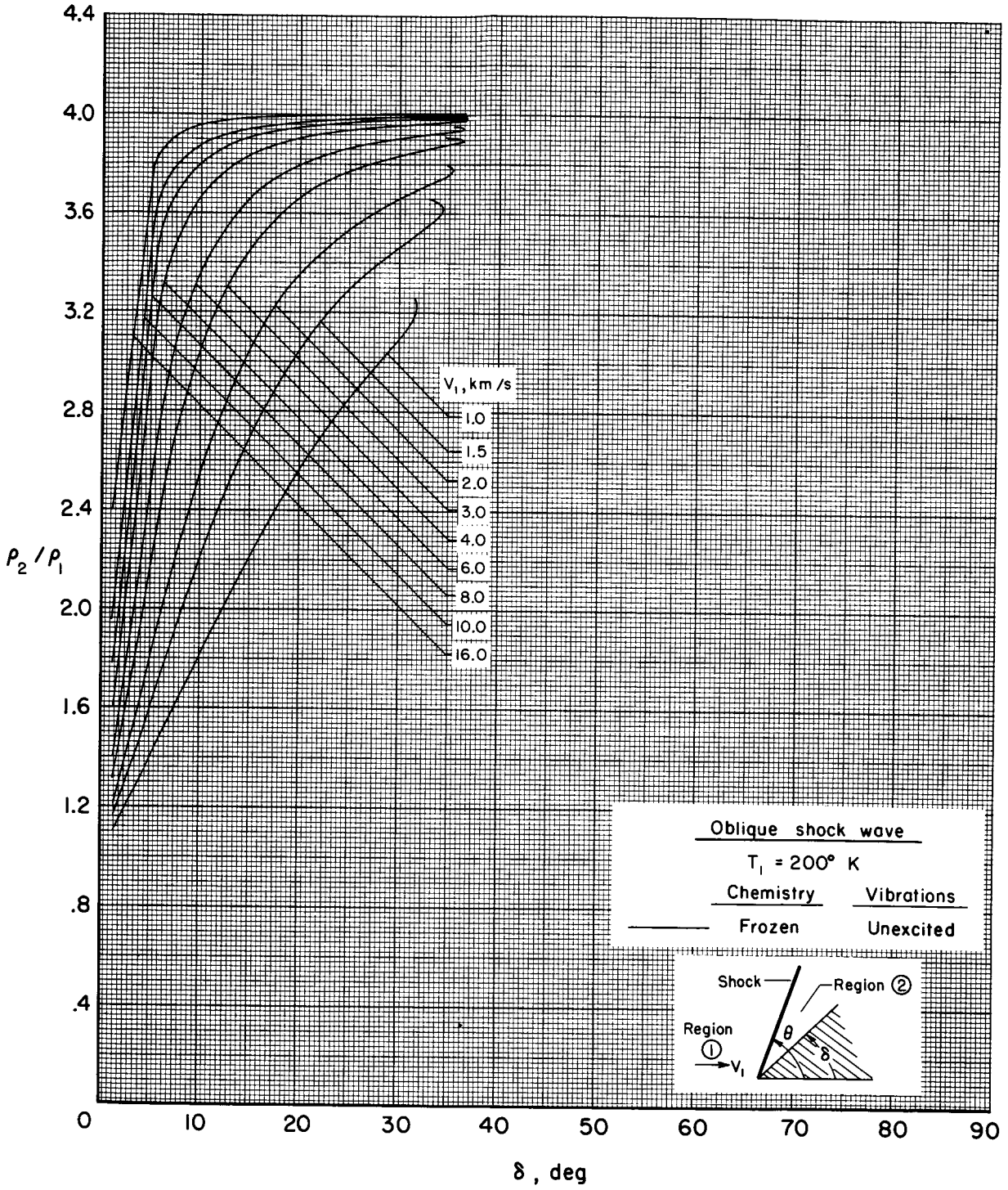
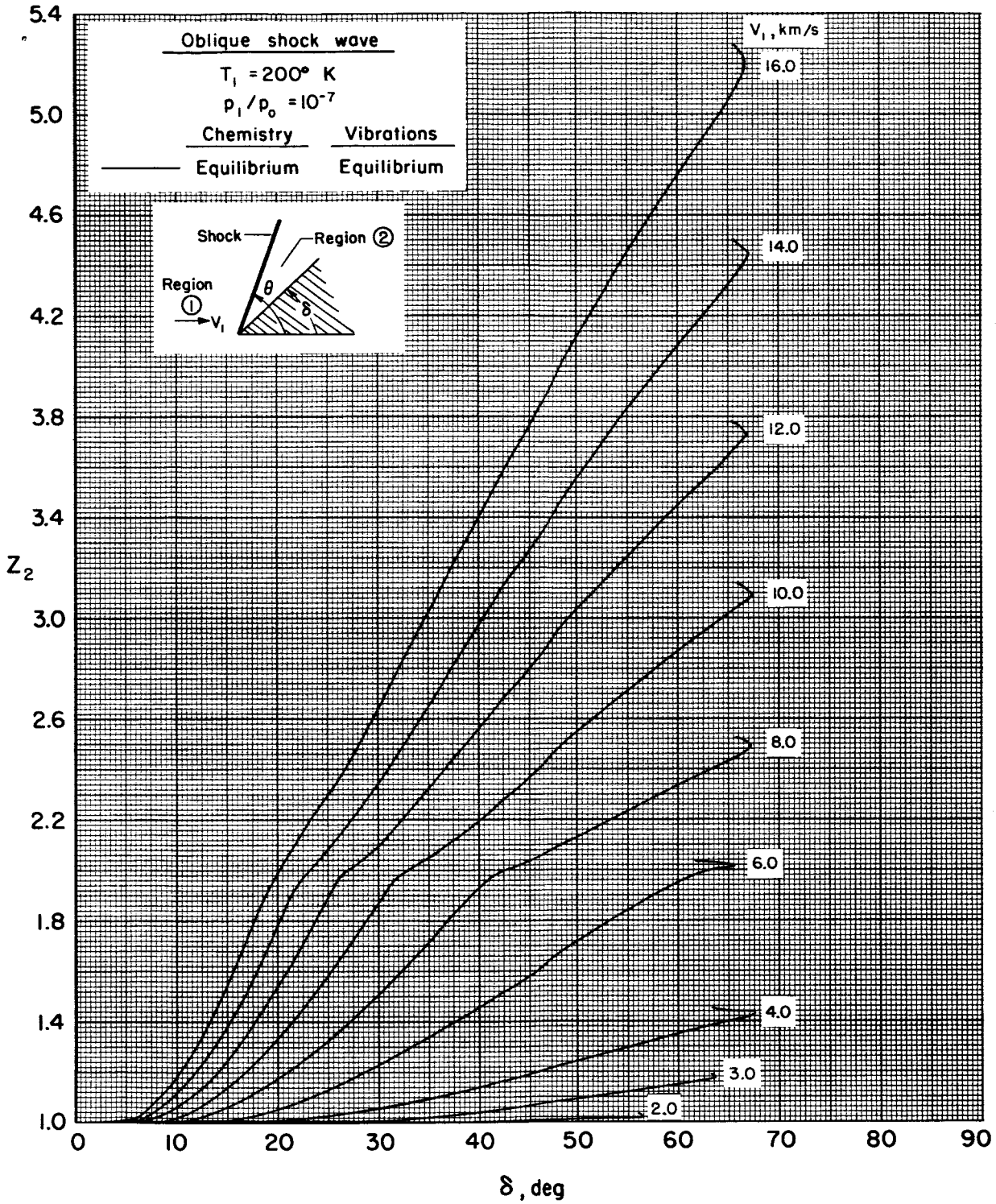
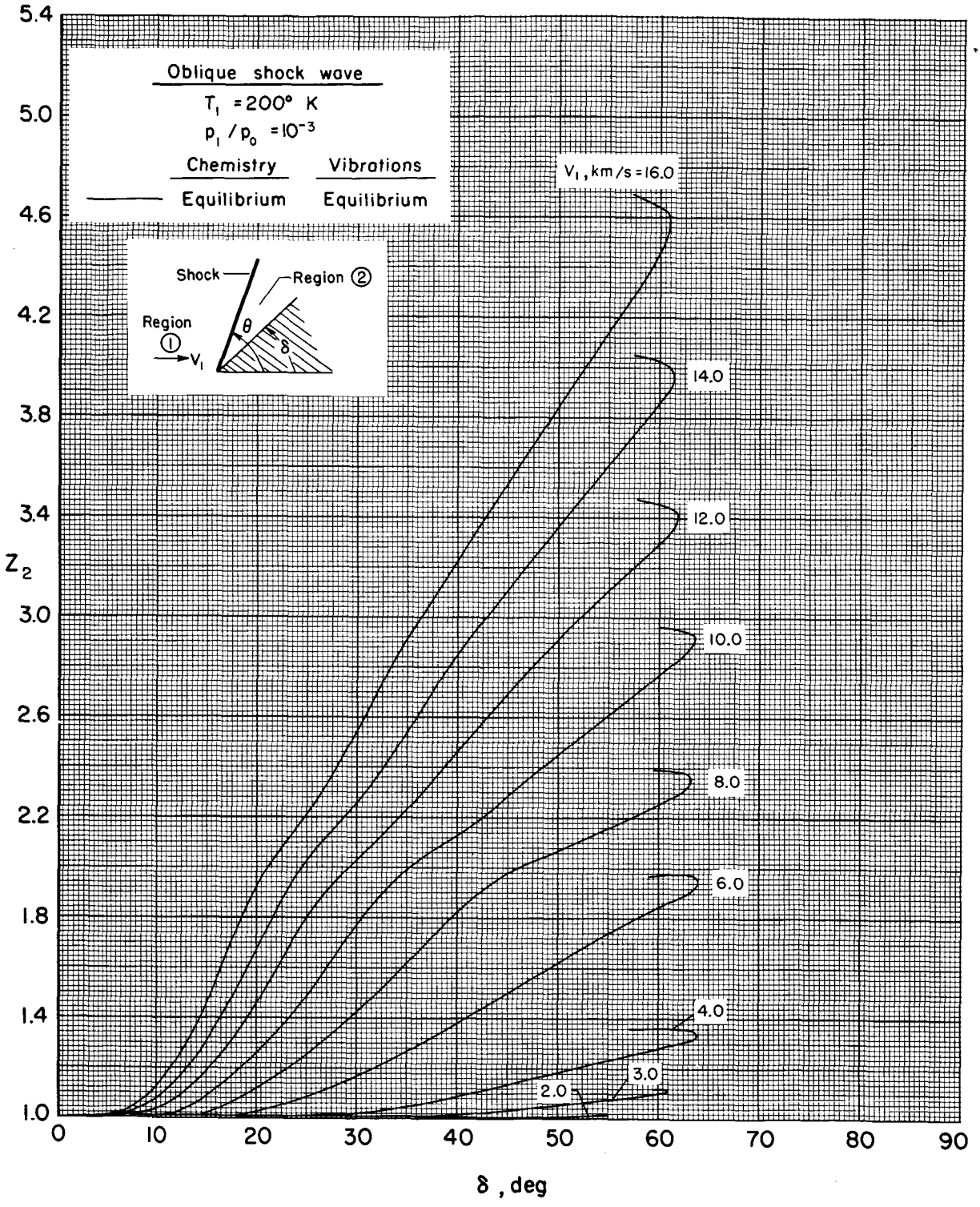


Chart 20. - Variation with wedge angle of the static density ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



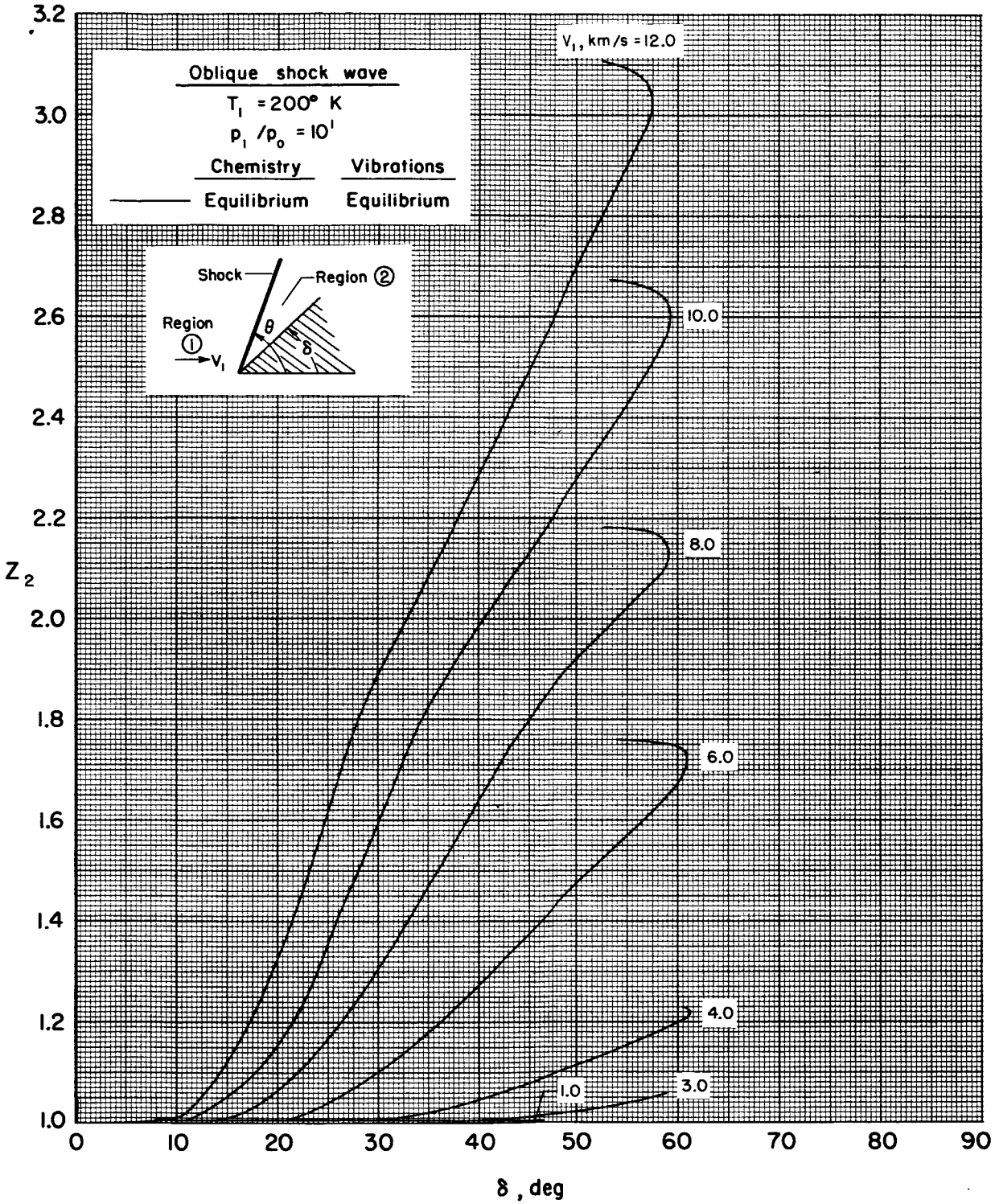
(a) $p_1/p_o = 10^{-7}$

Chart 21. - Variation with wedge angle of the compressibility factor downstream of an oblique shock wave. Chemistry and vibrations in equilibrium.



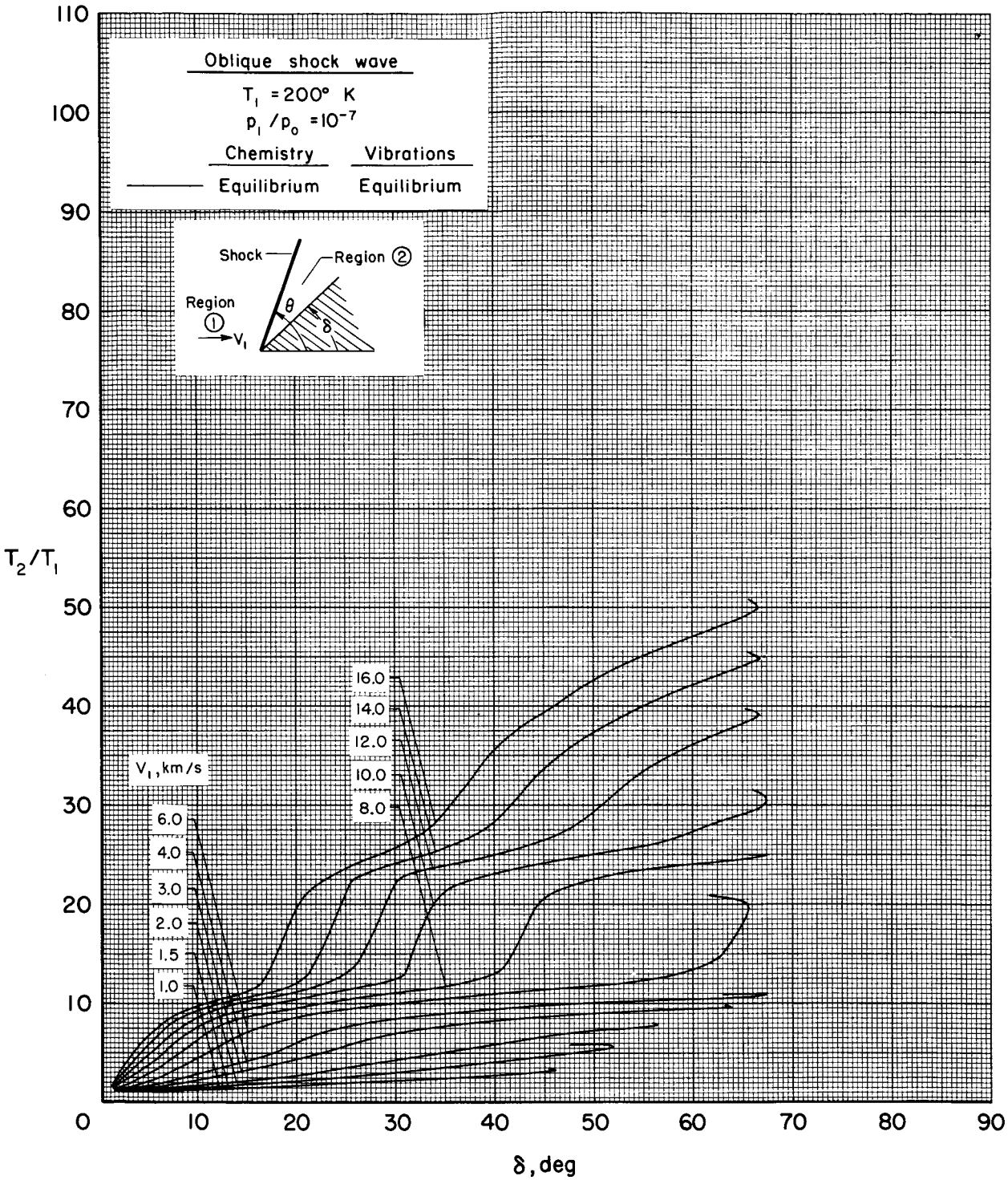
(b) $p_1/p_0 = 10^{-3}$

Chart 21. - Continued.



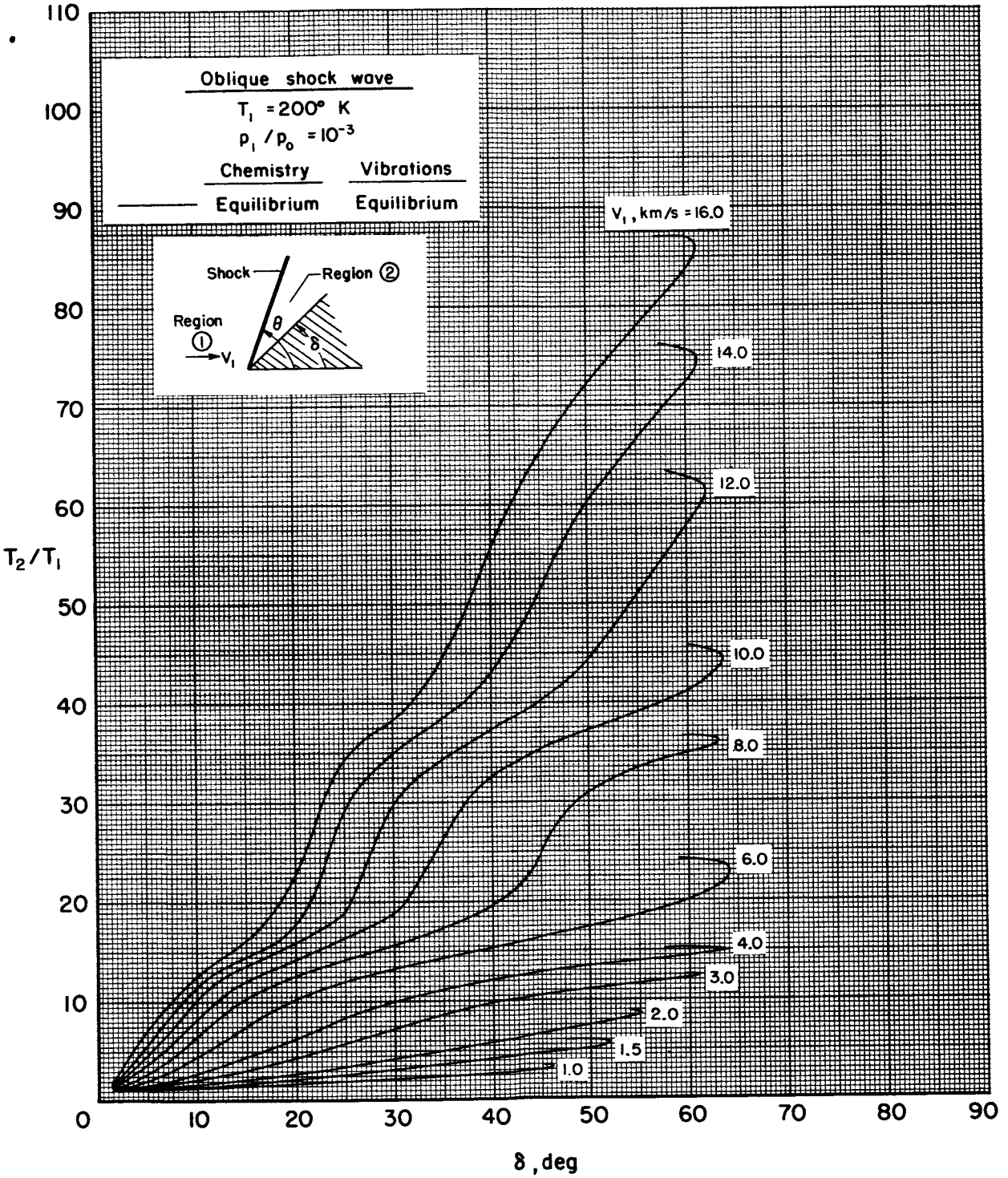
(c) $p_1/p_0 = 10^1$

Chart 21. - Concluded.



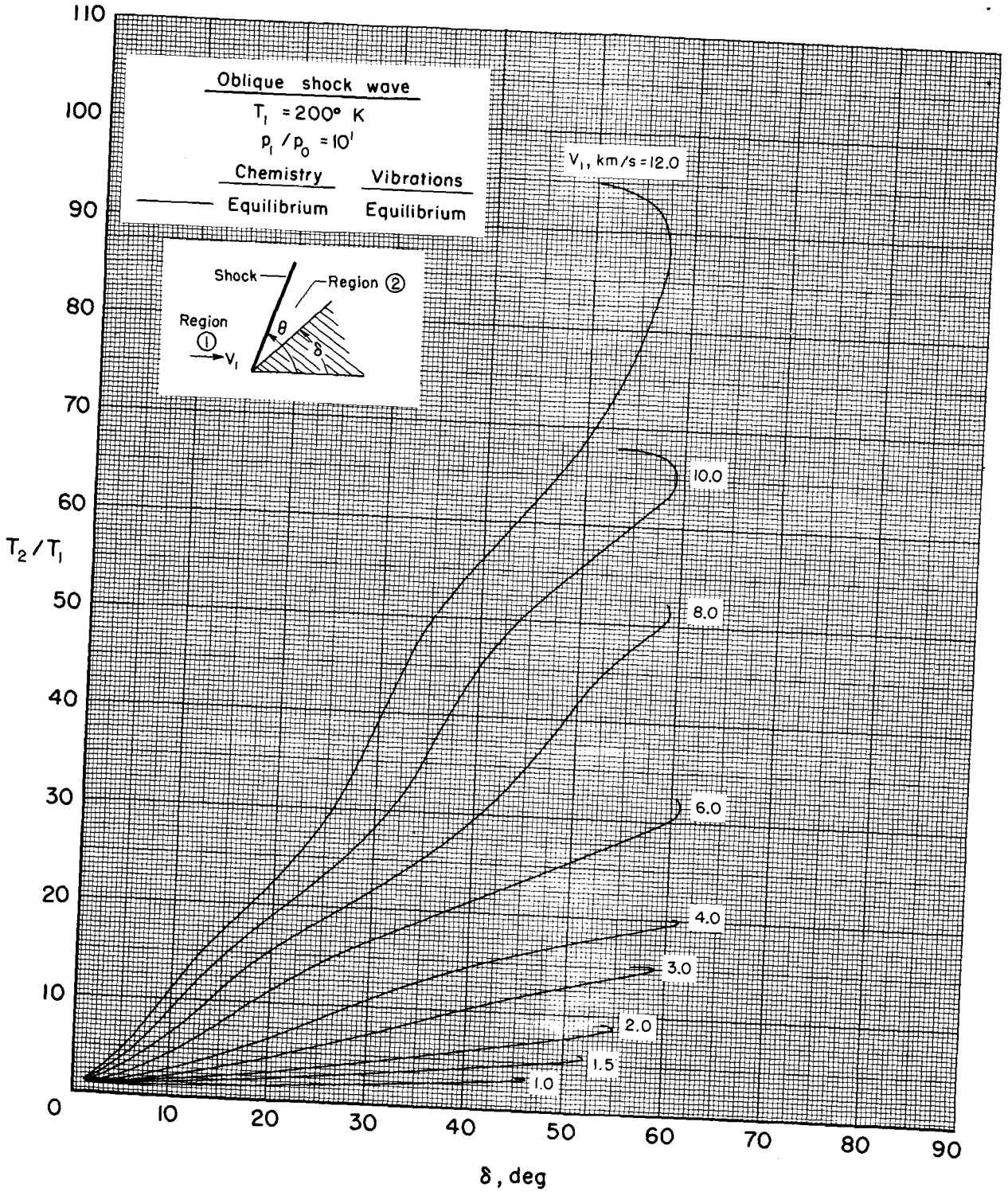
(a) $p_1/p_0 = 10^{-7}$

Chart 22. - Variation with wedge angle of the static temperature ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_0 = 10^{-3}$

Chart 22. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 22. - Concluded.

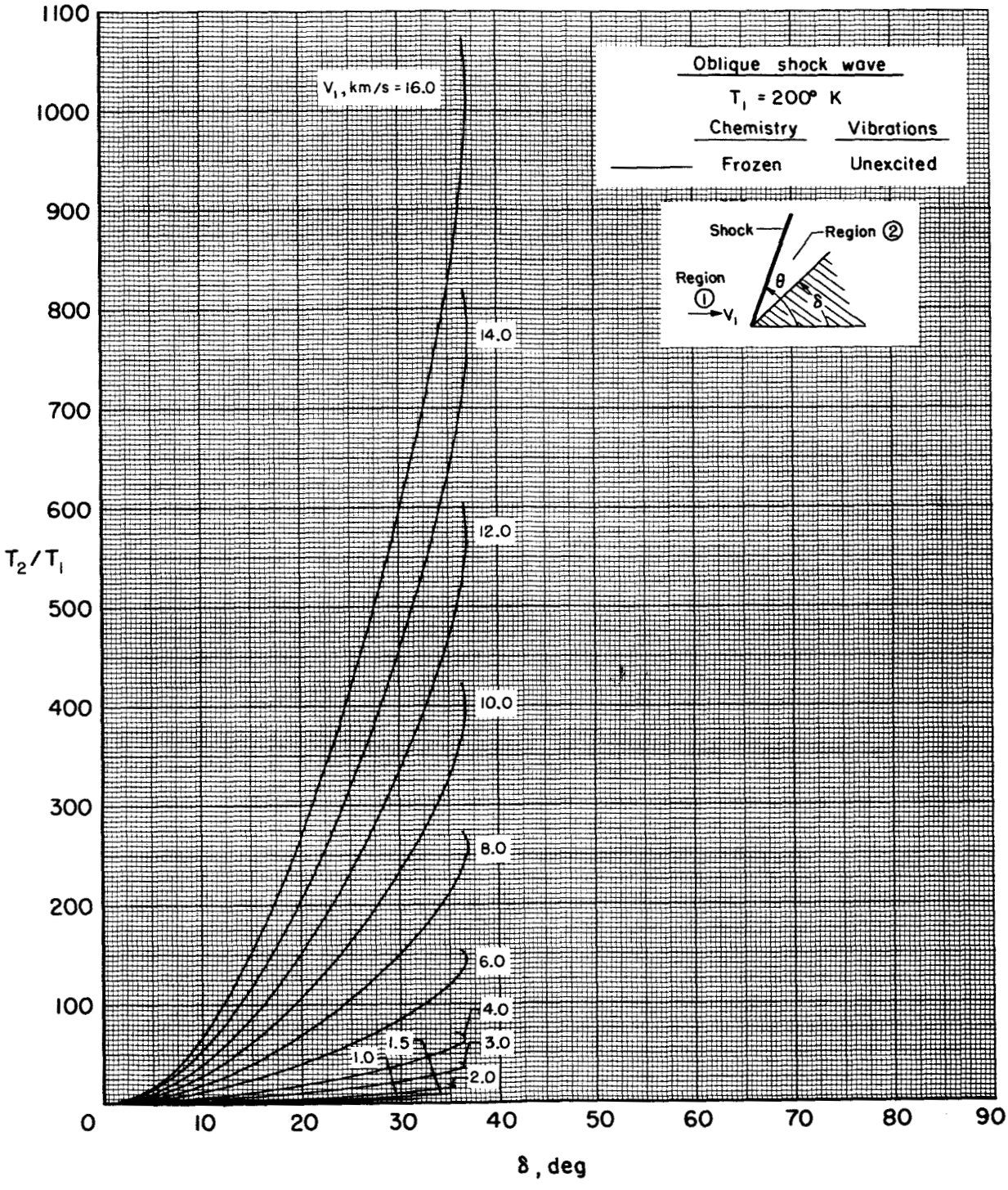
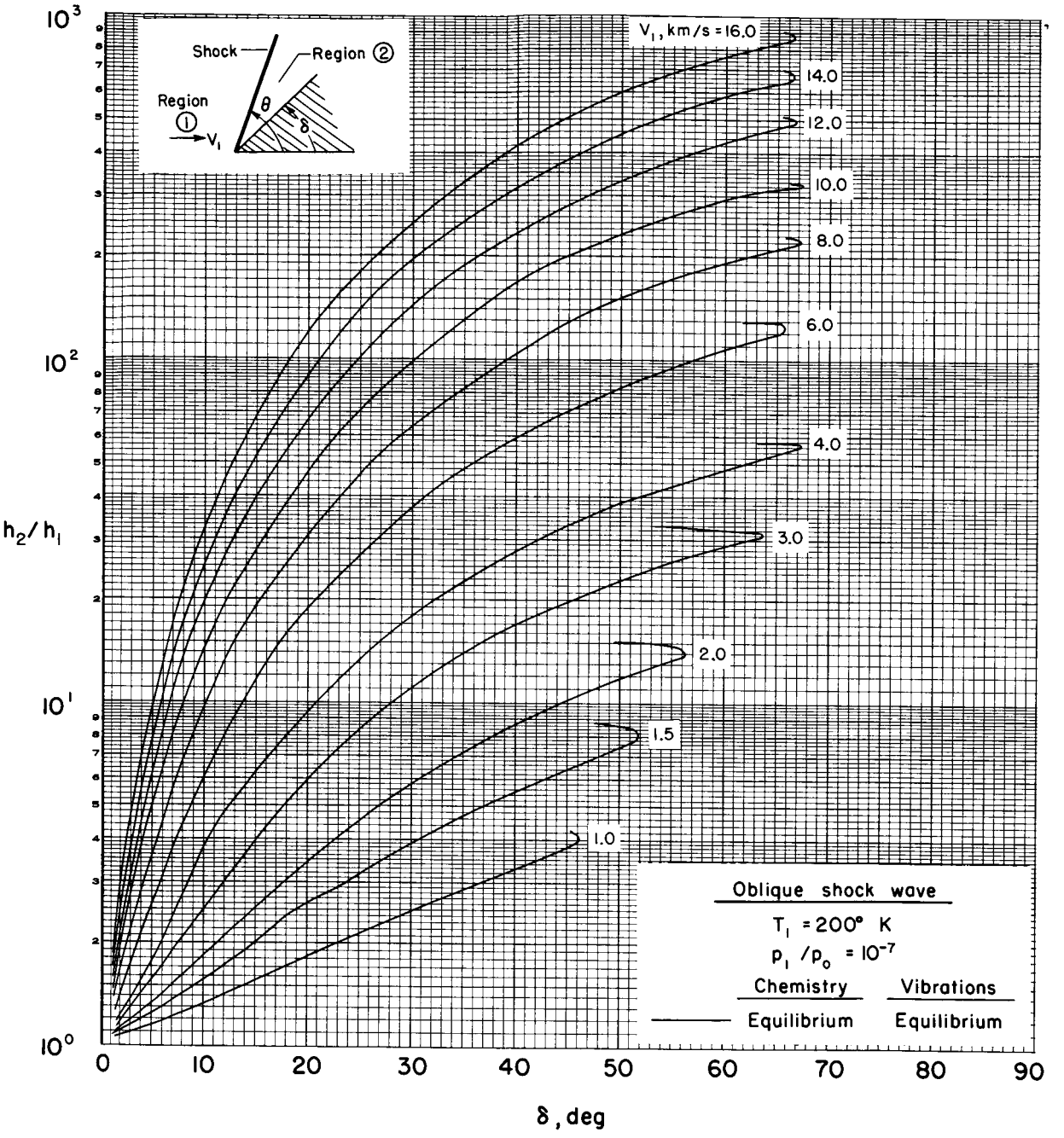
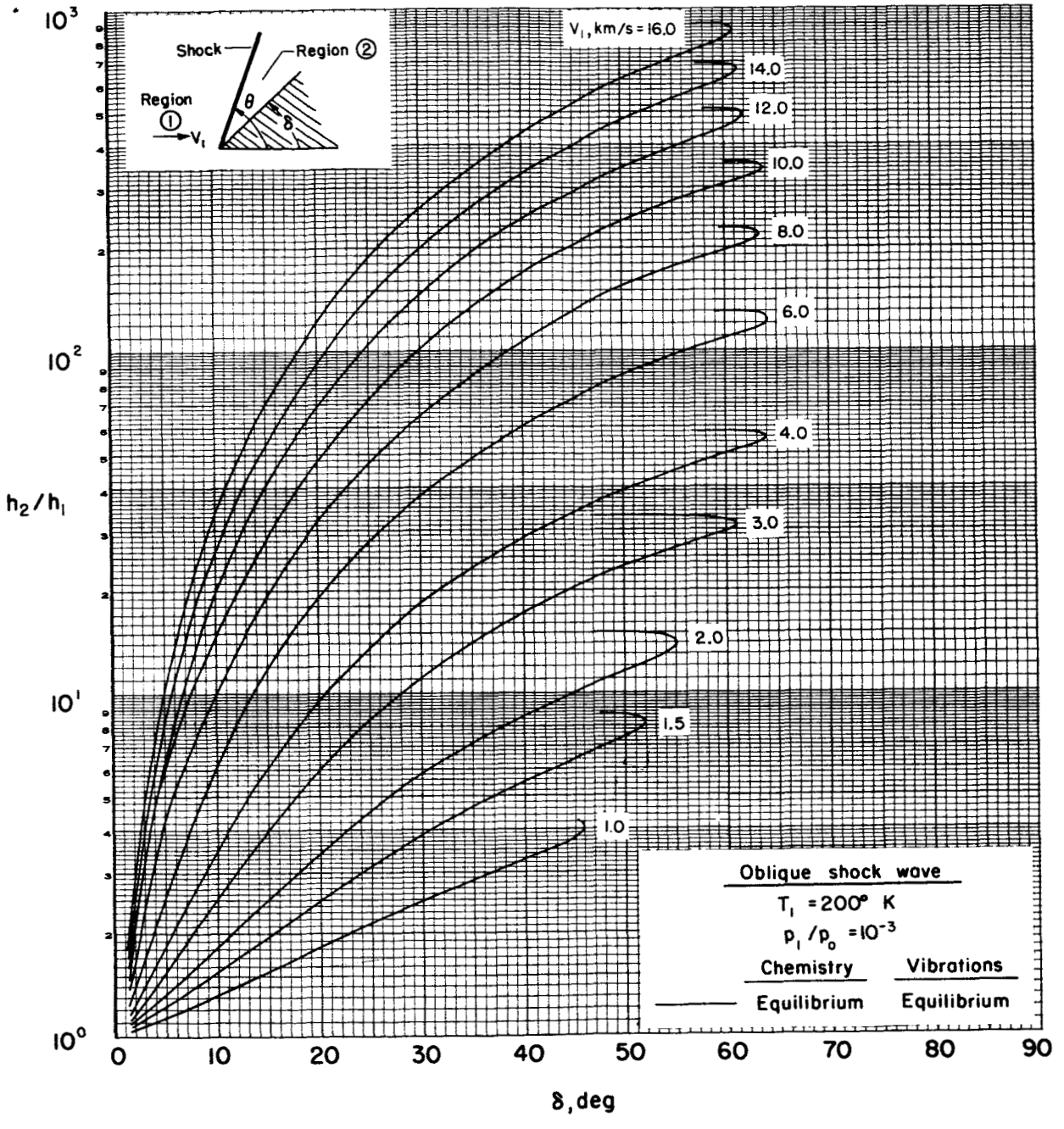


Chart 23. - Variation with wedge angle of the static temperature ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



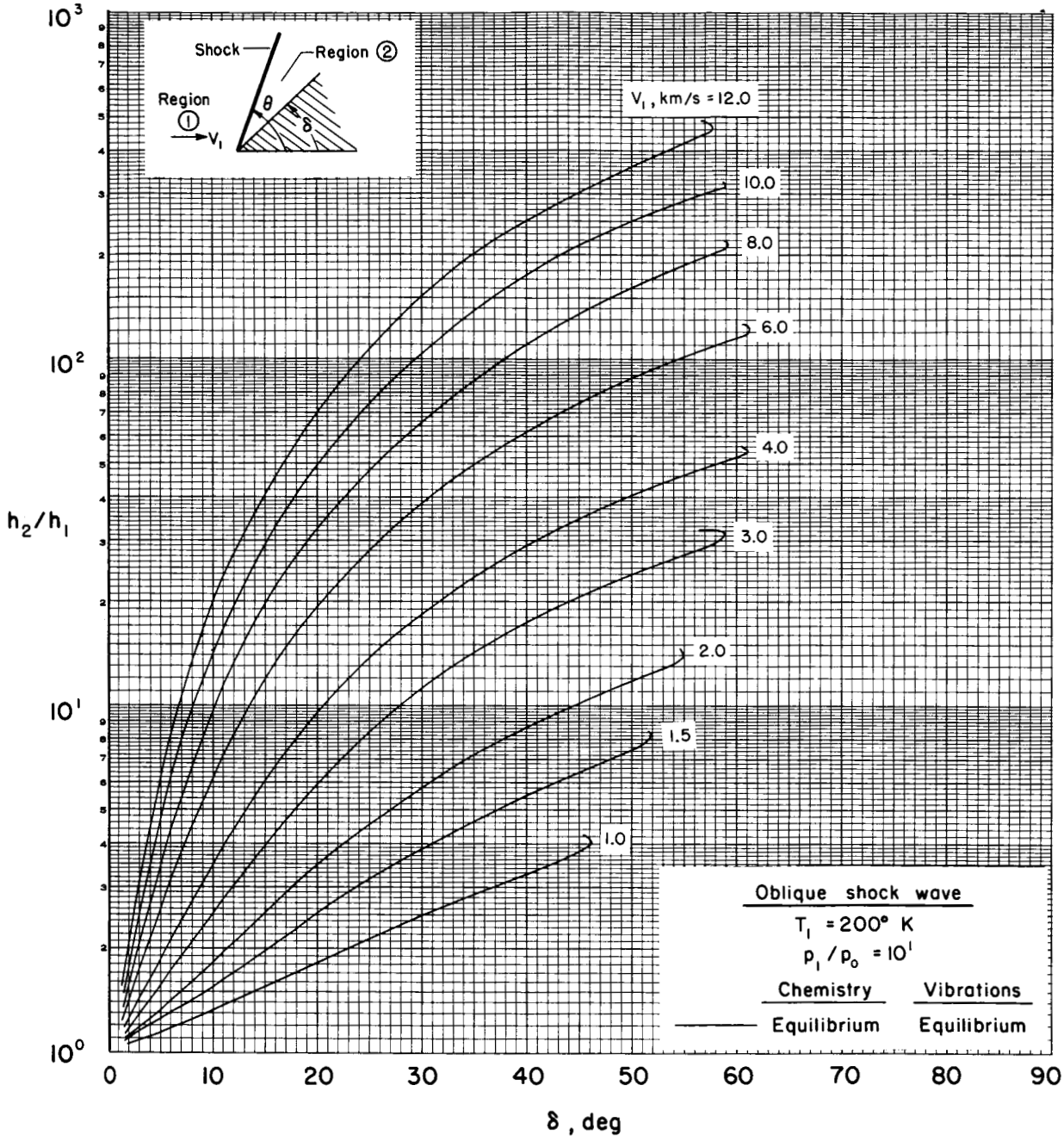
(a) $p_1/p_o = 10^{-7}$

Chart 24. - Variation with wedge angle of the static enthalpy ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_0 = 10^{-3}$

Chart 24. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 24. - Concluded.

