

Selected Properties of Hydrogen (Engineering Design Data)

R. D. McCarty

J. Hord

H. M. Roder

Center for Chemical Engineering
National Engineering Laboratory
National Bureau of Standards
Boulder, CO 80303

Edited and compiled
by J. Hord



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R. D. McCarty, J. Hord, and H. M. Roder

ABSTRACT

The National Bureau of Standards has been engaged in the compilation, review, analytical and experimental derivation, and publication of hydrogen properties for over 20 years. The properties data presented herein are compiled largely from those accumulated data; of course, pertinent data and work of other researchers in the field are also included.

The general interests of scientists and engineers engaged in energy systems studies were given top priority in choosing the properties material presented in this book. Hydrogen systems cut across many energy related fields, e.g., nuclear fusion, magnetohydrodynamics, electrolysis and thermochemical decomposition of water, coal and shale derivative fuels, solar and wind power, ocean energy, geothermal processes, etc. It is generally conceded that hydrogen could be used to satisfy virtually all fuel requirements that are currently being met with natural gas and oil. To satisfy the demand for properties data over this broad spectrum of interests, we have attempted to provide comprehensive coverage of physical properties over a wide range of pressures and temperatures.

Thermophysical properties of liquid, liquid-vapor, vaporous, and gaseous hydrogen are presented in Chapter 1 and the solid-liquid, solid-vapor, and solid phase properties are compiled in Chapter 2. Ortho-para modifications of the hydrogen molecule and attendant property variations are considered in both chapters. Combustion and safety data, pertinent to hazard analysis of hydrogen systems, is collected in Chapter 3. Important miscellaneous properties are compiled in Chapter 4, data figures are compiled in Chapter 5, data tables are collected in Chapter 6, and Chapter 7 summarizes symbols, units, and conversion factors used throughout the book.

Key words: Hydrogen; hydrogen computer codes; hydrogen design data; hydrogen-gas; hydrogen graphs; hydrogen handbook; hydrogen-liquid; hydrogen properties; hydrogen safety; hydrogen-solid; hydrogen tables; hydrogen thermophysical properties.

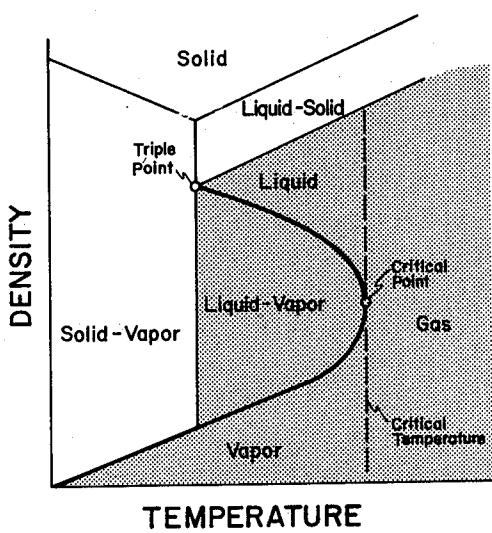
PREFACE

The National Bureau of Standards (NBS) has been engaged in the compilation, review, analytical and experimental derivation, and publication of hydrogen properties for over 20 years. The properties data presented herein are compiled largely from those accumulated data; of course, pertinent data and work of other researchers in the field are also included. This compilation was completed in March 1978 and data preparation, editorial review, and final manuscript revisions were completed in October 1980.

The general interests of scientists and engineers engaged in energy systems studies were given top priority in choosing the properties material presented in this volume. Hydrogen-energy systems cut across many energy related fields, e.g., nuclear fusion, magnetohydrodynamics, electrolysis of water, thermochemical decomposition of water, coal gasification, solar power, wind power, ocean energy, geothermal processes, etc. It is generally conceded that hydrogen could be used to satisfy virtually all fuel requirements that are currently being met with natural gas and oil. To satisfy the demand for properties data over this broad spectrum of interests, we have attempted to provide comprehensive coverage of physical properties over a wide range of pressures and temperatures. This new compilation provides 519 references, 62 data figures, and 30 data tables.

Chapter 1 is a heavily revised and updated version of NASA special publication SP-3089.* Tabulated data in this chapter have been revised to emphasize the higher temperature data for normal hydrogen and the lower temperature data for parahydrogen. This emphasis is necessary to provide coverage for a general audience that is interested in higher temperature processes (thermochemical decomposition, electrolysis, coal gasification, and other synthetic fuel production processes, etc.) as well as low temperature processes (cryogenic purification, subliming refrigerators, liquid transport and storage, etc.). NASA SP-3089 contained inconsistent and erroneous tabulated data for vapor pressures of normal hydrogen and for thermal conductivities, viscosities, thermal diffusivities, and Prandtl Numbers of fluid hydrogen in certain thermodynamic regions. These erroneous data have been eliminated in the new compilation, and appropriate uncertainty statements for each property have been included in the text. The source document for this chapter (NASA SP-3089) also contained numerous errors in text, formulae, tabular data, and figures. All errors have been eliminated in those portions of the original work that are included in this new compilation. In addition, new descriptive equations and computer codes were developed to generate the new data (tables and figures) for Chapter 1. This chapter deals with the thermally variant properties of liquid, liquid-vapor, vaporous, and gaseous hydrogen. These fluid state regions are illustrated by the speckled area on the density-temperature phase diagram that follows. Both normal (75% ortho and 25% para content) and parahydrogen (0.21% ortho and 99.79% para content) properties are presented.

*See Reference 6.



Chapter 2 is a compilation of the thermophysical properties of solid-liquid, solid-vapor, and solid hydrogen. These thermodynamic states are illustrated by the non-speckled area on the accompanying density-temperature phase diagram. Again ortho-para modifications of the hydrogen molecule are taken into consideration in presenting the properties. As might be expected, there is some overlap of properties data (at the phase boundaries) between Chapters 1 and 2, but the redundancy is minimal and essential for continuity of the properties across phase boundaries.

Chapter 3 is a collection of chemical and physical data pertinent to the combustion characteristics of hydrogen. These data are frequently used to perform safety assessments of fuels in various applications; therefore, methane and gasoline properties are included for comparative purposes.

Chapter 4 is a compilation of various properties of hydrogen that could not logically be included in the first three chapters of this volume. Some of these properties address topics of major engineering significance, e.g., pressurization and heat transfer parameters, mixture properties, slush hydrogen technology, ortho-para modification, isotopes, etc.

Chapter 5 is a collection of the various figures and charts pertaining to the properties described in the first four chapters.

Chapter 6 collects the tables of properties as described in the first four chapters.

Chapter 7 provides the nomenclature for this volume and lists the conversion factors needed to use the miscellaneous units of data collected and presented herein. In a compilation of this type, it is not practical to convert the voluminous data to SI units. Also, opportunities for introducing new errors abound when constructing new SI figures from non-SI figures; therefore, most of the original figures and charts are used and are presented herein exactly as they appeared in their original publication. Consequently, a full mix of engineering and scientific units are retained. We have adhered to the SI system of units in those cases where new figures and tables have been generated for this volume. To accelerate the use of SI units, we have also provided dual units or SI unit conversion factors throughout the text where original non-SI data are reported or discussed.

The authors gratefully acknowledge the expert assistance of Mary J. Pritchard and Grace R. Darr in the preparation of the text and the artistic efforts of Lewis J. Ericks in composing many of the thermodynamic diagrams.

J. Hord
Boulder, CO
October 1980

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CHAPTER ONE

**THERMOPHYSICAL PROPERTIES OF HYDROGEN FROM THE
FREEZING LIQUID LINE TO 3000 K AND 100 MPa**

Robert D. McCarty

1.1. INTRODUCTION

This chapter contains the available thermophysical properties of hydrogen in the liquid, liquid-vapor, and gaseous states. The work was performed at the Cryogenic Data Center of the National Bureau of Standards in Boulder, CO.

The Cryogenic Data Center has been collecting data and documents pertinent to the field for 20 years and presently has about 120,000 coded entries which may be computer searched to give bibliographies on the physical properties of materials at low temperatures. A computer search of the data center holdings produced a bibliography for hydrogen of about 2,500 references. All of these references were considered; only selected references appear here as a result of the review and editing process.

The scope of this chapter is defined as all physical properties of fluid hydrogen (chemical properties were excluded).

Papers on engineering processes utilizing hydrogen were specifically excluded in the bibliographic search and subsequent review. The subject of hydrogen embrittlement of materials is not treated here (see Reference 1).

The level of review of the properties of hydrogen varies from the extensive tabulations of "critically evaluated" thermodynamic and transport properties to the selection of a few representative values from the literature by persons knowledgeable in the field. In the latter case the data selected were judged to be the most useful to the largest number of potential users of these data. For those who need to pursue the subject in greater detail, a list of references is provided.

1.1.1. DESCRIPTIVE SHEETS

These sheets serve as the starting point for the use of this chapter.

For a given property each sheet usually contains the following:

- A. A brief description or definition of the property to distinguish between similar sounding terms.
- B. A locator of tabular values of the property. The range and units of the tables are given for convenience.
- C. A locator of graphs and charts of the property.
- D. Mathematical equations which represent the property provided that the functional form is simple.
- E. One or more values of the property, usually at fixed points to illustrate the range of the property.
- F. An estimate of uncertainty is usually given. It is made on a 2σ level of probability. This means that there is a 95% chance that new experimental measurements (of equal or greater accuracy) of the property will fall within a 2σ band of the quoted numbers. The estimate of the uncertainty of a property is seldom straightforward and is often made on the basis of the accuracy of the instrumentation used rather than the random scatter of a given set of data. In the case of a property that is tabulated over a wide range of pressures and temperatures, the stated uncertainty is for the most uncertain value, and the uncertainty of most of the tabular entries is much less. Exceptions to the above convention are noted individually on the descriptive sheets. The most common exception is the critical region where the uncertainty of most properties is greater than the stated value. In no case should the quoted uncertainty be associated with values from other than recommended sources or values extrapolated from the tables.
- G. A list of references is given with each descriptive sheet.

1.1.2. FIGURES

Chapter 5 of this volume is a collection of hydrogen property charts and diagrams. These figures were taken from the literature in the original form of presentation; consequently, the units are a complete mix of SI, metric, and English. In most cases the prime purpose of the figures is to illustrate the behavior of a property over a wide range of pressures and temperatures. Although the figures will provide adequate values for rough calculations, the tabular values are recommended for precise calculations.

1.1.3. TABLES

Tables of properties are collected in Chapter 6 of this volume. The extensive tabulations of thermodynamic and transport properties cover the range from the triple point to 3000 K, with pressures to 100 MPa. They are presented in SI units for both para and normal hydrogen.

1.1.4. COMPUTER PROGRAMS AND EXTRAPOLATION

In many instances a computer program is a convenient source of property data. In other instances, particularly where a large number of values is needed in a short time, a computer program to furnish these values is a necessity. For these and other reasons, the use of computer programs to furnish fluid property data has steadily increased in recent years. This increased usage has resulted in a variety of computer programs. At the present time there does not seem to be a single program that will satisfy every need, and a choice must often be made on the basis of the particular

job requirements. Table 1 lists the more important fluid property programs for hydrogen and some of the pertinent information needed to select the proper program for a particular job. A column-by-column description of Table 1 is given below.

A. Column 1 lists four general methods used to computerize the thermodynamic properties of fluids. The linear interpolation method is, as the name implies, tabular interpolation of property values stored in the computer. This method is fast but not very accurate and requires more computer core storage than the other methods. The most accurate method, if programmed properly, is polynomial interpolation. The disadvantages of the polynomial method are a lack of versatility and slow computations relative to the other methods. A good compromise and a widely used method is the equation-of-state approach using a modified Benedict Webb Rubin (MBWR) equation. This method offers accuracies only slightly worse than the polynomial interpolation method and has the advantages of being faster and more versatile and giving a continuous, thermodynamically consistent surface. The main disadvantage of the MBWR is that it is functionally incorrect in the critical region, i.e.,

$$\rho = \rho_c \pm 20\% \text{ and } T = T_c \pm 5\%$$

The nonanalytic equation-of-state approach (no programs using this method are listed in Table 1) gives theoretically correct results in the critical region, but these equations are usually difficult to use.

B. Column 2 gives the range of validity of a program in terms of pressure and temperature limits. Extrapolation of these programs beyond the stated limits is not recommended. If properties are needed beyond the stated

range of validity, the list of references given for that property in Section 1.2 should first be scanned, as references to properties at extreme temperatures and pressures have been noted there. If extrapolation of one of the programs is necessary, the modified BWR equation of state is the most convenient to use and least likely to yield large errors.

C. The symbols used in column 3 are defined as follows:

P = pressure
T = temperature
ρ = density
H = enthalpy
S = entropy
 λ = thermal conductivity
 η = viscosity
 c_p = specific heat capacity at constant pressure
 c_v = specific heat capacity at constant volume
 ϵ = dielectric constant
 γ = surface tension
E = internal energy
RI = refractive index
 ω = speed of sound

The units of the properties vary from program to program.

D. The accuracy of the properties calculated from these programs varies from property to property within a given program. The accuracies quoted in column 4 are for densities calculated from a P-T input. Since they are an estimate of the average accuracies, they are most useful as a basis of comparison with the other programs.

E. Column 5 is self-explanatory. Copies or use of the program may be obtained by contacting the agency listed.

F. For certain applications the mathematical continuity of the properties is important. In other words, the numbers coming from the program must not contain abrupt changes in the property or derivatives. Such requirements often occur in iterative calculations. If column 6 has a "no" in it, discontinuities may be expected.

G. The modification in column 7 refers to the relative orientation of the nuclear spin of the two hydrogen atoms in the molecule (see the explanation in Chapter 4 under ortho-para modifications).

H. The input to the various programs is given in column 8. The units of both input and output of the programs are not mentioned because in some cases a choice of units is available and in most cases the user converts the units to suit his/her particular need. An explanation of the input and output is furnished when the program is requested.

1.1.5. EVALUATION OF THE LITERATURE

The preparation of this review involved the evaluation of each reference to hydrogen data found in the literature. The Cryogenic Data Center's storage and retrieval system was queried for references pertaining to the physical properties of hydrogen (chemical properties excluded); this search yielded 2,543 references. The resulting bibliography from the Cryogenic Data Center was further cross referenced by property, which greatly aided the evaluation process.

In many cases preliminary examination of the bibliography for a given property was sufficient to determine whether or not an article should be included. In the final evaluation process a copy of each remaining article was then obtained, and evaluation was made on the basis of content of the article.

1.1.6. CRITICAL SELECTION OF "BEST VALUES"

When selecting so-called "best values" many factors must be considered. The first tendency is to equate "best" with most accurate; indeed, in some cases this is true, but in other cases it is not. For example, in many engineering problems a continuous and thermodynamically consistent set of properties is of utmost importance. This is not to say that accuracy is not important. In the selection process both factors were considered. Selections were made to provide the most accurate and consistent set of properties over the widest possible range of pressures and temperatures.

In that regard, Tables 2, 3, 8 and 9 are thermodynamically consistent and mathematically continuous. The properties given in these tables were calculated by means of a computer program (see Table 1) which is available from the Cryogenic Data Center.

1.1.7. ACKNOWLEDGMENTS

Much of this work was originally performed under the sponsorship of the Aerospace Safety Research and Data Institute of the NASA Lewis Research Center and was first published in 1975 as NASA SP-3089.⁶ Many changes in format and content have been made for presentation in this revised compilation. The author is also indebted to many of his colleagues for their original contributions to the preparation of this chapter--specifically, V. J. Johnson, Phil Angerhofer, Mildred Birchfield, and Salli Schiffmacher of the NBS and Paul Ordin and George Mandel of the NASA.