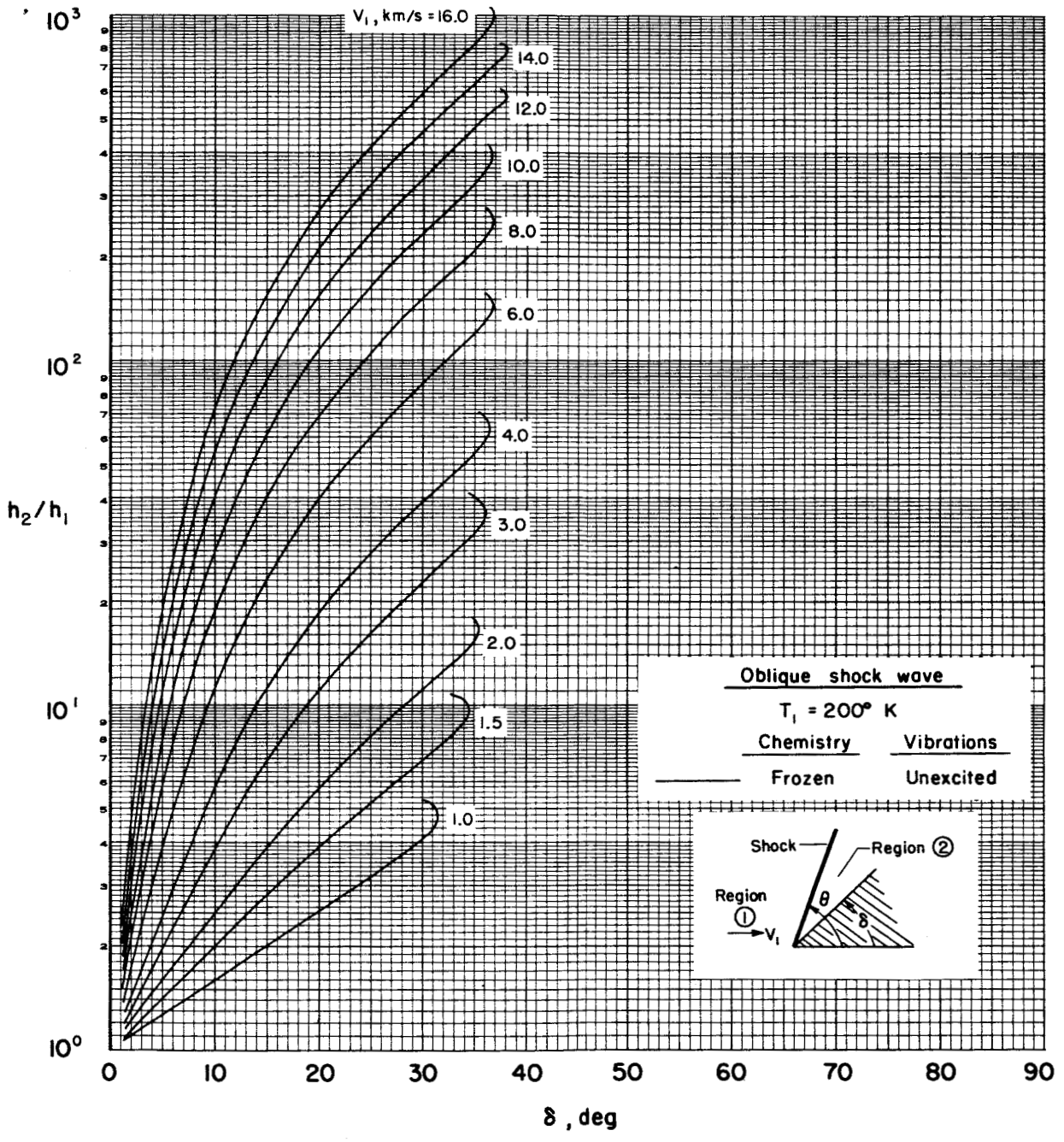
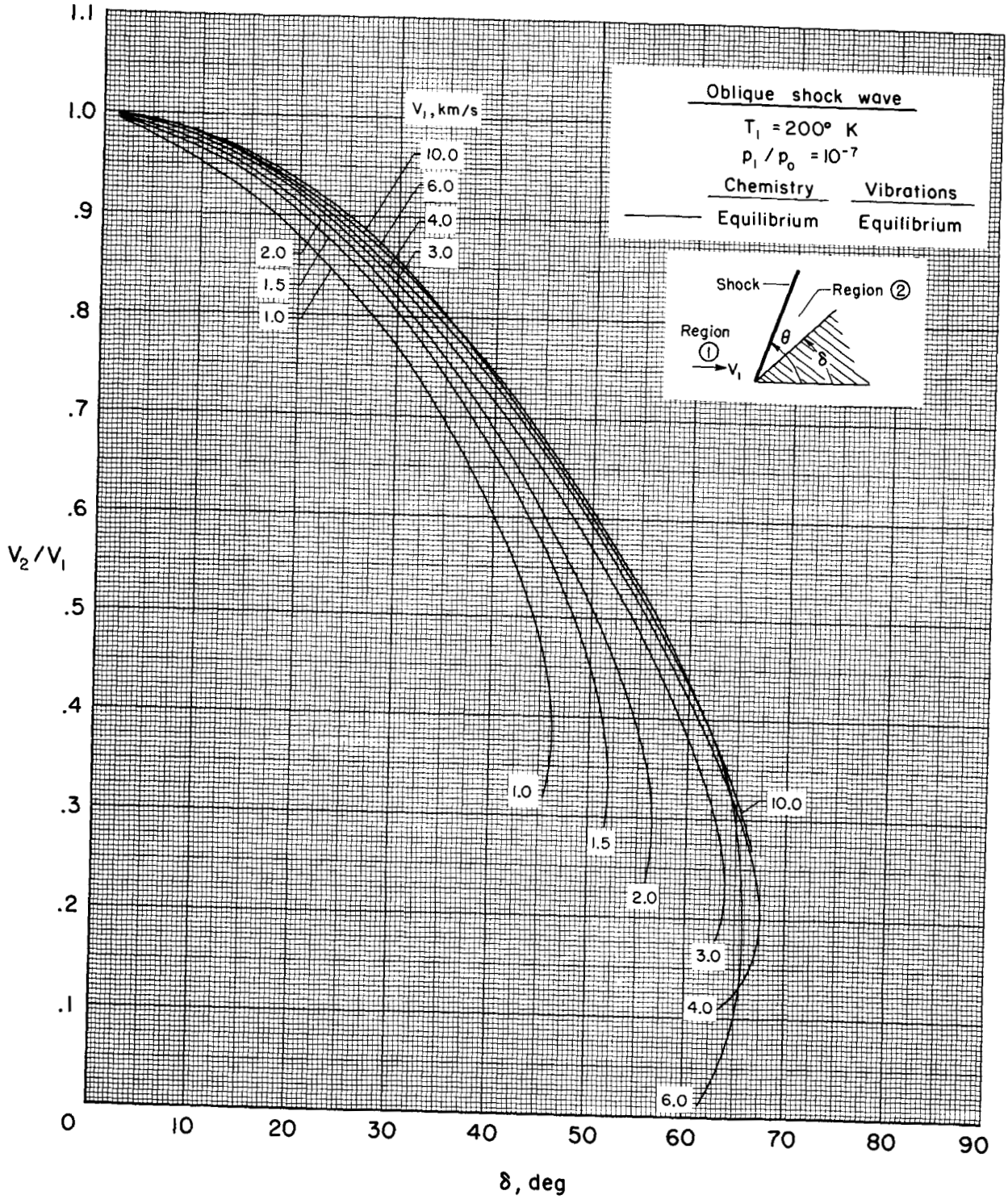
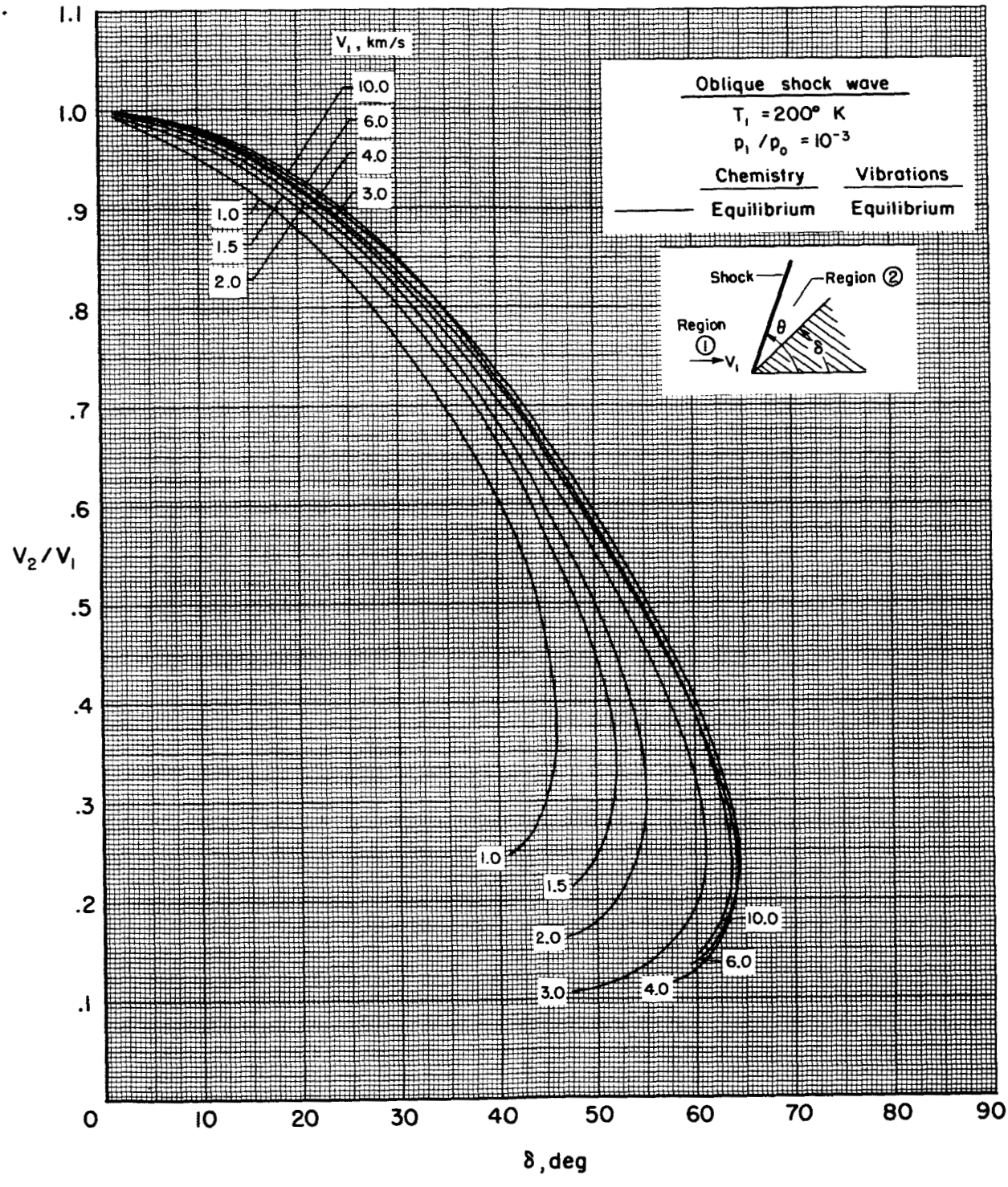


Chart 25. - Variation with wedge angle of the static enthalpy ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



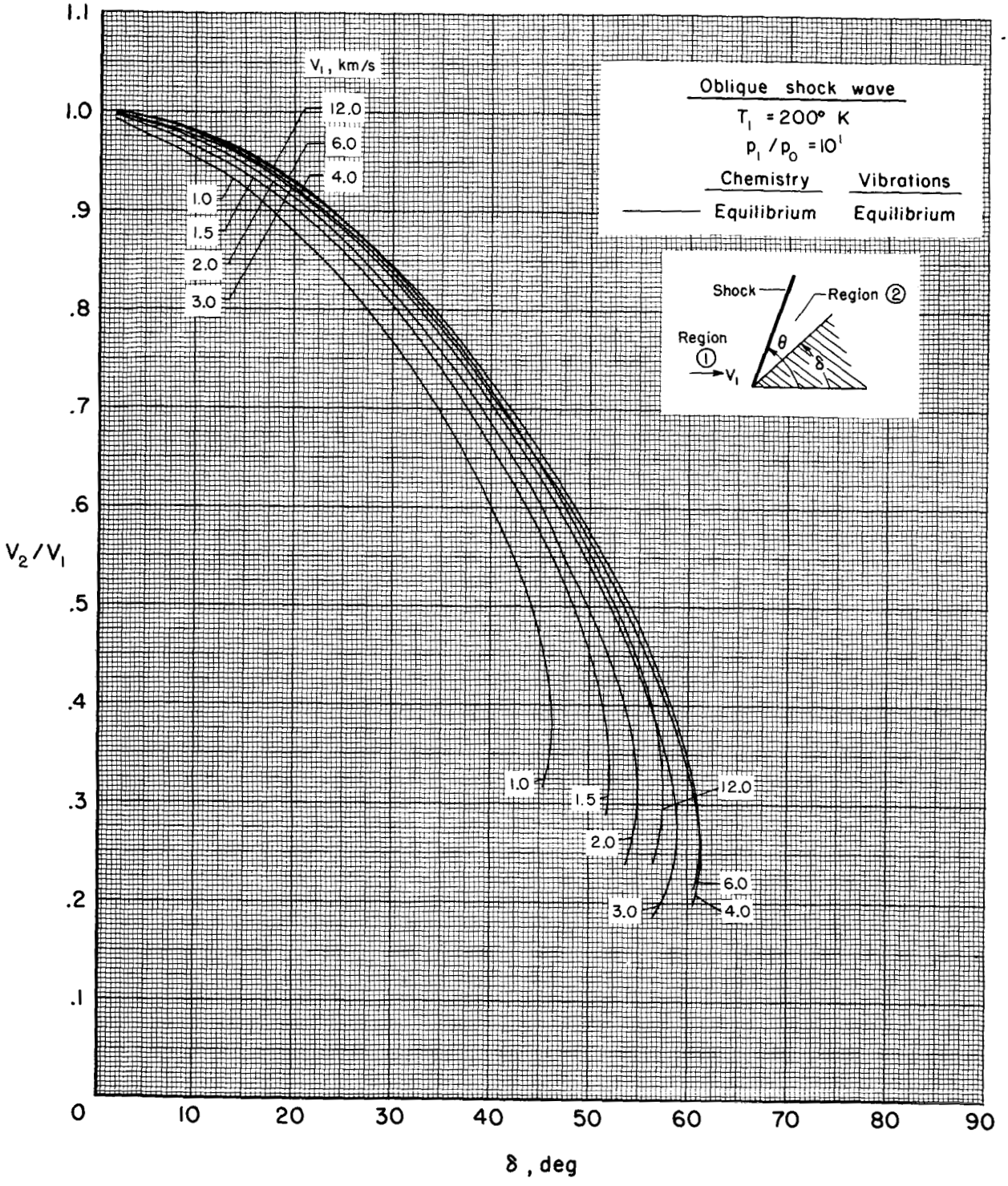
(a) $p_1/p_0 = 10^{-7}$

Chart 26. - Variation with wedge angle of the flow speed ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_0 = 10^{-3}$

Chart 26. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 26. - Concluded.

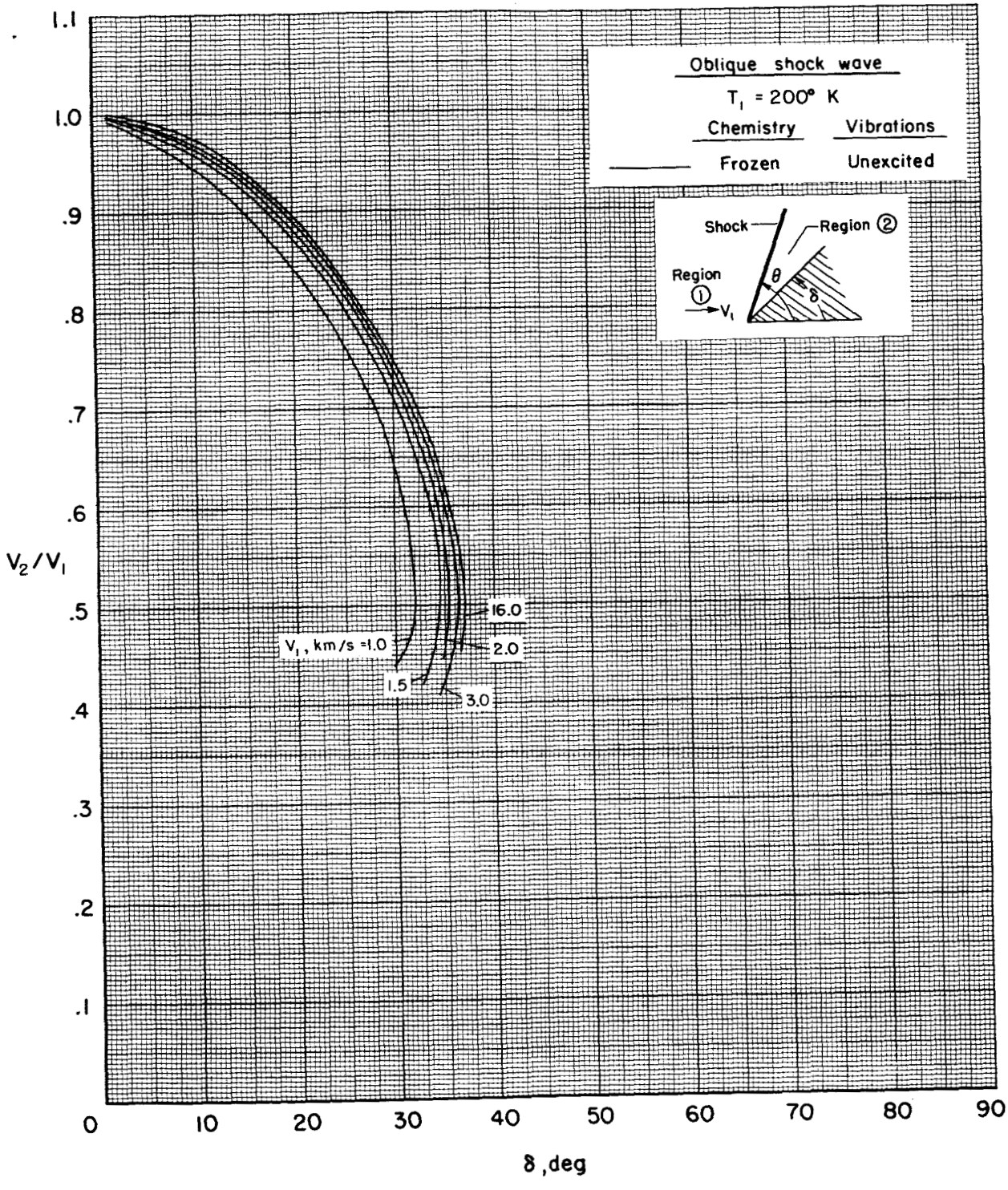
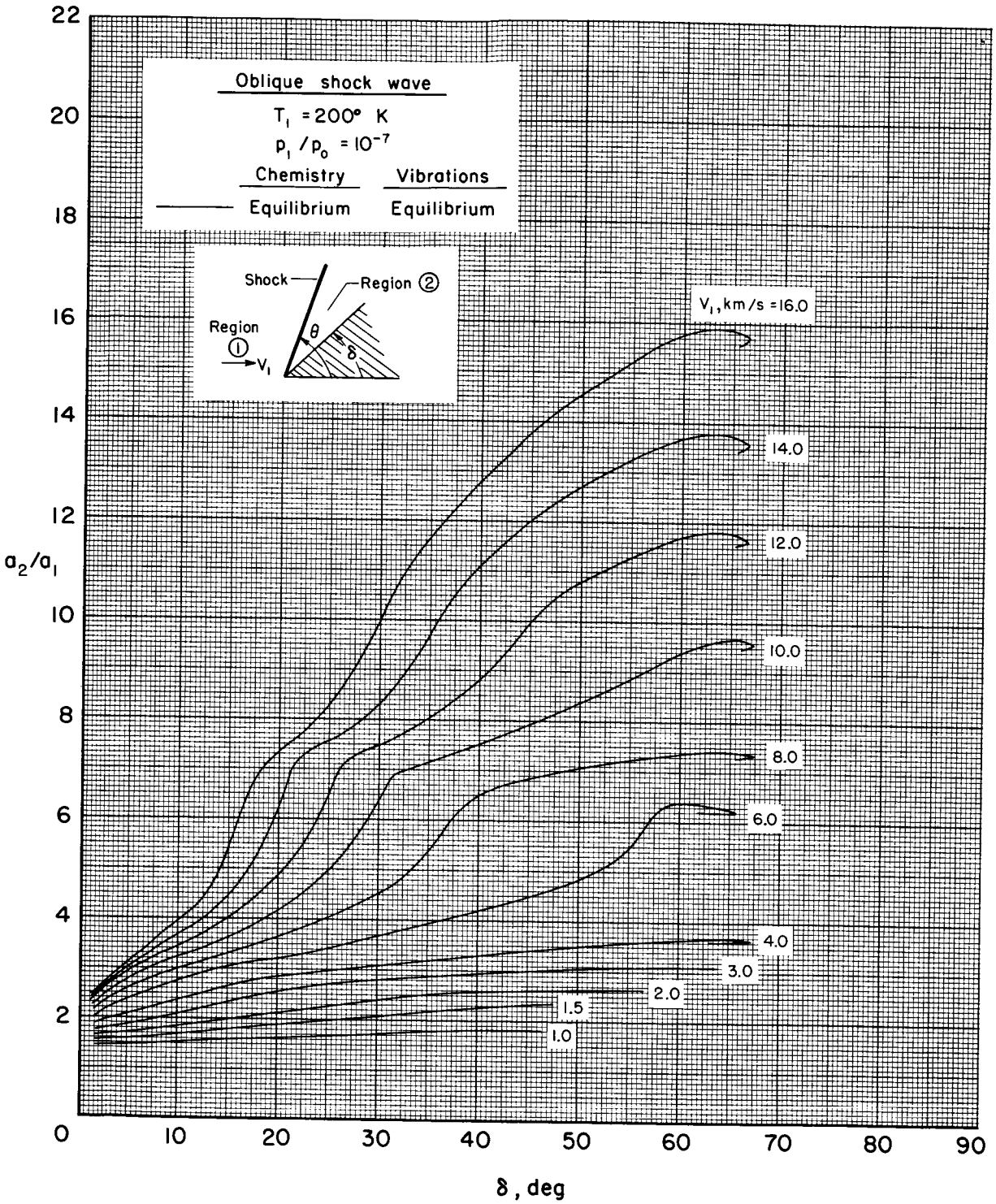
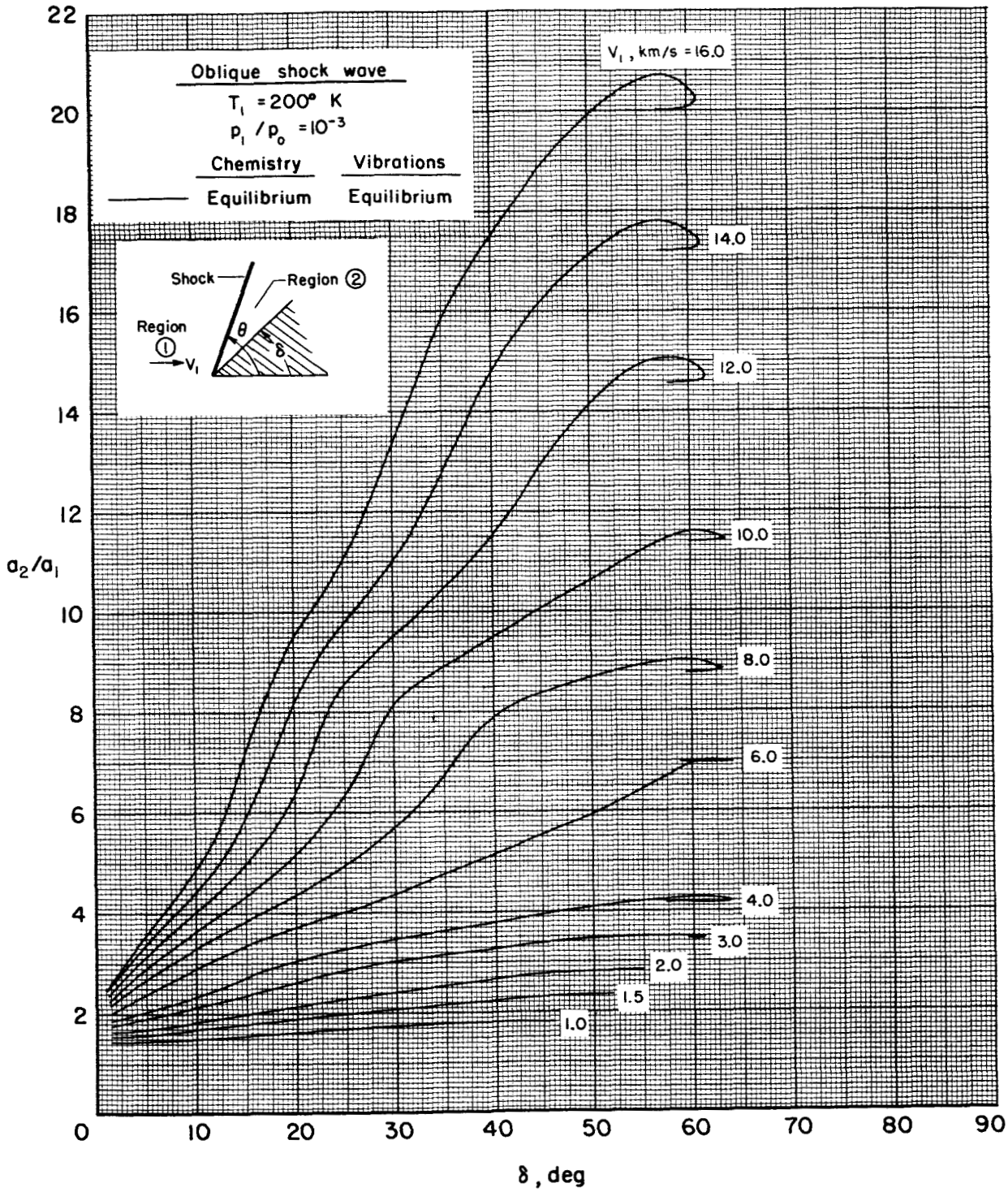


Chart 27. - Variation with wedge angle of the flow speed ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



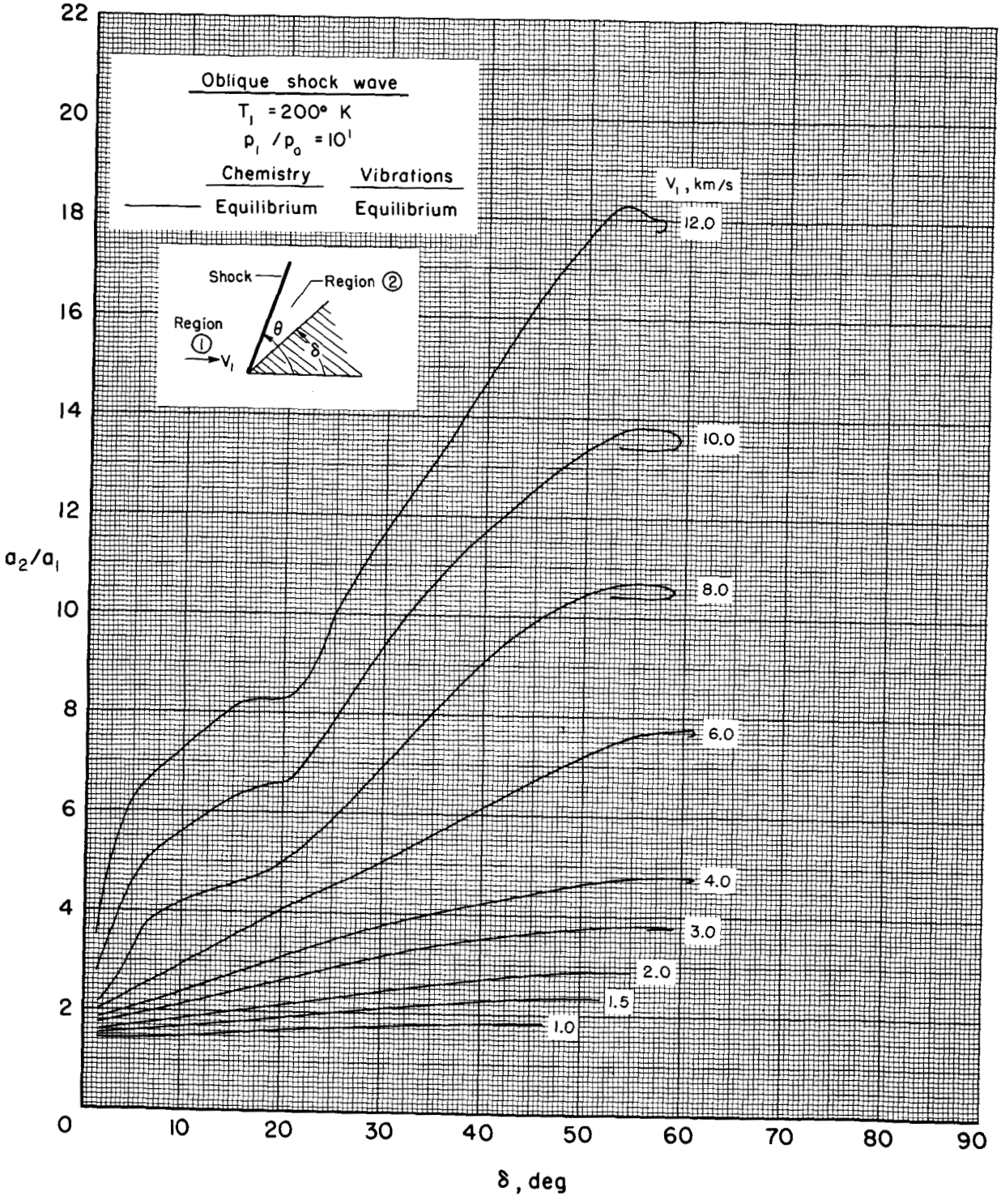
(a) $p_1/p_0 = 10^{-7}$

Chart 28. - Variation with wedge angle of the sound speed ratio across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_0 = 10^{-3}$

Chart 28. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 28. - Concluded.