1.2. DISCUSSION OF THE PROPERTIES

Hydrogen is the first element in the periodic table with the atomic number 1; therefore, it is the lightest of all gases. On the earth hydrogen occurs chiefly in combination with oxygen as water. It is the most abundant element in the universe. It is a colorless, tasteless, and odorless gas and liquefies at atmospheric pressure at 20.27 K. In recent years hydrogen has been used extensively as a chemical feedstock and as a rocket fuel in the space effort. It is now being seriously considered as a recyclable fuel substitute for petroleum and natural gas.

1.2.1. COMPRESSIBILITY COEFFICIENT^{4, 7, 8}

Definition - The compressibility coefficient is defined as

$$- \frac{P}{V} \left(\frac{\partial V}{\partial P} \right)_T$$

Tables of Values - This quantity is not tabulated here, but it may be easily obtained by forming the product of P times the isothermal compressibility (see Subsection 1.2.4). The reciprocal of the isothermal compressibility, $V(\partial P / \partial V)_T$, is tabulated in Tables 2, 3, 8, and 9.

Units	Range of table	Table location
Dimensionless	13.8 - 3000 K	0.01-100 MPa 2, 8
Dimensionless	Saturation boundary	3, 9

Note: The tables reflect no differences for this property due to ortho-para modifications.

Figure - None

Equation - See Subsection 1.2.12

Range of Values - Para and normal

Units	Triple point		Boiling point		Critical point	RTP*
	Liquid	Vapor	Liquid	Vapor		
Dimensionless	7.79×10^{-5}	1.02	2.02×10^{-3}	1.12	∞	1.0

Uncertainty - For values derived from tables listed above, the uncertainty varies from 0% in the low density limit to about 3 to 4% at 35 MPa and 10% at 100 MPa. In the critical region ($T_c \pm 5\%$ and $p_c \pm 20\%$) the uncertainties are greater and very difficult to estimate as the property diverges at the critical point.

1.2.2. ACCOMMODATION COEFFICIENT⁹

Definition - The accommodation coefficient, a , is defined as the ratio $a = (E_i - E_r)/(E_i - E'_r)$, where $(E_i - E_r)$ is the mean energy change of molecules colliding with a wall and $(E_i - E'_r)$ is the mean energy change if the molecules come into thermal equilibrium with the wall.

Discussion - The accommodation coefficients of gases on solids are used to estimate heat conduction by gases at low pressures ($P \leq 13.0$ Pa). The accommodation coefficient is a function of the gas, temperature, and characteristics of the solid surface, especially the smoothness and cleanliness. In general, the lighter the gas, the higher the temperature and the smoother and cleaner the surface, the smaller is the value of the accommodation coefficient. The coefficient is independent of the pressure if the pressure is sufficiently high ($P \geq 13.0$ Pa) to insure a monomolecular gas film on the solid surface.

* RTP = room (reference) temperature and pressure--300 K and 0.101325 MPa (1 atm).

Tables of Values - None

Figure - None

Equation - None

Range of Values -

At room temperature
Units $P \approx 13.0 \text{ Pa}$

Dimensionless $a = 0.311$ on platinum⁹

Uncertainty - The uncertainty is estimated to be +1%

1.2.3. COMPRESSIBILITY FACTOR^{4, 7, 8}

Definition - The compressibility factor is defined as $Z = PV/RT$.

Tables of Values - This quantity is not tabulated but may be simply obtained by forming PV/RT from Tables 2, 3, 8, and 9.

Figure - 1

Equation - See Subsection 1.2.12

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Dimensionless	0.00161	0.9852	0.01712	0.9060	0.3024	1.0006

Uncertainty - The uncertainty of Z derived from the tables in Chapter 6 will correspond to the uncertainty of the PVT in the above tables. McCarty and Weber⁷ estimated these uncertainties to be

Temperature range	Pressure range	Uncertainty in density
700 - 3000 K	1 - 100 MPa	1% (extrapolation)
300 - 700 K	1 - 35 MPa	0.5%
300 - 700 K	35 - 100 MPa	
13 - 300 K	1 - 100 MPa	0.1% (except critical region)
Critical region	$T_c \pm 5\%, P_c \pm 20\%$	6%

The uncertainties quoted here are for parahydrogen. The tables in Chapter 6 reflect no difference in Z between the normal and para modifications. To estimate the uncertainties for the normal hydrogen tables, add 0.1% for temperatures above 100 K, 0.2% for temperatures between critical and 100 K, and 0.4% for the compressed liquid region.

Ortho-para Differences^{4, 7} - There is probably a very small difference in densities (less than 0.1%) between the ortho and para modifications. An exception is the saturated vapor and liquid densities where the difference is larger due to a difference in the vapor pressure curve (see Chapter 4).

1.2.4. ISOTHERMAL COMPRESSIBILITY^{4, 7, 8}

Definition - The isothermal compressibility is defined as

$$\beta_T = \frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T$$

Tables of Values - The reciprocal of the isothermal compressibility is given in Tables 2, 3, 8, and 9.

Units	Range of table	Table location ^a
MPa ⁻¹	13.8 - 3000 K	0.01 - 100 MPa
MPa ⁻¹	Saturation boundary	2, 8

^aTo make the table entries positive, $-1/\beta_T$ is tabulated. The isothermal compressibility is a negative quantity.

Figure - None

Equation - See Subsection 1.2.12

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
MPa ⁻¹	-1.10×10^{-2}	-145	-1.99×10^{-2}	-11.1	∞	-10

Note: The tables in Chapter 6 reflect no differences in this property for the normal and para modifications.

Uncertainty - The uncertainty for values obtained from the tables in Chapter 6 varies from 0% in the low density limit to about 3 to 4% at 35 MPa and 10% at 100 MPa. In the critical region ($T_c \pm 5\%$ and $\rho_c \pm 20\%$) the uncertainties are much greater and very difficult to estimate as the property diverges at the critical point.

1.2.5. ADIABATIC COMPRESSIBILITY^{4,7,8}

Definition - Adiabatic compressibility is defined as

$$\beta_S = - \frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_S$$

A useful relation is

$$\beta_S = \frac{C_V}{C_P} \beta_T$$

where β_T is the isothermal compressibility.

Tables of Values - This quantity is not tabulated, but it may be obtained by means of the relationship $\beta_S = 1/\rho W^2$, where ρ is density and W is sound velocity, from the tables listed below.

Units	Range of table	Table location
MPa^{-1}	13.8 - 3000 K	0.01 - 100 MPa 2, 8
MPa^{-1}	Saturation boundary	3, 9

Figure - None

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para MPa ⁻¹	0.00807	8.56	0.0119	5.93	∞	7.29

Uncertainty - The uncertainty in the compressed liquid varies between 2% at low pressures to 4% at high pressures; in the gas, well above the critical temperature, it is 1%. In the critical region ($T_c \pm 5\%$ and $\rho_c \pm 20\%$) the uncertainties are undoubtedly larger; however, they are not experimentally defined as the property diverges at the critical point.

1.2.6. DIELECTRIC CONSTANT¹⁰⁻¹⁹

Definition - The dielectric constant of a material may be defined as $\epsilon = C(P,T)/C(0,T)$, where $C(P,T)$ is the capacitance of a capacitor whose plates are separated by the material at pressure P and temperature T, and $C(0,T)$ refers to the capacitance of the same capacitor in a vacuum. In practical situations corrections are often applied for pressure distortion of the capacitor. The equation assumes no stray capacitances, i.e., the electric field is affected only by the dielectric material. Note: The dielectric constant is also known as specific inductive capacity.

Tables of Values - This quantity is tabulated in the tables in Chapter 6.

Units	Range of table	Table location
Dimensionless	0.01 - 100 MPa	13.8 - 3000 K 2, 8
Dimensionless	Saturation boundary	3, 9

Figure - 2 and 3

Equation - The dielectric constant for the fluid parahydrogen may be calculated from

$$\frac{\epsilon - 1}{\epsilon + 2} = A\rho + B\rho^2 + C\rho^3$$

where $A = 0.99575$, $B = -0.09069$, $C = 1.1227$, and ϵ is the dielectric constant.

The density, ρ , must be in the units of grams per cubic centimeter. The equation is valid over the range of the tables and may be extrapolated in the fluid phase with reasonable results.

Range of Values -

Units	Triple point			Boiling point		Critical point	RTP
	Liquid	Vapor	Solid	Liquid	Vapor		
Dimensionless	1.252	1.0004	1.285	1.229	1.004	1.0980	1.00025

Uncertainty - The uncertainty of $\epsilon - 1$ is estimated to be no greater than 0.1% for the fluid phase and 0.2% for the solid phase.

1.2.7. DIELECTRIC BREAKDOWN

Liquid²⁰⁻²⁹ - Below some critical electric field gradient, called the "breakdown voltage," hydrogen is an insulator. In recent years there have been a few experiments to determine this breakdown voltage for liquid hydrogen. Two things seem evident from these experiments. First, there is a fairly large dispersion in the measurements (reproducibility in a single experiment commonly has a 25% scatter); second, the breakdown voltage is quite sensitive to pressure changes, i.e., an increase from 300 to 690 kV/cm was observed when the pressure was increased from 0.101325 to 0.506625 MPa (1 to 5 atm) at 20 K.²³

Gas^{20, 21, 23, 28, 30-44}- Hydrogen in the gaseous phase is, like the liquid, an insulator below some critical field gradient. When the critical voltage is reached, the gas ionizes, a corona results, and the conduction takes place. This breakdown voltage follows Paschen's law, which states the breakdown voltage, V, does not change as long as ρd is a constant and it is proportional to ρd , i.e., $V \propto \rho d$, where ρ is the density and d is the electrode spacing. This relation is surprisingly independent of temperature, although some investigators claim to have observed temperature dependence at low temperatures. Also, a minimum breakdown voltage for hydrogen has been observed at about 250 to 300 V at a ρd of 10^{-7} g/cm².

Electrical Conductivity^{29, 45-50}

Hydrogen is essentially an insulator with a negligible electrical conductance except when voltages in excess of the breakdown voltages are applied. At elevated temperatures where ionization occurs, the gas becomes an electrical conductor, and conductivities for hydrogen to 30,000 and 40,000 K have been calculated.^{36, 37} A significant experimental paper on electrical conductivity of the liquid is that of Willis.⁴⁷

1.2.8. DIFFUSION COEFFICIENT

Definition - The diffusion coefficient is defined as the coefficient relating the flux of a given species in a mixture to the concentration gradient of the species under isothermal conditions. For a binary mixture of species i and j: $J_i = -D_{ij} \text{ grad } C_i$, where J_i is the mass flux of i, C_i is the gradient of concentration, and D_{ij} is the diffusion coefficient. Diffusion is usually thought of as a property of mixtures; however, the term self-diffusion, as the name implies, refers to a diffusion of a single

species. There is, of course, no true means of measuring such a quantity, so the process is simulated using different isotopes of the same species. A third type of diffusion appears in the literature for hydrogen where the binary mixture is that of molecules with different nuclear spin orientation, i.e., ortho-para mixtures.

Thermal Diffusion

Definition - In a binary system where a temperature gradient exists, the above equation should be extended to $J_i = -D_{ij} \nabla C_i - D_{ij}^T \nabla \ln T$, where D_{ij}^T is the thermal diffusion coefficient. The same extension is made to isotopic and ortho-para mixtures.

The information on the diffusion of hydrogen has been categorized according to the above definitions; references are listed below.

Equations - From kinetic theory, for a dilute gas $D_{ij} \propto T^{3/2}$, and at room temperature D_{ij} for hydrogen systems is about $1 \text{ cm}^2/\text{s}$; T is temperature.

For liquid or gas dissolved in a liquid

$$\frac{D_{ij}\eta}{T} = \text{constant}$$

where η is the viscosity of the mixture and T is temperature. D_{ij} for H_2 in a liquid is about $10^{-4} \text{ cm}^2/\text{s}$.

References -

A. Diffusion

1. Isothermal⁵¹⁻⁵⁵
2. Thermal
 - a. Argon⁵⁶⁻⁵⁹
 - b. Krypton^{54, 56, 58, 59}
 - c. Xenon^{58, 60-64}
 - d. CO₂^{57, 65-67}
 - e. SO₂⁵³
 - f. H₂O^{53, 68}
 - g. N₂O⁶⁹
 - h. O₂^{70, 71}
 - i. CO⁷¹
 - j. N₂^{57, 58, 64, 66, 67, 70-73}
 - k. Ne^{74, 75}
 - l. (He⁴)^{58, 64, 70, 71, 76-84}
 - m. (He³)⁵⁹

B. Self-diffusion

1. Isothermal^{55, 79, 80, 85-89}
 - a. High temperatures^{37, 90}
 - b. Solids⁹¹
2. Thermal^{57, 76-78, 80, 92-101}
3. Ortho-para^{84, 99, 100, 102}

1.2.9. THERMAL DIFFUSIVITY^{4, 7, 8}

Definition - The thermal diffusivity, α , is defined as

$$\alpha = \frac{\lambda}{\rho C_p}$$

where λ is the thermal conductivity, ρ is the density, and C_p is the specific heat capacity at constant pressure.

Tables of Values - This quantity is tabulated in the tables in Chapter 6.

Units	Range of table	Table location
m^2/h	13.8 - 3000 K	0.01 - 100 MPa 2, 8
m^2/h	Saturation boundary	3, 9

Figure - None

Equation - None, except above and the equation of state (see Subsection 1.2.12).

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
m^2/h	0.00053	0.034	0.00052	0.0038	0	0.57

Note: Values for normal and para are the same at these state points but differ at other state points.

Uncertainty - The uncertainty of the values tabulated in Chapter 6 is estimated to be $\pm 14\%$, except in the critical region ($T_c \pm 5\%$ and $\rho_c \pm 20\%$) and for $T < 100$ K and $P > 35$ MPa where the uncertainty is unknown.

1.2.10. ENTHALPY^{4, 7, 8}

Definition - Enthalpy is defined by the equation $H = U + PV$, where U is the internal energy, H is the enthalpy, and PV is the product of pressure and volume. The change in enthalpy is a measure of the heat absorbed by a system in a constant pressure process. The enthalpy of a substance is a derived thermodynamic property and may be calculated by means of a thermodynamic relationship which requires the PVT surface (see Subsection 1.2.12) and the specific heat capacity (see Subsections 1.2.16 through 1.2.19).

Tables of Values - Tabulated in Tables 2, 3, 8, and 9.

Units	Range of table	Table location
J/g	13.8 - 3000 K	0.01 - 100 MPa 2, 8
J/g	Saturation boundary	3, 9

Figure - 4, T-S chart (para); 5, T-S chart (para); 6, T-S chart (normal); 7, T-S chart (normal); 8, T-S chart (normal).

Equation - None (see above)

Range of Values - The reference state for enthalpy is zero for the ideal gas at zero absolute temperature (see Subsection 1.2.20).

Units	Triple point		Boiling point		RTP
	Liquid	Vapor	Liquid	Vapor	
Para					
J/g	-308.8	140.3	-256.3	189.3	4199.4
Normal					
J/g	218.3	667.4	270.9	716.5	4226.9

Uncertainty - The uncertainties of the enthalpy values tabulated here vary somewhat with pressure and temperature. In the region of $T < 300$ K, uncertainty is estimated to range from 1.2 J/g at low densities to about 5.0 J/g in the liquid. For all densities at $300 < T < 500$ K the uncertainty is estimated to vary from 1 J/g at low pressures to about 15 J/g at the highest pressures. For temperatures above 500 K the uncertainty of the enthalpy at the lower densities could be much greater, especially for temperatures above about 1800 K where dissociation is a large factor.