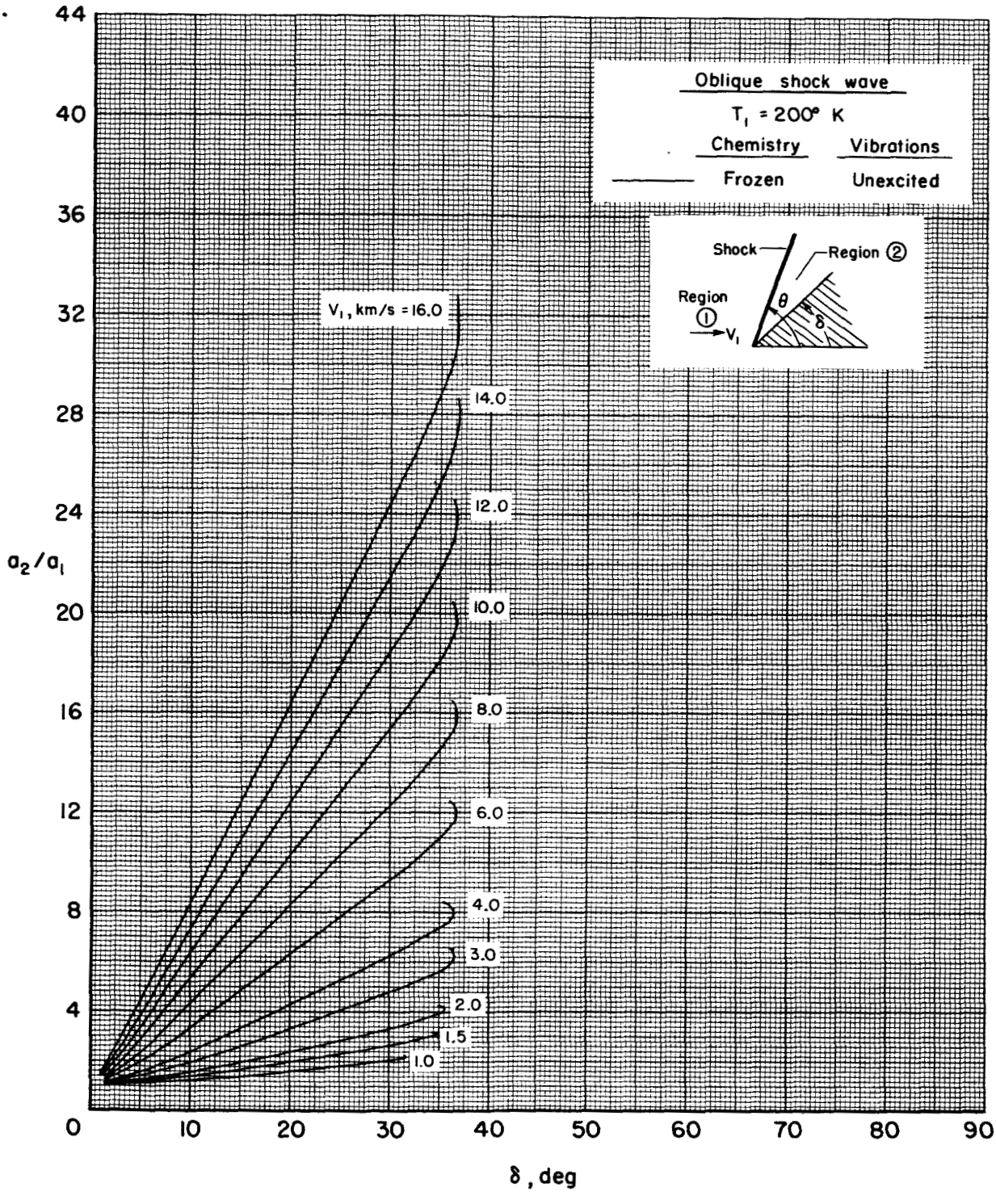
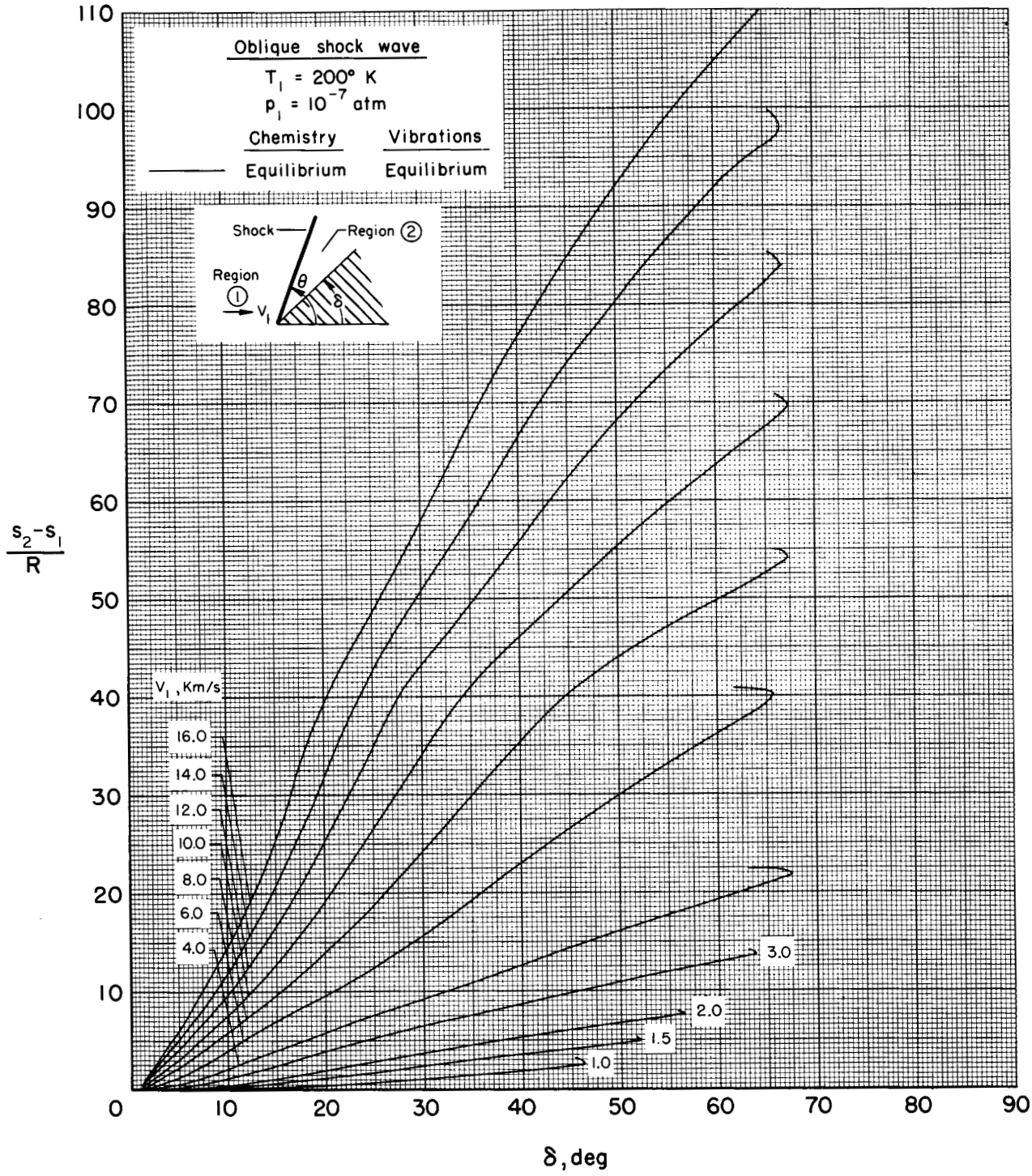
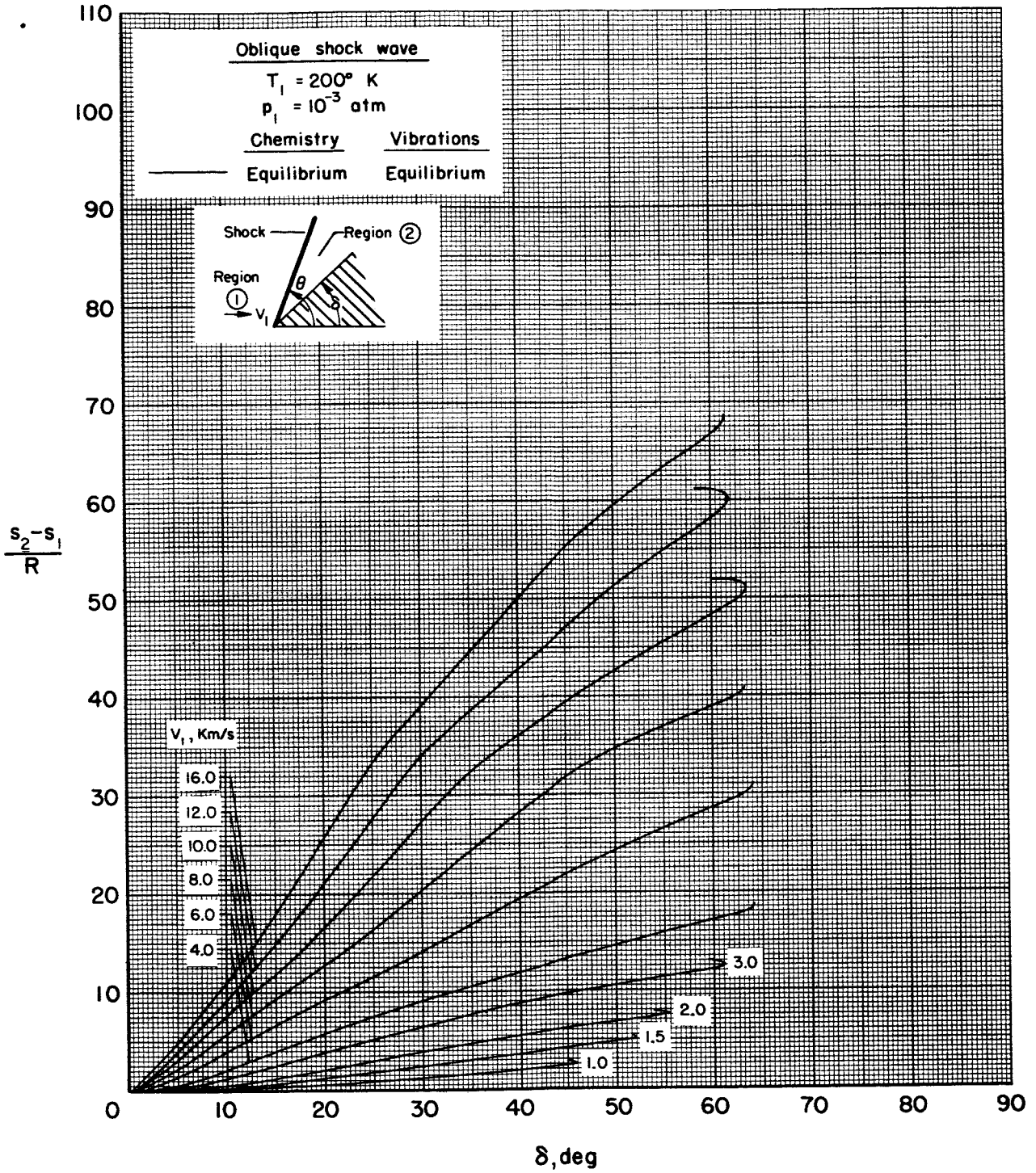


Chart 29. - Variation with wedge angle of the sound speed ratio across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.



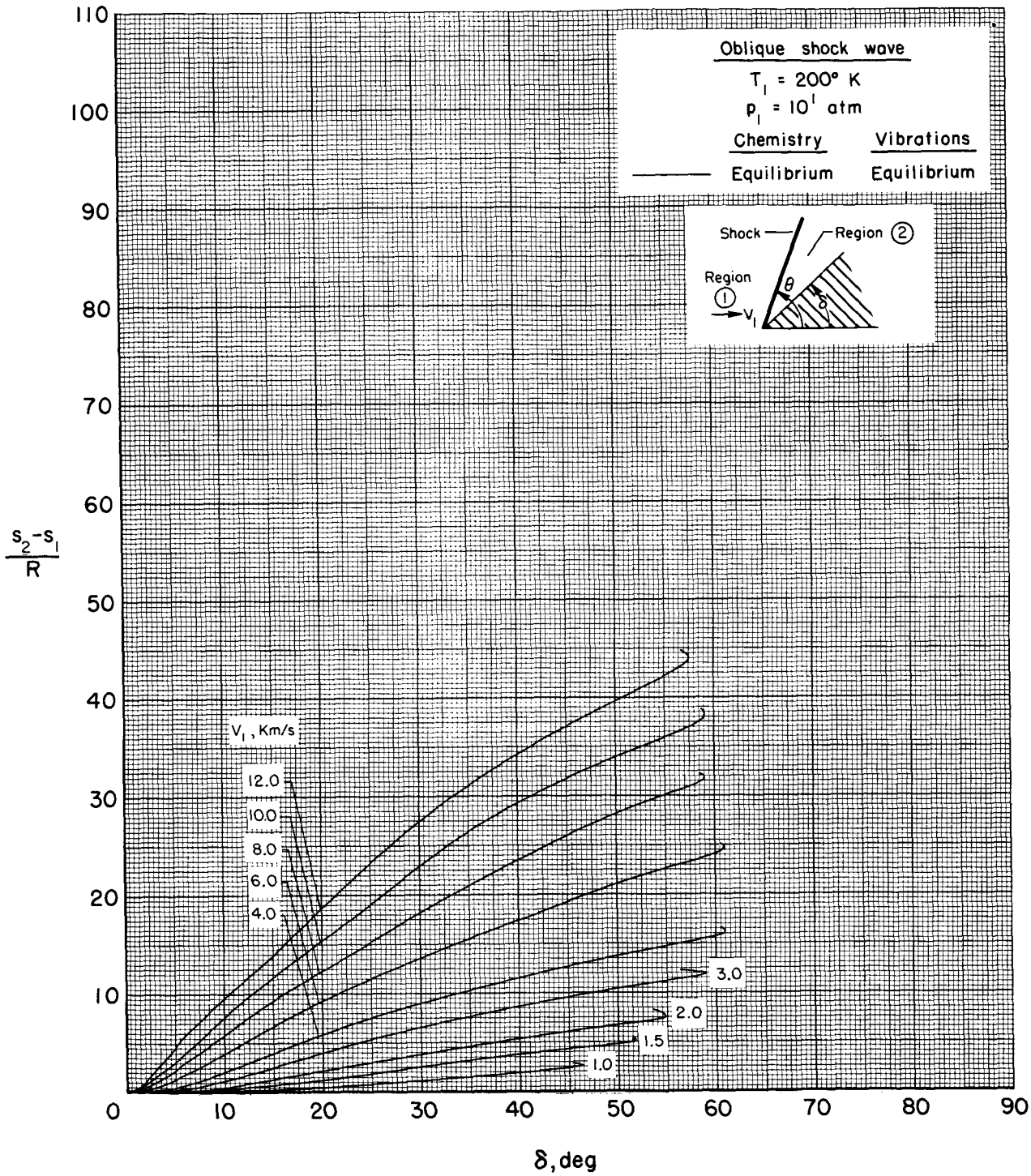
(a) $p_1/p_o = 10^{-7}$

Chart 30. - Variation with wedge angle of the entropy change across an oblique shock wave. Chemistry and vibrations in equilibrium.



(b) $p_1/p_o = 10^{-3}$

Chart 30. - Continued.



(c) $p_1/p_o = 10^1$

Chart 30. - Concluded.

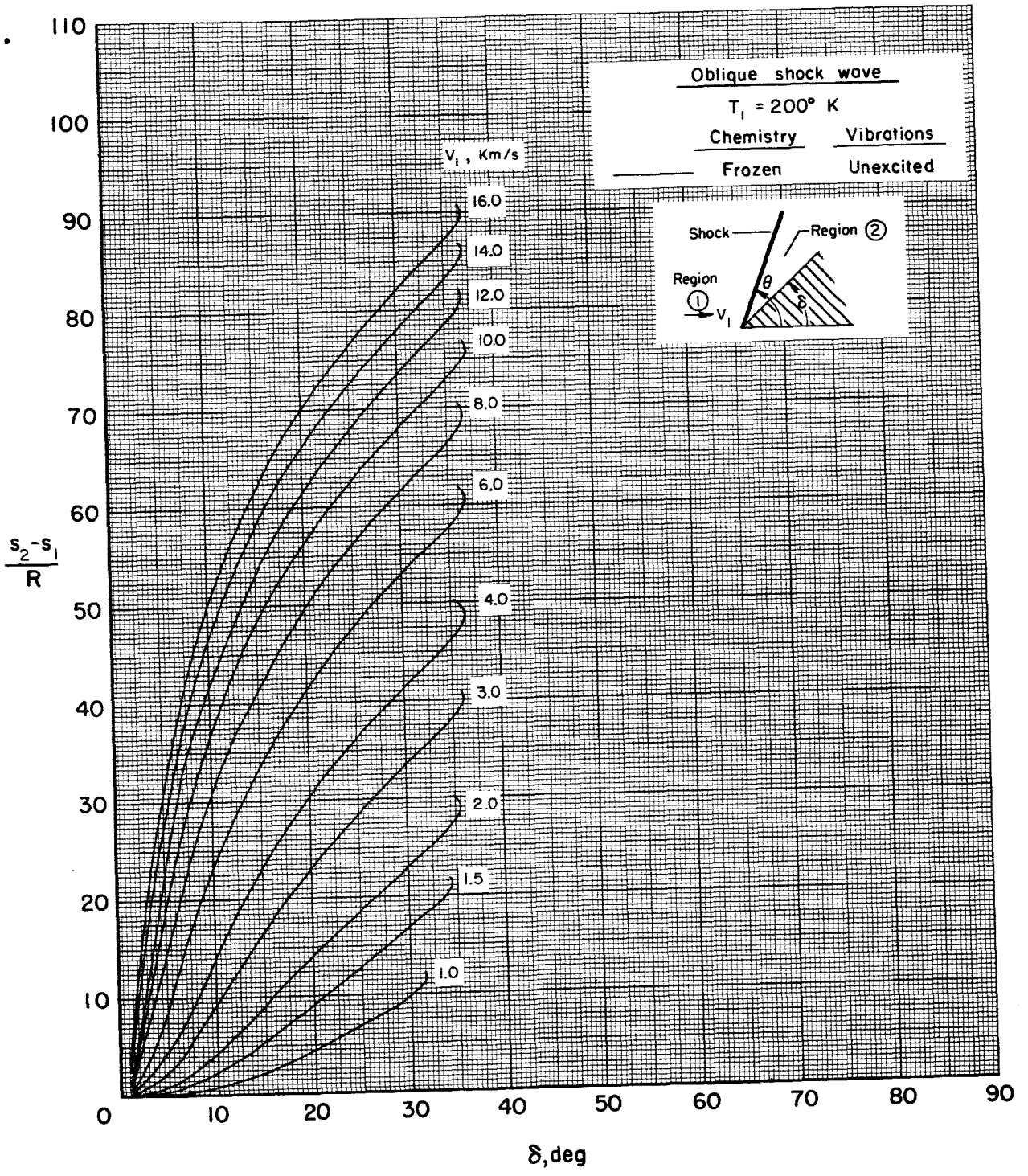


Chart 31. - Variation with wedge angle of the entropy change across an oblique shock wave. Chemistry frozen (molecular CO_2) and vibrations unexcited.

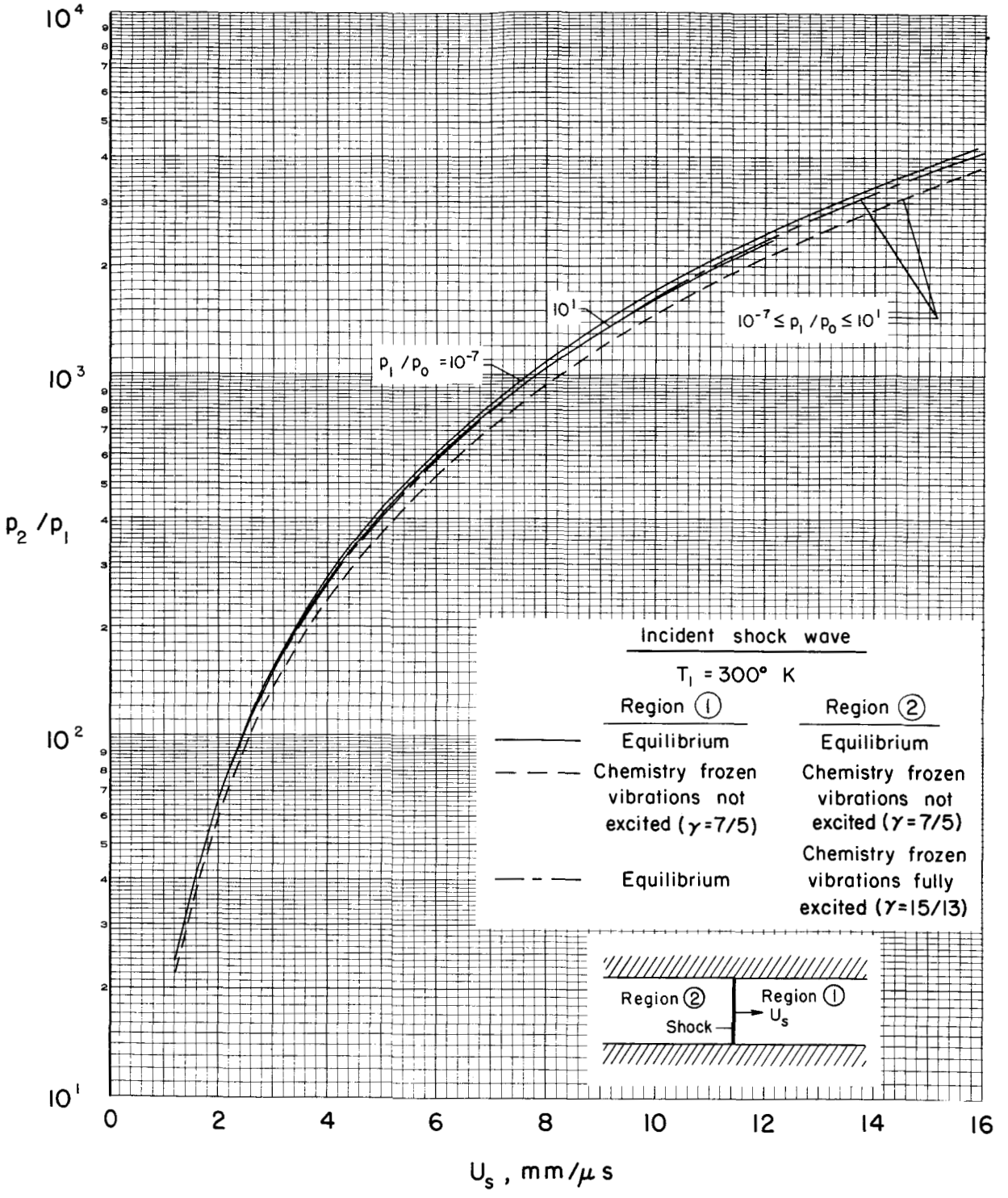


Chart 32. - Variation with shock wave speed of the static pressure ratio across an incident shock wave.

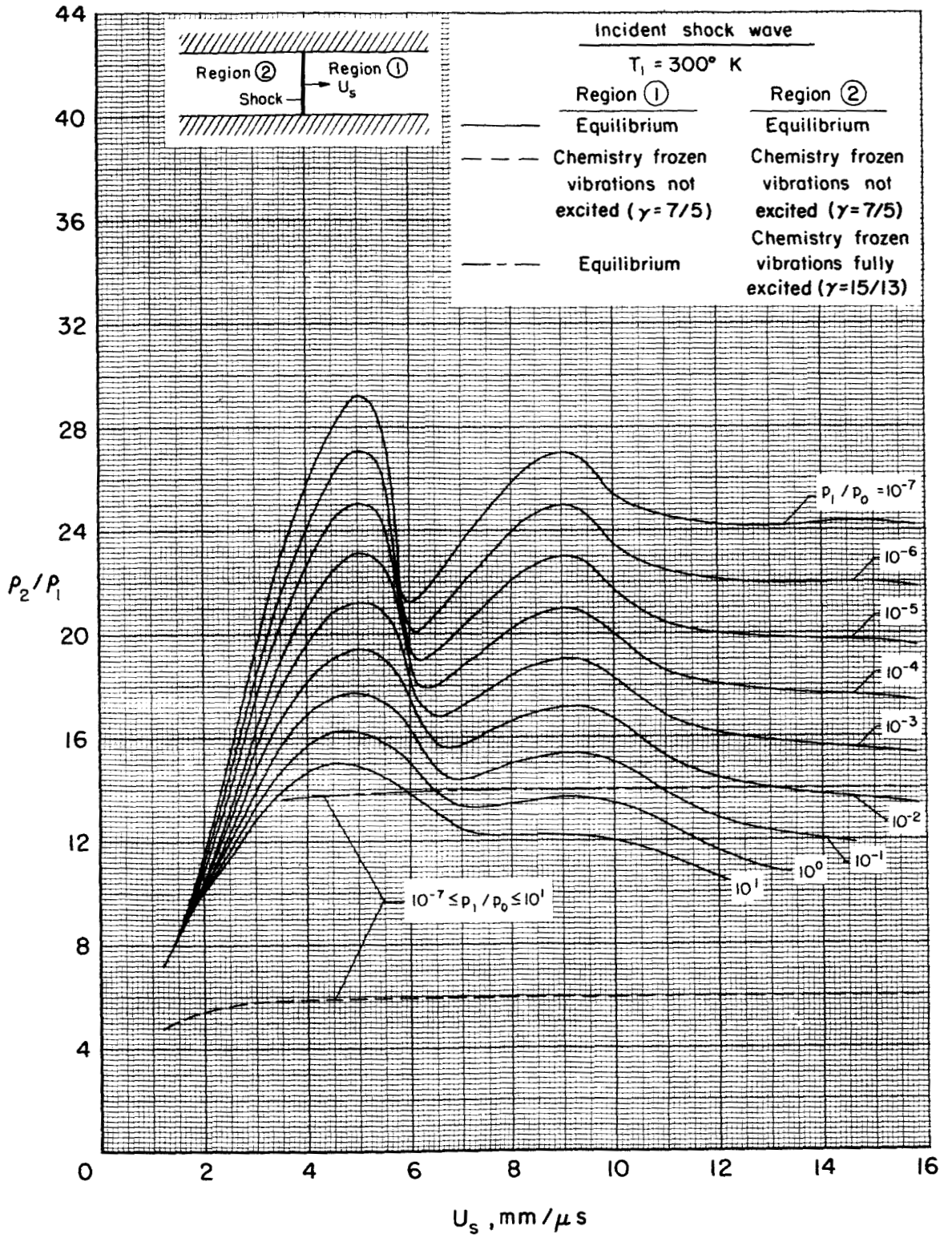


Chart 33. - Variation with shock wave speed of the static density ratio across an incident shock wave.

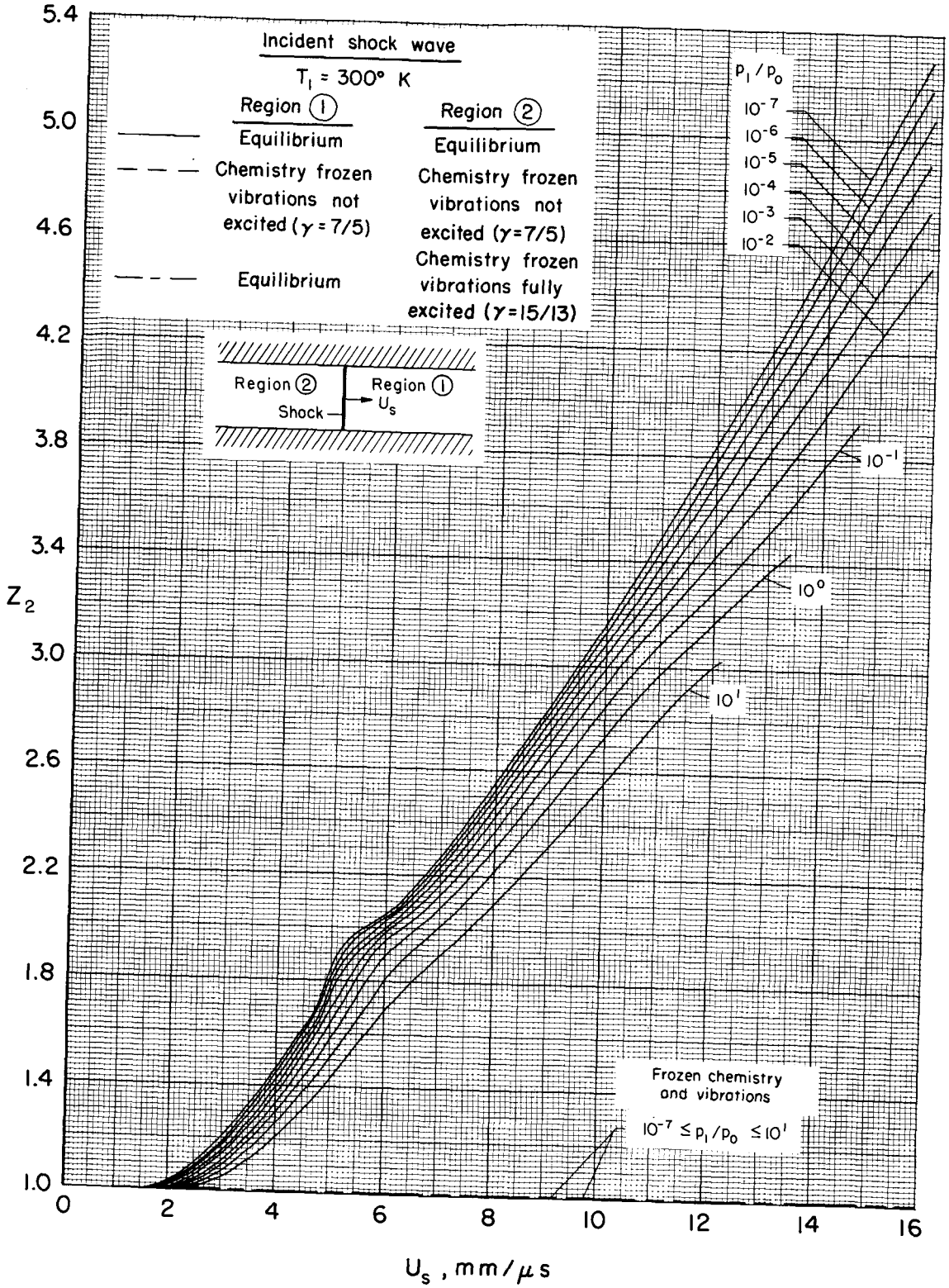


Chart 34. - Variation with shock wave speed of compressibility factor downstream of an incident shock wave.

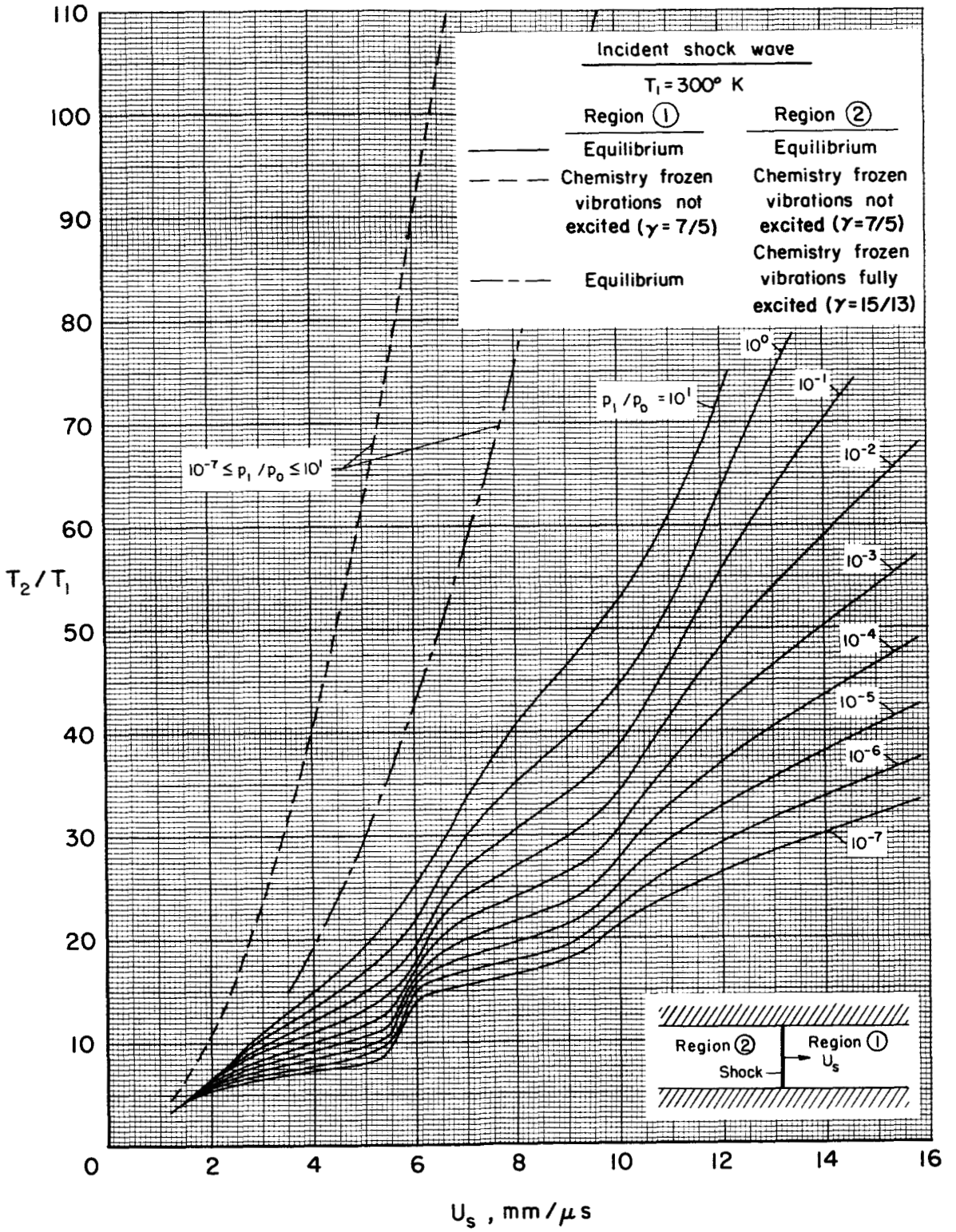


Chart 35. - Variation with shock wave speed of the static temperature ratio across an incident shock wave.

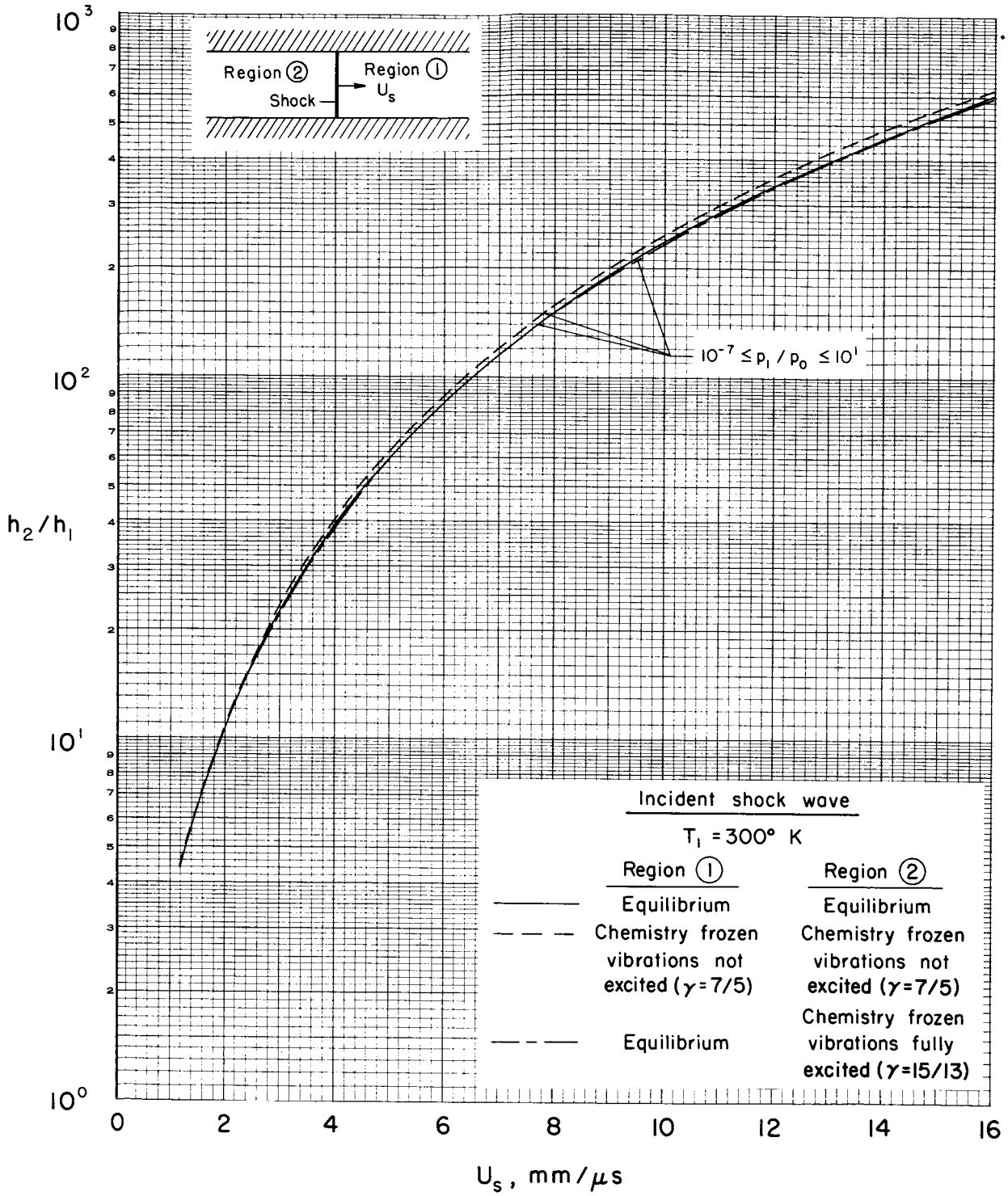


Chart 36. - Variation with shock wave speed of the static enthalpy ratio across an incident shock wave.

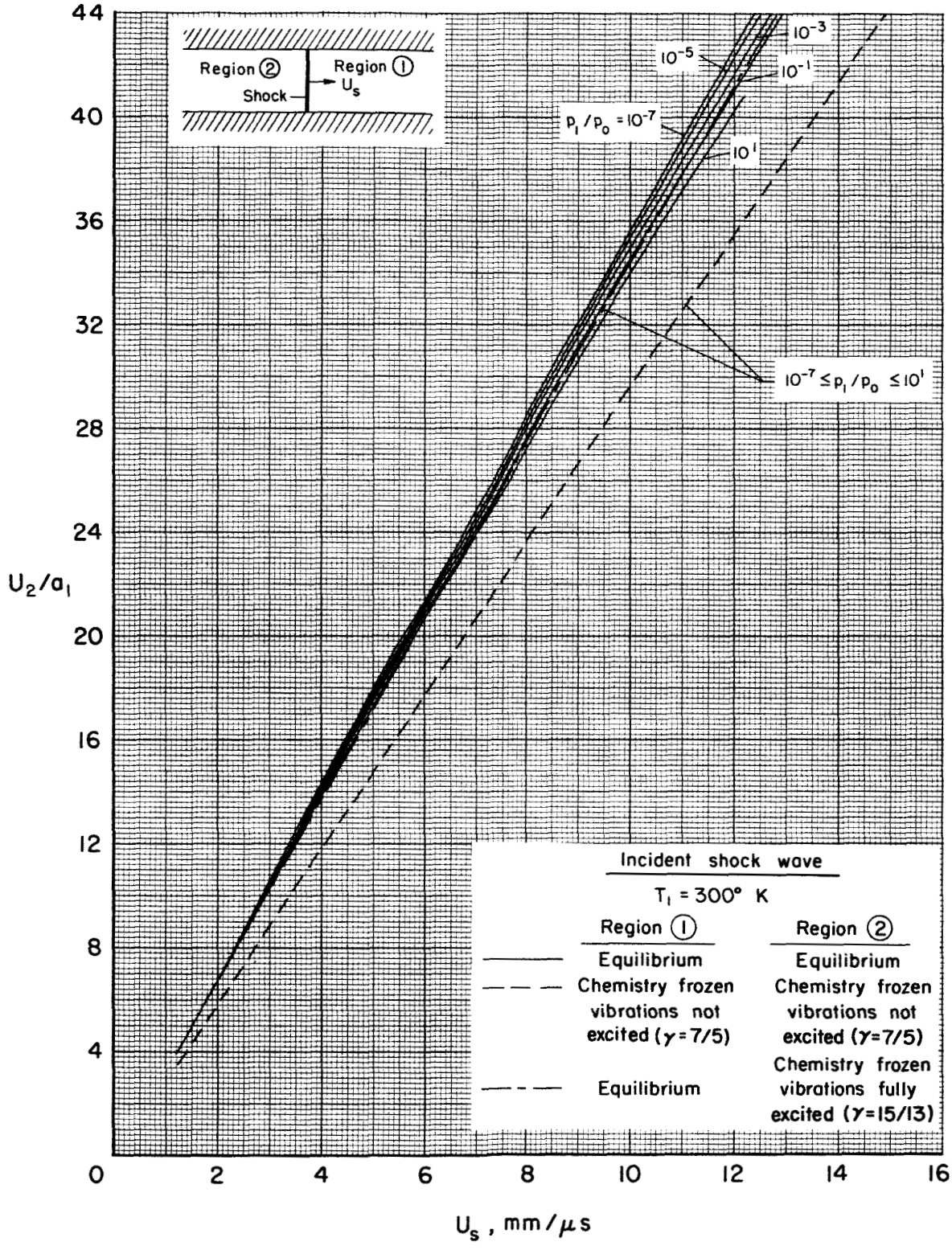


Chart 37. - Variation with shock wave speed of the flow speed ratio across an incident shock wave.

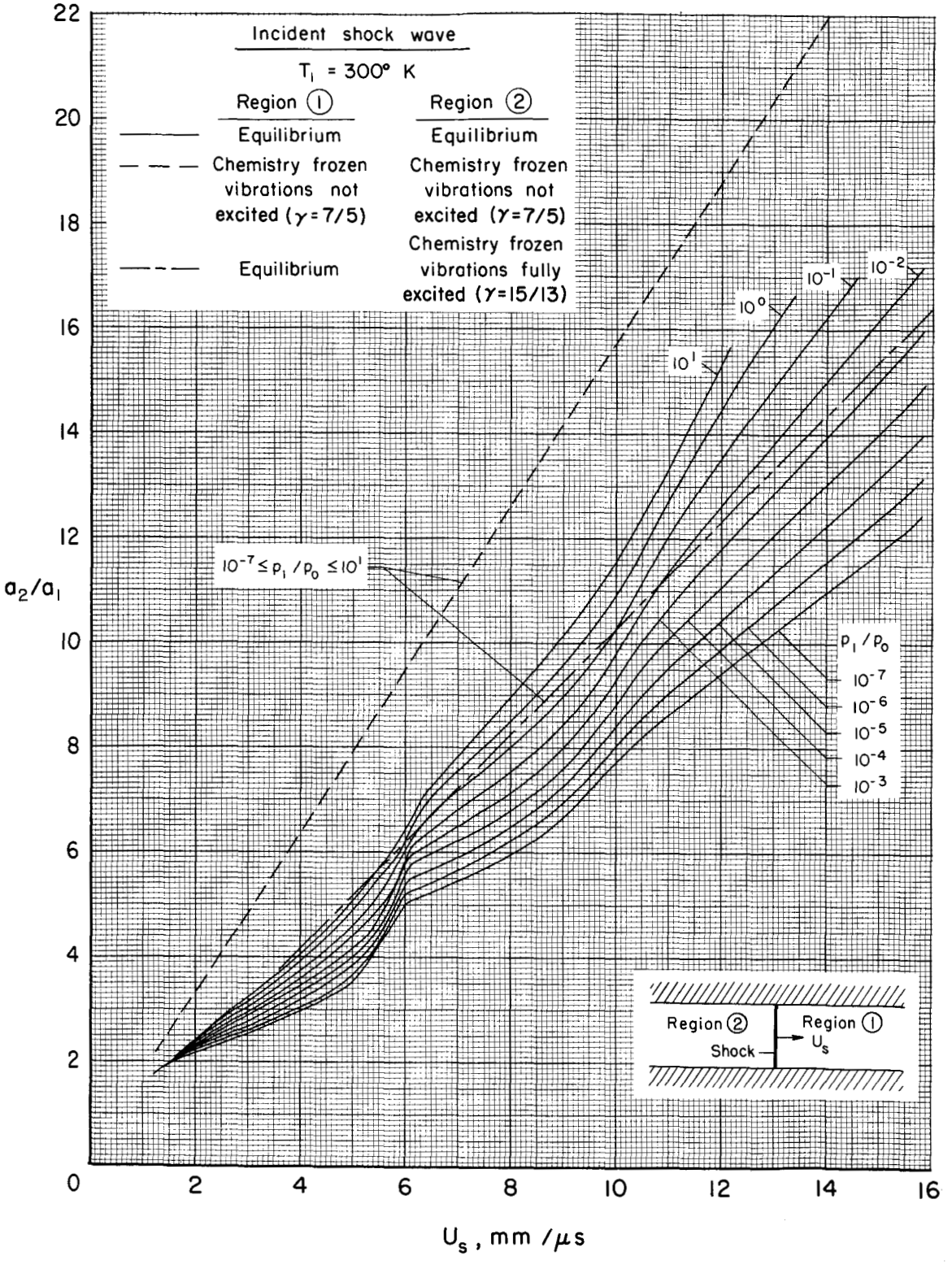


Chart 38. - Variation with shock wave speed of the sound speed ratio across an incident shock wave.

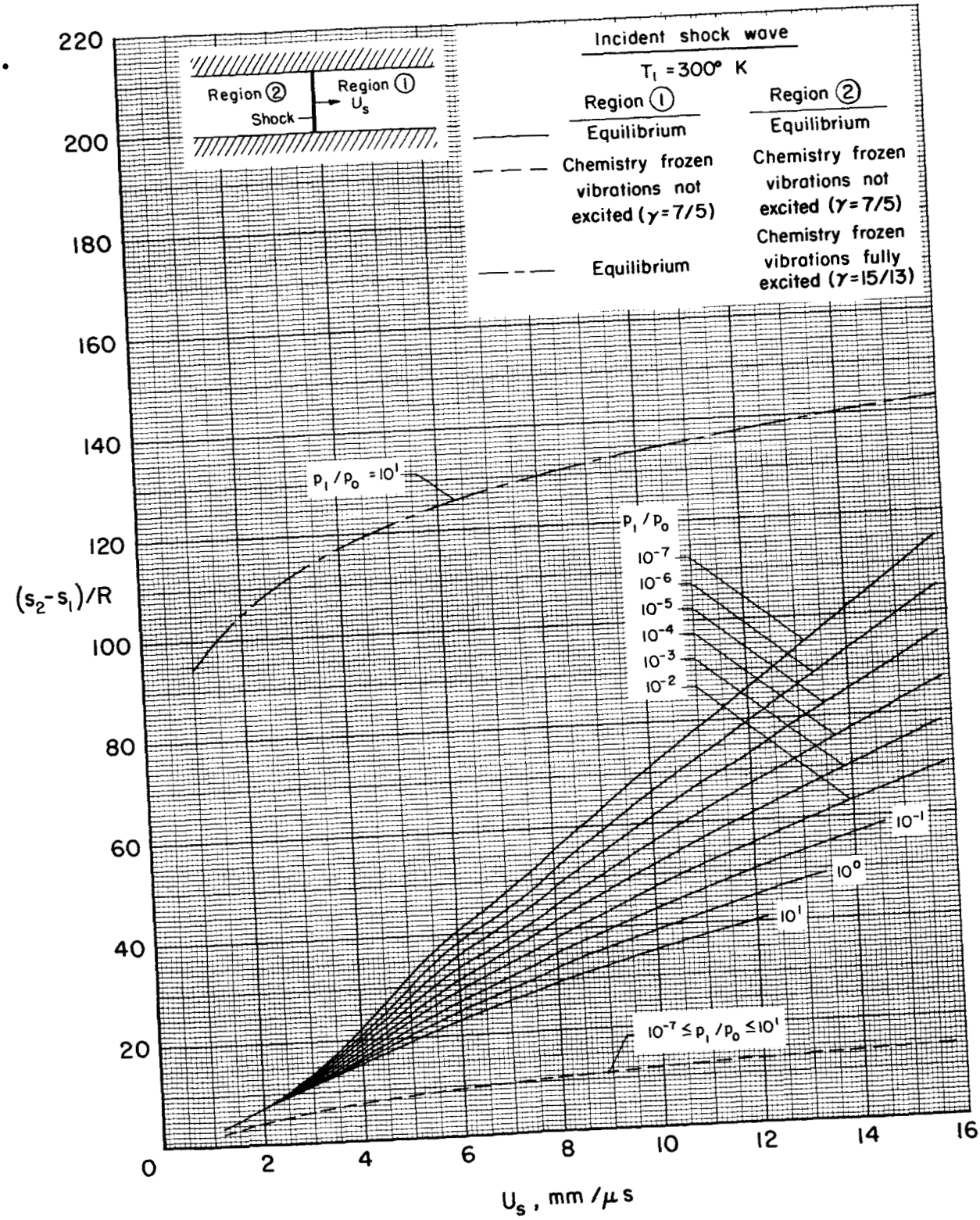
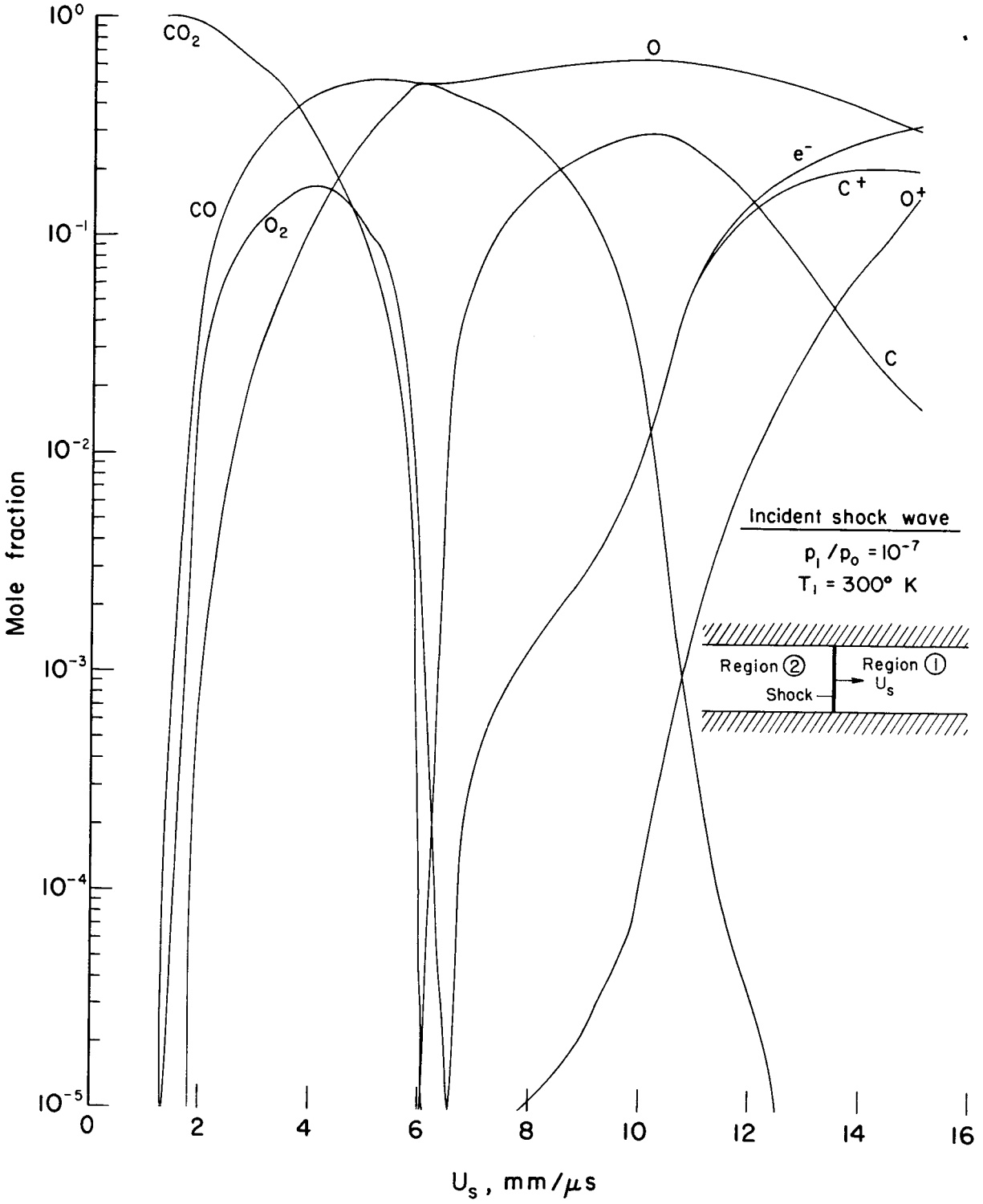
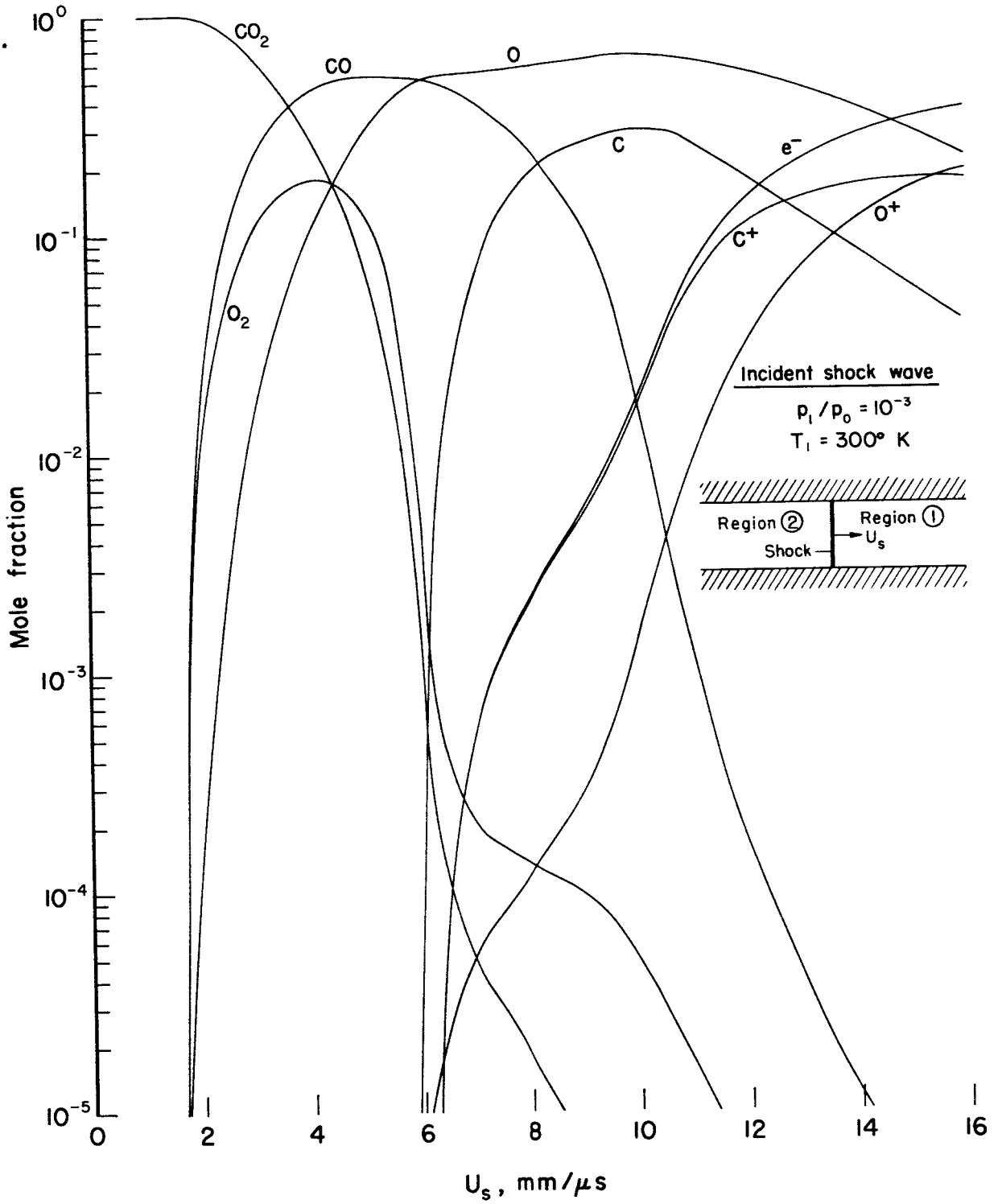


Chart 39. - Variation with shock wave speed of the entropy change across an incident shock wave.



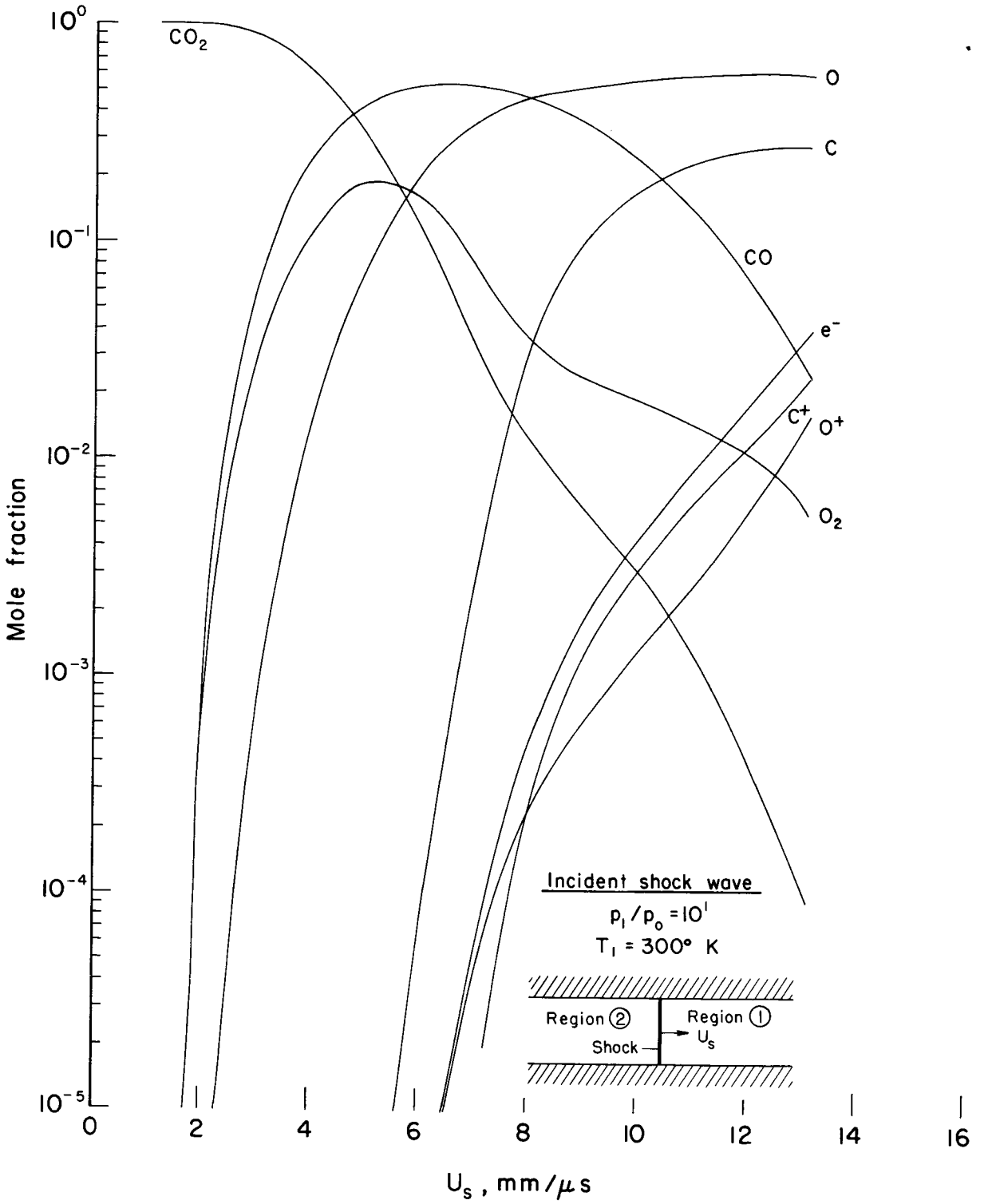
(a) $p_1/p_0 = 10^{-7}$

Chart 40. - Variation with shock wave speed of equilibrium flow chemistry downstream of an incident shock wave.



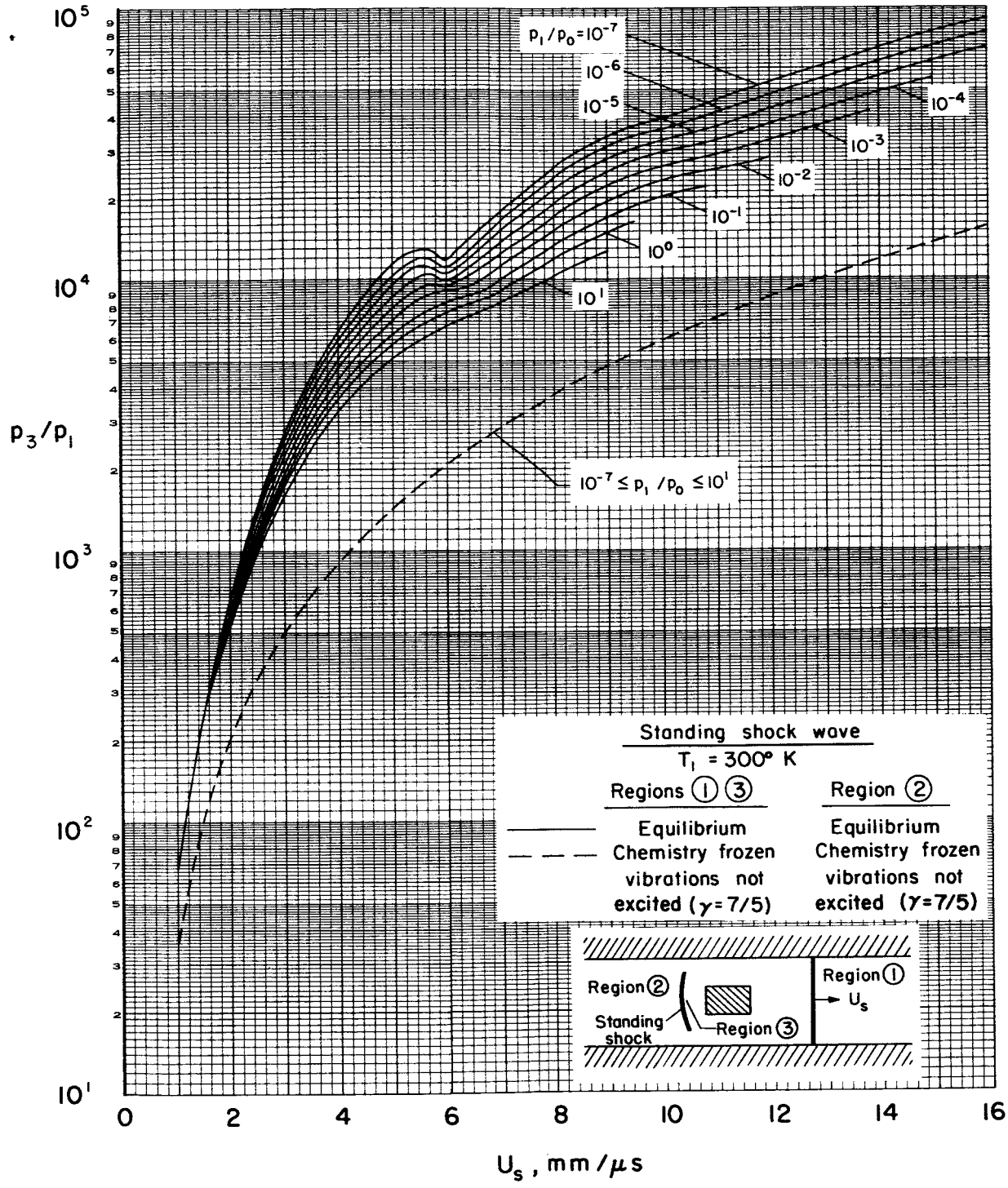
(b) $p_1/p_0 = 10^{-3}$

Chart 40. - Continued.



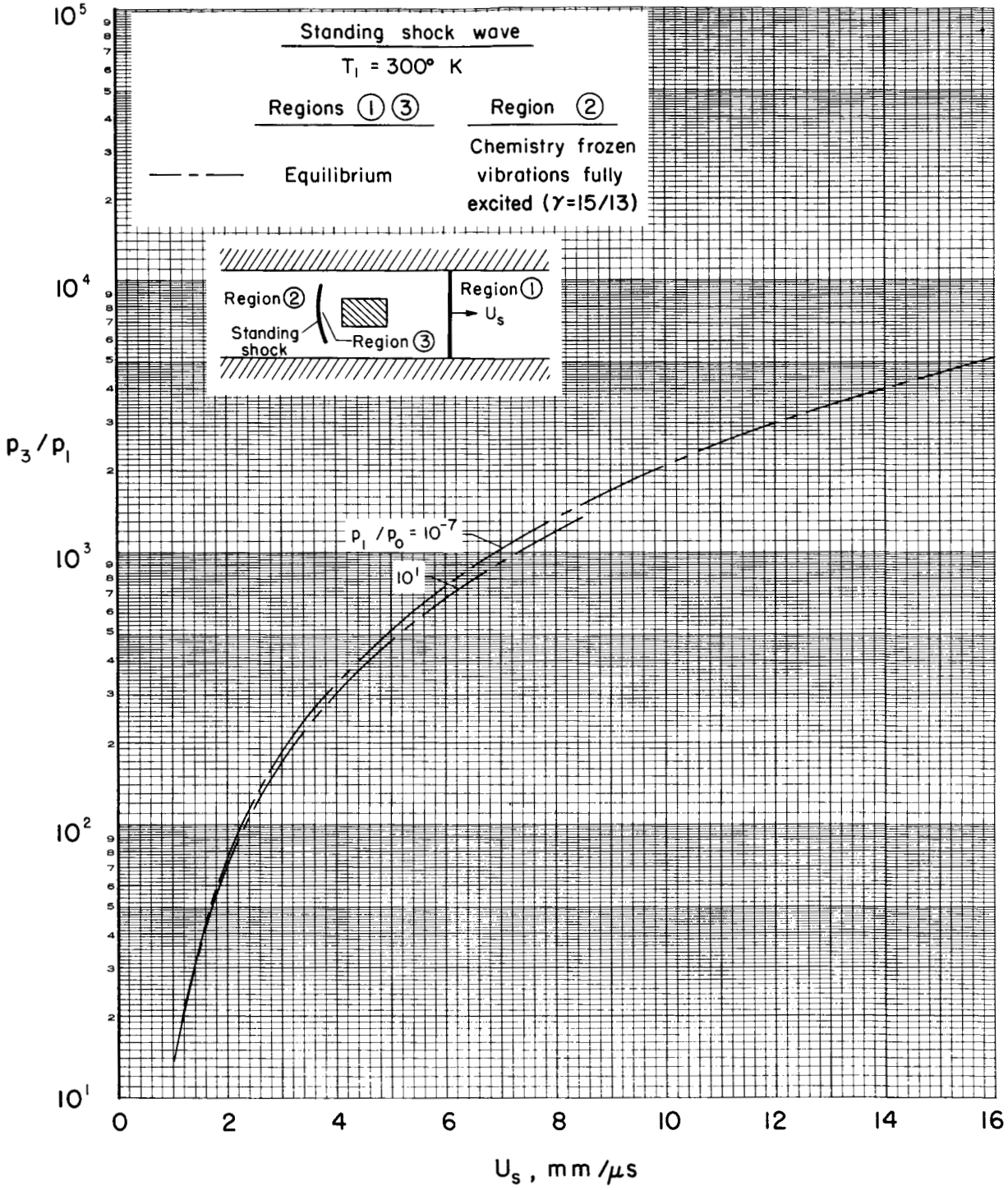
(c) $p_1/p_0 = 10^1$

Chart 40. - Concluded.



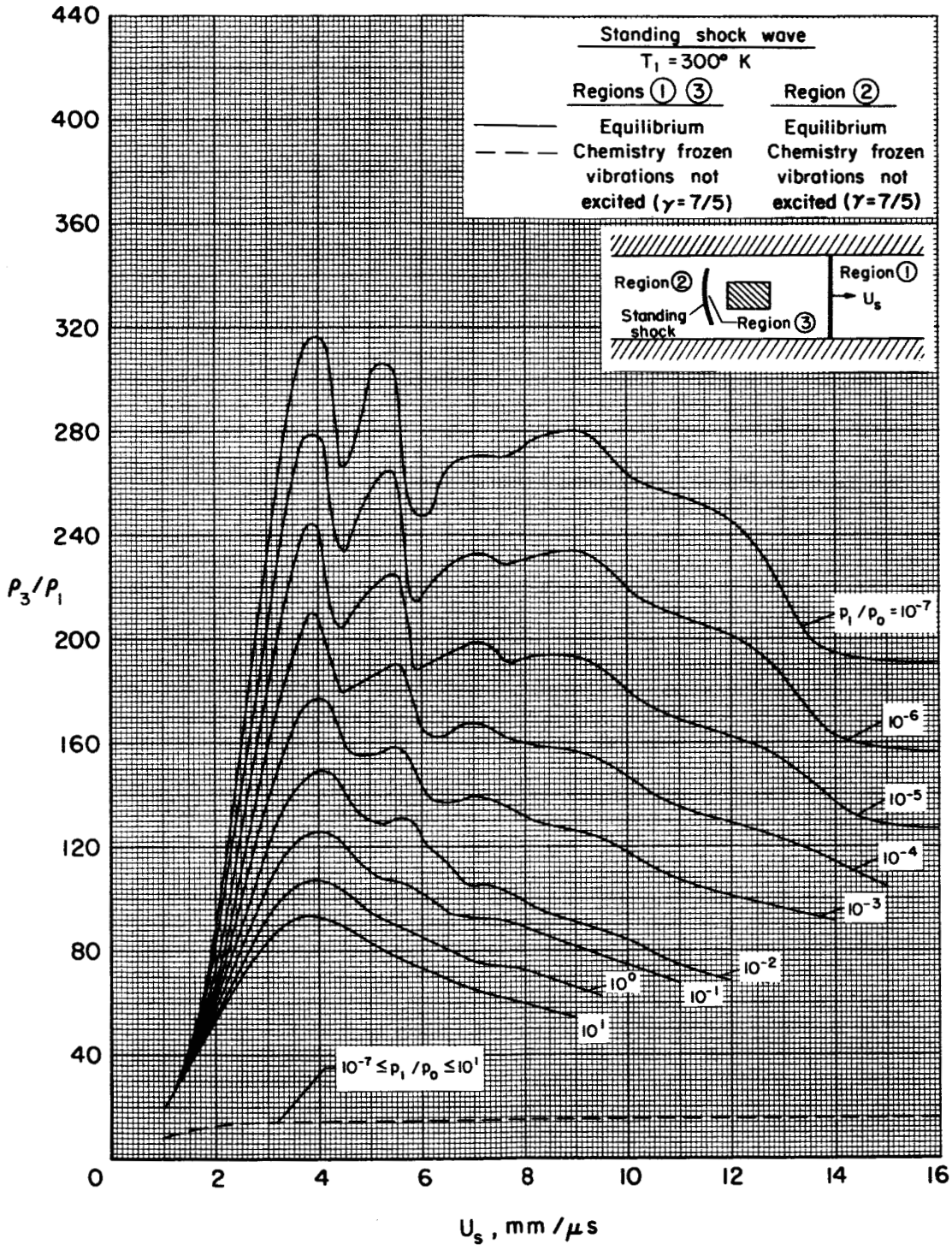
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 41. - Variation with incident shock wave speed of static pressure ratio across a standing shock wave.



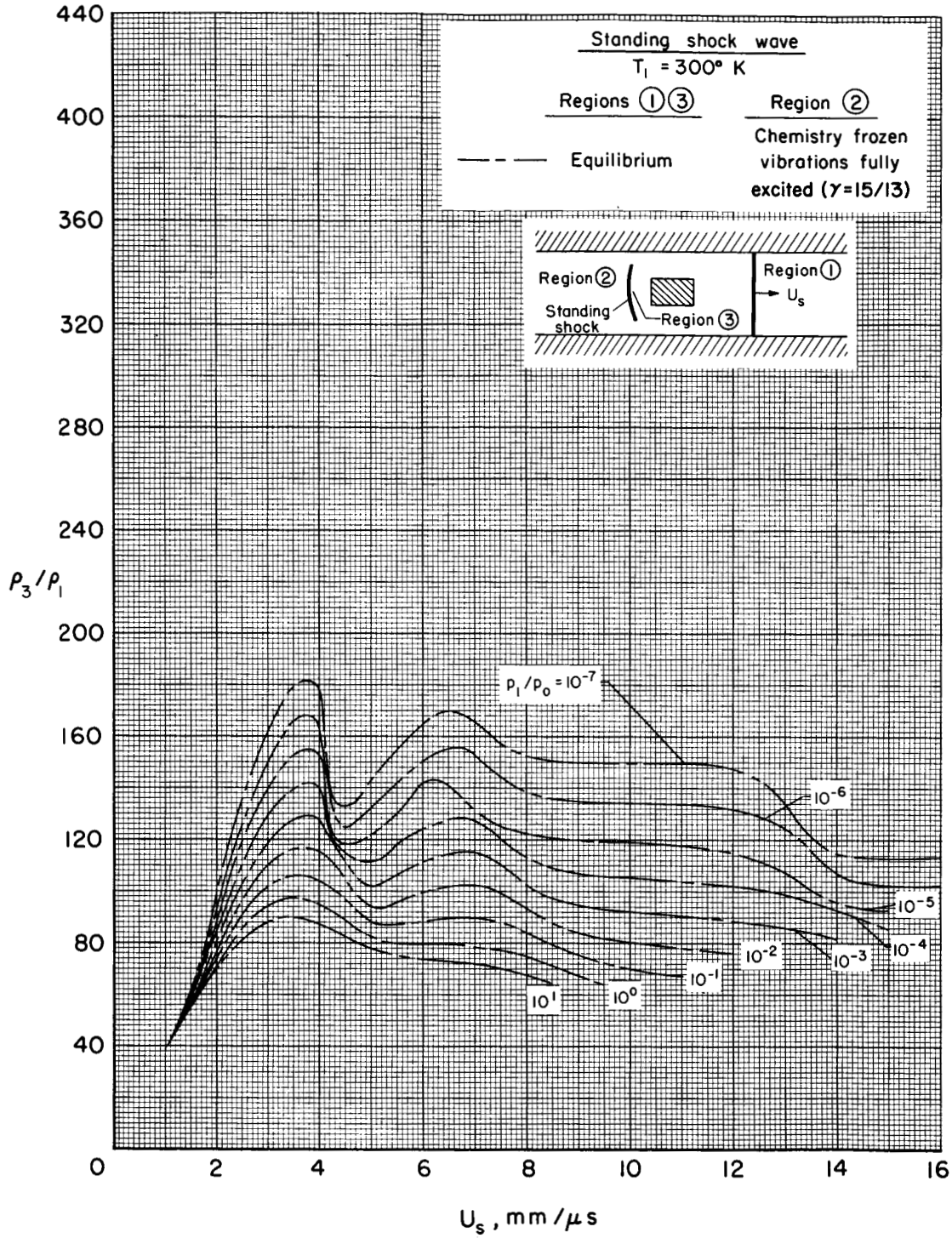
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 41. - Concluded.