1.2.11. ENTROPY^{4, 7, 8, 110}

Definition - Entropy is defined by the equation $dS = dQ/T$, or in any reversible process the change in entropy of a system is equal to the heat which it absorbs, divided by the absolute temperature. The entropy of a substance is a derived thermodynamic quantity, and many thermodynamic equations exist which relate the PVT surface of a substance to the changes in entropy. In addition to the PVT surface, or an equation of state, the specific heat capacity of a substance is needed to complete the calculation.

Tables of Values - This quantity is tabulated in Tables 2, 3, 8, and 9.

Units	Range of table	Table location
J/g-K	13.8 - 3000 K	0 - 100 MPa 2, 8
J/g-K	Saturation boundary	3, 9

Figure - 4, T-S chart (para); 5, T-S chart (para); 6, T-S chart (normal); 7, T-S chart (normal); 8, T-S chart (normal).

Equation - None (see definition)

Range of Values - The reference state for entropy is the ideal gas at 0.101325 MPa (1 atm) pressure and zero absolute temperature (see Subsection 1.2.20).

Units	Triple point		Boiling point		RTP
	Liquid	Vapor	Liquid	Vapor	
Para					
J/g-K	4.964	37.52	7.977	29.97	64.77
Normal					
J/g-K	14.08	46.64	17.09	39.08	70.58

Uncertainty - The uncertainty of the entropy values tabulated here varies somewhat with pressure and temperature. In the region $T < 300$ K, the uncertainty is estimated to range from 0.04 J/g-K at low pressures to 0.17 J/g-K at the higher pressures. For all P at $300 < T < 500$ K the uncertainty

is estimated to vary from 0.05 J/g-K at low pressures to about 1.0 J/g-K at the highest pressures. For temperatures above 500 K the region is again one of extrapolation and the uncertainties are greater, especially for the low pressures at temperatures above 1800 K where dissociation becomes significant.

Figures 6, 7, and 8 are the best available T-S diagrams for normal hydrogen. These data will differ from those presented in Tables 8 and 9 because the tables and the figures are derived from different references; however, both the tables and the figures are internally consistent so that either the figures or the tables may be used for engineering calculations, but data should not be transposed or transferred from one to the other.

1.2.12. EQUATION OF STATE^{2,4,7,8,103-105}

Definition - The relationship between the pressure, temperature, and density of a substance is called the equation of state. This section will be concerned with the mathematical model of the equation of state. Because of the speed and availability of today's digital computers, the mathematical equation of state is an extremely useful tool. There are literally hundreds of these to be found in the literature. To recommend an equation of state, the detailed requirements must be known, or, to put it another way, there is no single mathematical model of the equation of state that will be the best choice for every purpose.

Equations - For the equations used to generate Tables 2, 3, 8, and 9, see References 4, 7, 8, and 104, 105. For a more versatile but not quite as accurate equation of state, see Reference 2. For an equation of state designed for extremely high-speed computation but less accuracy, see Reference 103. See also the main text on computer programs and Subsection 1.2.13.

1.2.13. VIRIAL COEFFICIENTS^{4,7,8}

Definition - The virial coefficients are commonly defined in two ways, as follows: $P = RT\rho[1 + B(T)\rho + C(T)\rho^2 + \dots]$ and $PV = RT + B'(T)P + C'(T)P^2$.

The first two terms of these series may be inverted by the following:

$$B(T) = B'(T) \text{ and } C'(T) = \frac{C(T) - B(T)^2}{RT}$$

where P is pressure; T is temperature; ρ is density; V is $1/\rho$; R is the gas constant; and $B(T)$, $B'(T)$ and $C(T)$, $C'(T)$ are virial coefficients of a power series expansion in density and pressure, respectively. Both series are theoretically infinite in length; however, the coefficients beyond the first two [$B(T)$ and $C(T)$] are of less interest because of their complexity. The temperature at which $B(T) = 0$ is called the Boyle temperature. Either of the above two equations is adequate to describe the PVT surface for densities up to about one half the critical density. The coefficients $B(T)$ and $C(T)$ for the density expansion are given in Table 4. Most equations of state may be algebraically arranged so that they are in a virial expansion form; therefore, these equations of state may be used to calculate the virial coefficients (see Subsection 1.2.12 for equations of state).

Tables of Values -

Units	Range of table	Table Location
$B(\text{cm}^3/\text{mol})$, $C(\text{cm}^3/\text{mol})^2$	14 - 500 K	4

Figure - None

Equation - The values in Table 4 have been calculated from the following expressions. For temperatures below 100 K,

$$B(T) = (b_1 T + b_2 + b_3/T + b_4/T^2)/RT$$

where $b_1 = 1.9397741 \times 10^3$, $b_2 = -1.9279522 \times 10^5$, $b_3 = -2.2890051 \times 10^6$, $b_4 = 1.1094088 \times 10^7$, $R = 82.0597 \text{ cm}^3\text{-atm/mol-K}$ and $T = \text{Kelvin temperature.}$

For $T < 55 \text{ K}$,

$$C(T) = (C_1 T^2 + C_2 T + C_3 + C_4/T + C_5/T^2 + C_6/T^3)/RT$$

There are two sets of C_1 coefficients: one for temperatures below $T_c = 32.957$,

$$C_1 = 1.0541776 \times 10^5$$

$$C_2 = -1.6597141 \times 10^7$$

$$C_3 = 1.0431411 \times 10^9$$

$$C_4 = -3.2538718 \times 10^{10}$$

$$C_5 = 5.1405848 \times 10^{11}$$

$$C_6 = -3.3123453 \times 10^{12}$$

and a second set for temperatures between T_c and 55 K,

$$C_1 = 1.6971294 \times 10^3$$

$$C_2 = -5.0854223 \times 10^5$$

$$C_3 = 6.7284118 \times 10^7$$

$$C_4 = -3.8045171 \times 10^9$$

$$C_5 = 1.0789413 \times 10^{11}$$

$$C_6 = -1.1515642 \times 10^{12}$$

For $55 < T < 100$,

$$C(T) = a_1 e^{a_2/T} [1 - e^{a_3} \{1 - (T/a_4)^{a_5}\}]$$

where $a_1 = 388.682$, $a_2 = 45.5$, $a_3 = 0.6$, $a_4 = 20.0$, and $a_5 = 4.0$.

For temperatures above 100 K,

$$B(T) = \sum_{i=1}^4 b_i x_i^{(2i-4)/4}$$

and

$$C(T) = C_0 x_2^{1/2} [1 + C x_2^3] [1 - \exp(1 - x_2^{-3})]$$

where $b_1 = 42.464$, $b_2 = -37.1172$, $b_3 = -2.2982$, $b_4 = 3.0484$, $x_1 = 109.781/T$, $C_0 = 1310.5$, $C = 2.1486$, and $x_2 = 20.615/T$.

Range of Values -

Units	20K	100 K	200 K	300 K
B(T)cm ³ /mol	146.7	-2.51	10.73	14.38
C(T)(cm ³ /mol) ²	-1503	608.6	421.7	343.8

Boyle Point (B = 0) - 112.4 K

Uncertainty - The uncertainty of B is probably a maximum of 5% at the highest and lowest temperatures. The uncertainty of C is a minimum of 5% between 55 and 100 K and as much as 20% for temperatures below critical temperature.

1.2.14. INTERMOLECULAR POTENTIAL FUNCTION¹⁰⁶⁻¹⁰⁹

Definition - The intermolecular potential function is the potential energy of interaction that exists between pairs of molecules. Mathematical models of this function are used to calculate macroscopic properties with kinetic theory and statistical mechanics.

General Comments - The potential energy of interaction between unlike molecules, i.e. hydrogen and some other fluid, has not been considered here. Only those papers with some relevance to H₂ - H₂ interactions have been used.

The Lennard-Jones Potential - The most common potential in the literature is the Lennard-Jones or 12-6 potential

$$\phi(r) = 4\epsilon \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^6 \right]$$

where $\phi(r)$ is the potential energy of interaction, r is the intermolecular separation, ϵ is the maximum energy of attraction, and σ is the intermolecular separation for which $\phi(r) = 0$. σ is sometimes referred to as the molecular diameter. Typical values for hydrogen¹⁰⁶ are $N\sigma = 15.6 \text{ cm}^3/\text{mol}$ and $\epsilon/K = 36.7$ where N is Avogadro's number and K = Boltzmann's constant. The above parameters for the Lennard-Jones potential have been shown¹⁰⁷ to be temperature and property dependent. A new potential model has been developed^{108,109} which has shown significant improvement over the Lennard-Jones; unfortunately, parameters for hydrogen are not yet available.

1.2.15. FIXED POINTS^{4,19,110-112}

Discussion - Below is a summary of the P-ρ-T data at selected fixed points. To be consistent with the property tables in Chapter 6, the temperatures in the para-equilibrium column are on the NBS-55 scale. The temperatures in the column labeled "normal" are also on the NBS scale. For relationships between the IPTS-68 scale and the NBS-55 scale, see Reference 112.

Para or equilibrium	Normal
Critical point	
$T = 32.976 \pm 0.05 \text{ K}$	33.19 K
$P = 1.2928 \text{ MPa (12.759 atm)}$	1.315 MPa (12.98 atm)
$\rho = 31.43 \text{ kg/m}^3 (15.59 \text{ mol/L})$	30.12 kg/m ³ (14.94 mol/L)
Normal boiling point	
$T = 20.268 \text{ K}$	20.39 K
$P = 0.101325 \text{ MPa (1 atm)}$	0.101325 MPa (1 atm)
$\rho(\text{liquid}) = 70.78 \text{ kg/m}^3 (35.11 \text{ mol/L})$	71.0 kg/m ³ (35.2 mol/L)
$\rho(\text{vapor}) = 1.338 \text{ kg/m}^3 (0.6636 \text{ mol/L})$	1.331 kg/m ³ (0.6604 mol/L)
Triple point	
$T = 13.803 \text{ K}$	13.957 K
$P = 0.00704 \text{ MPa (0.0695 atm)}$	0.00720 MPa (0.0711 atm)
$\rho(\text{solid}) = 86.50 \text{ kg/m}^3 (42.91 \text{ mol/L})$	86.71 kg/m ³ (43.01 mol/L)
$\rho(\text{liquid}) = 77.03 \text{ kg/m}^3 (38.21 \text{ mol/L})$	77.2 kg/m ³ (38.3 mol/L)
$\rho(\text{Vapor}) = 0.126 \text{ kg/m}^3 (0.0623 \text{ mol/L})$	0.130 kg/m ³ (0.0644 mol/L)

Solid-solid Transition - Solid hydrogen does undergo such transitions (see, for example, Reference 19).

Molecular Weight - 2.01594 on the C¹² scale.¹¹¹

Other Properties at the Fixed Points - See Tables 2, 3, 5, 8, 9, and 10.

1.2.16. SPECIFIC HEAT (HEAT CAPACITY) AT CONSTANT PRESSURE^{4,7,8}

Definition - The heat capacity at constant pressure is defined as $C_p = (\partial H / \partial T)_p$, where H is enthalpy.

Tables of Values -

Units	Range of values		Table location	
J/g-K	13.8	- 3000 K	0.1 - 100 MPa	2, 3, 8, 9

Figure - 9, 10

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
J/g-K	6.36	10.52	9.66	12.15	∞	14.85
Normal						
J/g-K	6.36	10.52	9.66	12.15	∞	14.31

Uncertainty - The uncertainty is estimated to vary from 0.02% in the low density limit to 3% at 35 MPa and 8% at 100 MPa. In the critical region ($T_c \pm 5\%$, $\rho_c \pm 20\%$) the uncertainties are greater but difficult to estimate.

1.2.17. SPECIFIC HEAT (HEAT CAPACITY) AT CONSTANT VOLUME^{4,7,8}

Definition - The heat capacity at constant volume is $C_v = (\partial U / \partial T)_v$, where U is internal energy, T is temperature, and v is specific volume.

Tables of Values -

Units	Range of tables		Table location
J/g-K	13.8 - 3000 K	0.01 - 100 MPa	2, 3, 8, 9

Figure - 11, 12

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
J/g-K	4.67	6.21	5.78	6.50	∞	10.72
Normal						
J/g-K	4.67	6.21	5.78	6.50	∞	10.18

Uncertainty - The uncertainty is estimated to vary from 0.02% in the low density limit to 3% at 35 MPa and 8% at 100 MPa. In the near critical region ($T_c \pm 5\%$, $\rho_c \pm 20\%$) the uncertainties are greater but difficult to estimate.

1.2.18. SPECIFIC HEAT RATIO^{4,7,8}

Definition - $\gamma = C_p / C_v$

Tables of Values - The specific heat ratio is not tabulated in the tables; however, C_p and C_v are tabulated and should be used to form the ratio as defined above.

Figure - None

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
Dimensionless	1.38	1.69	1.69	1.88	∞	1.38
Normal						
Dimensionless	1.38	1.69	1.69	1.88	∞	1.41
Uncertainty - The uncertainty is estimated to vary from 0.02% in the low density limit to 3% at 35 MPa and 8% at 100 MPa. In the near critical region ($T_c \pm 5\%$, $\rho_c \pm 20\%$) the uncertainties are greater but difficult to estimate.						

1.2.19. SPECIFIC HEAT (HEAT CAPACITY) OF THE SATURATED LIQUID AT CONSTANT SATURATION¹¹³

Definition - $C_\sigma = T(\partial S/\partial T)_\sigma = (dH/dT)_\sigma - V(dP/dT)_\sigma$ where the subscript σ denotes constant saturation.

Tabulated Values - None

Figure - None

Equation -

$$C_\sigma = \frac{AT}{(T_c - T)^n} + B + CT + DT^2 + ET^3 + FT^4 + GT^5$$

where T is temperature in kelvin, n = 0.10, A = 1.6815742, B = -32.80279, C = 6.8169871, D = -0.73194341, E = 0.033574357, F = -0.0007682974, G = 0.0000069029224, and $T_c = 32.984$. C_σ is cal/mol-K.^{*}

Units	Triple point	Boiling point	Critical point
Para only			
J/g-K	6.33	9.59	∞

Uncertainty - The uncertainty is estimated by Younglove and Diller¹¹³ to be 0.3% except near the critical point.

1.2.20. IDEAL GAS PROPERTIES, THERMODYNAMIC¹¹⁰

Discussion - All properties tabulated here are based on thermodynamic properties of the ideal gas. These ideal gas properties are derived from spectroscopic measurements and statistical mechanics; they are taken from Reference 110. The reference state for these properties is the ideal gas at 0 K where the molar internal energy, E°_0 , is at its lowest quantized value. By convention the values of S° , C_p° , $-(F^\circ - E^\circ_0)/T$ and $H^\circ - E^\circ_0$ are tabulated¹¹⁰ for 0.101325 MPa (1 atm) pressure; S° is molar entropy, C_p° is molar heat capacity at constant pressure, F° is molar free energy, H° is molar enthalpy and T is kelvin temperature. All symbols refer to the ideal gaseous state.

Tables of Values - For normal, equilibrium and parahydrogen, see Reference 110.

Properties	Units	Range of table	Table location
C_p° , S° , $-(F^\circ - E^\circ_0)/T$	Cal/mol-K [*]	10-5000 K	Reference 110
$H^\circ - E^\circ_0$	Cal/mol ^{**}		

Figure - None

* (Cal/mol-K) x 2.0755 = J/g-K

** (Cal/mol) x 2.0755 = J/g

Equation - None

Uncertainty - The uncertainty for C_p° is estimated to be 0.2% to 700 K increasing to 0.4% at 5000 K. The uncertainty for S° and E_0° is estimated to be an order of magnitude less.

1.2.21. INDEX OF REFRACTION^{7, 114}

Definition - The index of refraction n_{λ} of a medium is the ratio of the speed of light in a vacuum to the speed of light in the medium, $n_{\lambda} = C/C_m$.

Discussion - The refractive index of a nonpolar fluid depends on the wavelength of the incident light, the density of the fluid and, to a lesser extent, the temperature. The dependence on temperature is usually small enough to be neglected, as it has been in the equation given below. Figure 13 gives an indication of the temperature dependence for parahydrogen. Reference 7 gives a comparison between the index of refraction for normal and parahydrogen.

Table of Values -

Units	Range of values	Table location
Dimensionless	Saturated liquid (Para)	6

Figure - 13.

Equation -

$$n_{\lambda}(\rho) = \left(\frac{2\rho r_{\lambda}(\rho) + 1}{1 - \rho r_{\lambda}(\rho)} \right)^{1/2}$$

where $r_{\lambda}(\rho) = 0.99575 - 0.09069\rho + 1.227\rho^2 + 0.7799569 \times 10^6/\lambda^2 + 0.495126 \times 10^{12}/\lambda^4$, the specific refraction $r_{\lambda}(\rho)$ is in cubic centimeters per gram, densities are in grams per cubic centimeter, and the wavelengths, λ , are in angstroms*.

* Angstrom $\times 10^{-10}$ = meter

Range of Values -

Units	Boiling point liquid	RTP	λ
Dimensionless	1.1137	1.0001	435.8 nm (4358 angstroms)

Uncertainty - The uncertainty of the tabulated values is estimated to be less than 0.1%.

1.2.22. INTERNAL ENERGY^{4, 7, 8}

Definition - Internal energy is defined by the equation $\Delta U = Q - P\Delta V$, where Q is the heat absorbed in a system, ΔU is the change in internal energy, P is the pressure, and ΔV is the change in volume. The internal energy of a system is a derived thermodynamic property and may be calculated by means of thermodynamic relationships which require the PVT surface (see Subsection 1.2.12) and the specific heat capacity (see Subsections 1.2.16 through 1.2.19). The most common method of calculating the internal energy is by using $H = U + PV$ where H is the enthalpy (see Subsection 1.2.10) and PV is the pressure volume product.

Tables of Values -

Units	Range of values	Table location
J/g	13.8 - 3000 K	0.1 - 100 MPa
J/g	Saturation boundary	2, 8

Figure - None

Equation - None, see definition

Range of Values - The reference state for internal energy is zero for the ideal gas at zero absolute temperature (see Subsection 1.2.20).

Units	Triple point		Boiling point		RTP
	Liquid	Vapor	Liquid	Vapor	
Para J/g	-309.0	84.2	-257.7	113.6	2961.38
Normal J/g	218.2	611.4	269.5	640.7	2989.0

Uncertainty - The uncertainty of the internal energy values tabulated here is estimated to be the same as the enthalpy (see Subsection 1.2.10).

1.2.23. JOULE-THOMSON COEFFICIENT^{4, 7, 8, 115}

Definition - The Joule-Thomson coefficient, μ , is defined as $\mu = -C_p^{-1}(\partial H/\partial P)_T = (\partial T/\partial P)_H$. The sign of μ indicates whether a gas expansion will cause an increase or decrease in the temperature. If μ is positive, the expanding gas will be cooled. The locus of points where $\mu = 0$ is called the Joule-Thomson inversion curve. These data are given in Table 7. Values of the Joule-Thomson coefficient are tabulated by Michels et al.¹¹⁵ for pressures up to 253.31 MPa (2500 atm).

Tables of Values - This quantity is not tabulated here but it may be calculated from the property tables in Chapter 6.

Figure - 14, the inversion curve, T vs. P for parahydrogen.

Equation - None (may be calculated using an equation of state)

Range of Values -

Units	Pressure	40 K	110 K	180 K
K/MPa	10.1325 MPa	-0.424	0.247	-0.075
(K/atm)	(100 atm)	(-4.3 x 10 ⁻²)	(2.5 x 10 ⁻²)	(-7.6 x 10 ⁻³)

Uncertainty - The uncertainty is estimated to be 5%.

1.2.24. HEATS OF TRANSITION^{4, 7, 8, 19, 116, 117, 129, 130}

Definition - A heat of transition is equated to the energy associated with a phase change. In addition to the solid-liquid (fusion), solid-vapor (sublimation) and liquid-vapor (vaporization) transitions, hydrogen has two known solid-solid transitions.¹⁹ The energy changes due to these solid transitions are not known but are thought to be small. For values of the latent heats of fusion^{19, 116, 117} and sublimation^{19, 129, 130} see Chapter 2. The latent heat of vaporization is presented in Subsection 1.2.25.

1.2.25. LATENT HEAT OF VAPORIZATION^{4, 7, 8, 19}

Definition - The latent heat of vaporization is the amount of heat required to convert a unit mass of a substance from the liquid to the vapor state at constant pressure.

Tables of Values - This quantity is not tabulated but values are easily obtained from Tables 3 and 9 by subtracting the liquid enthalpy from that of the vapor at the same temperature and pressure.

Figure - 15, 16, heat of vaporization vs. T.

Equation - None

Range of Values -

Units	Triple point	Boiling point	Critical point
Para			
J/g	448.2	445.5	0
Normal			
J/g	449.1	445.6	0

Uncertainty - The uncertainty is estimated to be 1.24 J/g for para and 2.5 J/g for normal.

1.2.26. MELTING CURVE^{7, 8, 19, 118}

Definition - The melting curve is the boundary between the solid and liquid regions in a phase diagram.

Tables of Values - The density of the saturated liquid in coexistence with the solid phase is found on the first line of each page of isobar data in Tables 2 and 8. The liquid and solid densities of three state points are given here. For more extensive tabulations, the reader is referred to Reference 19.

Figure - 17 and 18

Equation - See subsection 1.2.27 for melting pressures

Range of Values -

Units	Triple point		10.1325 MPa (100 atm)		30.3975 MPa (300 atm)	
	Liquid	Solid	Fluid	Solid	Fluid	Solid
kg/m ³	77.0	86.9	81.8	89.9	88.7	96.0

Note: These values are for parahydrogen. For an estimate of normal-para density differences, see Chapter 4.

Uncertainty - The uncertainty is estimated to be 0.1% for the liquid phase and 0.5% for the solid phase.

1.2.27. MELTING PRESSURE^{7, 14, 19, 119, 120}

Definition - The relationship between pressure and temperature along the solid-liquid boundary.

Tables of Values - The melting temperature for a given pressure is found on the first line of each page of isobar data in Tables 2 and 8.

Units	Range of table	Table location
MPa	13.8 - 34.2 K	2, 8

Figure - 17 and 18, melting curve (T vs. P) for parahydrogen.

Equation - See Reference 7

Range of Values -

Units	Triple point	20 K	50 K
MPa	0.00704	22.71	221.1

Uncertainty - The uncertainty of the pressures is about 0.1%.

1.2.28. PHASE DIAGRAM^{4, 7, 8}

Definition - Phase diagrams indicate the boundaries between the solid, liquid, and gas phases. The diagrams that were referenced here are only those which yield the PVT of the phases. For a diagram of the phases in other coordinates, consult the subsection on the particular property desired.

Figure - 19 and 20

Uncertainty - The uncertainty of values taken from the above (or any other) diagrams is determined by the resolution of the individual chart.

1.2.29. VOLUME EXPANSIVITY^{4, 7, 8}

Definition - the volume expansivity is defined as

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P$$

Volume expansivity is often simply called expansivity or coefficient of volume expansion. The property is one of the compressibilities of a gas, where here the path (condition) of the compression is at constant pressure.

Tables of Values - This quantity is tabulated in Tables 2, 3, 8, and 9.

Units	Range of table	Table location
K^{-1}	13.8 - 3000 K	0.01 - 100 MPa 2, 8
K^{-1}	Saturation boundary	3, 9

Figure - None

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para and						
Normal						
K^{-1}	0.0102	0.0752	0.0164	0.0642		0.00333

Uncertainty - The uncertainty in the compressed liquid is 2 to 3%; in the gas and supercritical fluid, 1 to 2%. In the critical region ($T_c \pm 5\%$, $\rho_c \pm 20\%$) the uncertainties are larger; however, they are not experimentally defined since the property diverges at the critical point.

1.2.30. PRANDTL NUMBER⁷

Definition - The Prandtl number, Pr , is defined by the relation $Pr = C_p \eta / \lambda$, where C_p is the specific heat at constant pressure, η is the viscosity, and λ the thermal conductivity.

Tables of Values -

Units	Range of table	Table location
Dimensionless	13.8 - 3000 K	0.01-100 MPa 2, 8
Dimensionless	Saturation boundary	3, 9

Figure - 21 and 22

Equation - None, other than above defining relationship

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Dimensionless	2.24	0.623	1.29	0.809	∞	0.685

Uncertainty - The uncertainty is estimated to be 17% except in the critical region, where it is greater. All data at pressures greater than 35 MPa and at temperatures below 200 K are extrapolated (uncertainty unknown).

1.2.31. PVT^{4, 7, 8, 110}

Definition - PVT stands for pressure, volume, and temperature, the fundamental variables of the state of a pure fluid at equilibrium. Any two of three variables may be specified; the third is then a unique value for a given fluid, except where two or more phases coexist, in which case the pressure is a unique function of the temperature, but the volumes of the phases differ.

Tables of Values - The properties are tabulated in Tables 2, 3, 8, and 9.

Figure 1, 19, and 20.

Equation - See Subsections 1.2.12., 1.2.13., 1.2.27., and 1.2.38.

Range of Values -

Property	Units	Range of tables	Table location
Pressure	MPa	0.01 - 100	2, 8
Volume	m ³ /kg	0.0097 - 1538	2, 8
Temperature	K	13.8 - 3000	2, 8

Note: The tables for normal and parahydrogen do not reflect any difference for PVT (see Chapter 4 for a more detailed discussion of ortho-para differences).

Uncertainty - The uncertainty is estimated to be

Temperature range	Pressure range	Uncertainty in density, %
700 - 3000 K	0.1 - 100 MPa	1
300 - 700 K	0.1 - 100 MPa	0.5
13 - 300 K	50 - 100 MPa	0.2
13 - 300 K	0.1 - 50 MPa	0.1
Critical region	$T_c \pm 1\%$, $\rho_c \pm 20\%$	6
Solid	34.45 - 70.93 MPa	1

1.2.32. SATURATION PROPERTIES

Definition - The term saturation refers to a state condition where two or more phases coexist in equilibrium.

Tables of Values - Saturation properties of the coexisting liquid and vapor phases are tabulated from the triple point to the critical point in Tables 3 and 9. The individual properties which are tabulated in these tables are listed below along with the subsection in which they are discussed in more detail.

Property	Subsection	Property	Subsection
Temperature	1.2.31	Constant pressure heat capacity	1.2.16
Pressure	1.2.31	Velocity of sound	1.2.33
Volume (or density)	1.2.31	Surface tension	1.2.35
Internal energy	1.2.22	Thermal conductivity	1.2.36
Enthalpy	1.2.10	Viscosity	1.2.39
Entropy	1.2.11	Thermal diffusivity	1.2.9
Constant volume heat capacity	1.2.17	Dielectric constant	1.2.6
		Prandtl number	1.2.30

For tables of PVT below the triple point, see Reference 19.

Figure - See pages listed above.

1.2.33. SOUND VELOCITY^{4, 7, 8, 19}

Definition - The thermodynamic (isentropic) sound velocity, W , is defined by

$$W^2 = -V \left(\frac{\partial P}{\partial V} \right)_S$$

where P is pressure, V is specific volume, and S is entropy; since entropy is not usually a variable in the mathematical models for the equation of state, calculations are more easily made using

$$W = \left[\frac{C_p}{C_v} \left(\frac{\partial P}{\partial \rho} \right)_T \right]^{1/2}$$

which is thermodynamically equivalent to the above equation. C_p and C_v are the specific heat capacity at constant pressure and constant volume, respectively; P is again pressure, T is temperature, and ρ is the density. Sound velocity can be experimentally measured quite accurately.

Tables of Values -

Units	Range of table	Table location
m/s	13.8 - 3000 K	0.01 - 100 MPa 2, 3, 8, 9
m/s	0 - 12 K (para)	Saturated solid Reference 19
m/s	4.2 - 13.96 K (normal)	Saturated solid Reference 19

Figure - 23 and 24

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
m/s	1264	305.7	1089	355	0 ^a	1309

^aTheoretically the velocity of sound should go to 0 at the critical point. Experimentally only very low velocities have been measured in the critical region.

Uncertainty - The uncertainty of the tabulated values has been estimated by comparing tabulated and experimental sound velocities. The uncertainty varies with pressure from 1 to 2% in the liquid and is about 0.5% in the vapor or in the gas above the critical temperature. In the critical region ($T_c \pm 5\%$, $\rho_c \pm 20\%$) the uncertainties are larger but not estimable.

1.2.34. SOUND ABSORPTION^{121, 122}

Definition - The experimental attenuation α_{exp} is defined by the relation

$$P = P_0 e^{-x\alpha_{exp}}$$

where x is the distance between the point where the peak pressure due to the sound wave is P_0 and the point where it is P . The so-called "classical" sound absorption α_{cal} is often calculated from:

$$\alpha_{cal} = \frac{2\pi^2}{\gamma W} \left[\frac{4}{3}\eta + \frac{\gamma - 1}{C_p} \lambda \right] f^2 / P$$

where γ is the specific heat ratio, $\frac{C_p}{C_v}$, w is velocity of sound, f is frequency, P is pressure, η is the shear viscosity, and λ is the thermal conductivity.

Papers found in the literature report sound absorption in many different ways; some of these are as follows:

$$\alpha_{\text{excess}} = \alpha_{\text{exp}} - \alpha_{\text{cal}}$$

$$\text{nepers} = \ln (P/P_0)$$

$$\alpha_{\text{exp}}/\alpha_{\text{cal}}$$

$$\alpha_{\text{exp}}/f$$

$$\alpha_{\text{exp}}\lambda \text{ (where } \lambda \text{ is wavelength)}$$

Liquid - α_{exp} for the saturated liquid¹²¹ at 17 \pm 1 K is reported to be $0.11 \text{ cm}^{-1} \pm 10\%$ for the frequency of 44.4 MHz.

Gas - Values of α_{exp}/f for both normal and parahydrogen at temperatures of 293, 90, and 77 K are given as a function of f/P in Reference 122.

Range of Values -

Temperature K	f/P Hz/Pa	α_{exp}/f (normal) $(\text{cm} \cdot \text{MHz})^{-1}$	α_{exp}/f (para) $(\text{cm} \cdot \text{MHz})^{-1}$
293	14.61	1.48	0.491
293	15.10	1.53	0.483
77	15.79	1.60	0.677
77	20.73	2.10	0.314

Uncertainty - The uncertainty of α is 10% for the liquid value and 5% for the gaseous data.

1.2.35. SURFACE TENSION^{7, 123, 124}

Definition - Surface tension is defined as the amount of work required to increase the surface area of a liquid by one unit of area. Note that this property is defined only for liquid in coexistence with the vapor phase.

Tables of Values -

Units	Range of table	Table location
dyne/cm*	13.8 - 32.976 K	3, 9

Figure - 25 and 26

Equation - $\gamma = \gamma_0 (1 - T/T_c)^{1.065}$ (see discussion below), where γ is surface tension in dyne/cm, γ_0 is 5.328 for parahydrogen and 5.369 for normal hydrogen, and T_c is 32.976 K for parahydrogen and 33.18 K for normal hydrogen.