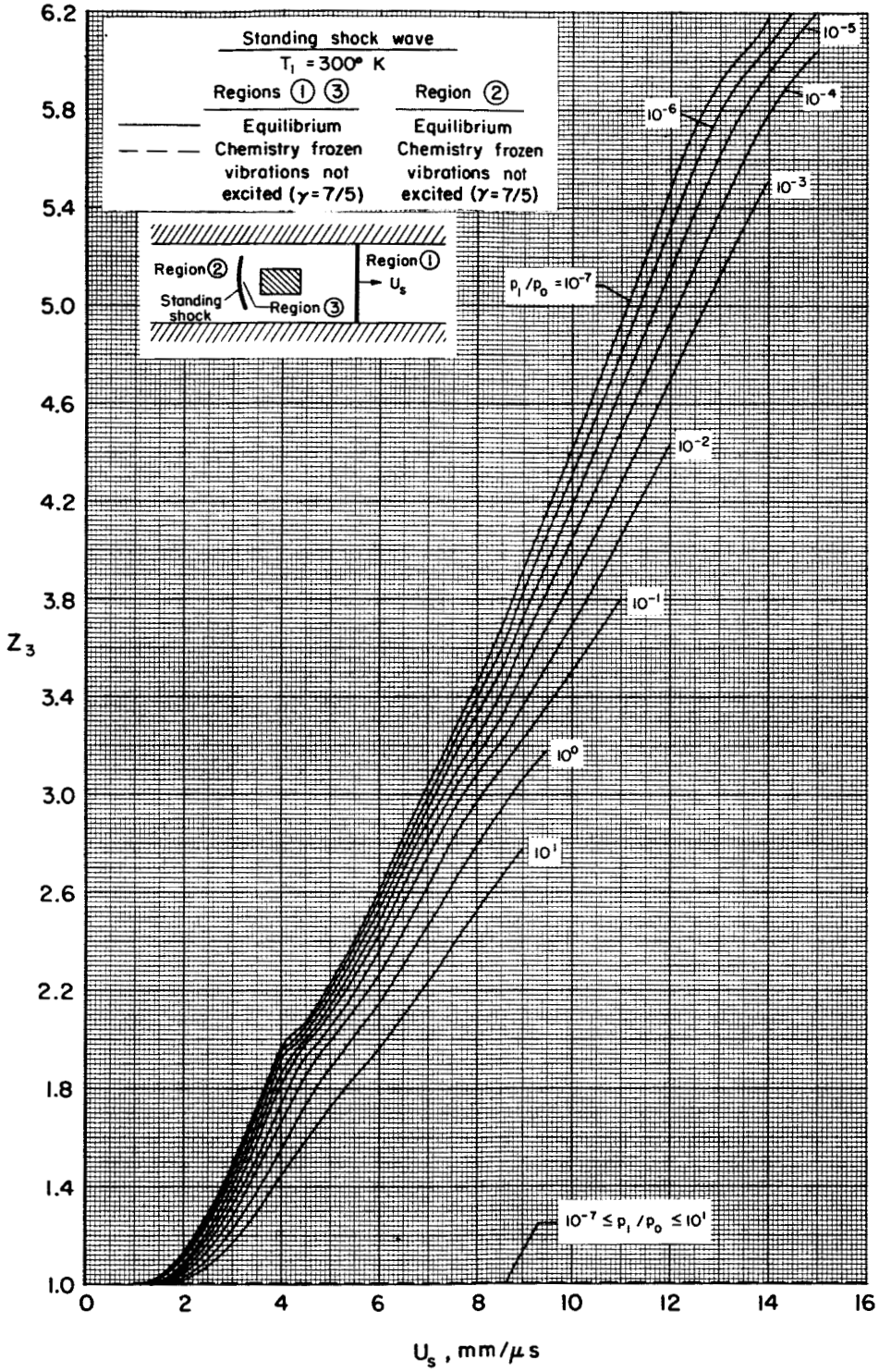
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 42. - Variation with incident shock wave speed of static density ratio across a standing shock wave.



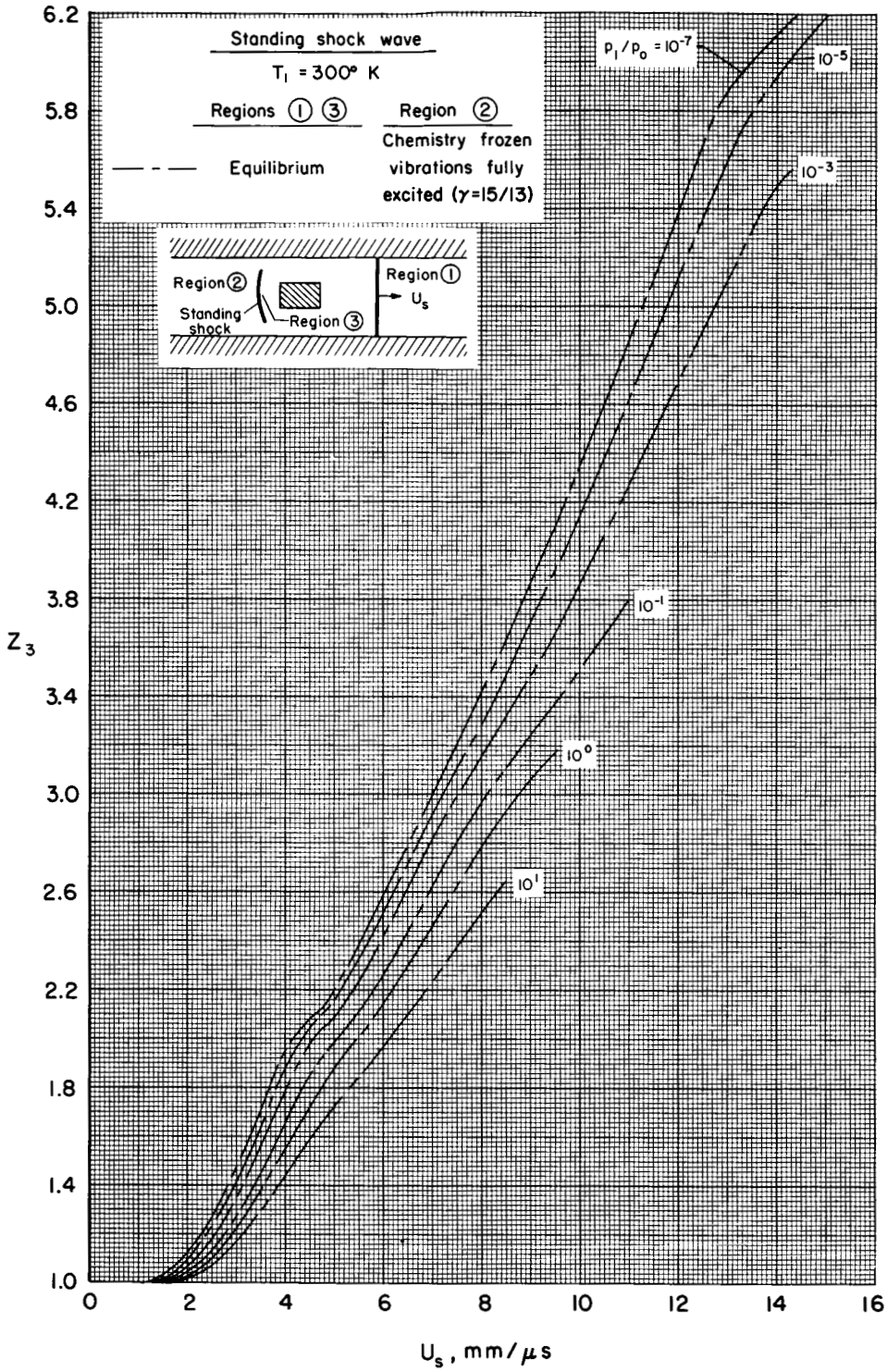
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 42. - Concluded.



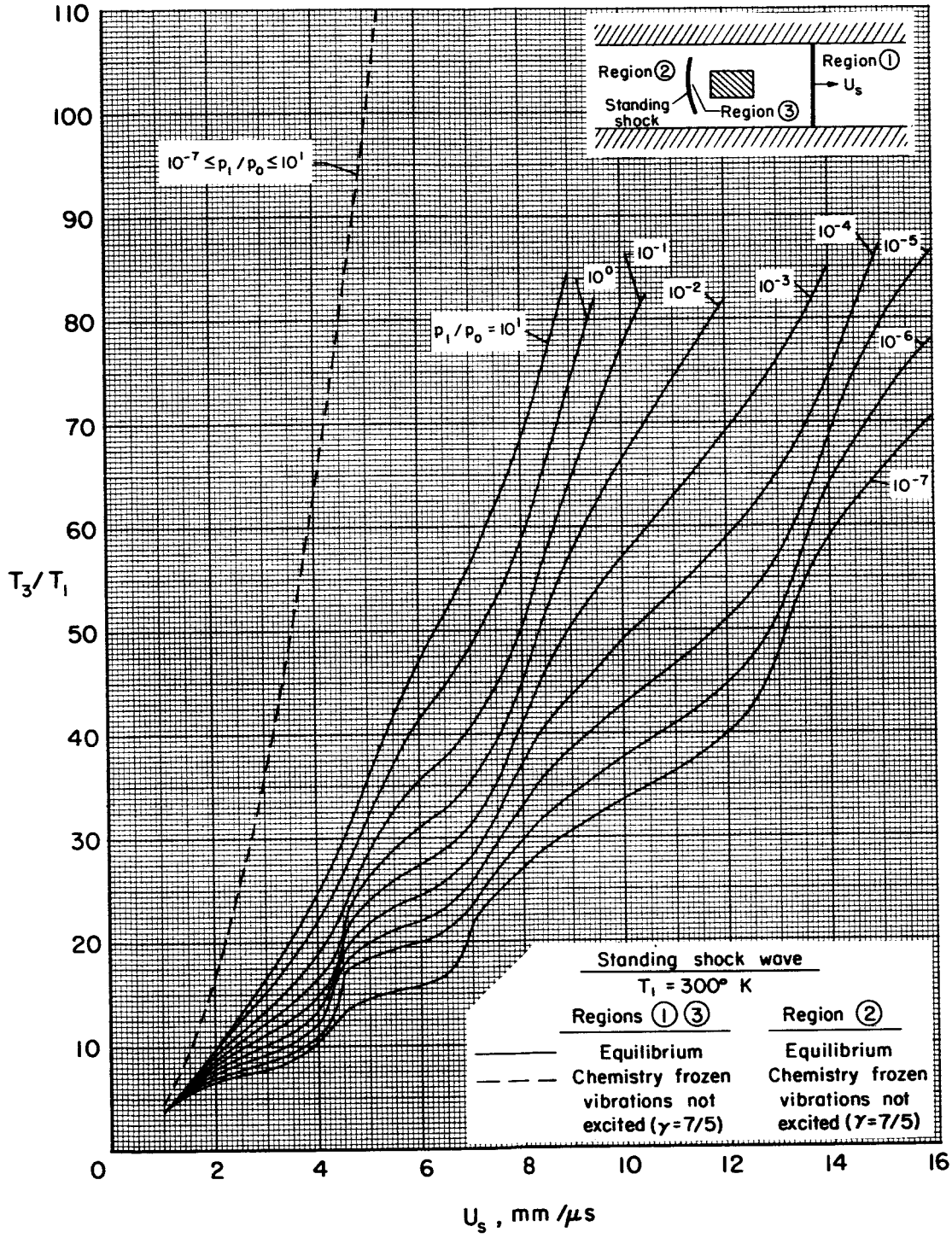
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 43. - Variation with incident shock wave speed of compressibility factor downstream of a standing shock wave.



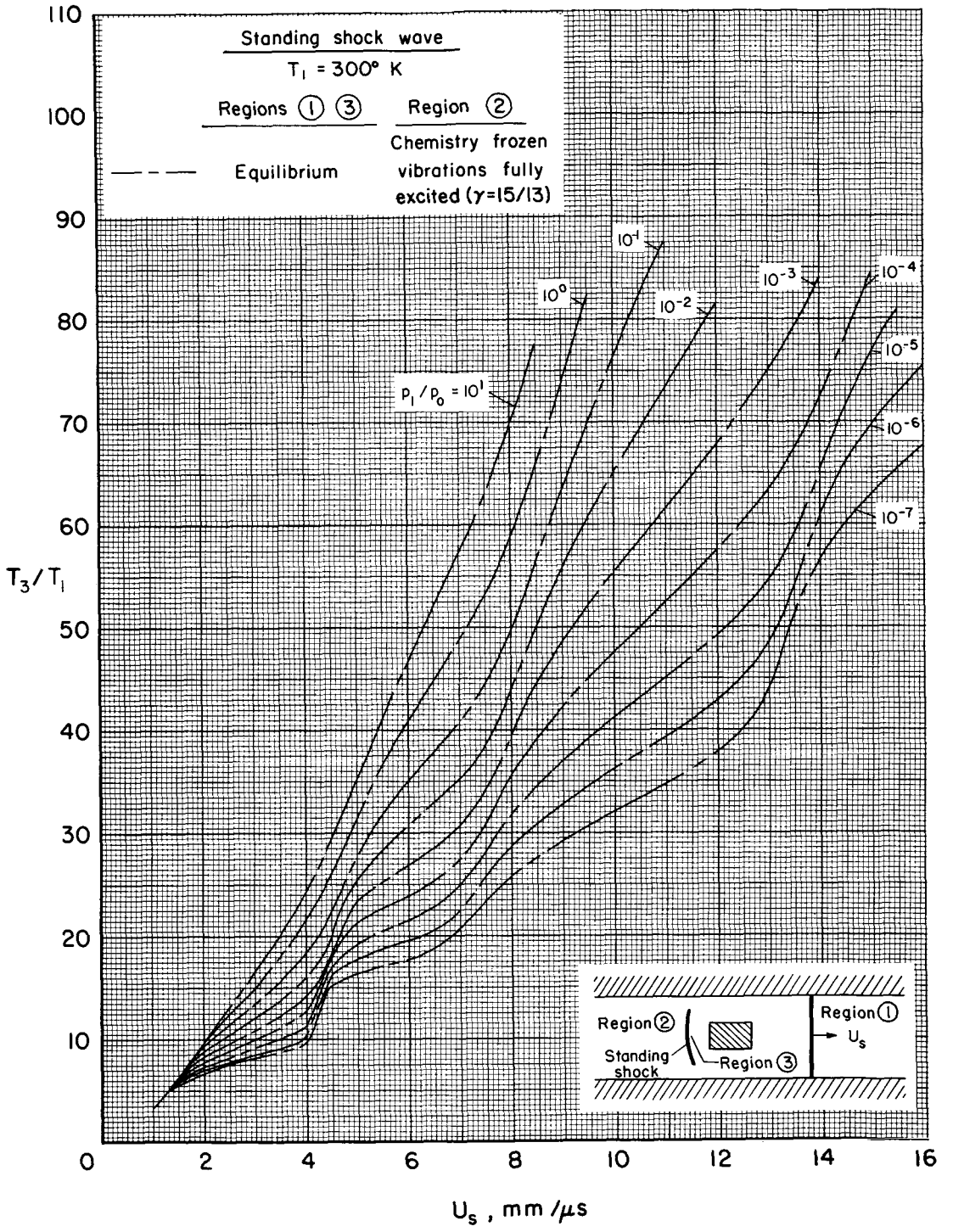
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 43. - Concluded.



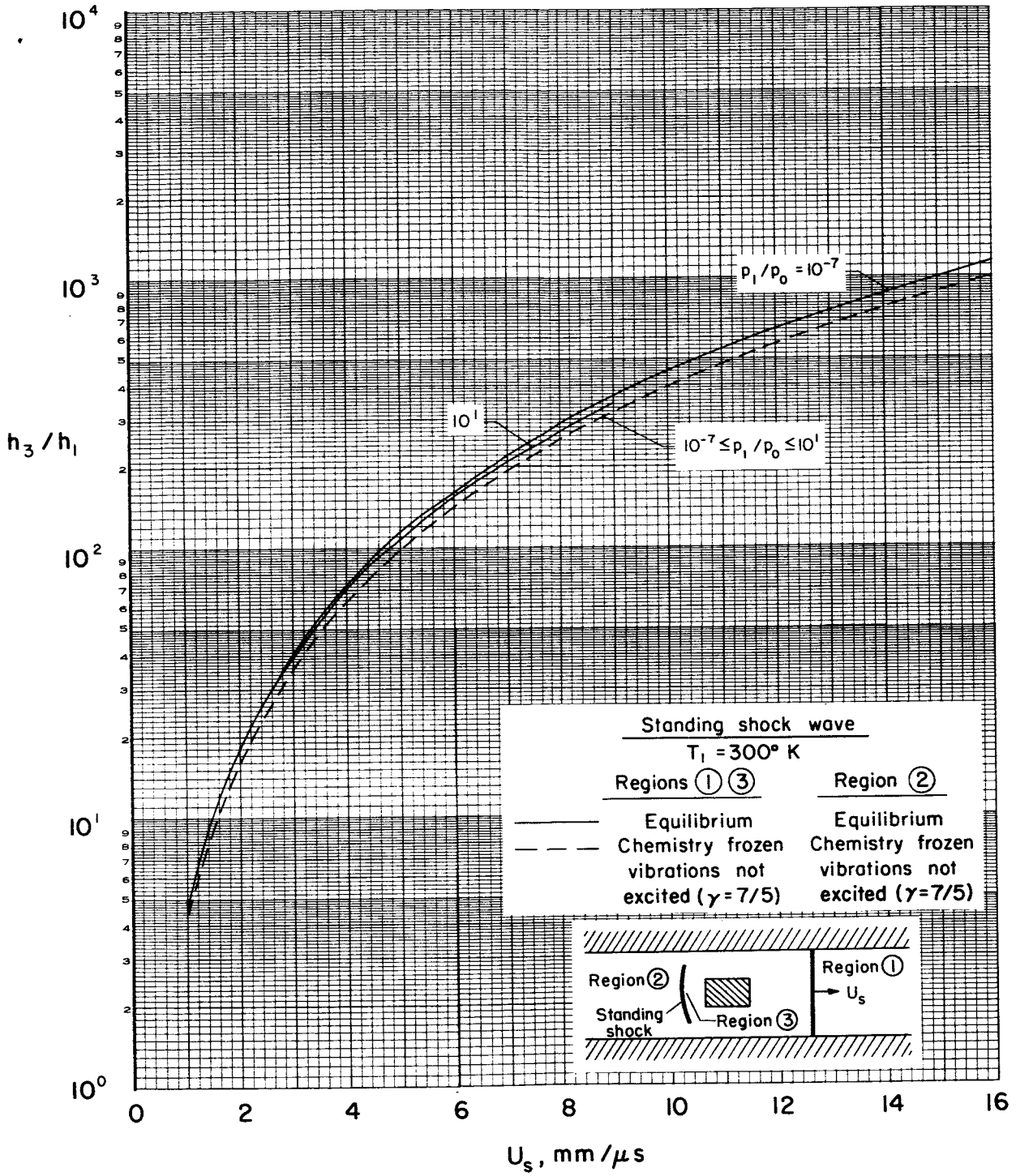
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 44. - Variation with incident shock wave speed of static temperature ratio across a standing shock wave.



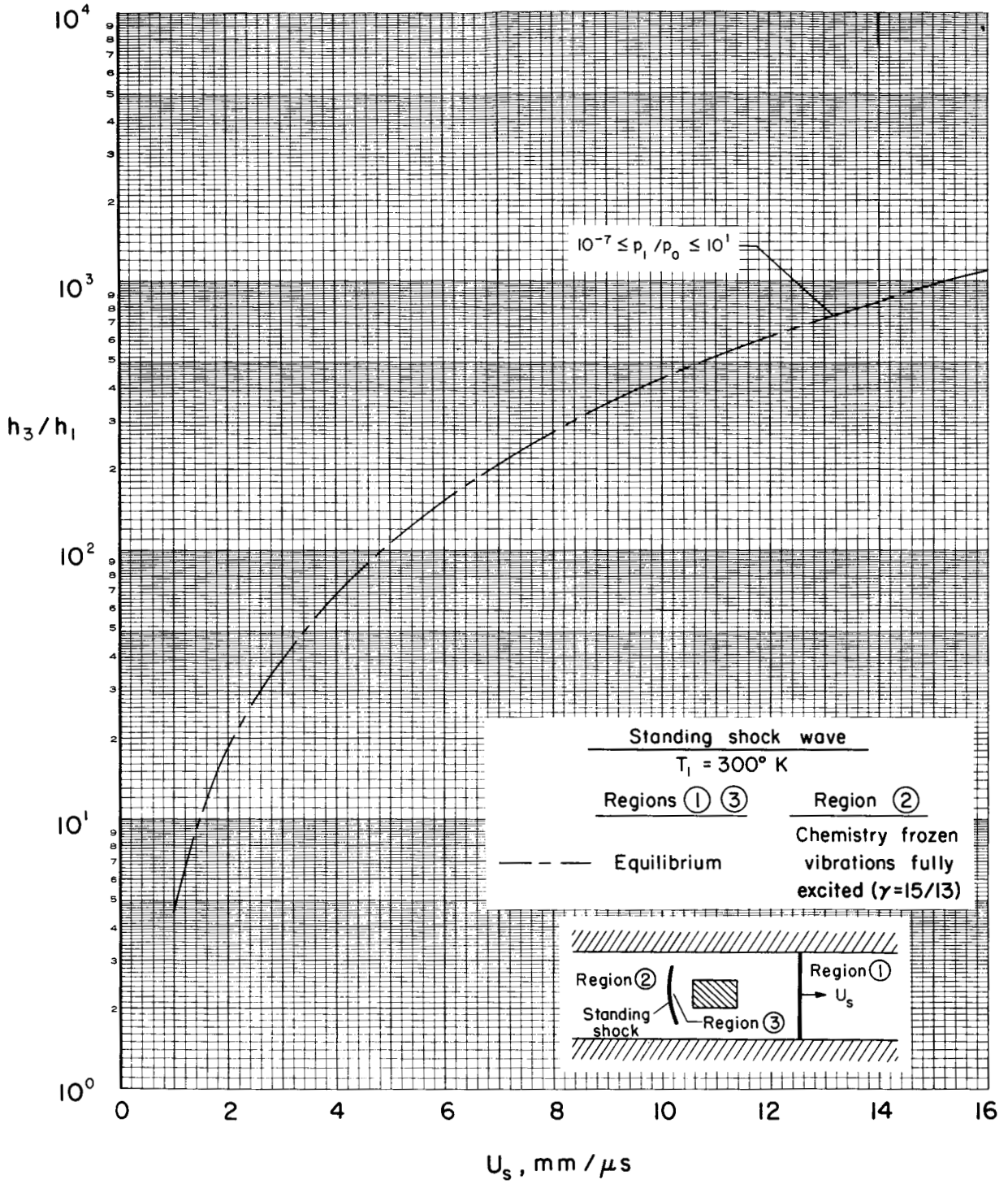
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 44. - Concluded.



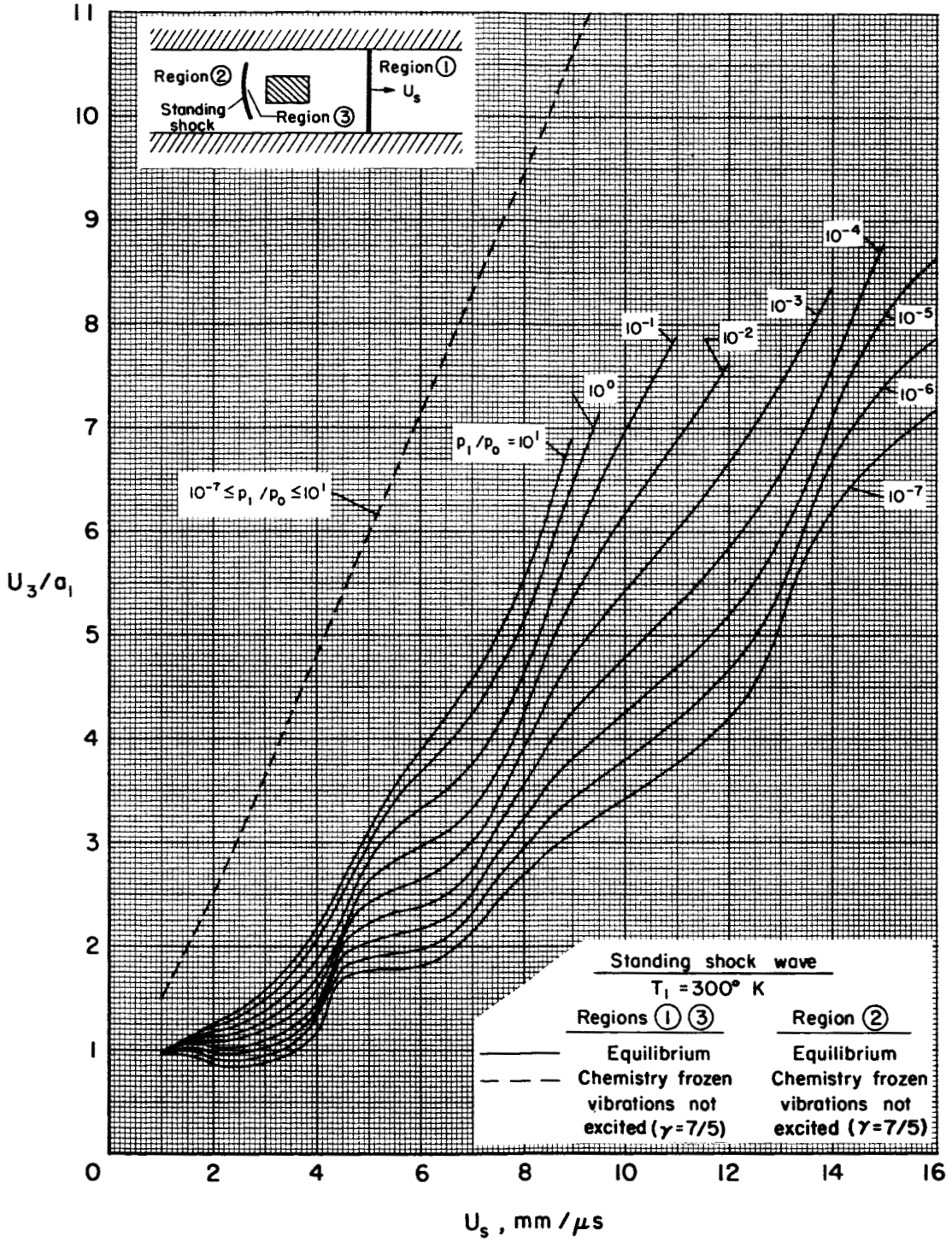
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 45. - Variation with incident shock wave of static enthalpy ratio across a standing shock wave.



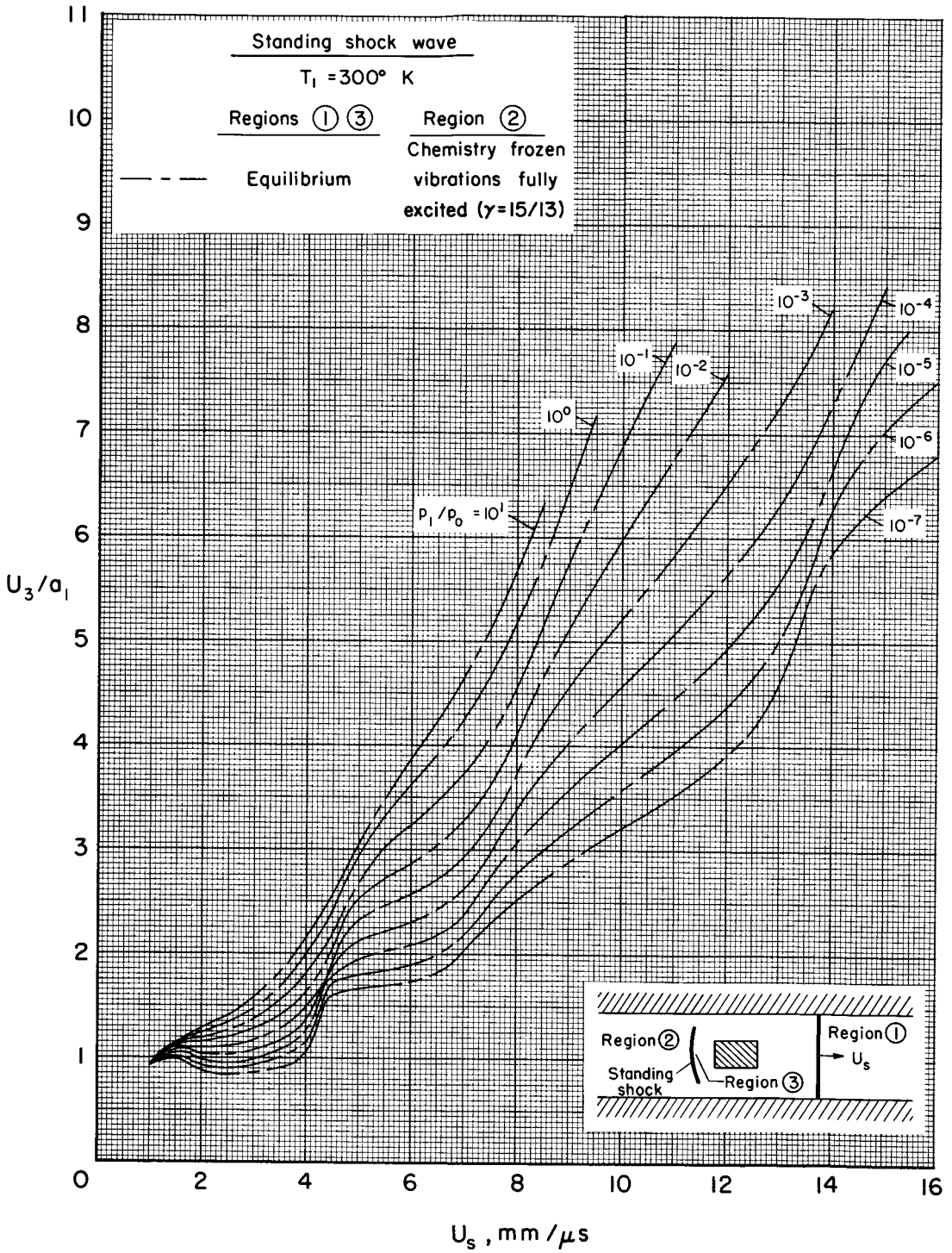
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 45. - Concluded.



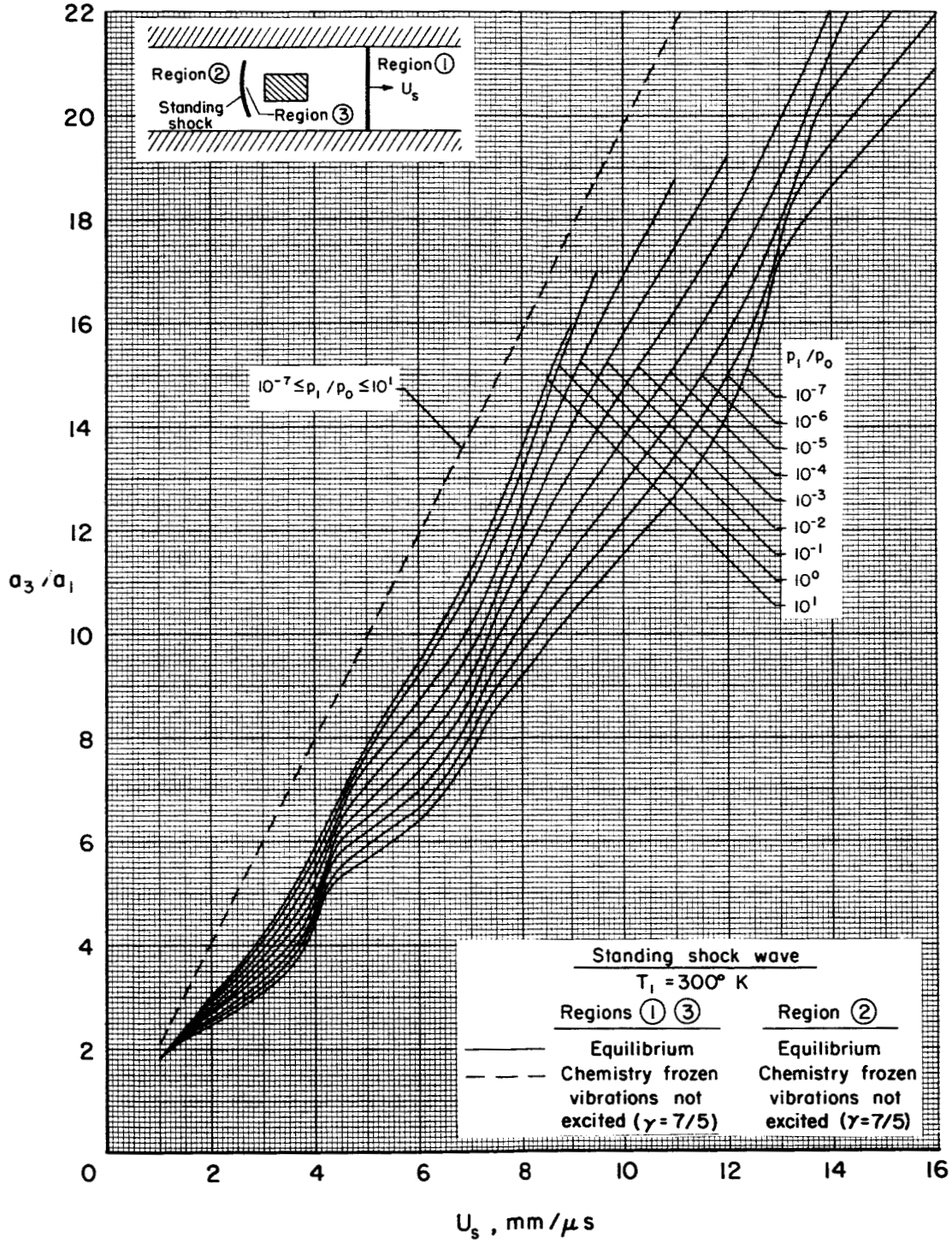
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 46. - Variation with incident shock wave of flow speed ratio across a standing shock wave.



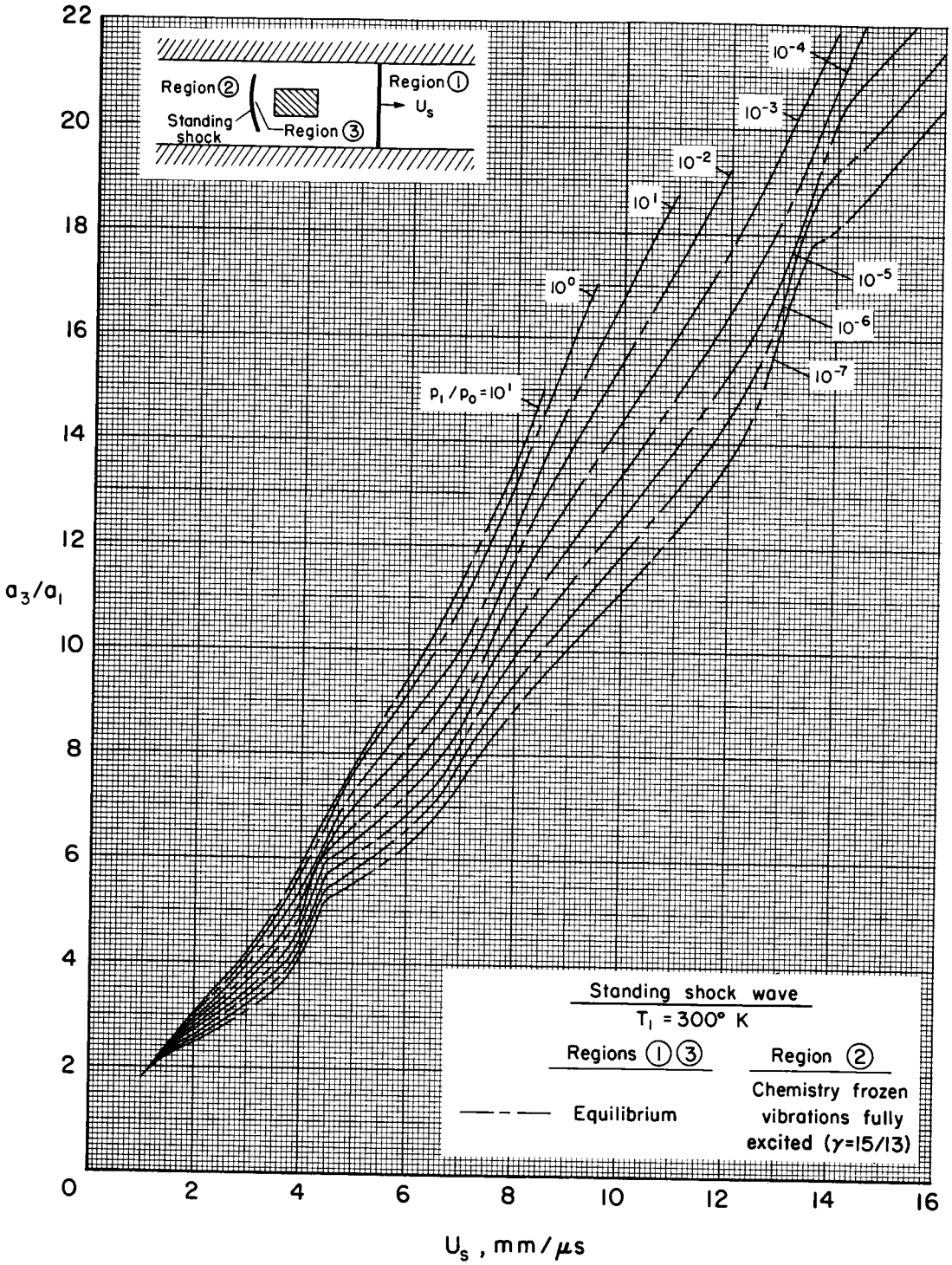
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 46. - Concluded.