Range of Values -

Units	Triple point	NBP	Critical point	300 K
Para				
N/m	0.00299	0.00193	0	Not defined
(dyne/cm)	(2.99)	(1.93)	(0)	Not defined
Normal				
N/m	0.003	0.00195	0	Not defined
(dyne/cm)	(3.00)	(1.95)	(0)	Not defined

Discussion - Since Corruccini¹²³ correlated the older experimental data, a new set of experimental data for normal hydrogen¹²⁴ has appeared in the literature. These new data are consistently about 70×10^{-6} N/m (0.07 dyne/cm) lower at all temperatures below 31.5 K than those calculated from the above equation. These differences cannot be explained on the basis of differences in temperatures or densities used in the calculations, but the experimental apparatus used by Blagoi and Pashkov¹²⁴ does not inspire confidence in their data. The capillary

* (dyne/cm) $\times 0.001 = \text{N/m}$.

rise technique was used, which is the most common technique but is beset with difficulties because of the corrections that must be applied. In the older hydrogen surface tension experiments, these corrections amounted to about 10% of the measured capillary rise. Because of the size of the capillaries used by Blagoi and Pashkov¹²⁴ the measured capillary rise must be corrected by about 40 to 50%.

Uncertainty - The uncertainty of the tabulated values is estimated to be 1% for temperatures below the normal boiling point and increasing to about 5% for temperatures above $0.8 T_c$.

1.2.36. THERMAL CONDUCTIVITY^{7, 19, 125, 126}

Definition - The thermal conductivity coefficient relates the transfer of heat through a material via molecular interaction due to a temperature gradient across the material. $q = -\lambda \text{ grad } T$, where q is the heat flux (heat per unit area per unit time), $\text{grad } T$ is the temperature gradient, and λ is the thermal conductivity coefficient.

Discussion - The literature search revealed no experimental data outside the P-T range of these tabulations. The tabulations include extrapolations to higher densities and temperatures of experimental data by Roder and Diller.¹²⁵ An alternative method of calculating thermal conductivity is provided by the modified Enskog theory.¹²⁶ The most popular method of correlating thermal conductivity data is to separate the property into a number of additive parts that are temperature and density dependent: $\lambda = \lambda_o(T) + \lambda_E(\rho, T) + \lambda_c(\rho, T)$ where $\lambda_o(T)$ is the dilute gas contribution (a function of T only), $\lambda_E(\rho, T)$ is the so-called excess function, and $\lambda_c(\rho, T)$ gives the enhancement due to the critical point behavior. $\lambda_E(\rho, T)$ and $\lambda_c(\rho, T)$ are taken to be the same

for the para and normal modifications but $\lambda_o(T)$ shows marked differences for the para and normal modifications. A survey of the thermal conductivity of the solid is given in Reference 19.

Tables of Values - 2, 3, 8, and 9.

Units	Range of table	Table location
Para and normal		
mW/cm-K	13.8 - 3000 K	0.01 - 100 MPa 2, 3, 8, 9

Figure - 27 and 28

Equation - None

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
mW/cm-K	0.7259	0.1243	0.9892	0.1694	∞	1.94
Normal						
mW/cm-K	0.7259	0.1243	0.9892	0.1694	∞	1.87

Uncertainty - The uncertainty of the tabulated data is estimated to be 7% except in the dilute gas--all temperatures and pressures less than 0.101325 MPa (1 atm) --where the uncertainty is estimated at 4% and in the critical region ($T_c \pm 5\%$ and $\rho_c \pm 20\%$) where it is 20%. All data at pressures greater than 35 MPa and at temperatures below 100 K are extrapolated (uncertainty unknown).

1.2.37. THERMODYNAMIC DIAGRAMS^{4,7}

Discussion - The thermodynamic diagrams listed below are based on the PVT work of Roder et al.⁴ and McCarty and Weber.⁷ These diagrams have been prepared very carefully and are accurate to the precision to which they may be read. For other figures the primary consideration in many cases was availability and in others the range of P and T covered by the chart.

**Figure - 1, compressibility factor chart for normal hydrogen; 4,
temperature-entropy chart (para); 5, temperature-entropy chart (para).**

1.2.38. VAPOR PRESSURE^{19, 104, 127}

Definition - The vapor pressure is the pressure, as a function of temperature, of a liquid in equilibrium with its own vapor.

Tables of Values -

Units	Range of table	Table location
Para		
MPa	13.8 - 32.976 K	3
Normal		
MPa	13.95 - 33.180 K	9, 11

Figure - 29 - 32

Equation - Parahydrogen: ¹⁰⁴ $\ln(P/P_t) = n_1x + n_2x^2 + n_3x^3 + n_4(1-x)^{n_5}$, where $n_1 = 3.05300134164$, $n_2 = 2.80810925813$, $n_3 = -0.655461216567$, $n_4 = 1.59514439374$, $n_5 = 1.5814454428$, $x = (1 - T_t/T)/(1 - T_t/T_c)$, $T_t = 13.8$ K, $T_c = 32.938$ K, and $P_t = 0.007042$ MPa.

Normal hydrogen: ¹²⁷ $\log P(\text{kg}/\text{cm}^2) = A + B/T + C \log T$, where $A = -1.55447$, $B = -31.875$, $C = 2.39188$ and T is in kelvin.

This equation was used to calculate the vapor pressure data given in Table 11 and is restricted to the temperature range of 20.555 to 32.276 K. These data differ slightly from those tabulated in Tables 8 and 9 because the normal hydrogen thermodynamic properties tables were generated using the parahydrogen PVT surface and the ideal gas thermodynamic properties of normal hydrogen. Table 11 data are preferred where accurate normal hydrogen vapor pressures are desired; however, Tables 8 and 9 are internally consistent and sufficiently accurate for all engineering calculations.

1.2.39. VISCOSITY

Dynamic^{7,128}

Definition - The viscosity coefficient of a fluid relates the flux of momentum in a fluid to the traceless symmetric part of the velocity gradient: $J = -2\eta D$, where J is the flux of momentum, D is the traceless symmetric part of the velocity gradient, and η is the viscosity coefficient. Note: The coefficient η as defined is sometimes called the shear or dynamic viscosity.

Discussion - The viscosity of a fluid may be separated into two additive parts: $\eta = \eta_0(T) + \eta_E(\rho, T)$, where $\eta_0(T)$ is the dilute gas contribution and is a function of temperature only and $\eta_E(\rho, T)$ is called the "excess" viscosity and is a strong function of density. When compared on a density basis, there does not seem to be a significant dependence on ortho-para composition.

Tables of Values -

Units	Range of table	Table location
kg/m-s	13.8 - 3000 K	0.01 - 100 MPa
kg/m-s	Saturation	2, 8

Figure - 33

Equation - Equations are presented in Reference 519.

Range of Values -

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para and Normal						
kg/m-s	255.1×10^{-7}	7.36×10^{-7}	132.0×10^{-7}	11.28×10^{-7}	35.43×10^{-7}	89.48×10^{-7}

Uncertainty - The uncertainty of the tabulations is estimated to be 5% except in the dilute gas--all temperatures and pressures less than 0.101325 MPa (1 atm)--where the uncertainty is estimated at 3% and in the critical region ($T_c \pm 5\%$ and $\rho_c \pm 20\%$) where it is 10%. All data at pressures greater than 35 MPa and at

temperatures below 200 K are extrapolated (uncertainty unknown). The dotted lines on Figure 33 represent a graphical smoothing of two algebraic functions that represent high and low temperature experimental data and are extrapolated to join in this temperature region.

Bulk

The shear viscosity should not be confused with the bulk viscosity. The bulk viscosity relates the flow of momentum in a fluid to the divergence of the velocity: $J = 2\eta D - \eta_v I \operatorname{div} u$, where I is the unit tensor, $\operatorname{div} u$ is the divergence of the velocity of the fluid, and η_v the coefficient of bulk viscosity.

Kinematic

Definition - The kinematic viscosity, γ , is defined as $\gamma = \eta/\rho$, where η is the shear viscosity and ρ is the density.

1.2.40. FREE ENERGY^{4,7}

Definition - The Gibbs free energy, G , is defined as $G = H - TS$, where H is enthalpy, T is absolute temperature, and S is entropy. Similarly, the Helmholtz free energy, F , is $F = U - TS$, where U is internal energy.

Tables of Values - These quantities are not tabulated but may be simply obtained, using the formula above, from the following tables.

Units	Range of table	Table location
J/g	13.8 - 3000 K	0.01 - 100 MPa
J/g	Saturation boundary	2, 8

Figure - None

Equation - None

Range of Values - (Gibbs free energy)

Units	Triple point		Boiling point		Critical point	RTP
	Liquid	Vapor	Liquid	Vapor		
Para						
J/g	-377	-377	-420	-420	-542	-15,233
Normal						
J/g	-21.9	17.0	-66.5	-80.3	-138	-16,945

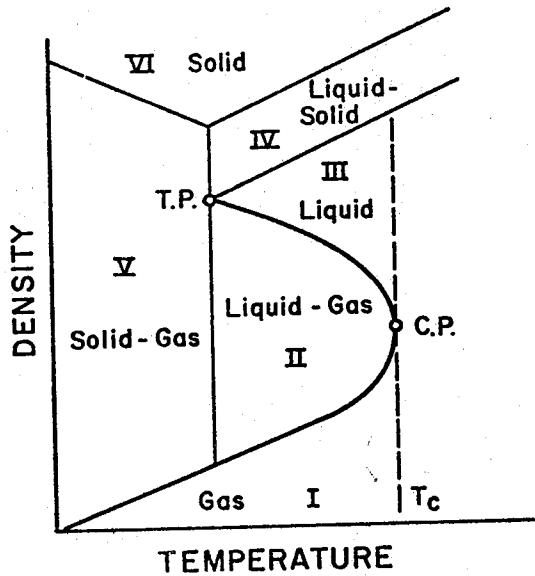
Uncertainty - The uncertainty varies from about 0.5 J/g in the low density limit to about 15 J/g in the liquid.

CHAPTER TWO
THERMOPHYSICAL PROPERTIES OF HYDROGEN IN THE
SOLID, SOLID-GAS, AND SOLID-LIQUID STATES

Hans M. Roder

2.1. INTRODUCTION

This chapter is quite similar to Chapter 1 except that the properties covered pertain to the solid phase. Definitions for nearly all properties are found in Chapter 1. We include the single phase compressed solid state as well as the solid-vapor and solid-liquid two phase regions, i.e., phases IV, V, and VI shown in the schematic density-temperature phase diagram below.



Ordinarily data are not measured in the coexisting regions solid-liquid, or solid-gas, rather they are established from the phase boundaries in terms of a variable called quality. The phase boundaries are included in the description of the adjacent single phase region.

This chapter is based on an earlier survey¹⁹ done by the National Bureau of Standards for the Lawrence Livermore Laboratory, which covered a wide range of properties including PVT, thermodynamic, thermal, transport, electrical, radiative, and mechanical. Only the ortho-para modifications of hydrogen have been included here. For properties of the other isotopes of hydrogen the reader should consult Reference 19 or the successor surveys prepared by the Lawrence Livermore Laboratory, Reference 139. A second more recent review has

been given by Silvera¹⁴⁰, while the Russian work has been summarized in a volume edited by Rabinovich.¹⁴¹ Temperatures are limited to those below the critical point, i.e., below 33 K. The pressure range is not restricted, however, very little data exist at pressures other than saturation.

The literature surveyed includes all references available to the Cryogenic Data Center through March of 1973, some 1500 items. A literature search covering 1973 to March 1978 disclosed an additional 310 references. Some of these references have been included in this chapter, particularly if they contained firm data. The evaluation of these references was, however, only cursory, i.e., coverage to March of 1978 is not claimed.

In selecting sources of data, a critical evaluation was not made, however, the following guide was used:

- a) If several sets of data exist, which, in our judgment, are the "best data?"
- b) Are these values consistent with other properties presented?
- c) Are tables or graphs available? Are they in a convenient form?
- d) Can we find any values at all - even if estimated?

Many inconsistencies or discontinuities exist in the data presented because the values originate from many diverse sources. Considerable effort would be required to reconcile the discrepancies between different sources. It is best that the user be forewarned; therefore, we list a few of the discrepancies which are most vexing.

First, of course, is the matter of temperature scales. The NBS-39 scale, the NBS-55 scale, and more recently the IPTS-68 scale have been in common use, and their interrelation is fairly well understood. For example, the triple point temperatures are 13.803 K, on the NBS-55 scale, 13.813 K on the NBS-39 scale, and 13.810 K on the IPTS-68 scale. The values differ by 0.01 K. Next

is the matter of pressure at the triple point. Vapor pressure equations for solid and liquid as well as the melting curve should intersect mathematically at the triple point, yet they rarely do. Finally, different authors choose different reference states for entropy and enthalpy. For example, the reference enthalpy, $H_0 - E_0^\circ$, is zero for the ideal gas at 0.101325 MPa (1 atm) and 0 K for the upper part of Table 12, while the reference enthalpy is zero for the ideal crystal at 0 K for the lower part. The enthalpies of the solid at 10 K compare as follows: -753.7 J/mol and 6.2 J/mol (1.479 cal/mol in Table 12).

Computer Programs

A significant portion of the tables and figures presented in this chapter were prepared with the aid of computer programs. Both the slush hydrogen program¹⁴² and the equation of state¹⁰⁵ for liquid and vapor were developed by NBS for Johnson Space Center of the NASA. The programs are integrated in a way which avoids all of the inconsistencies mentioned above. They are available from the NBS Thermophysical Properties Division, Boulder, CO 80303.

2.2. DISCUSSION OF THE PROPERTIES

2.2.1. CRYSTAL STRUCTURE¹⁴³⁻¹⁶¹

Discussion - Hydrogen is an extremely interesting solid because for certain isotopic compositions it may undergo a transition at low temperatures. This transition has been studied by X-ray diffraction, electron diffraction, neutron diffraction, NMR¹⁴³, and infrared absorption.¹⁴⁴ In general all hydrogen isotopes solidify in the hexagonal close packed (hcp) structure, particularly if cooled from the liquid state. Parahydrogen appears to be stable in hcp down to the lowest temperatures investigated. In contrast,

hydrogen rich in the ortho component (> 60%) undergoes a transition to the face centered cubic (fcc) structure in the temperature range 1.2 to 4.2 K. In addition, there is considerable evidence that unconverted hydrogen if condensed from the vapor in thin films is in fcc form.¹⁴⁵ Other experiments show that the substrate can affect the lattice spacing, introducing the fcc structure, and that plastic deformation initiates the fcc structure.¹⁴⁶

The transition temperature is a function of ortho-para concentration¹⁴⁸ as well as density or pressure.¹⁴⁹ The volume change of the transition is small, 1.3%, but has been measured.¹⁴⁷ The transition corresponds to the λ anomaly in the specific heat but exhibits considerable hysteresis. It is obvious that the difference in energy of the two close packed structures of hydrogen is exceptionally small. It is also well known that solid phases frequently undercool and remain in a metastable form; thus hysteresis is often encountered in such a martensitic transformation.¹⁴⁶ A different explanation is that the changes in thermodynamic properties are due mainly to the order-disorder transition of the rotational motions, and not to the crystalline phase change.¹⁵⁰

Parahydrogen exhibits a second phase transition in the compressed solid close to the melting line. This transition was predicted¹⁵¹, its volume change has been measured^{153,154} to be 0.15%, the singularity in the melting line has been measured,¹⁵⁷ and the structure of the new solid has been determined to be fcc.^{155,156}

Studies¹⁵² of the Raman spectra initially were interpreted to show a fcc structure at pressures of around 100 MPa (1 kbar) at temperatures near 4 K. In subsequent studies¹⁵⁸ the authors were unable to confirm their earlier report. A short paper by Mills¹⁵⁹ attempts to connect these transitions. The controversy is far from being settled because in a most recent paper

Silvera, et al.¹⁶⁰ attribute this phase to an instrumentation effect rather than a true transition. The discrepancies in the various diagrams are shown clearly in Figures 34a, b, and c where 34a is based on the measurements of Dwyer et al.¹⁶¹ as interpreted in References 19, 142, and 151, while 34b is taken from Reference 159, and 34c from Reference 160.