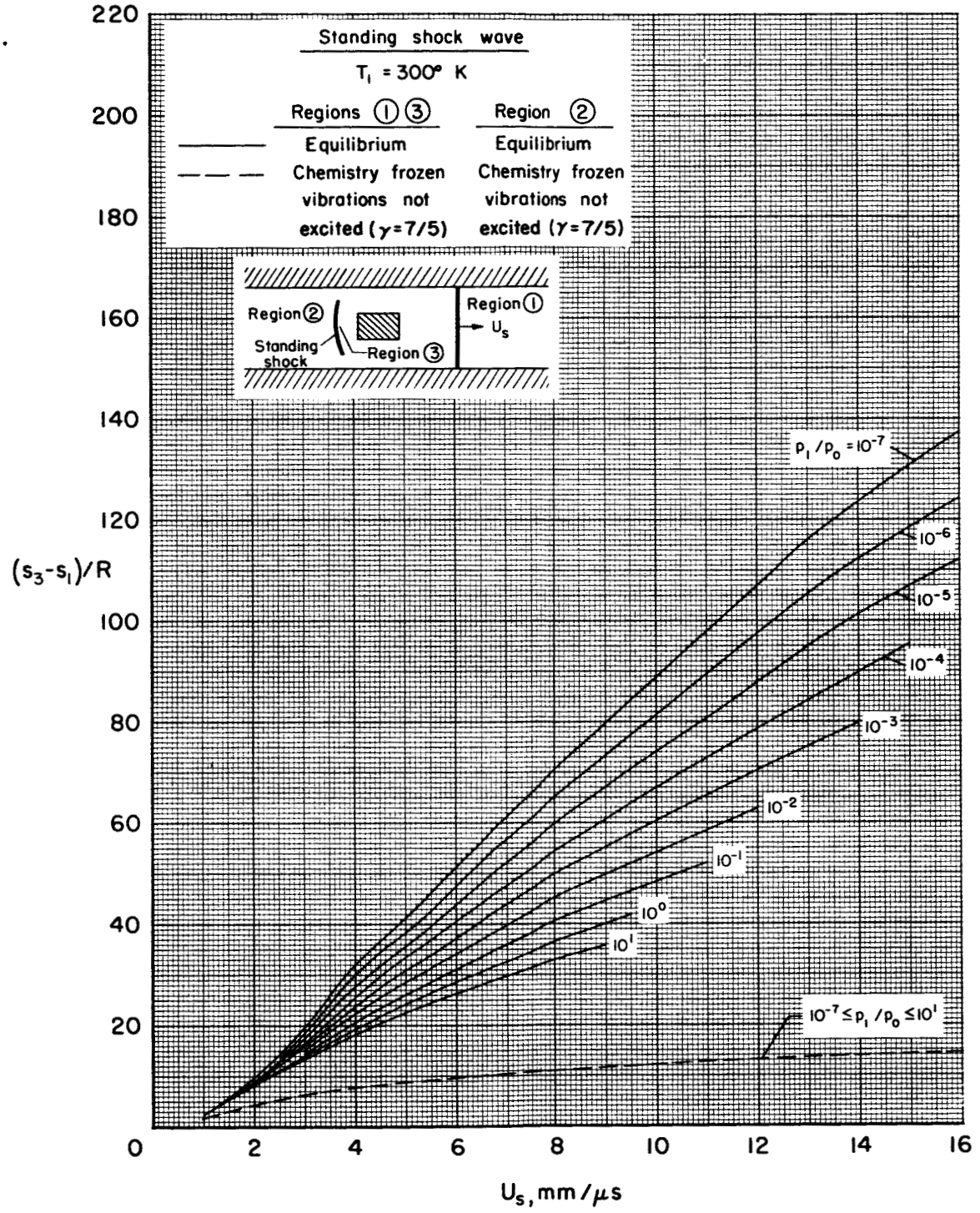
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 47. - Variation with incident shock wave speed of sound speed ratio across a standing shock wave.



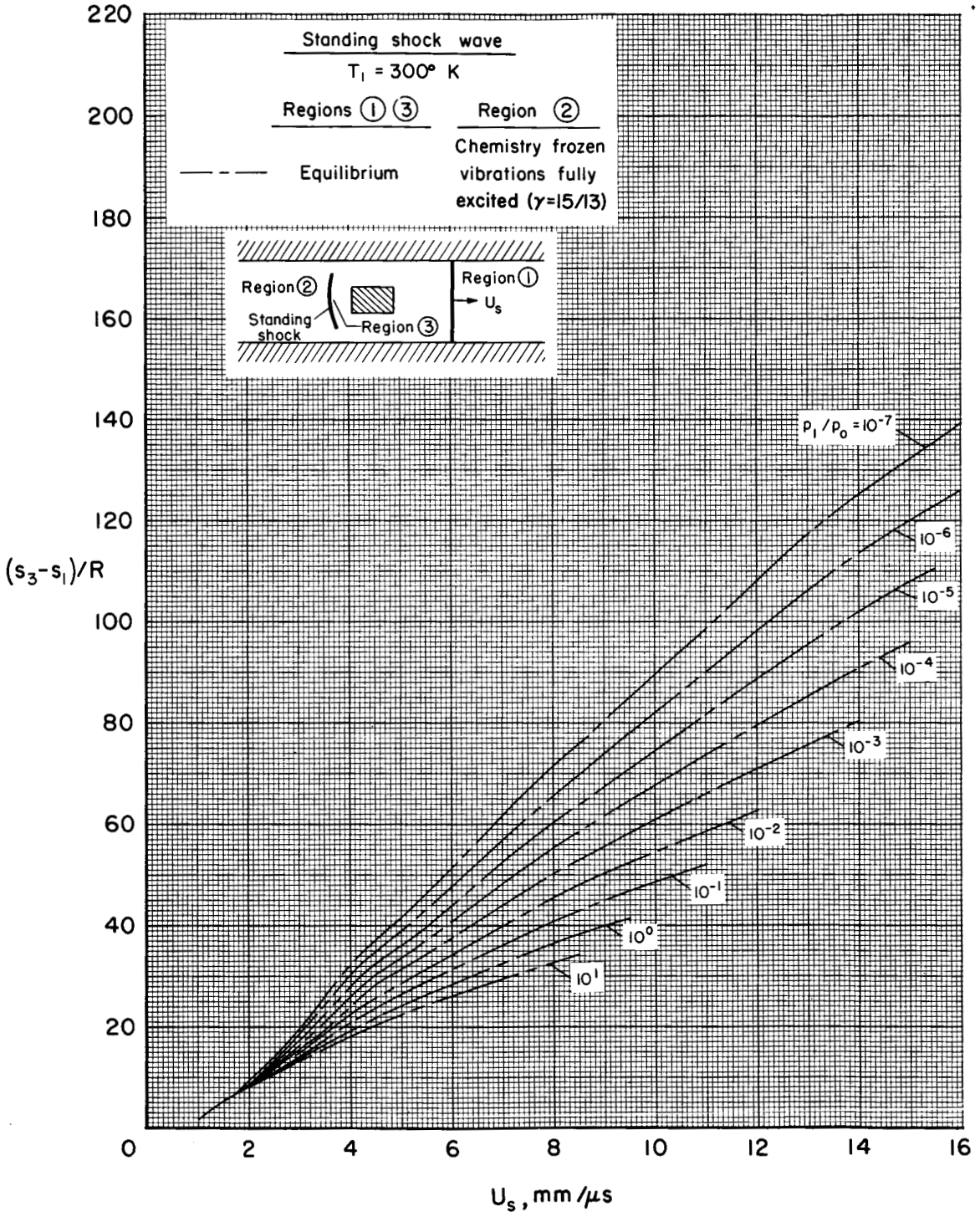
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 47. - Concluded.



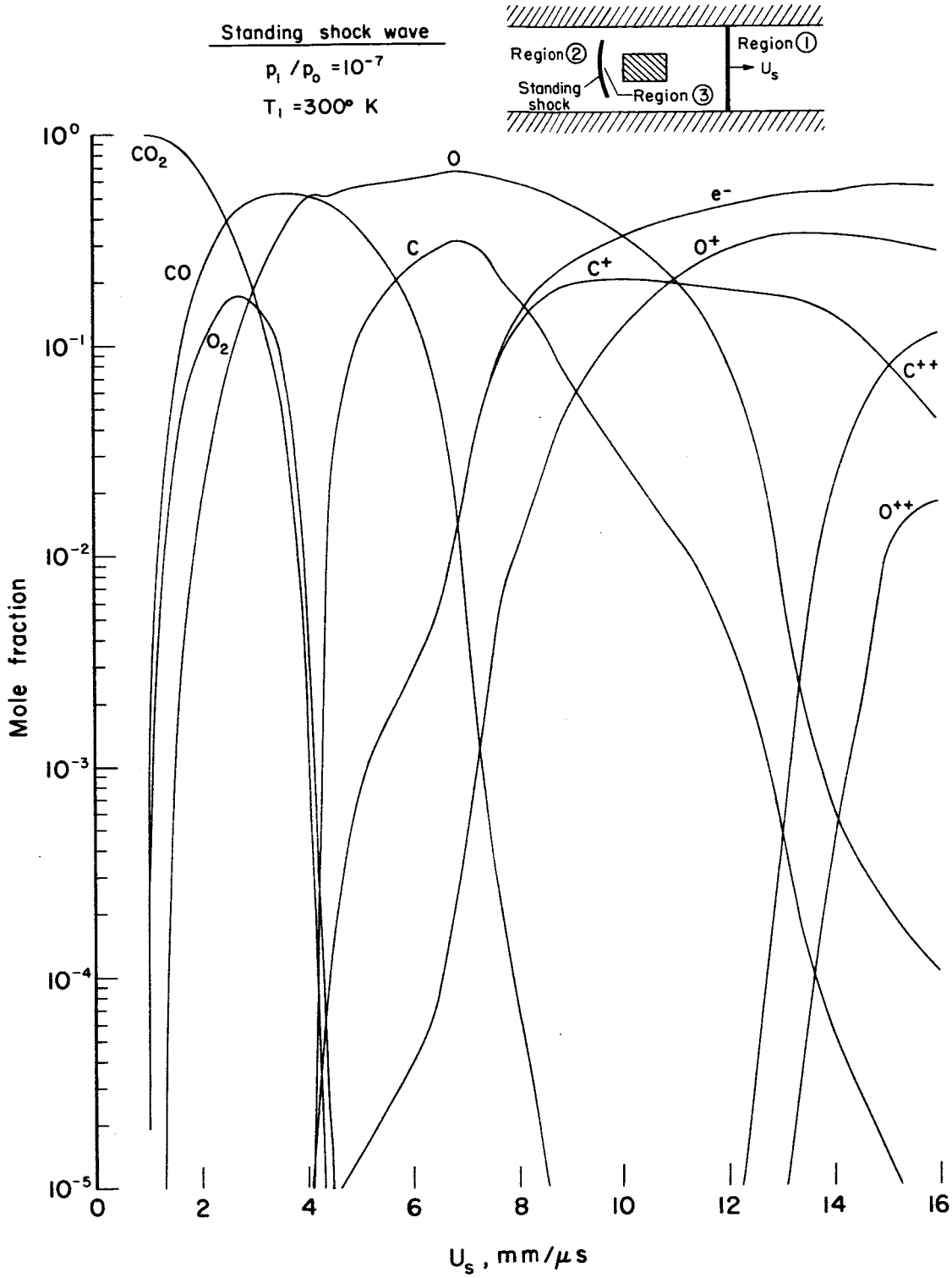
a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 48. - Variation with incident shock wave speed of entropy change across a standing shock wave.



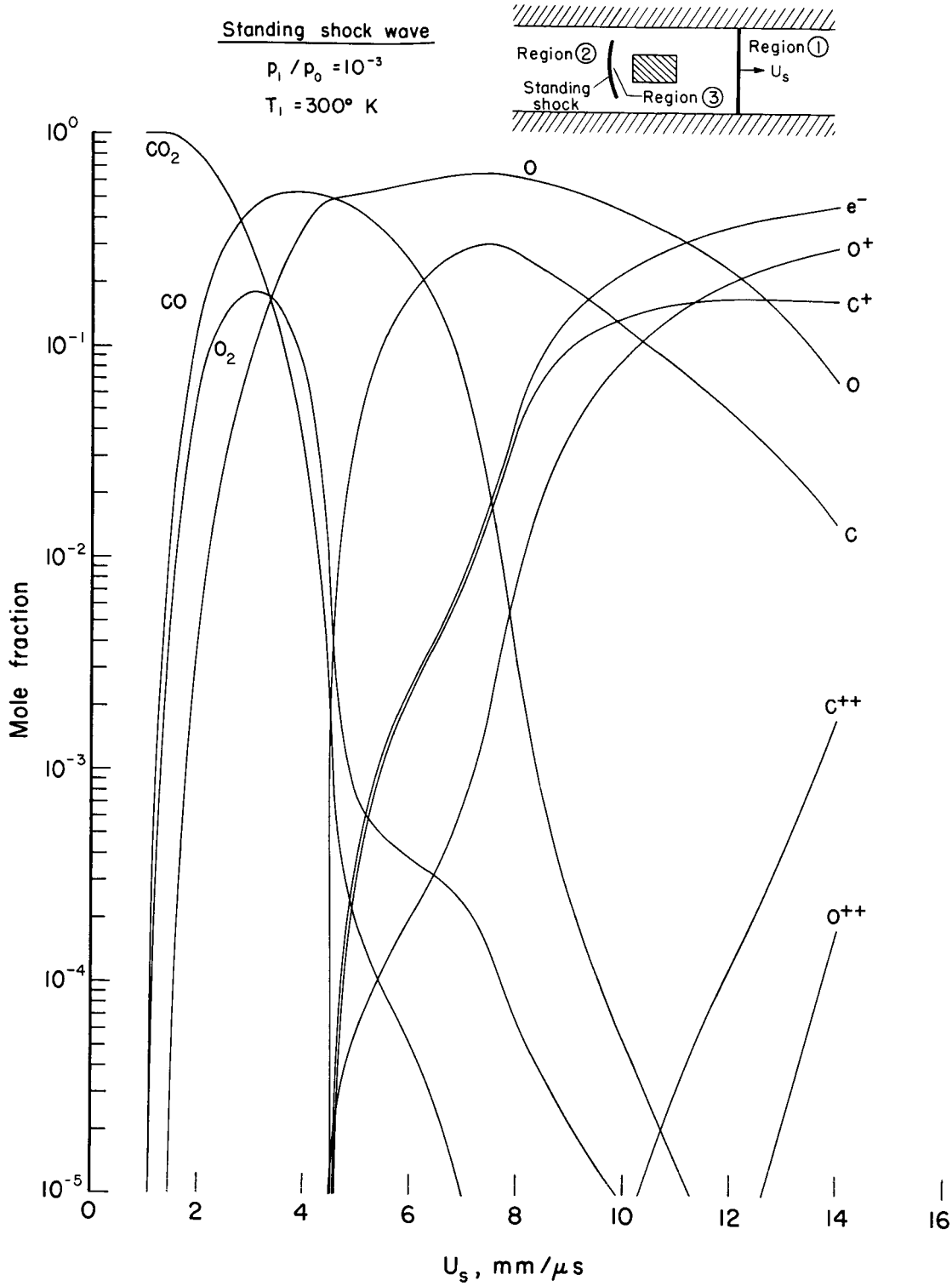
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 48. - Concluded.



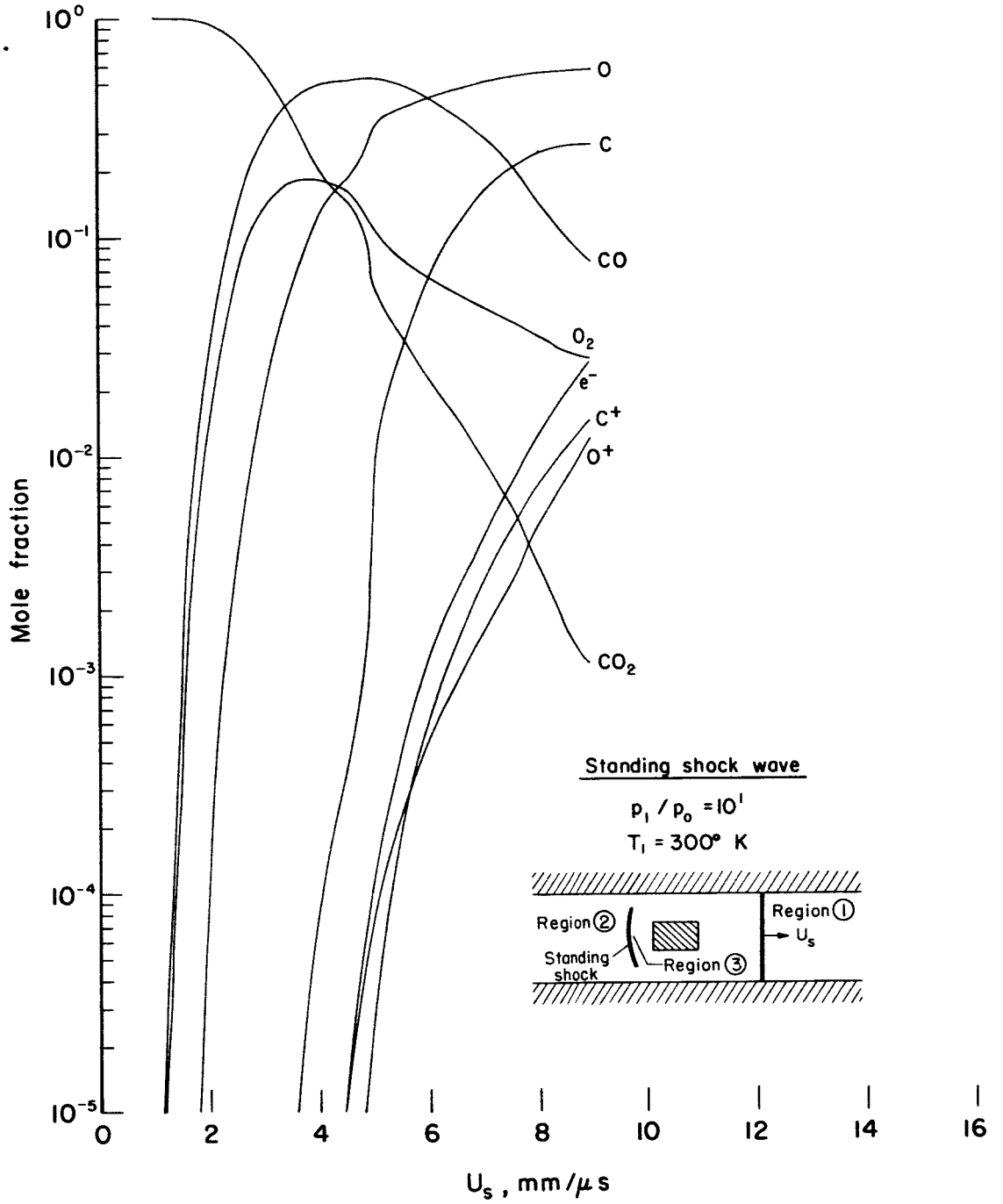
(a) $p_1/p_0 = 10^{-7}$

Chart 49. - Variation with incident shock wave speed of equilibrium flow chemistry downstream of a standing shock wave.



(b) $p_1/p_0 = 10^{-3}$

Chart 49. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 49. - Concluded.

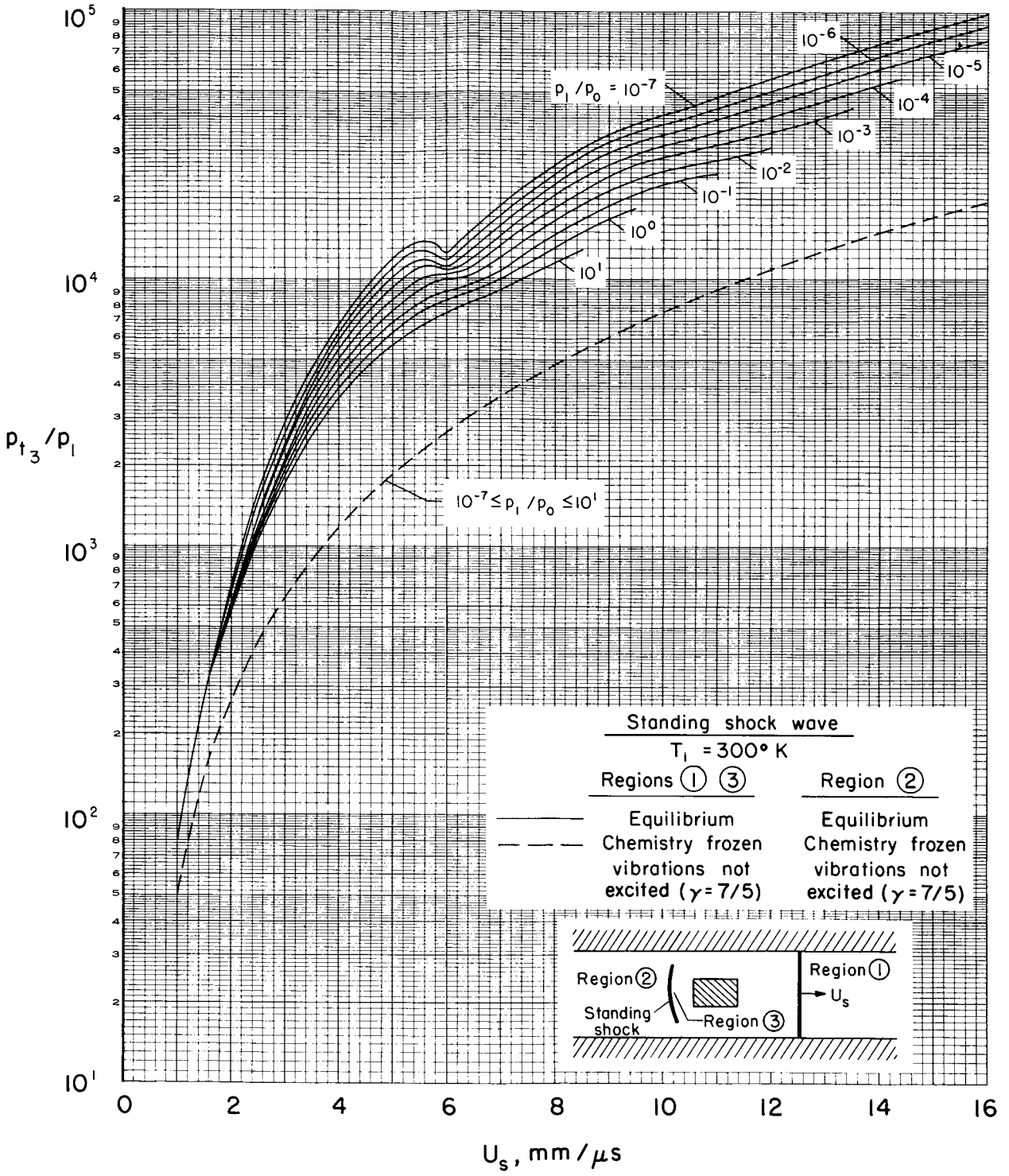


Chart 50. - Variation with incident shock wave speed of total pressure downstream of a standing shock wave.

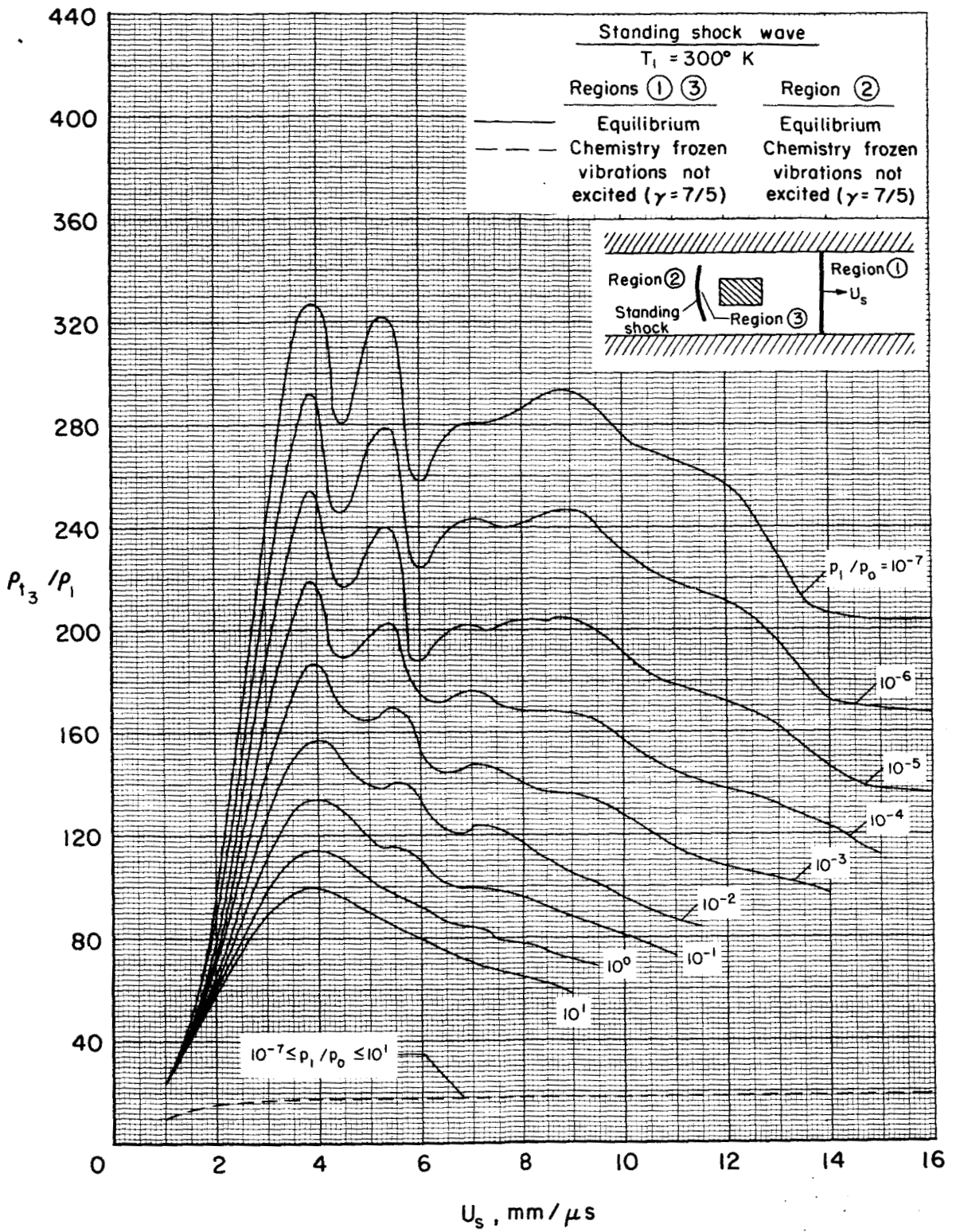


Chart 51. - Variation with incident shock wave speed of total density downstream of a standing shock wave.

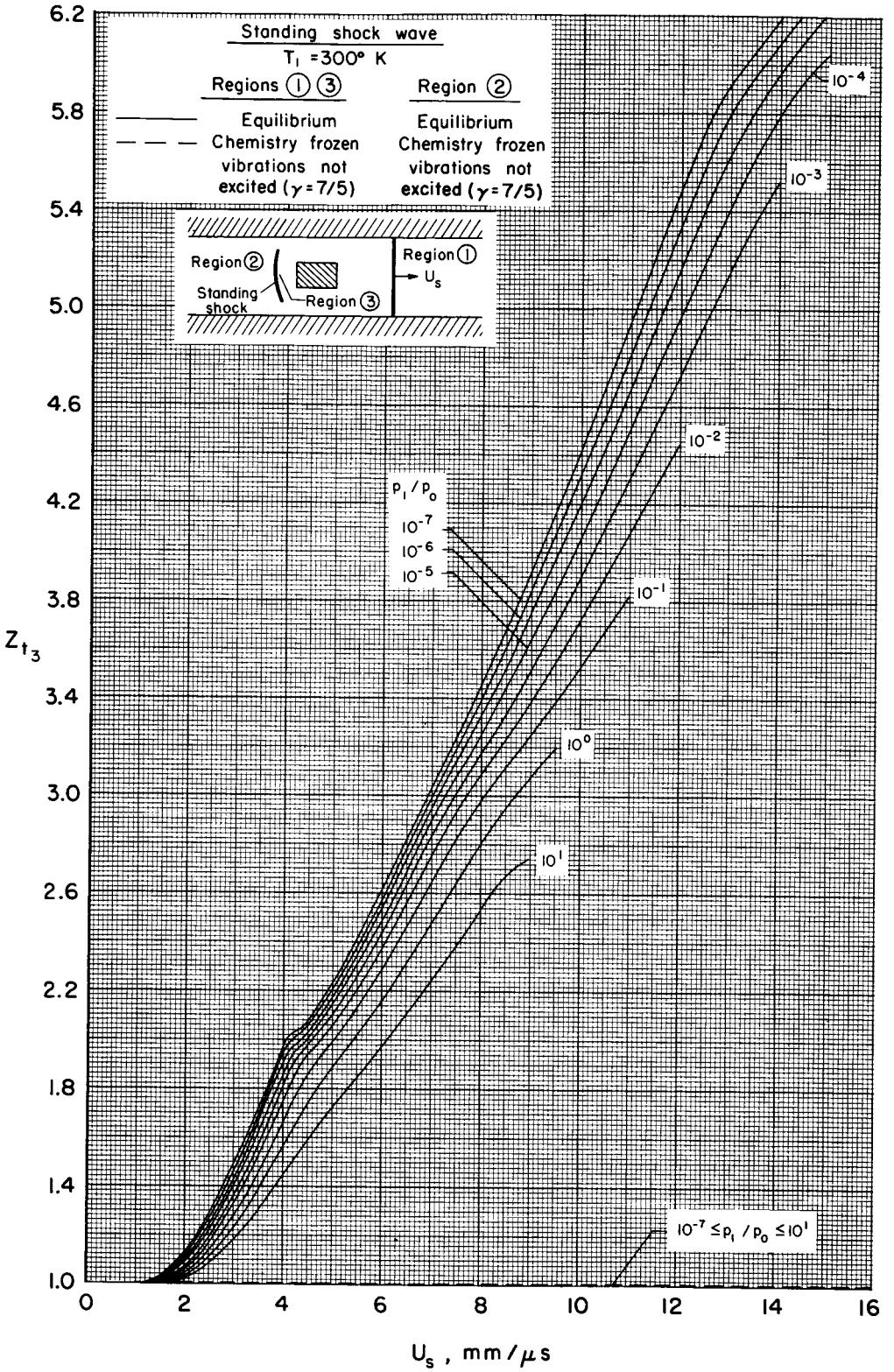


Chart 52. - Variation with incident shock wave speed of total compressibility factor downstream of a standing shock wave.

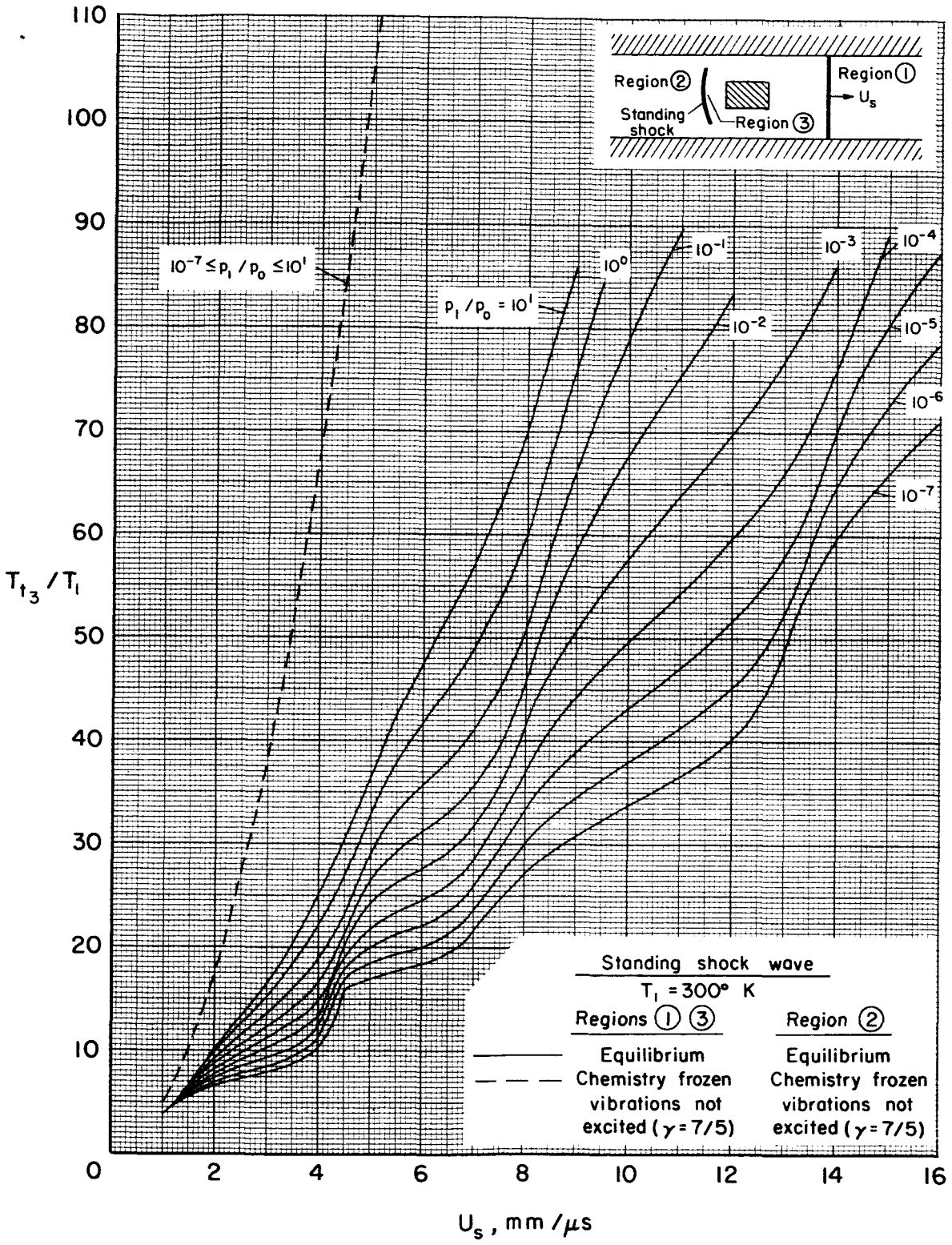


Chart 53. - Variation with incident shock wave speed of total temperature downstream of a standing shock wave.