Figure - 34a, b, c

Range of Values - see lattice parameters, Subsection 2.2.15

2.2.2. DIELECTRIC CONSTANT^{12,14,16,18,19,162-164}

Discussion - It is important for the user to realize that correlation or analysis of the dielectric constant is almost always handled through the Clausius-Mossotti relation $M(\epsilon-1)/(\epsilon+2)\rho = P$, or solved for $\epsilon = (1 + 2P\rho)/(1 - P\rho)$, where ϵ is the dielectric constant, M the molecular weight, ρ the density, and P the molar polarizability. Polarizability is most often expressed in cm^3/g ; a nominal value for parahydrogen is $1.004 \text{ cm}^3/\text{g}$. However, to compare polarizabilities of hydrogen isotopes it is best if P is expressed in molar units, thus the nominal value for parahydrogen becomes $2.02 \text{ cm}^3/\text{mol}$.

Parahydrogen

The most extensive measurements have been made on parahydrogen. A composite plot of the results, Figure 35 shows that the polarizability is a very slowly varying function of density. Stewart¹⁸ is able to correlate his entire set of measurements with a single equation (see Subsection 1.2.6). Younglove's¹⁴ measurements extend to higher liquid densities and include values for the solid. He represents his solid measurements by the equation $P = 1.011 - 0.049091\rho$ where P is in cm^3/g and ρ in g/cm^3 . As shown in Figure 35, Younglove reports a difference of about 0.5% in P between liquid and

solid. This value has recently been called to question by Udovidchenko and Manzhelii¹⁶ and by Wallace and Meyer^{162, 163} who report a change of no more than 0.2%. The difference may be explained by the fcc solid phase near the melting line (see Subsection 2.2.1).

Since the dielectric constant is proportional to density, a plot of ϵ vs. T is very similar to a density-temperature phase diagram. For parahydrogen, liquid and solid boundaries are shown in Figure 36.

Normal Hydrogen

To estimate values of the dielectric constant for normal hydrogen, we use the results of Kogan and Milenko¹² who measured the difference in dielectric constant for various concentrations of ortho-parahydrogen in the liquid state. As recalculated¹⁹ the difference is:

	molar polarizabilities, cm^3/mol	difference	conditions
n-H ₂	2.0372	p-H ₂ 2.0279	0.0093 saturated liquid

More recent measurements of the normal-para difference in the solid state have been reported by Haase and Meyer.¹⁶⁴ The dielectric constant for normal hydrogen is then estimated using the following steps:

- a. find density or state at point desired (mol/cm^3)
- b. calculate polarizability of p-H₂ at an equivalent density (mol/cm^3)
- c. adjust polarizability by the difference (0.0093)
- d. calculate desired dielectric constant

The measurements reported in Reference 165 are probably not valid because the measured dielectric constant should increase as the temperature is lowered.

The measurements on solid hydrogen in Reference 166 are probably not valid because the experimenters did not succeed in filling the cell completely.

Figures - 35, 36

Equation - see discussion for equation of solid

Uncertainty - the uncertainty in the molar polarizability of the solid can be as large as 0.3%.

2.2.3. ENTHALPY^{129,142,161,167-169}

Discussion - The coverage for parahydrogen is nearly complete. It is the only isomer for which values in the compressed solid can be obtained, primarily because the specific heats were measured by Ahlers.¹⁶⁹ Enthalpy estimates for the compressed solid are presented in Table 14. This table was assembled from the reports of Dwyer and Cook.^{161,167,168}

Tables of Values - parahydrogen, solid-vapor two phase region, Table 12; parahydrogen, solid-liquid two phase region, Table 13; single phase compressed solid, Table 14

Figure - 43, T-S chart

Uncertainty - as estimated in Reference 142

enthalpy: 1.2 J/mol for solid-liquid;
1.5 J/mol for solid-vapor

2.2.4. ENTROPY^{129,142}

Tables of Values - parahydrogen, solid-vapor two phase region, Table 12; parahydrogen, solid-liquid two phase region, Table 13

Figure - 43, T-S chart

Uncertainty - as estimated in Reference 142

entropy: 0.08 J/mol-K for solid-liquid;
0.146 J/mol-K for solid vapor

2.2.5. EQUATION OF STATE^{104, 105, 129, 142, 169-173}

Equations - In the correlation by Mullins, et al.¹²⁹ a virial representation of the gaseous PVT surface is extrapolated to temperatures below the triple point. The correlation of the solid-vapor and solid-liquid two phase regions¹⁴² is achieved by having a specific 33 term MBWR equation of state^{104, 105} supply all properties for the saturated vapor below the triple point as well as all properties on the liquid side of the melting curve. While the two correlations are reasonably consistent, discontinuities between them exist as shown in Table 12. Whatever equation of state is used for the liquid PVT surface, care must be exercised for densities near the melting line, or the equations will fail to correctly predict the specific heats.¹⁷³ The equation of state for the solid has been described on theoretical grounds by Anderson, et al.¹⁷²

For the compressed solid a review which includes the so-called "metallic hydrogen" is given by Douglas and Beckett.¹⁷⁰ Numerous equations of state are presented, most of which are based on some kind of intermolecular potential. Ahlers¹⁶⁹ calculates some of the derived properties such as compressibility from the Grüneisen equation. The equation proposed by Burshtein and Rabinovich¹⁷¹ while "anchored" with experimental densities along the solid melting line is not satisfactory because it does not yield the proper densities of the solid under its own vapor pressure. None of these equations of state account for the phase change near the melting line of the solid. Therefore, a unique equation of state from which one could calculate the PVT properties at an arbitrary point in the solid does not exist; however a paper that gives an equation of state for the compressed solid without the phase change and is based on a large number of PVT measurements is in preparation.¹⁶⁰

2.2.6. FIXED POINTS^{105, 142}

Discussion - See also Subsection 1.2.15. We note here values for the triple point used in the most recent correlation for parahydrogen¹⁴² which differ very slightly from those selected in Subsection 1.2.15 because the underlying equation of state¹⁰⁵ is slightly different. In addition, so called values of V_o , i.e., the molar volume of saturated solid hydrogen at the helium boiling point (4.2 K) is of interest for work in X-ray or neutron diffraction. The most consistent and recent correlation of these values is given by Silvera et al.¹⁶⁰

Triple Point

$$T = 13.800 \text{ K}$$

$$P = 0.0070420875 \text{ MPa (0.0695 atm)}$$

$$\rho(\text{solid}) = 86.51 \text{ kg/m}^3 (42.91 \text{ mol/L})$$

$$\rho(\text{liquid}) = 77.04 \text{ kg/m}^3 (38.21 \text{ mol/L})$$

$$\rho(\text{vapor}) = 0.1258 \text{ kg/m}^3 (0.06238 \text{ mol/L})$$

$$V_o(\text{solid}) = 23.14 \pm 0.08 \text{ cm}^3/\text{mol at } 4.2 \text{ K}$$

2.2.7. SPECIFIC HEAT (HEAT CAPACITY) AT CONSTANT PRESSURE^{161, 169}

Discussion - See also Subsection 2.2.9. Experimental values for this property have not been measured. Values for C_p in the compressed solid states were estimated by Dwyer and Cook¹⁶¹ from the C_v measurements of Ahlers.¹⁶⁹ Ahlers estimated values of C_p at the saturated solid boundary from his single phase C_v measurements.

Tables of Values - C_p on the saturated solid boundary, Table 12; C_p in compressed solid states, Table 14

Figure - 37

Uncertainty - About 2% at 4 K rising to around 5% at the triple point.

2.2.8. SPECIFIC HEAT (HEAT CAPACITY) AT CONSTANT VOLUME^{169, 174}

Discussion - See also Subsection 2.2.9. Experimental values for this property have been measured in the single phase compressed solid by Ahlers¹⁶⁹ and by Roberts and Daunt.¹⁷⁴

Tables of Values - Table 14

Uncertainty - About 2% at 4 K rising to around 5% at the triple point.

2.2.9. SPECIFIC HEAT (HEAT CAPACITY) OF THE SATURATED SOLID^{142, 161, 169, 174-178}

Discussion - We distinguish between heat capacity at saturation (C_{σ}), heat capacity at constant pressure (C_p), and heat capacity at constant volume (C_v). The property most commonly measured is C_{σ} , where for the isotopes having ortho-para isomers a large dependence of specific heat on composition is found in the solid.

A composite picture for the heat capacity of the solid (C_{σ}) is shown in Figure 38. Values for parahydrogen are given in Table 12; they are based on values taken from Ahlers.¹⁶⁹ Values for other ortho-para compositions are primarily from the paper by Hill and Ricketson.¹⁷⁵ Shown, but not in any detail is the λ -transition near 2 K, the best description of which is given by Ahlers and Orttung.^{177, 178} Ahlers¹⁶⁹ also measured the specific heat C_v for three molar volumes of parahydrogen in compressed solid states. The values are given in Table 14; they were converted to estimated values of C_p by Dwyer and Cook.¹⁶¹ The estimated values of C_p are presented in Figure 37. More recent measurements by Roberts and Daunt¹⁷⁴ are in very good agreement with those of Ahlers.¹⁶⁹ Heat capacities at low ortho concentrations and very low temperatures were examined by Popov, et al.¹⁷⁶

The general features of the property for hydrogen are as follows: Below about 14 K the heat capacity (C_{σ}) of the solid shows a broad anomaly for

compositions between para and normal; with increasing ortho concentration in this temperature range the heat capacity increases; for ortho concentrations larger than 60%, a λ transition exists at low temperatures (~ 1.3 to 4.2 K). The values of C_{σ} are commonly taken to be the same as C_p ; the values of C_v are lower than C_{σ} at all temperatures but the difference is negligible below 5 K; a significant difference exists between C_{σ} of the solid and the liquid.

Tables of Values - Table 12

Figure - 38

Equation - The representation of Ahlers' values¹⁶⁹ as given in Reference 142 is : $C_{\sigma} = -101. + 87.75 T - 26.95833333 T^2 + 4.25 T^3 - 0.041666667 T^4$ with C_{σ} in mJ/mol and T in K for T ranging from 3 K to the triple point.

Uncertainty - About 2% at 4 K rising to around 5% at the triple point.

2.2.10. HEATS OF TRANSITION

Definition - A heat of transition is the energy associated with a phase change. Besides the solid-liquid and liquid-gas transition, hydrogen has two known solid-solid transitions, (see Subsections 2.2.1 and 2.2.15). The energy changes due to these solid transitions are not known but are thought to be small. For values of the latent heats of fusion, sublimation and vaporization, see Subsections 2.2.13, 2.2.14 and 1.2.25.

2.2.11. INTERNAL ENERGY¹⁴²

Tables of Values - parahydrogen, solid-vapor two phase region, Table 12; parahydrogen, solid-liquid two phase region, Table 13

Uncertainty - as estimated in Reference 142.

Internal energy: 1.2 J/mol for solid-liquid;
1.5 J/mol for solid-vapor

2.2.12. ISOTHERMAL COMPRESSIBILITY^{16, 179-181}

Tables of Values - Table 15 and Table 22

2.2.13. LATENT HEAT OF FUSION^{19, 110, 116, 117, 142, 169, 182, 183}

Definition - The latent heat of fusion is the amount of heat required to melt a unit mass of a substance at constant temperature and pressure at temperatures at the triple point and above.

Discussion - The latent heats of fusion are summarized in Table 16. Most of the experimental work was conducted at essentially triple point temperatures; however, some measurements have been made at elevated pressures, and others as a function of ortho-para composition. If the authors indicated the triple point temperature in the paper, then the value of that temperature is given in brackets in the temperature column. For the measurements at elevated pressures, both the temperature and the pressure at which the measurements were made are shown. In the heat of fusion column the values which are underlined are the ones which are given in Subsection 1.2.15 in the fixed point tables. The value selected in the correlation¹⁴² is 117.277 J/mol for the heat of fusion at the triple point, partially to remain consistent with the earlier thermodynamic calculations, and partially because this value is quite close to the average of all experimental determinations (see Table 16).

Tables of Values - Table 16

Figure - None

Equation - The heats of fusion at elevated pressures were determined experimentally by Dwyer, et al.¹¹⁷ The authors represent the experimental

results by a straight line in pressure. Using the value selected above (117.277 J/mol) the equation used in Reference 142 for the heats of fusion becomes:

$$\Delta H_{\text{fusion}} = (28.02693164 + 0.044149P) \cdot 4.184$$

where ΔH_{fusion} is in J/mol and P is in atm.

Range of Values -

Units	Triple point	15.54 K	21.19 K
J/g	58.17	63.92	83.60
(cal/mol)	(28.03)	(30.80)	(40.28)

Note: Values are for parahydrogen.

Uncertainty - The estimate of uncertainty based on the existing data is about 0.52 J/g, or around 1%.

2.2.14. LATENT HEAT OF SUBLIMATION^{19, 129, 130, 142, 184, 185}

Definition - The latent heat of sublimation is the amount of heat per unit mass required to vaporize the solid phase.

Discussion - The latent heat of sublimation like the heat of vaporization is temperature dependent. Experimental measurements of the latent heat of sublimation are rare.¹⁸⁵ The property is usually calculated from the Clausius-Clapeyron equation requiring values of the solid volumes, the vapor volumes, and the temperature derivative of the vapor pressure curve. The difficulty is to select a proper equation of state for the vapor, because the vapor volumes predominate in the calculation. For temperatures involved, the extrapolation of the virial coefficient B(T) is quite extended, therefore the ideal gas equation is often used for the vapor volumes. At the triple point the latent heat of sublimation should equal the sum of the latent heat of vaporization

and the latent heat of fusion. The equality offers a severe test of thermodynamic consistency, in particular, of the various vapor pressure derivatives used in the calculations.

The heat of sublimation at 0 K is of particular interest theoretically, and a number of papers are concerned with this extrapolation. Clusius¹³⁰ calculated a value of 380.6 J/g (183.4 cal/mol) for hydrogen, while Eyring, et al.¹⁸⁴ have calculated values of 376.8 J/g (181.56 cal/mol) for parahydrogen and 379.6 J/g (182.92 cal/mol) for normal hydrogen.

Thermodynamically consistent calculations on parahydrogen are given by Mullins. et al.¹²⁹ and by Roder.¹⁴²

Tables of Values - This quantity is tabulated in Table 12

Figure - None

Equation - None

Range of Values

Units	0 K	Triple point
Para J/g	376.7	507.4
(cal/mol)	(181.5)	(244.5)
Normal J/g	379.6	--
(cal/mol)	(182.9)	--

Uncertainty - The uncertainty is estimated to range from 6.9 J/g at 3 K to about 4 J/g at the triple point.

2.2.15. LATTICE PARAMETERS^{146, 155, 186-190}

Discussion - The ranges of the lattice parameters have been assembled from various sources into Table 17. It should be emphasized, though, that the references given in the table are not exhaustive, only representative.

Lattice parameters combined with crystal structure are very often the only way in which molar volumes for the solid can be obtained.