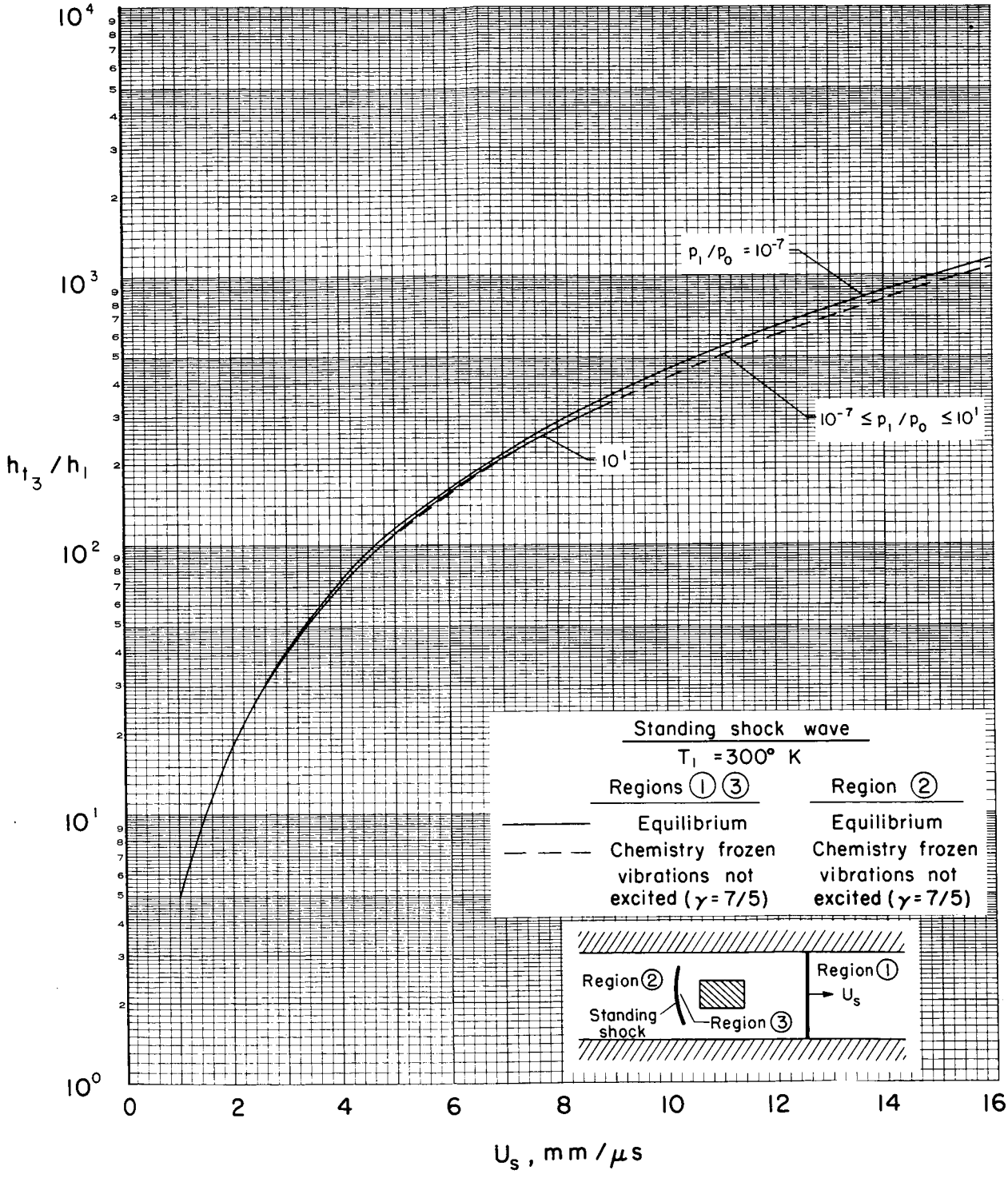
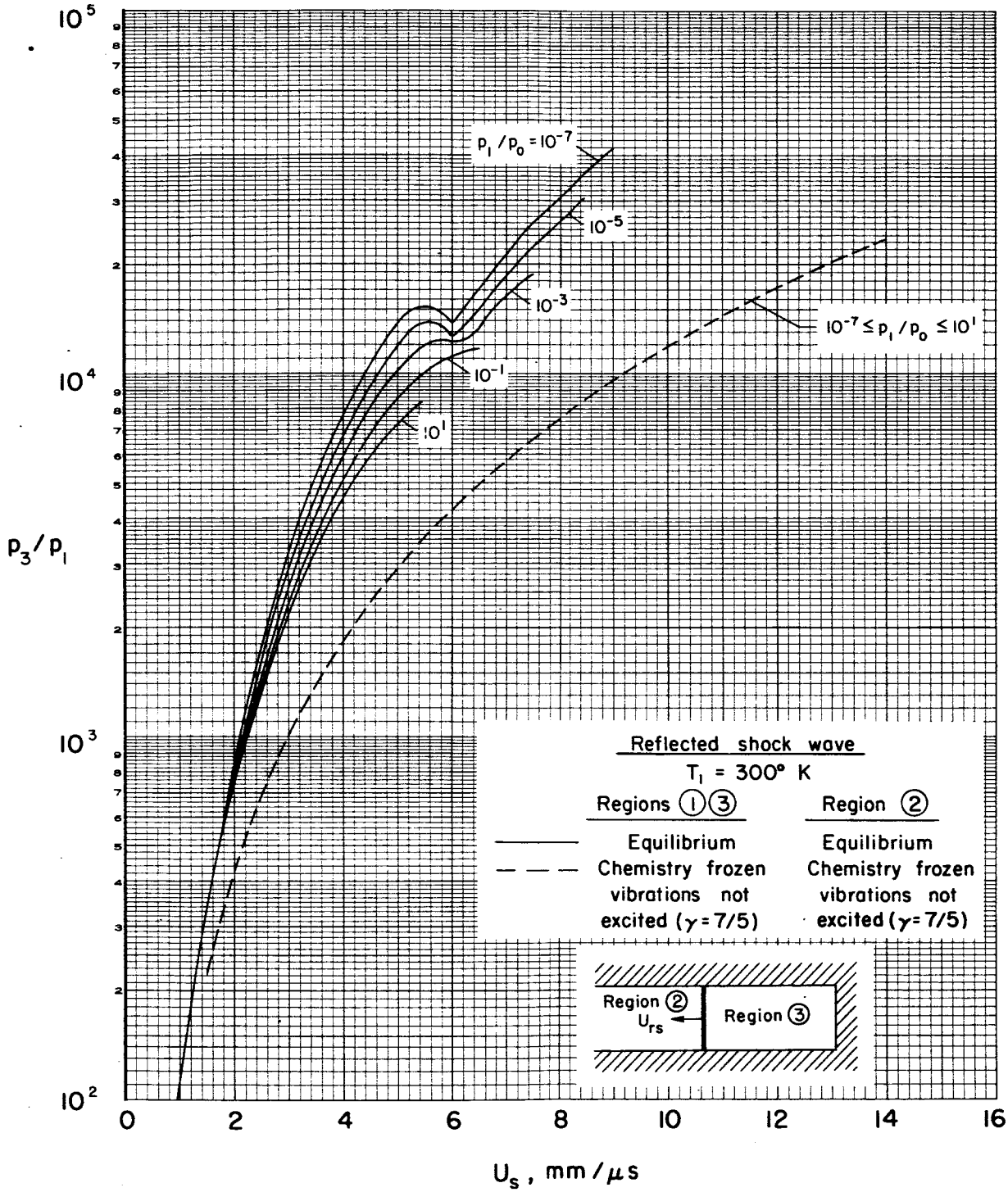
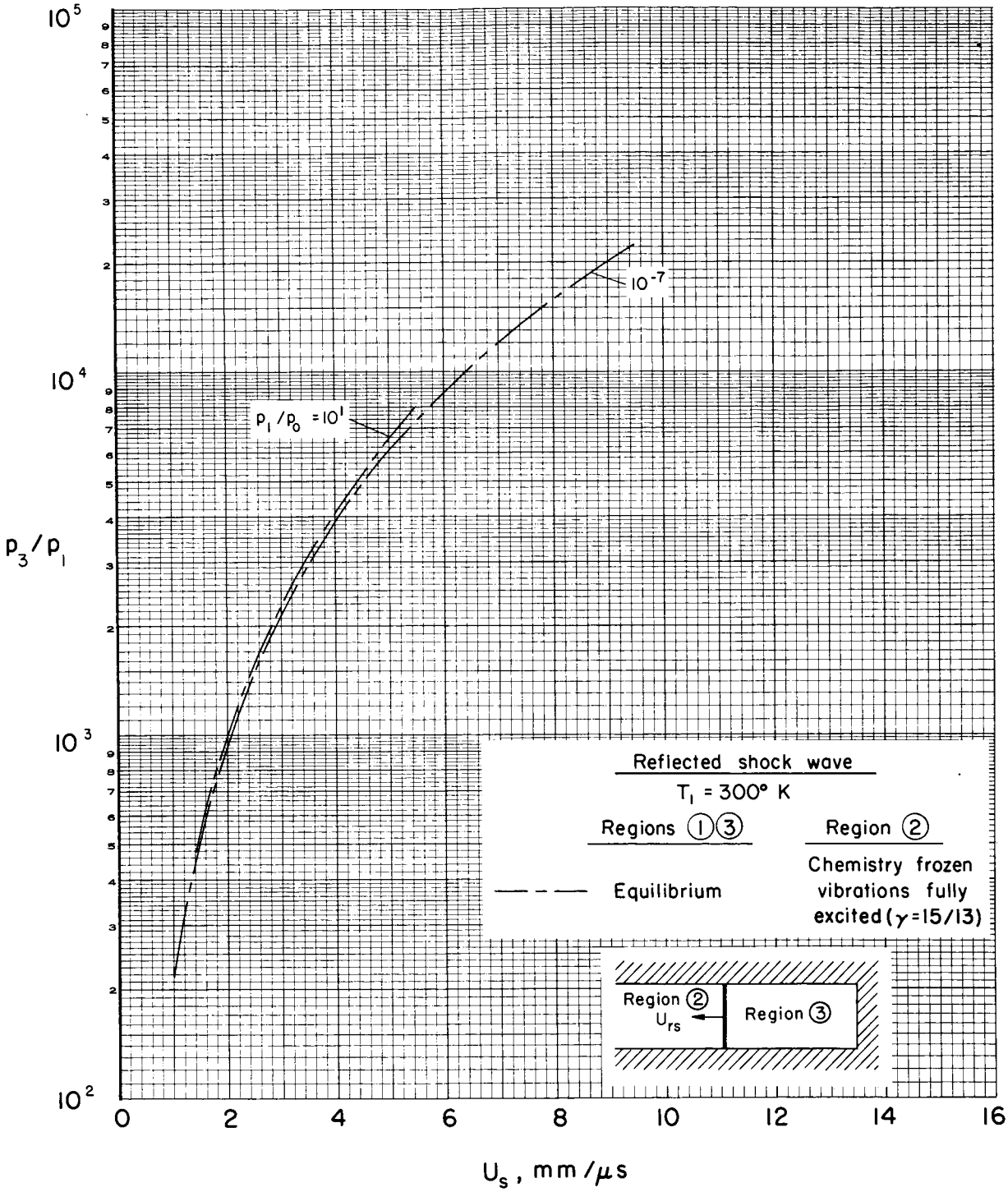


Chart 54. - Variation with incident shock wave speed of total enthalpy downstream of a standing shock wave.



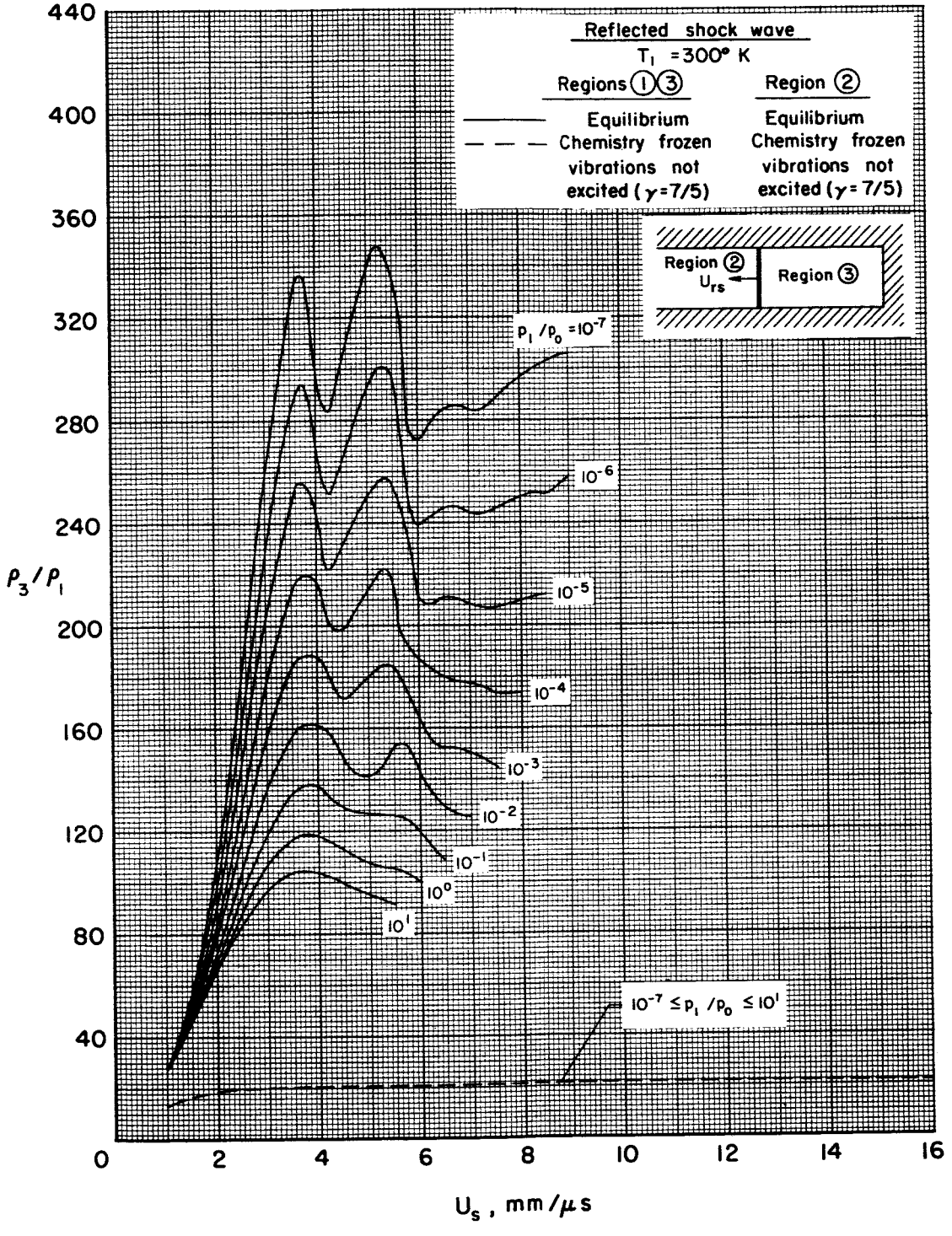
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 55. - Variation with incident shock wave speed of static pressure ratio across a reflected shock wave.



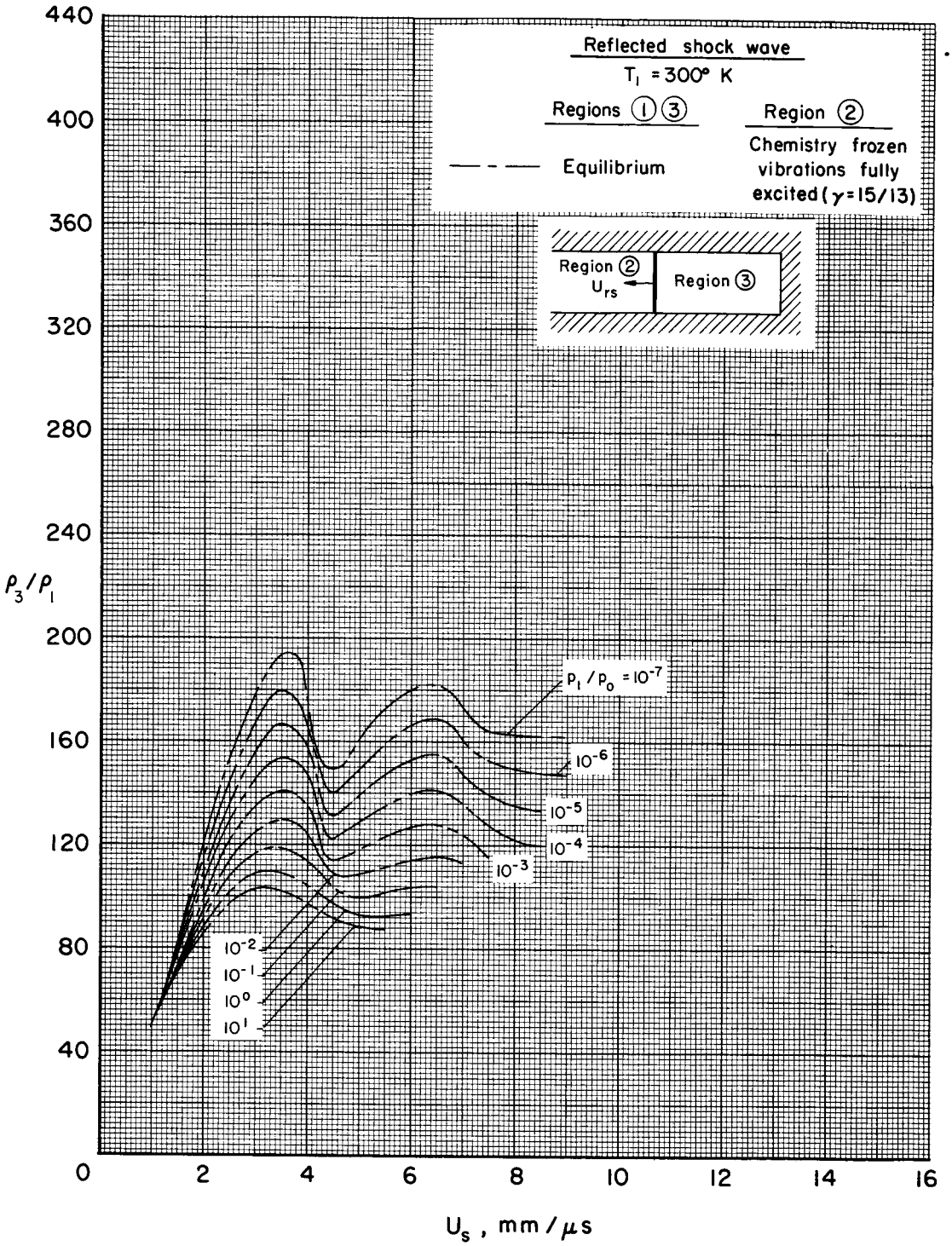
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 55. - Concluded.



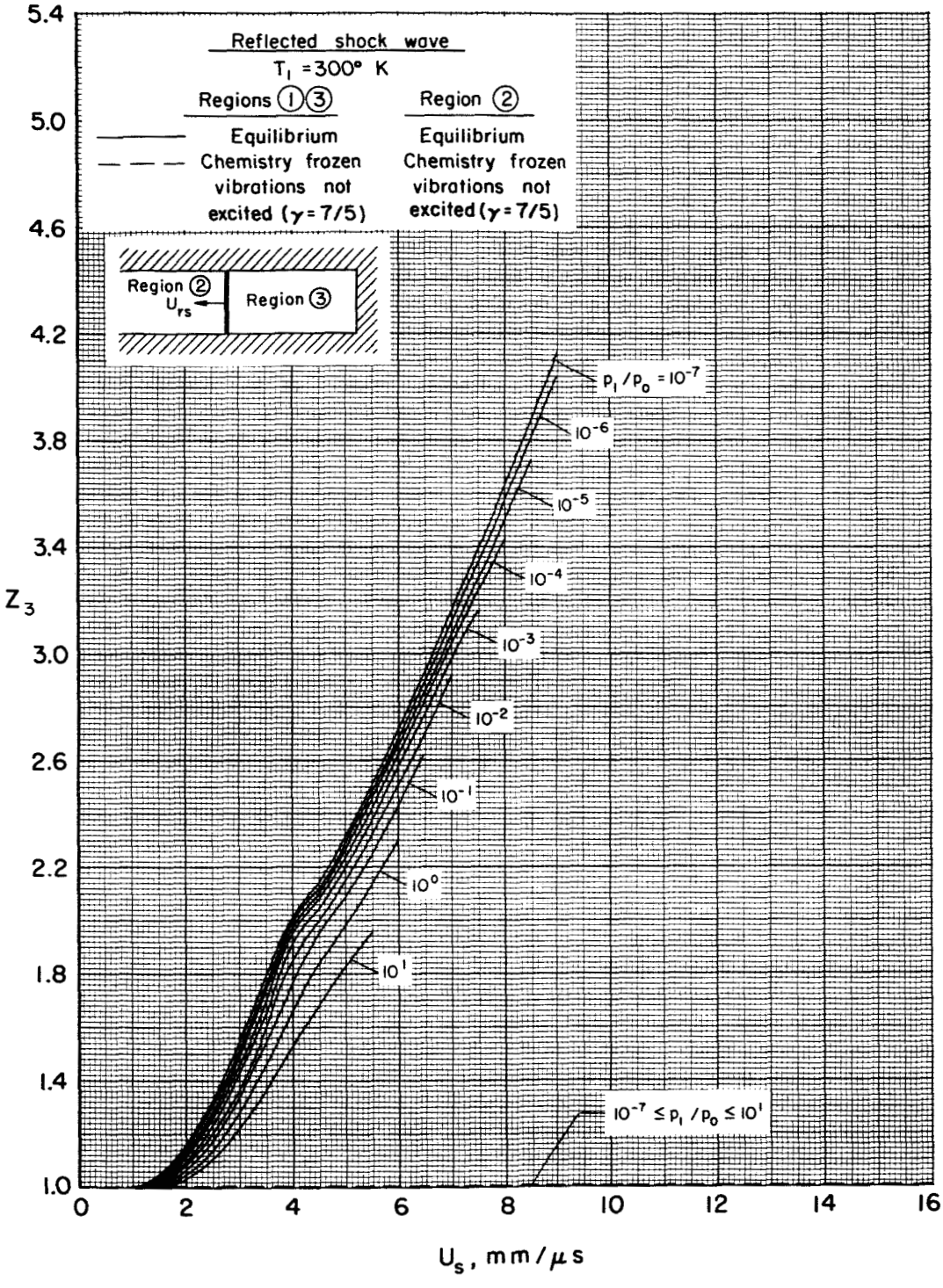
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 56. - Variation with incident shock wave speed of static density ratio across a reflected shock wave.



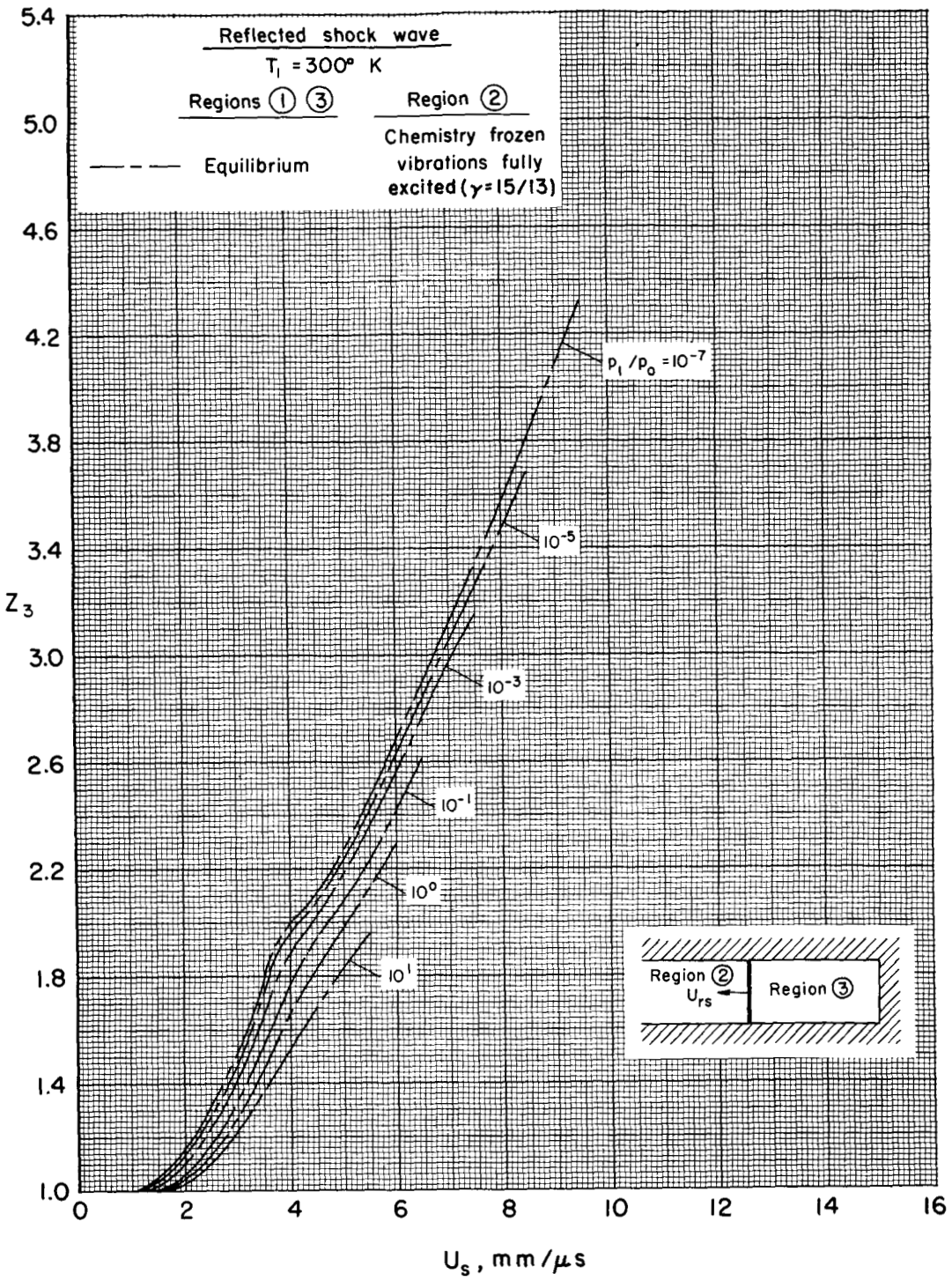
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 56. - Concluded.



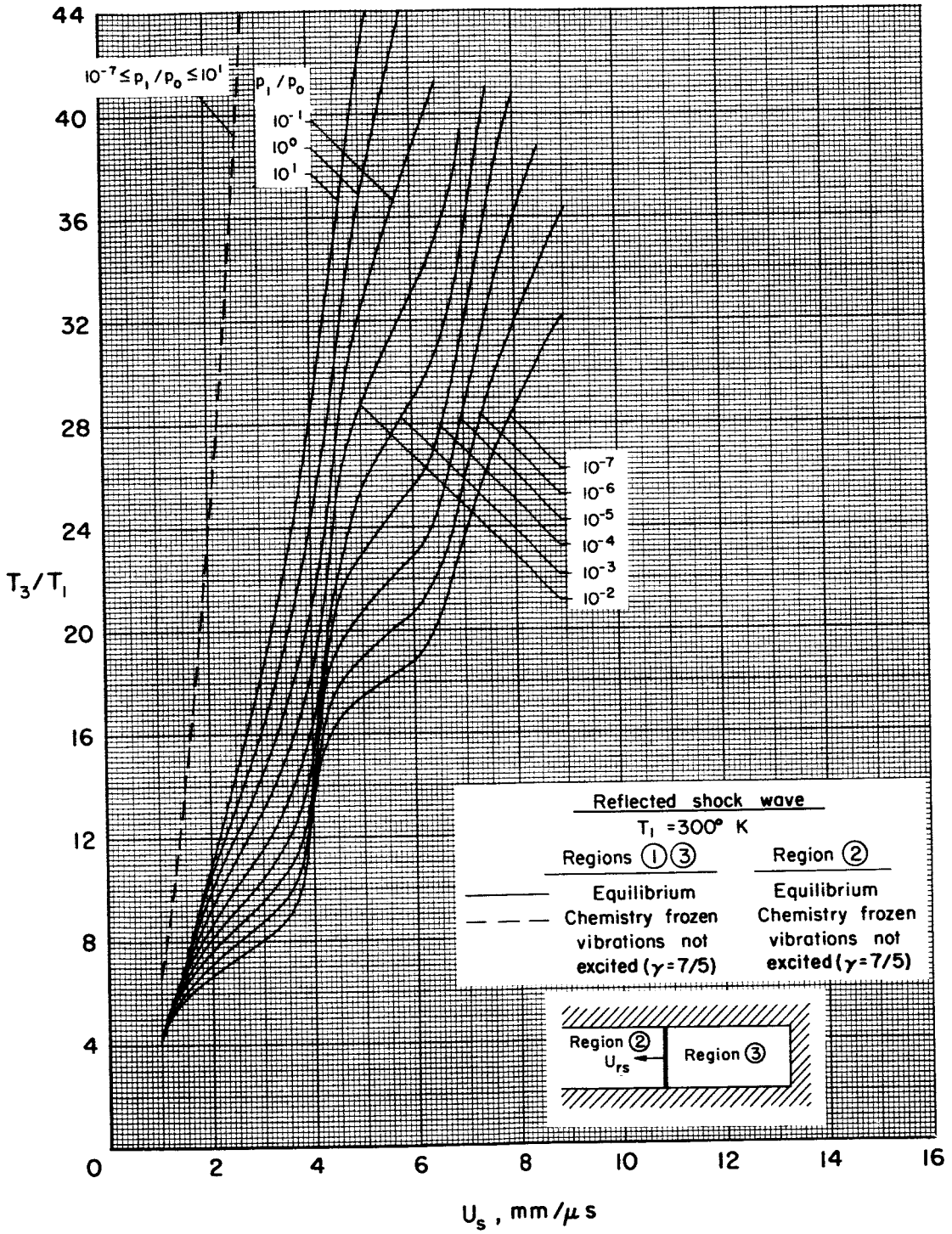
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 57. - Variation with incident shock wave speed of compressibility factor downstream of a reflected shock wave.



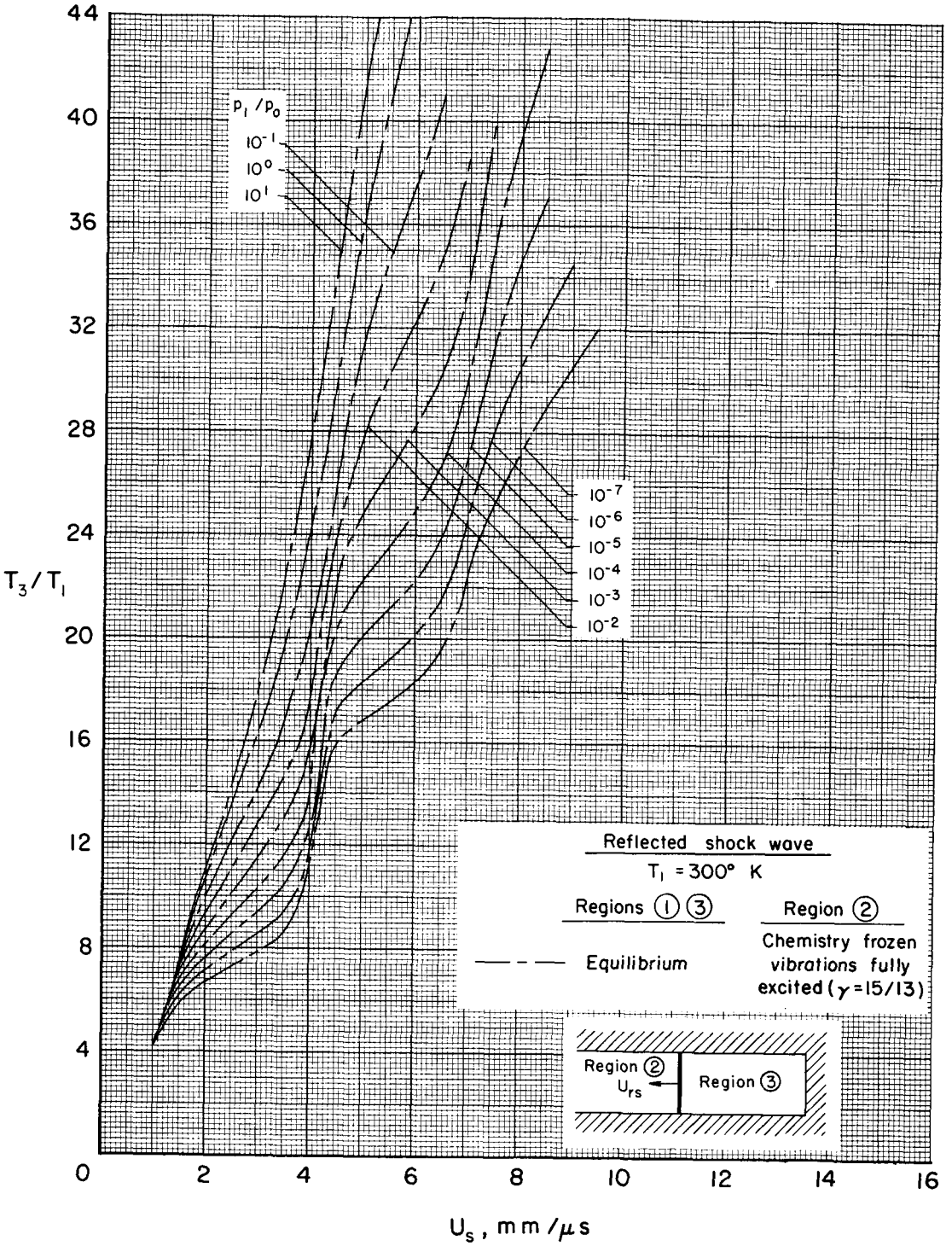
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 57. - Concluded.



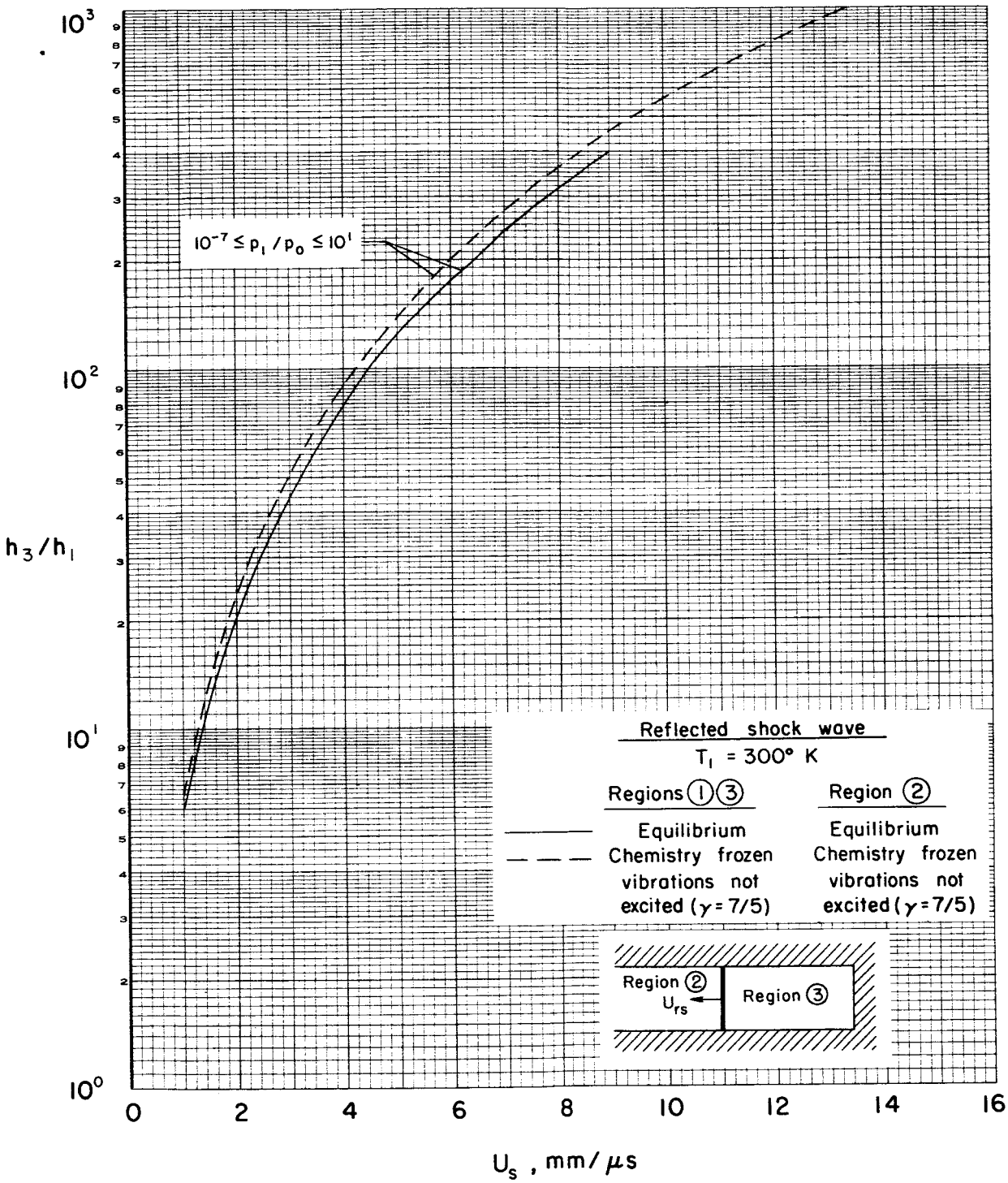
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 58. - Variation with incident shock wave speed of static temperature ratio across a reflected shock wave.