Tables of Values - Table 17

Uncertainty - The accuracy in the determination of lattice parameters from X-ray diffraction is seldom better than about 1%.

2.2.16. MECHANICAL PROPERTIES^{169,174,191-201}

Discussion - In other sections values for several mechanical properties such as the velocity of sound of the solid (Subsection 2.2.25) and thermal expansion of the solid (Subsection 2.2.28) are presented. In this Subsection the remainder of the mechanical properties of the solid phase are discussed.

Experimental measurements of uniaxial loading have been conducted by Bolshutkin, Stetsenko and their co-workers on polycrystalline parahydrogen¹⁹⁵ and on polycrystalline normal hydrogen.¹⁹² In these papers the authors present values of Young's modulus, shear modulus, tensile strength, nominal yield stress, and relative elongation. Values for normal and parahydrogen are summarized in Figure 39 which is taken from Reference 192.

Experimental measurements of the velocity of sound in solid hydrogen^{196,197} yield calculated values of Poisson's ratio as well as values of adiabatic and isothermal compressibilities. These values are found in Table 24. In addition, the papers report values of the Debye θ , elastic constants, and the adiabatic bulk modulus, all of which together with a few calorimetric Debye θ 's are given in Table 18. Note that the calorimetric Debye θ 's are consistent, and the mechanical Debye θ 's are consistent, but that the results of the two methods differ considerably as pointed out in Reference 196. The explanation that "This discrepancy is due to incorrect elimination of the anomalies in the temperature dependence of C_V ..." needs further study,

particularly as the recent results on C_V of Roberts and Daunt¹⁷⁴ are in excellent agreement with those of Ahlers.¹⁶⁹ Ahlers' measurements are at constant volume; technically the correct way to determine a Debye θ is from C_V data. In addition, Ahlers' θ 's vary from 128 to 106 for his lowest isochores, that is for temperatures from 0 to 15 K, and they vary considerably more for changes in density.

Finally there are measurements of shear strength as a function of applied pressure. Initial values of extrusion pressures were reported by Stewart.¹⁹⁴ These measurements have since been refined by Towle¹⁹¹ and Bignell.¹⁹³ Towle's values are given in Table 19. Plastic deformation is discussed by Bol'shutkin and Coworkers.^{198,199} Deformation curves for hydrogen are given in Reference 199, and a graph of creep is given in Reference 201. Calculation of elastic constants using several different experiments were made by Goldman.²⁰⁰

Tables of Values - Debye θ , adiabatic bulk modulus, elastic constants - Table 18; shear strength - Table 19; Poisson's Ratio, adiabatic and isothermal compressibilities - Table 24

Figure - Young's modulus, shear modulus, tensile strength, nominal yield stress, relative elongation - Figure 39

2.2.17. MELTING CURVE^{105, 120, 142}

Discussion - See also Subsections 2.2.5 Equation of State and 2.2.21 PVT. In the most recent correlation¹⁴² the properties on the liquid side of the melting curve are supplied by a specific equation of state¹⁰⁵ and its intersection with the melting pressure equation¹²⁰ as given in Subsection 2.2.18.

Tables of Values - Table 13

Figures - 17, 18

2.2.18. MELTING PRESSURE^{14,110,119,120,142,202}

Discussion - Parahydrogen: The equation used is the one developed by Goodwin,¹²⁰ except that the temperature scale has to be shifted by 0.003 K to match the triple point temperature and pressure of the liquid vapor pressure curve used with the 33-term MBWR equation. The shift insures that the melting pressure equation and the liquid vapor pressure equation intersect at the triple point, 13.800 K and 0.00704 MPa (0.0695 atm), which are the values chosen for the basic 33-term equation of state. Additional experimental values for the melting pressures of parahydrogen have been published by Younglove¹⁴ and by Kechin et al.²⁰²; these values have not yet been incorporated into a melting pressure analysis.

Normal hydrogen: The equation used is the one developed by Goodwin¹²⁰ which is based upon the experimental results quoted by Woolley, et al.¹¹⁰ and Mills and Grilly.¹¹⁹

Tables of Values - Parahydrogen, Table 13; normal hydrogen, Table 20

Figures - 17, 18

Equation -

$$(P - P_t)/(T - T_t) = [A \exp(-\alpha/T)] + BT$$

where A = 30.3312 atm/K, α = 5.693 K, B = 2/3 atm/K², and values of the triple point parameters are as follows:

	p-H ₂	n-H ₂
T _t , K	13.803	13.947
P _t , MPa (atm)	0.00704 (0.0695)	0.00719 (0.071)

For parahydrogen in Reference 142 the Kelvin temperature shift is T(shifted) = T + 0.003.

Uncertainty - The uncertainty of the melting pressures is about 0.1%.

2.2.19. ORTHO-PARA MODIFICATIONS²⁰³⁻²⁰⁶

Discussion - See also Subsection 4.2.6.

The user should be aware that temperature dependent ortho-para changes continue to influence properties in the solid state. Several properties such as specific heat (Subsection 2.2.9), thermal conductivity (Subsection 2.2.26), and thermal diffusivity (Subsection 2.2.27) are highly sensitive to actual ortho-para composition.

For solid hydrogen Ahlers²⁰³ made measurements of the ortho-para conversion as a function of the molar volume of the solid. These measurements are in excellent agreement with the experimental values obtained at very low pressure by Cremer.²⁰⁴ More recent measurements have been reported by Schmidt²⁰⁵ and calculations have been performed by Milenko and Sibileva.²⁰⁶

2.2.20. PHASE DIAGRAM²⁰⁷

Definition - Phase diagrams indicate the boundaries between the solid, liquid, and gas phases. A schematic phase diagram was used in the introduction, Section 2.1. The different phases are quite often shown in the diagrams of other properties, even though it may not be possible to obtain the PVT of the point in question. As a guide to the user all such diagrams are indicated below. A phase diagram which includes metallic hydrogen is given in Reference 207.

<u>Figure coordinates</u>	<u>Figure number</u>
Pressure-temperature	34a,b,c
Dielectric constant- temperature	36
Molar volume-temperature	40a,b
Temperature-entropy	43
Vapor pressure-temperature	44

Uncertainty - The uncertainty of values taken from the above (or any other) diagrams is determined by the resolution of the individual chart.

2.2.21. PVT^{4,14,16,19,110,118-120,129,142,151,153,154,158-161,169,179-181,208-211}

Discussion - As indicated in the introduction, we distinguish three separate regions, the solid-vapor and solid-liquid two phase regimes and the single phase compressed solid states. Experimental data for the two phase regions include vapor pressures,^{110,208,209} melting pressures,^{14,119,120} saturated solid densities,^{110,169,179} liquid densities along the melting line,^{4,118} and volume changes on fusion.²¹⁰ Saturated solid densities are also obtained from the crystal structure, Subsection 2.2.1, and the lattice parameters, Subsection 2.2.15. The data for the solid-vapor region have been correlated by Mullins, et al.,¹²⁹ while the data for parahydrogen in both two phase regimes have been correlated more recently.¹⁴² Data for the single phase compressed solid^{16,118,153,154,158,161,169,180,181,211} largely remain uncorrelated. An exception is the PVT measurements by Silvera et al.¹⁶⁰ These authors ascribe the phase transition near the melting line to an instrumentation effect rather than a true transition. The diagrams illustrate that the controversy is far from settled. Figure 40a is based on the measurements of Dwyer et al.¹⁶¹ as adjusted in References 19, 142, 151 and shows two phase change points on the melting line. Figure 40b is taken from Mills¹⁵⁹ and features only one phase change point along the melting line. In comparison, figure 34c taken from Reference 160 shows no phase change along the melting line.

Separate tables for normal hydrogen illustrate differences in PVT. The differences, however, are very slight and can be neglected for most practical applications.

Tables of Values - parahydrogen, solid-vapor two phase region, Table 12; parahydrogen, solid-liquid two phase region, Table 13; normal hydrogen, Tables 20, 22, 23, 27; single phase compressed solid, Tables 14, 21, 22

Figures - 34c, 40a,b, 41, 43

Uncertainties - as estimated in Reference 142

temperature 0.01 K

pressure 1% at the triple point increasing to 200% at very low temperatures. Negligible for pressures above 0.101325 MPa (1 atm).

density 0.2% at temperatures above triple point. 0.4% at the triple point increasing to 1.5% at 4 K.

2.2.22. SATURATION PROPERTIES

Discussion - the reader is referred to the various subsections on the specific property desired.

Tables of Values - solid-vapor two phase region, Tables 12, 25 (solid only); solid-liquid two phase region, Table 13

Properties covered in Tables 12 and 13

pressure, temperature, volume, density, enthalpy, entropy, internal energy, heat capacity at saturation, heat capacity at constant pressure, heat of sublimation, heat of fusion

Properties covered in Table 25

temperature, density, heat capacity at saturation, thermal conductivity, thermal diffusivity

Figures - 36, dielectric constant

38, heat capacity at saturation

40a,b, PVT

43, thermodynamic functions

44, vapor pressure

2.2.23. SLUSH HYDROGEN PROPERTIES^{105, 142}

Discussion - See also Subsection 4.2.9.

Slush is the term used to designate a mixture of solid and liquid phases of the gas under consideration. There are two major reasons for the current interest in slush. First, since solid is more dense than liquid, slush offers a way to carry a larger quantity of the cryogen in a container of fixed volume, as compared to the liquid alone. Second, as the solid melts, absorbing heat, slush offers a way to lengthen the time that the cryogen can be stored in a fixed volume container before venting has to occur.

In Reference 142, the solid-liquid and the solid-vapor two phase regions are treated. The solid-vapor region is included because slush is currently produced by a freeze-thaw process. This means the properties of the vapor at temperatures just below the triple point are also of concern. Further, the properties of this two phase region are of interest in other applications, such as subliming refrigerators, which are used to cool infrared detectors, and in making solid hydrogen targets for fusion experiments.

Computer Program Description - The thermodynamic properties of hydrogen can be obtained from the computer program described in Reference 142 for temperatures both below and above the triple point. Values of the various physical properties required for the computations are either taken from the literature, or are extrapolated. If extrapolated, the extrapolations are based on the known behavior of other simple fluids. Inputs to the program are temperature and quality. The properties returned include pressure, density, enthalpy, entropy and internal energy. The present programs for slush hydrogen are an extension of and dependent upon the equations of state developed previously for these gases.¹⁰⁵

Program		List of						
Name	P-T Range	Properties	Accuracy	Availability	Continuous	Modifications	Input	
SLH2*	0-35 MPa	T,Q,TP,P, O,H,S,U	0.1-1%	NBS Cryogenic Data Center	Yes	Para	T,Q,TP	

*Basic Equation of State H2PROPS is also required.

Comments - The program (by shifting, adjusting, or constraining) avoids the vexing problem of inconsistencies in data which originate from many diverse sources. The quality, Q, used for both solid-vapor and solid-liquid regimes is defined in analogy to the more familiar quality used in liquid-vapor problems. The triple point key, TP, is used to specify either solid-vapor or solid-liquid regimes for the case in which the temperature, T, is exactly equal to the triple point. The program has been used to calculate the major tables of this chapter, i.e., Tables 12 and 13 as well as the values used to plot Figure 43.

2.2.24. SOLID TRANSITIONS

Discussion - See also Subsections 2.2.1 and 2.2.15.

Solid transitions are known to occur for hydrogen. One transition is dependent on ortho-para compositions and involves a change in structure from hcp to fcc. Typical transition temperatures range from 1.2 to 4 K. A second transition also involves a change in structure from hcp to fcc. It occurs for a limited range of elevated pressures along the melting line.

2.2.25. SOUND VELOCITY^{196,197,212-215}

Discussion - The velocity of sound has been measured by a number of authors. Bezuglyi and Minyafaev measured the longitudinal and transverse velocity of sound in polycrystalline normal hydrogen.²¹² Bezuglyi, et al.¹⁹⁶ made similar measurements on parahydrogen. Their results are reproduced in Table 24. The transverse velocities agree very well with later measurements on single crystal hydrogen and deuterium made by Wanner and Meyer.^{197,213-215} The longitudinal velocities, however, differ by about 10%. These measurements were made in the compressed solid states but have not been correlated with the available PVT data to any extent.

Tables of Values - Table 24

Uncertainty - For polycrystalline samples about 5%; for the longitudinal velocity in single crystals up to 10%.

2.2.26. THERMAL CONDUCTIVITY²¹⁶⁻²²¹

Discussion - The thermal conductivity of solid hydrogen, similar to the heat capacity, is highly dependent on ortho-para composition. It also depends on crystal quality, and should depend on density for the compressed solid states. However, most of the experimental measurements have been made at or near saturation pressure. Experimental measurements on hydrogen have been conducted by Hill and Schneidmesser^{216,217}, Dwyer, et al.,²¹⁸ and Bohn and Mate.²¹⁹

Thermal conductivity of solids is usually analyzed in terms of the thermal resistance $W = 1/k$. The intrinsic resistance, W_i , that is phonon-phonon scattering, follows a T^n dependence for nonmetals where n ranges from 1 to 3. For parahydrogen, the value of n is between 3 and 4 if estimated

from the results of Hill and Schneidmesser for temperatures between 4 and 11 K. The results of Dwyer, et al.²¹⁸ are in apparent disagreement with this temperature dependence; they are too low in W (too high in k). The disagreement probably occurs because the measurements were taken along the melting curve at elevated pressures, i.e., the densities are higher than those prevailing at the triple point. Solid heat transfer studies were made by Contreras and Lee.² Experimental results on deuterium are contrasted to hydrogen in Reference 221.

Figure - 42

Uncertainty - We note that the hydrogen results of Hill and Schneidmesser (1% ortho) and those of Bohn and Mate (1.1% ortho) differ by almost an order of magnitude. This uncertainty should decrease to about 3% as the temperature approaches the triple point.

2.2.27. THERMAL DIFFUSIVITY

Discussion - Values of thermal diffusivity have been calculated from values given in other subsections, thermal conductivity (Subsection 2.2.26), density (Subsection 2.2.21), and C_p (Subsection 2.2.7). Applicable property values and calculated thermal diffusivities are shown for solid para and normal hydrogen in Table 25.

Tables of Values - Table 25

Uncertainty - The uncertainty in thermal diffusivity near the triple point is about 3% as obtained from the errors in the other variables. Since the solid thermal conductivity is very sensitive to ortho-para content, the value of thermal diffusivity of parahydrogen near 4 K has to be considered uncertain by one order of magnitude. Note that values of thermal diffusivity for para and normal hydrogen differ by several orders of magnitude for the lower temperatures of the solid.

2.2.28. THERMAL EXPANSION^{169,222}

Discussion - Explicit values for any of the hydrogens were not found in the literature. We can, however, estimate the thermal expansion from the volume change. In the absence of preferred orientation the linear expansion is to a very good approximation one-third of the volume expansion. Solid parahydrogen contracts by about 1% in contrast to a typical metal which contracts very little if at all in the same temperature range. Calculated values of the thermal expansion coefficient for solid parahydrogen were taken from Ahlers.¹⁶⁹ A more recent paper by Udovidchenko, et al.²²² covers thermal expansion at a pressure of 0.4053 MPa (4 atm) in the solid, i.e., at pressures below the fcc form.

Table of Values - Table 26

Uncertainty - Since the molar volume of the solid is uncertain by about 1.5%, the uncertainty in thermal expansion is at least that large.