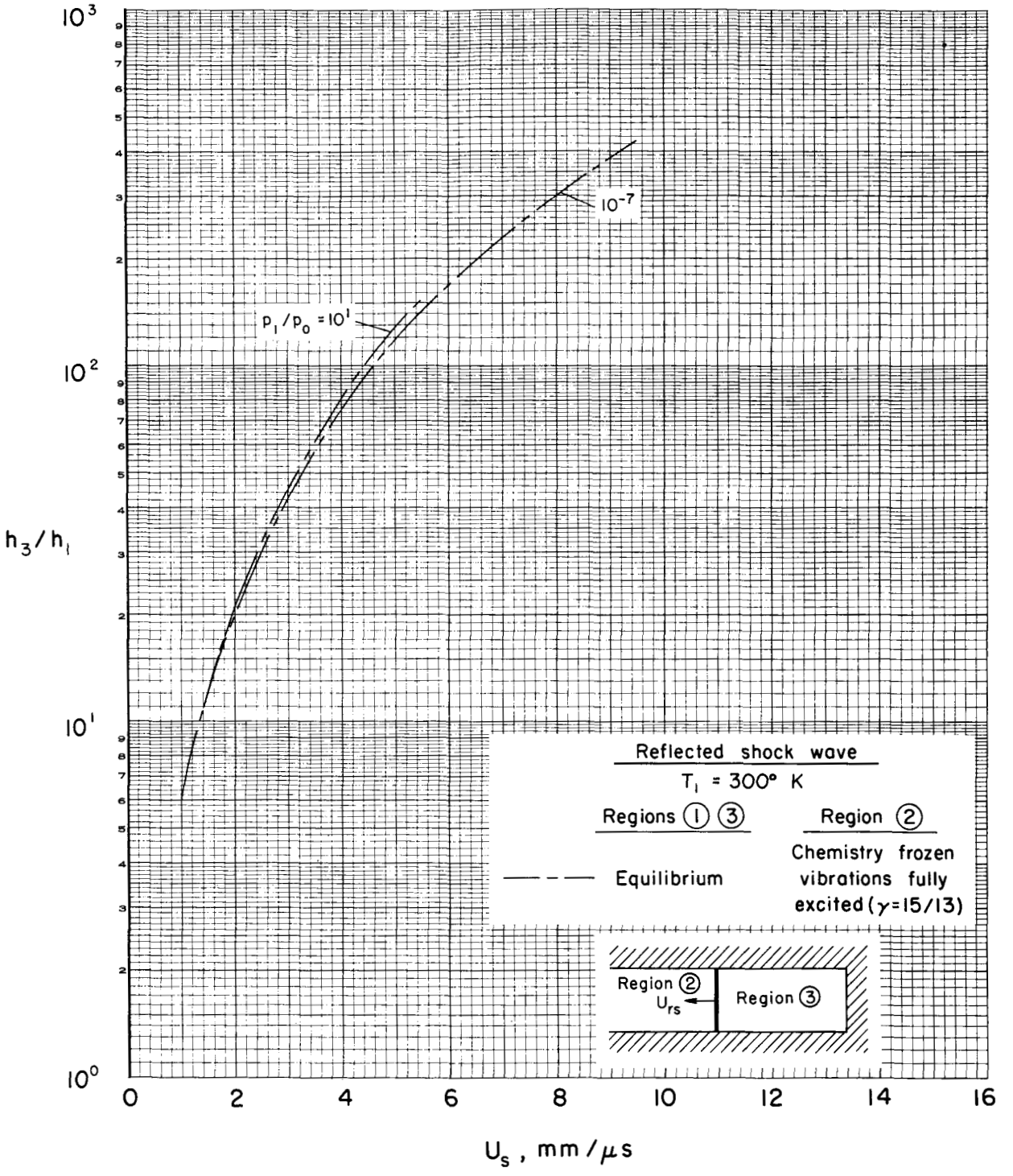
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 58. - Concluded.



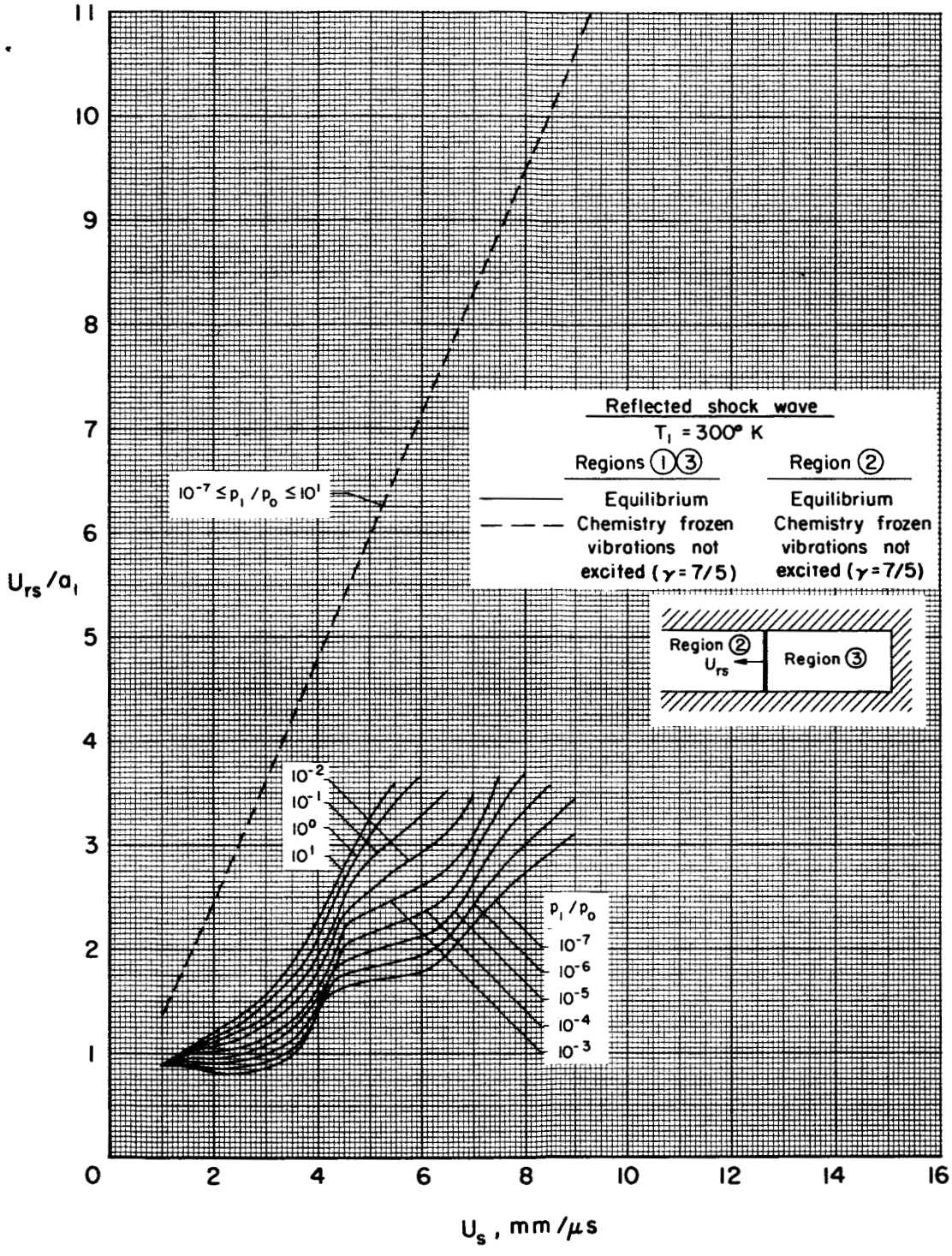
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 59. - Variation with incident shock wave of static enthalpy ratio across a reflected shock wave.



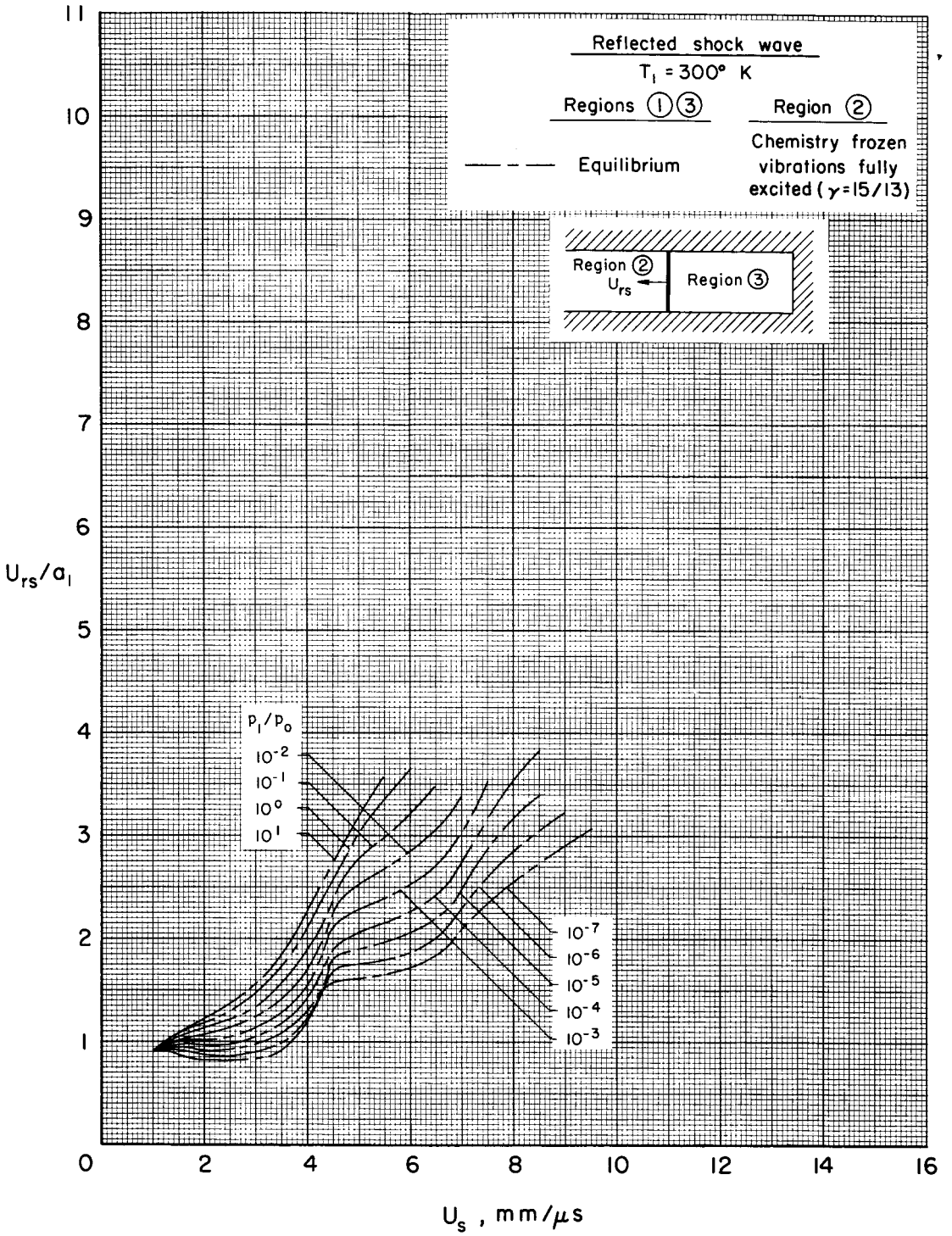
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 59. - Concluded.



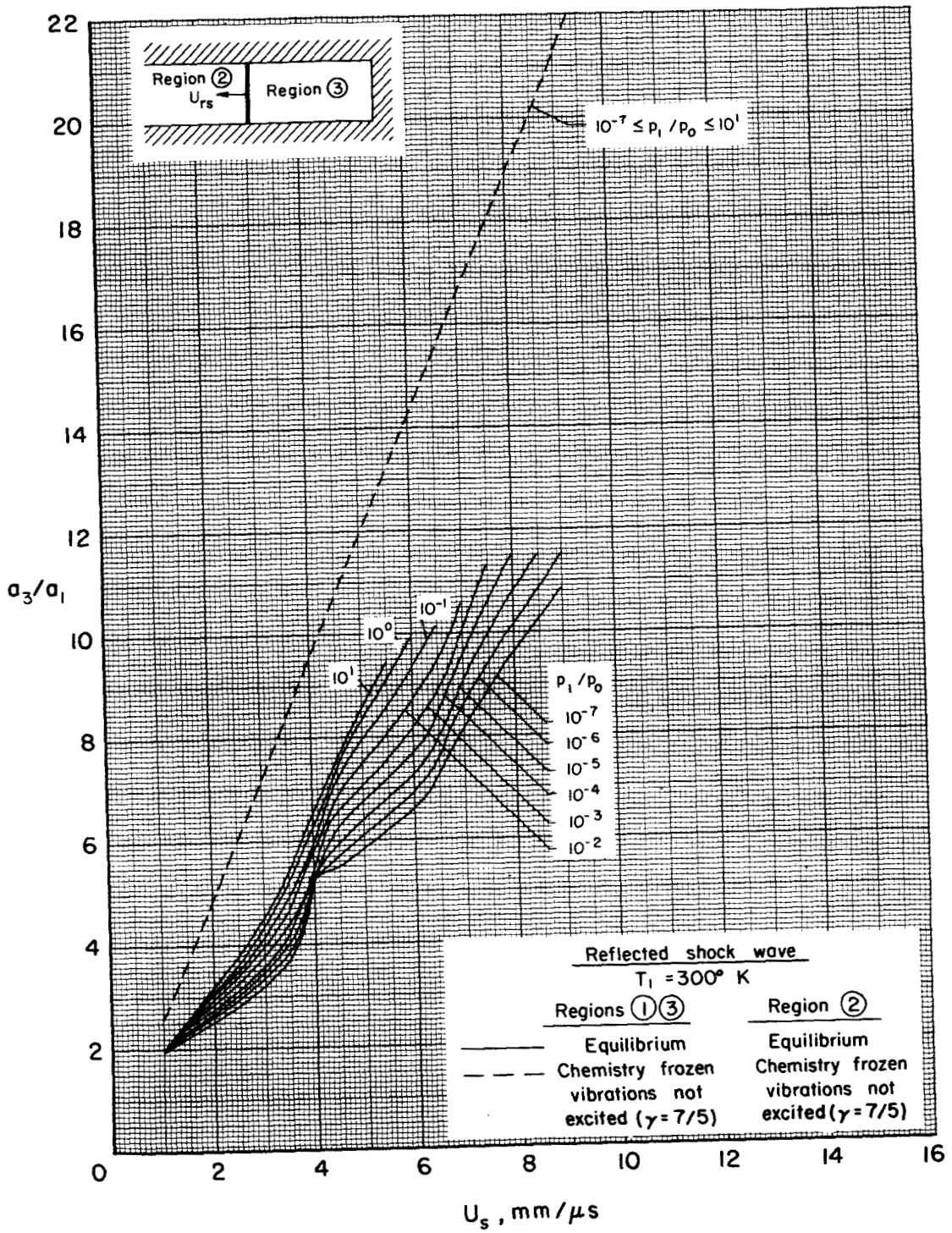
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 60. - Variation with incident shock wave of flow speed ratio across a reflected shock wave.



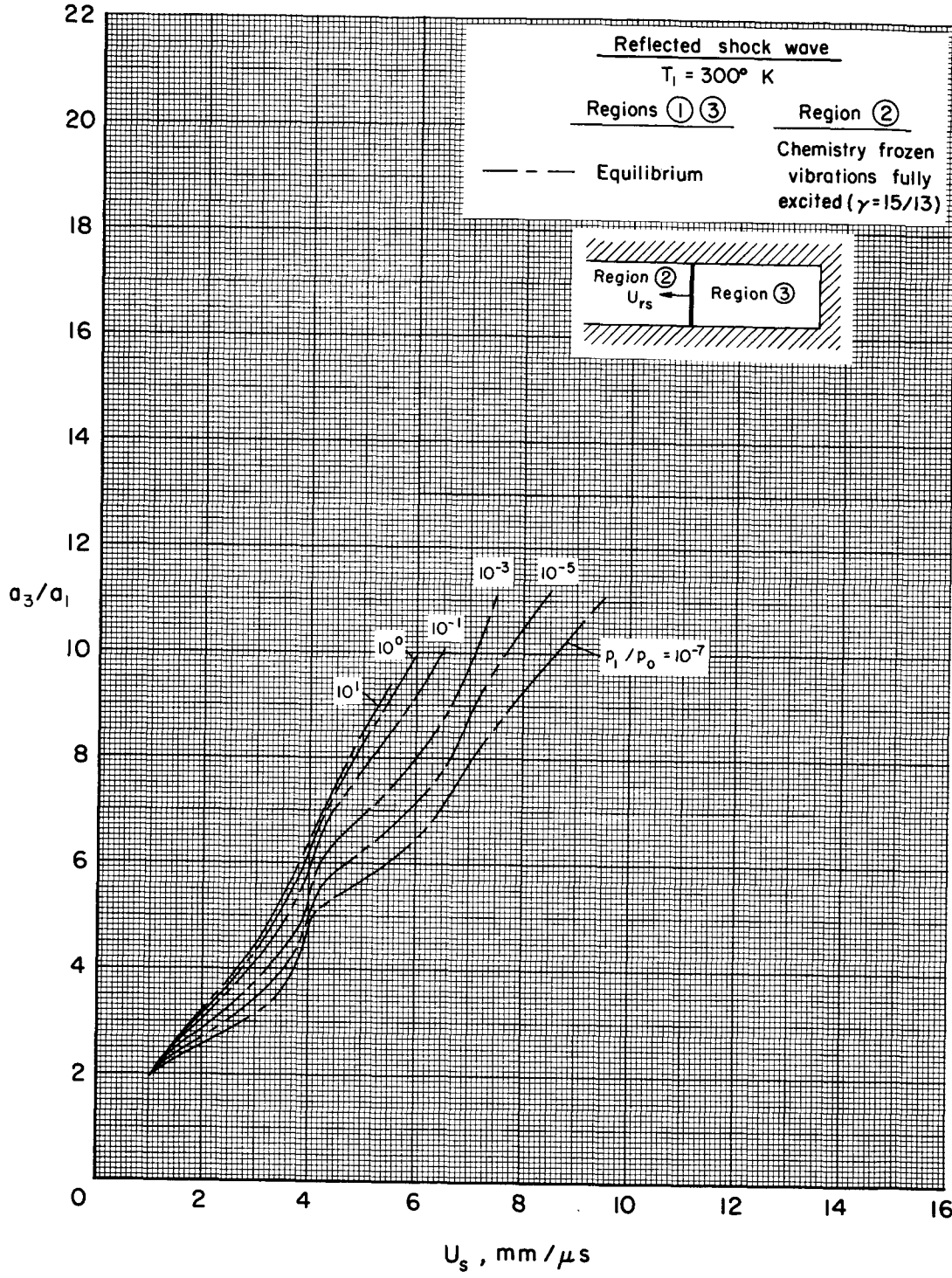
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 60. - Concluded.



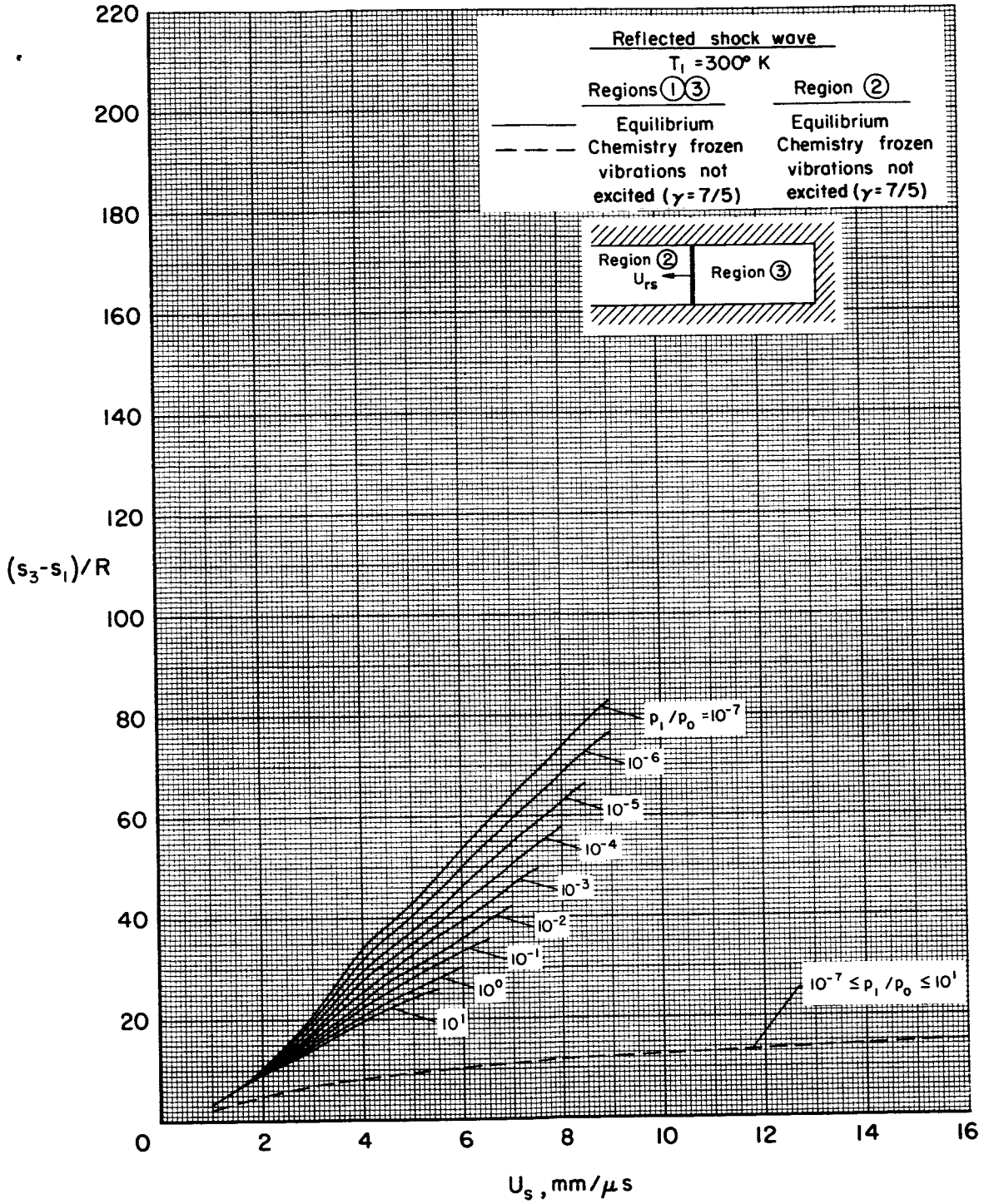
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 61. - Variation with incident shock wave speed of sound speed ratio across a reflected shock wave.



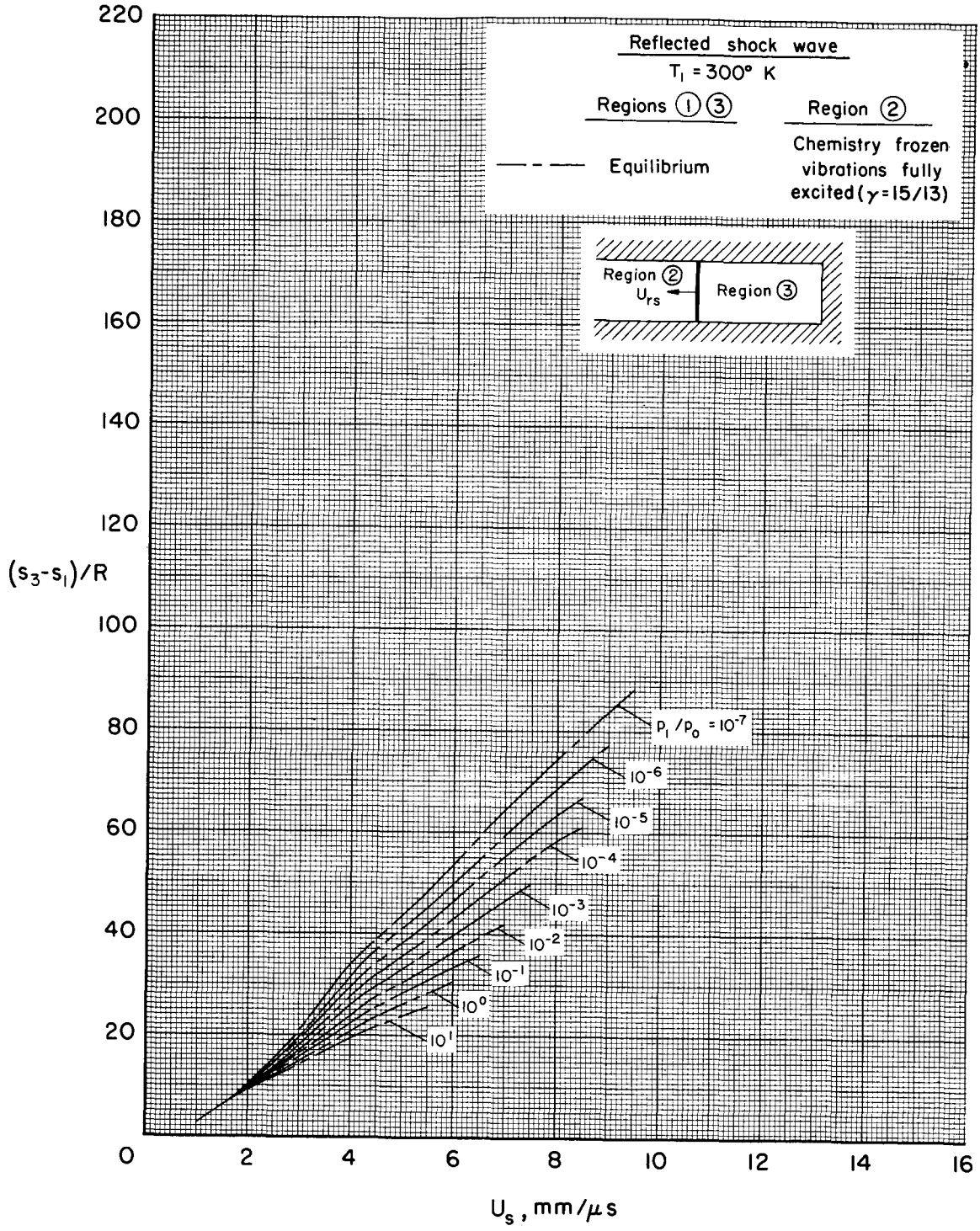
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 61. - Concluded.



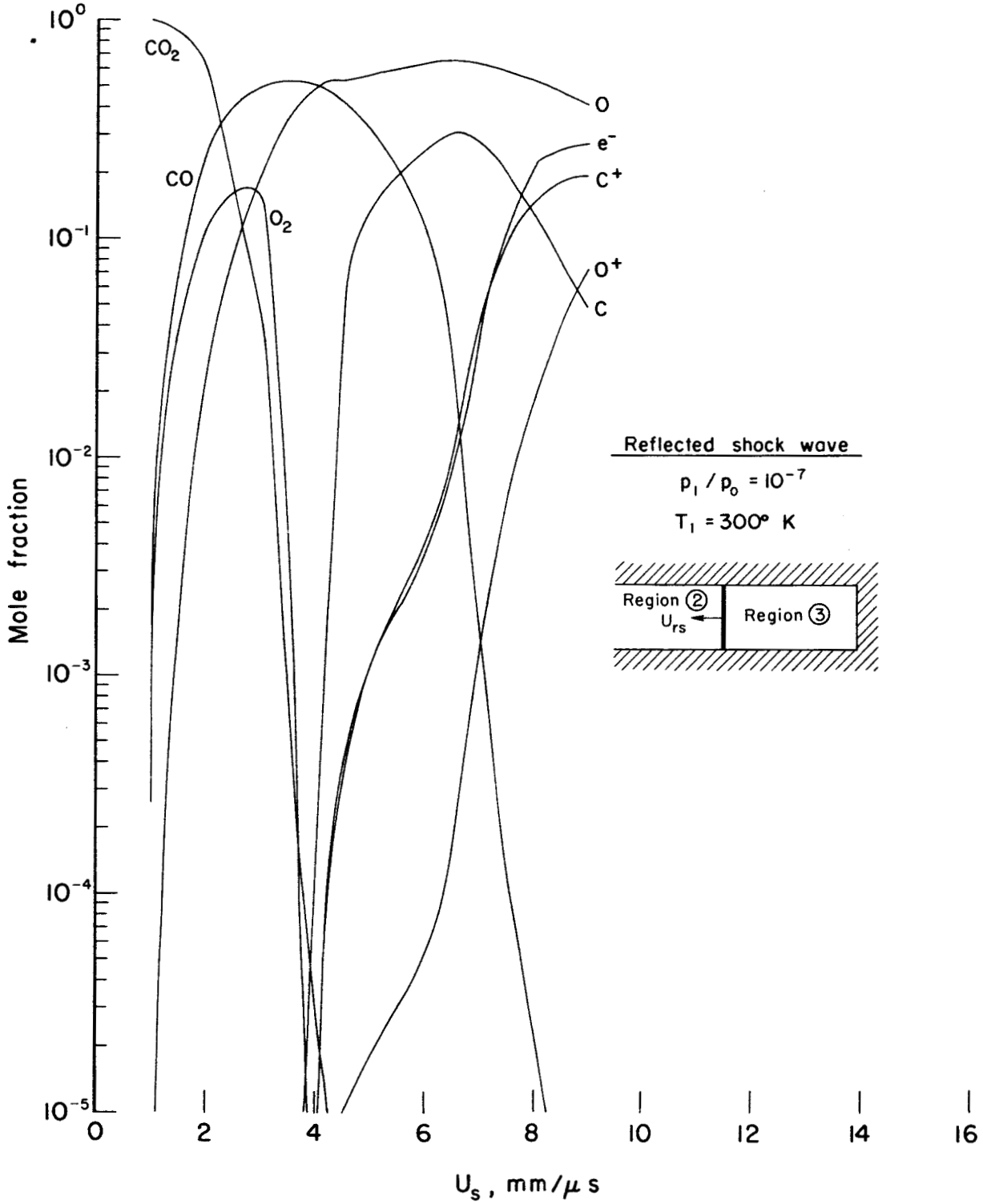
(a) Chemistry and vibrations in equilibrium in all regions and chemistry frozen with unexcited vibrations in all regions.

Chart 62.- Variation with incident shock wave speed of entropy change across a reflected shock wave.



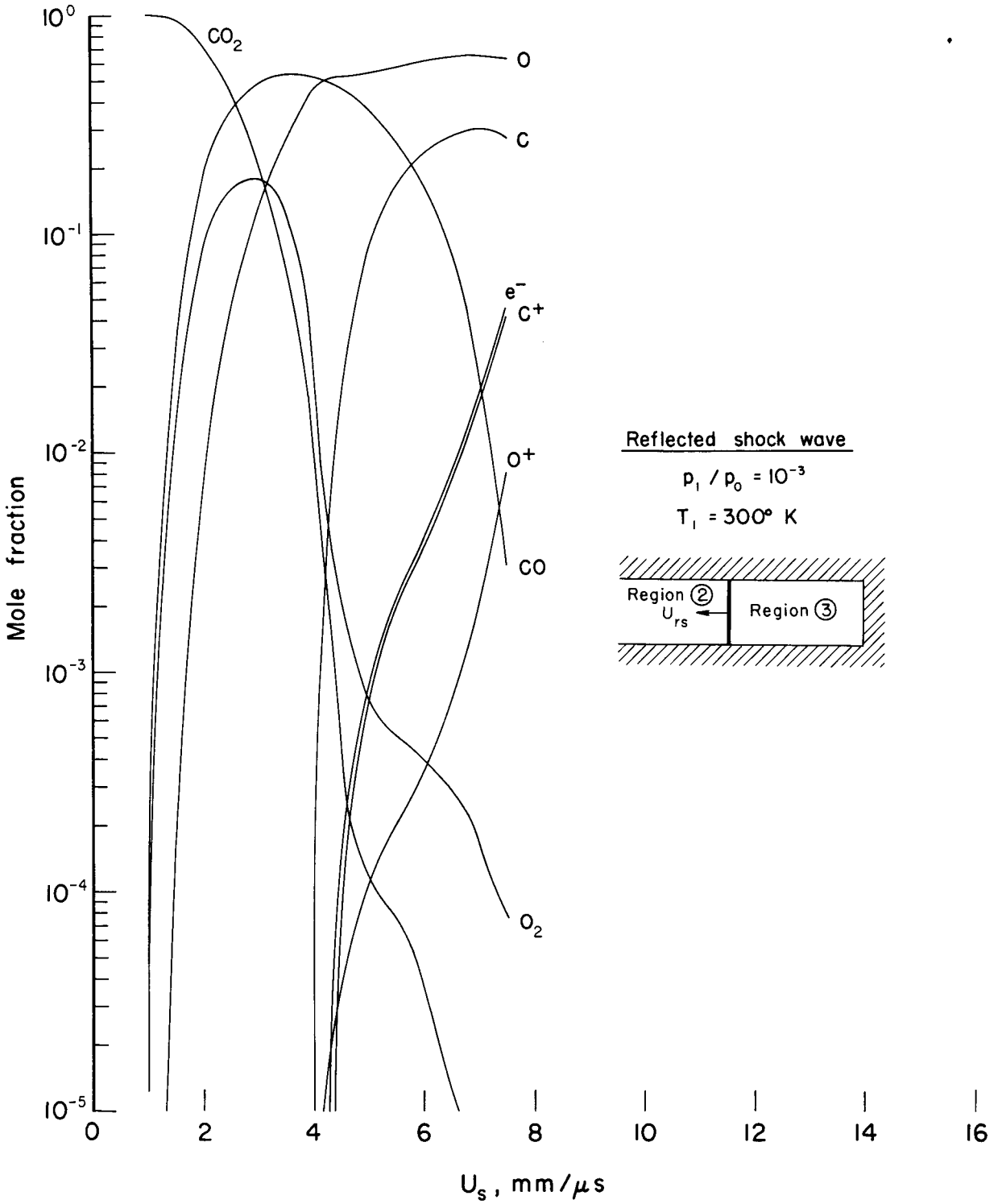
(b) Chemistry and vibrations in equilibrium in regions 1 and 3 and chemistry frozen with fully excited vibrations in region 2.

Chart 62. - Concluded.



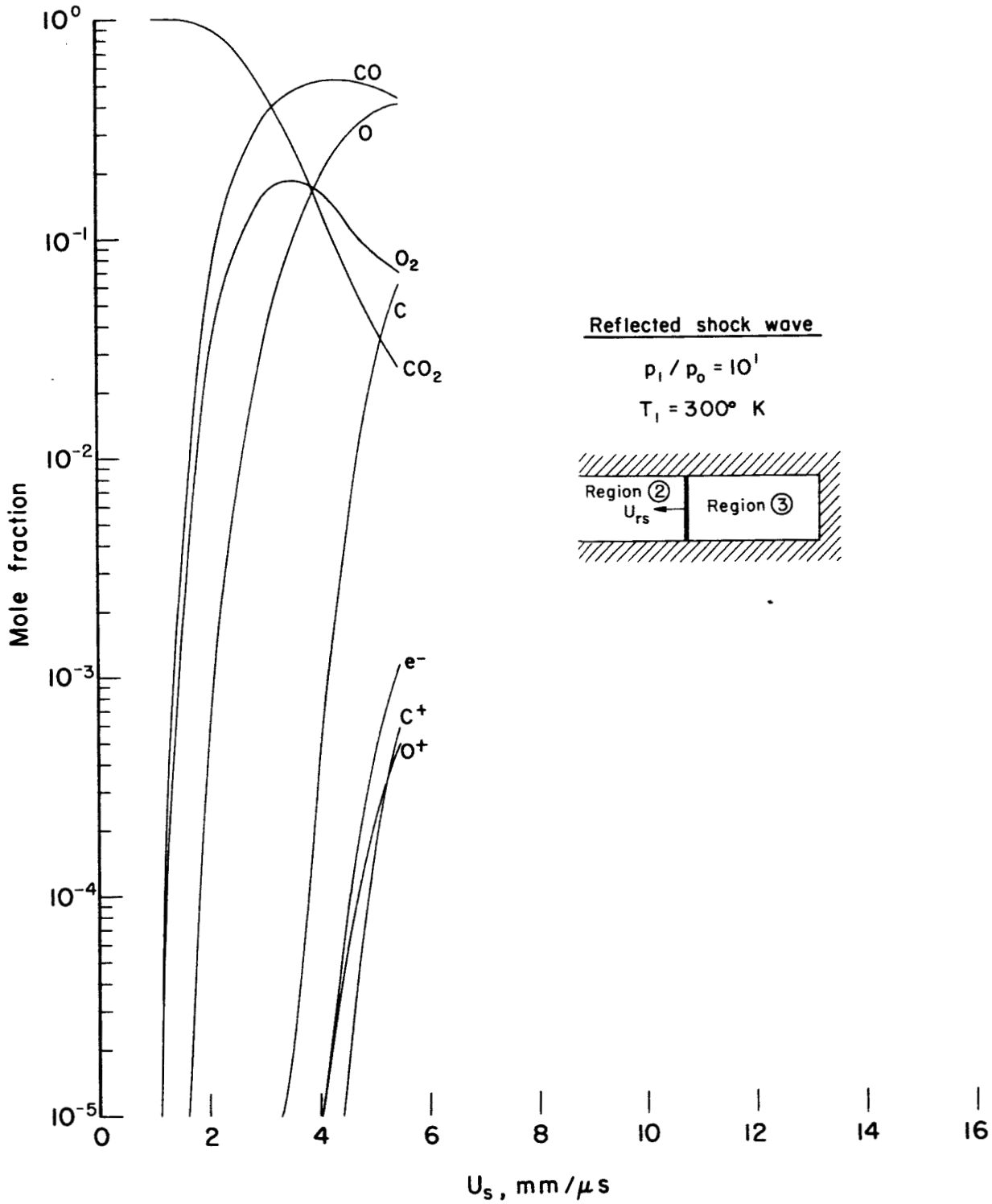
(a) $p_1/p_0 = 10^{-7}$

Chart 63. - Variation with incident shock wave speed of equilibrium flow chemistry downstream of a reflected shock wave.



(b) $p_1/p_0 = 10^{-3}$

Chart 63. - Continued.



(c) $p_1/p_0 = 10^1$

Chart 63. - Concluded.