2.2.29. THERMODYNAMIC DIAGRAMS^{129,142,223}

Discussion - Thermodynamic diagrams or Mollier charts are used by the engineer in many applications because these charts summarize in one place the phase diagram, the PVT surface, and some of the derived thermodynamic properties. A temperature-entropy chart, for example, contains the phase boundaries, lines of constant pressure, volume, enthalpy, and quality. The earliest of these charts was prepared by Mullins, et al.¹²⁹; however, it lacks information on the solid-liquid two phase region. The more recent version by Sindt and Mann²²³ includes both solid-liquid and solid-vapor two phase regions. It has since been updated by Roder.¹⁴²

Figure - 43

2.2.30. VAPOR PRESSURE^{110, 129, 142, 208, 209, 224}

Discussion - We are interested here only in vapor pressures at temperatures below the triple point (~ 13.8 K). These vapor pressures are often called sublimation pressures. Measurements or correlations prior to 1948, i.e., the paper of Woolley, et al.¹¹⁰ are not reviewed. We note that differences in vapor pressure measurements by different observers are nearly always attributable to differences in the temperature scales used.

Direct experimental vapor pressure measurements on solid n-H₂ between 3.4 and 4.5 K were made by Borovik, Grishin, and Grishina.²⁰⁸ Hydrogen gas was condensed on a cooled surface in a high vacuum. After establishment of equilibrium, the pressure was measured at which the rate of condensation and the rate of evaporation were equal. Errors in the measurement of temperature did not exceed ± 0.02 K, and pressure measurement error did not exceed 10% as reported by the authors.

Harrison, Fite, and Guthrie²⁰⁹ experimentally determined the vapor pressure of solid n-H₂ from 4.7 to 11.1 K. For the two experimental temperature ranges, 4.7 - 5.2 K and 6.5 - 11.1 K, the pressure readings were taken at room temperature using a gauge connected by a tube to the low temperature region containing the solid hydrogen, and corrections were made in the calculations when necessary.

A much more recent survey of the vapor pressure of the hydrogen isotopes has been prepared by Souers, et al.²²⁴

Tables of Values - parahydrogen, Table 12; normal hydrogen, Table 27

Figure - 44

Equations - One of the drawbacks of the earlier calculation by Mullins, et al.¹²⁹ is that the authors presented no explicit equation for the vapor pressure of the solid. Indeed they could not because one can either force

exact thermodynamic consistency or use an explicit vapor pressure equation, but not both. The form of the vapor pressure equation is dictated by thermodynamics. Integration of the Clausius-Clapeyron equation assuming the vapor phase to be an ideal gas leads to the Kirchoff-Rankine equation:

$$\log P = A/T + B \log T + C.$$

Parahydrogen

For parahydrogen the equation is constrained to the triple point $P_t = 0.00704$ MPa (0.0695 atm), $T_t = 13.800$ K, and in other ways to force thermodynamic consistency.¹⁴² The coefficients are:

$$A = -90.77568949 \quad B = 2.489830940 \quad \text{and} \quad C = 4.009857354$$

where P is in mmHg* and T is in K.

Normal Hydrogen

Harrison, Fite and Guthrie²⁰⁹ represent their data by the equation

$$\log_{10} P = -\frac{43.39}{T} + 2.5 \log_{10} T + 2.047$$

which is used in Figure 44 for temperatures up to 10 K, where P is in mm Hg* and T is in K. Above 10 K the results of Wooley et al.¹¹⁰ are shown in Figure 44.

Uncertainty - For parahydrogen¹⁴² intercomparison to the available experimental vapor pressures shows the maximum deviation in pressure down to 10 K is less than 1%. The simple equation cannot, however, represent the data down to low temperatures, say 3 or 4 K. In this temperature range the departure between predicted and experimental vapor pressures (for normal hydrogen) increases to nearly 200%. Additional terms in the vapor pressure equation improve the representation of the vapor pressures but not the heats of sublimation calculated from the vapor pressure derivative. For normal

* (mmHg) $\times (1.3332 \times 10^{-4}) = \text{MPa}$

hydrogen the departures between experimental and calculated vapor pressures are on the order of 5%, however the cross-correlation with the heats of sublimation has not been done, and larger deviations are to be expected if thermodynamic consistency is forced.

2.2.31. VIRIAL COEFFICIENTS

Discussion - No virial coefficients have been measured experimentally for temperatures at or below the triple point. Extrapolation from temperatures where these coefficients have been measured is often done. As with any extrapolation, care must be taken so that the results remain physically realistic. A check on the contribution that each extrapolated term makes to any given virial expansion is highly recommended.

CHAPTER THREE
SELECTED THERMOPHYSICAL, CHEMICAL, AND
COMBUSTION PROPERTIES OF HYDROGEN

Jesse Hord

3.1. INTRODUCTION

Only those properties deemed appropriate for safety analyses are treated in this chapter. Certain physical, chemical, and combustion properties of hydrogen are essential ingredients for intelligent safety studies in any potential fuel application. Evaluation of the safety hazards of a particular fuel is a highly complex task requiring interpretation of these specific technical data and intercomparisons with other fuels. To permit insight and provide perspective for the relative safety of hydrogen, comparative data are given in Table 28 for hydrogen, methane, and gasoline. Methane is the major constituent of most compressed natural gases and of liquefied natural gas. The technical data, listed in Table 28, were obtained from numerous sources and are believed to be the best available. Some of the data given in Table 28 were obtained by giving weighted consideration to several sources of data and by performing appropriate computations.

Most of the properties listed in Table 28 will be familiar to the average reader and have been discussed in Chapters One and Two; however, each of the combustion properties will be briefly described in this chapter because of their importance to safety analyses and because some of them are not commonly used properties. The thermophysical properties conform with the conventionally accepted definitions; however, explanatory notes are provided at the bottom of Table 28 to explain the bases for some of the "gasoline" properties. The heats of fusion and sublimation are taken at the triple point (at the freezing point for gasoline) and the heats of vaporization are taken at the normal boiling point. The combustion properties are defined in the following subsections. For extended discussions of these properties and hydrogen fire and explosion hazards, see Hord.²²⁵ References 225-343 pertain to hydrogen safety.

3.2. DISCUSSION OF THE PROPERTIES

3.2.1. LIMITS OF FLAMMABILITY IN AIR^{232, 237, 238, 242 264}

These limits are defined as the range of concentrations of gaseous fuel in air at which the mixture will burn, i.e., a homogeneous fuel-air mixture will propagate a flame within a limited range of compositions. These limits are determined experimentally²⁶⁴ by visually observing upward propagation of flames through flammable mixtures in vertical tubes. The wide flammability limits of hydrogen are of practical significance only when fuel leakage into enclosed spaces is a major concern. In this case the flammable limits of hydrogen are sufficiently wide to enhance the probability of combustion from a random ignition source. This flammability characteristic should not preclude the use of hydrogen because the lower flammable limit (LFL) is the vital one in most applications. The LFL is important because ignition sources are nearly always present when a leaking fuel first reaches combustible proportions in air.

3.2.2. LIMITS OF DETONABILITY IN AIR^{239, 243, 244, 259, 265}

These limits are defined as the range of concentrations of gaseous fuel in air at which the mixture will detonate, i.e., the flame front will propagate at supersonic speed. These limits are usually determined by measuring the rate of propagation^{243, 259, 265} of combustion-supported pressure waves in long horizontal tubes filled with combustible mixtures of fuel in air.

3.2.3. STOICHIOMETRIC COMPOSITION IN AIR

This composition defines the concentration of fuel in air at which all of the fuel and oxygen in the mixture are consumed by the reaction and maximum combustion energy is realized.

3.2.4. MINIMUM ENERGY FOR IGNITION IN AIR^{240, 245, 266, 267, 286}

This energy is defined as the minimum spark energy required to ignite the most easily ignitable concentration of fuel in air. The most easily ignited mixture of fuel in air is usually not the stoichiometric composition. To determine the minimum ignition energy, a calibrated capacitor is charged to a specified voltage and discharged through an arc between parallel plate electrodes that are immersed in the combustible mixtures of gases. Ignition energy is calculated from $(1/2)CV^2$ (see References 266, 267).

The minimum spark energy required for ignition of hydrogen in air is about an order of magnitude less than that for methane or gasoline; however, the ignition energy for all three fuels is sufficiently low that ignition is relatively assured in the presence of thermal (weak) ignition sources, e.g., sparks, matches, hot surfaces, or open flames. Even a weak spark due to the discharge of static electricity from a human body may be sufficient to ignite any of these fuels in air -- 10 mJ sparks may be produced in such electrostatic discharges.²⁸⁶

3.2.5. AUTOIGNITION TEMPERATURE^{232, 241, 242, 268}

The minimum temperature at which a combustible mixture of fuel and air can be ignited by a hot surface is the autoignition temperature.

Although hydrogen has a higher autoignition temperature than methane or gasoline, its low ignition energy characteristic makes it more readily ignitable than either of the hydrocarbon fuels. The hot air-jet ignition temperature (Subsection 3.2.6.) is highest for methane and lowest for hydrogen; therefore, hydrogen is easiest to ignite by jets of hot combustion products emitted from an adjacent enclosure. The flash point (see Subsection 3.2.20) is meaningless for the cryogenic fuels, hydrogen and methane, within

the temperature range of interest because these fuels will flash at all temperatures above their normal boiling points. The boiling points of the cryogenic liquid fuels are so low that these fuels are considered to behave like gases. The flash point of gasoline is also well below room temperature; therefore, all three fuels must be considered volatile and will generate sufficient vapor to create a fire hazard at earth surface temperatures. Then, all three fuels are relatively easy to ignite. Hydrogen is most susceptible while methane and gasoline appear to be equally susceptible to ignition.

3.2.6. HOT AIR-JET IGNITION TEMPERATURE^{246, 269, 270}

This ignition temperature is defined as the temperature of a jet of hot air as it enters pure fuel vapors or a combustible fuel-air mixture at NTP (1 atm and 20°C) and causes ignition to occur. The data given in Table 28 represent the jet temperature of hot air as it enters pure fuel vapors at NTP. The jet diameter for these data is 0.4 cm. This ignition temperature decreases with increasing jet diameter and for a given jet diameter the hot gas jet ignition temperature increases if hot jets of nitrogen gas (rather than air) are squirted into combustible fuel-air mixtures.²⁶⁹ The hot gas jet ignition temperature is dependent upon the composition of the combustible mixture and the velocity of the jet of hot gas.

3.2.7. FLAME TEMPERATURE IN AIR^{247, 248, 271}

The flame temperature in air is defined as the temperature within the flame when premixed stoichiometric fuel-air mixtures are burned in the open

air. Fires at the scenes of fuel spills or leaks more closely simulate stationary gaseous diffusion flames which burn at lower temperatures.

Detailed discussions on this topic and experimental techniques are reviewed by Lewis and von Elbe.²⁷¹

3.2.8. PERCENTAGE OF THERMAL ENERGY

RADIATED FROM FLAME TO SURROUNDINGS^{249, 250}

The percentage of thermal energy radiated from a flame to its surroundings is defined as the percentage of the heat of combustion (high) that is radiated from the combustion zone to its surroundings. The higher heating value of every flame is eventually dissipated by radiative processes. The data given in Table 28 are for flames fueled by vaporization of pools of liquid fuels in an air environment. These data are similar to those obtained in laboratory experiments with stationary gaseous diffusion flames.^{249, 250} Atmospheric moisture absorbs thermal energy radiated from a fire and can reduce the values recorded in Table 28. Hydrogen fires benefit most from this absorption effect,²⁴⁹ e.g., it is estimated that 45 percent of radiant hydrogen flame energy is absorbed within a distance of 8 m in 25°C air containing water vapor at 0.002 MPa (15 mmHg) partial pressure.

3.2.9. BURNING VELOCITY IN NTP^a AIR^{242, 243, 248, 251, 252, 255, 287-289, 311}

The burning velocity in NTP air is defined as the subsonic velocity at which a flame propagates through a flammable fuel-air mixture. This velocity is usually determined in the laboratory by measuring the velocity of gas flow to a bunsen burner.²⁵¹

^a

NTP = Normal temperature and pressure (1 atm and 20 C).

The burning velocity is a fundamental property of a combustible gas mixture and should not be confused with the flame speed.²⁸⁷ The burning velocity influences the severity of the explosion and along with quenching gap is important in the design of flame arresters.²⁸⁷ Higher burning velocities indicate a greater tendency for the combustible gas mixture to support the transition from deflagration to detonation in long tunnels or pipes. The instantaneous pressure rise due to the ignition of a fuel-air mixture contained in a spherical vessel is proportional to the cube of the burning velocity.²⁸⁸ Available data²⁸⁹ indicate that the pressure rise ratios for adiabatic combustion of stoichiometric mixtures of hydrogen-air and methane-air in closed vessels are nearly identical. Similar data²⁵⁵ produced pressure rise ratios for hydrogen-air that were 20 to 40 percent higher than those for gasoline-air. In long tubes or tunnels, hydrogen-air mixtures will transit to detonation more rapidly than methane-air or gasoline-air mixtures; therefore, overpressure hazards in confined spaces are enhanced in hydrogen systems. Thus, the high burning velocity of hydrogen is an indication of its high explosive potential and of the difficulty of confining or arresting hydrogen flames and explosions. Industrial equipment is currently available to safely confine hydrogen explosions but pipeline flame arresters, though successful in certain hydrogen-air combustion applications, are not yet considered reliable.³¹¹

3.2.10. DETONATION VELOCITY IN NTP AIR^{243,253,254,259}

The detonation velocity is the supersonic velocity at which a flame (and accompanying pressure wave) propagates through a detonable fuel-air mixture.

3.2.11. DIFFUSION COEFFICIENT IN NTP AIR²⁷²

The diffusivity or coefficient of diffusion is a parameter used in Fick's equation to describe the rate at which a gaseous fuel diffuses through air. For a given fuel concentration gradient the mass diffusion flow rate is proportional to the diffusion coefficient. This coefficient can be computed from an empirical expression²⁷² that is based on the kinetic theory of gases.

3.2.12. DIFFUSION VELOCITY IN NTP AIR²⁷³

The diffusion velocity is simply the velocity at which a gaseous fuel diffuses through air. For a specified fuel concentration gradient the diffusion velocity is proportional to the diffusion coefficient and can be estimated from Stefan's equation.²⁷³ Diffusion velocity varies with temperature according to $T^{3/2}$ and consequently low temperature gases produced by cryogenic liquid fuel spills will diffuse more slowly than NTP fuel gases. The values recorded in Table 28 are based on NTP fuel gas and NTP air densities and fuel concentrations that vary from 99.99 percent to 0.0 percent over path lengths of 3 cm to 30 m.

3.2.13. BUOYANT VELOCITY IN NTP AIR^{249, 250, 274, 275, 282, 320}

The buoyant velocity is the velocity at which gaseous fuels rise in air under the influence of buoyant forces. This velocity cannot be determined in a direct manner as it is dependent upon drag and friction forces that oppose buoyant forces acting on the rising volume of gaseous fuel. Atmospheric turbulence as well as shape and size of the rising volume of gas can affect the terminal velocity of the buoyant gas. Buoyant forces are related to the

difference in air and fuel densities; therefore, cold, dense fuel gases produced by cryogenic fuel spills will rise more slowly than NTP fuel gases. The buoyant velocities recorded in Table 28 were estimated from fundamental principles of dynamics and with the aid of empirical data^{274, 275}; it was assumed that the radii of the buoyant masses of NTP fuel gas varied from 3 cm to 1.5 m.

The rate at which fuel vapors mix with air is indicated by their diffusion velocities and their buoyant velocities. The buoyant effect is dominant for hydrogen and methane and from the data listed in Table 28 it is apparent that hydrogen can be expected to mix with air more rapidly than methane or gasoline -- the latter is obviously the slowest mixing fuel of the three fuels considered. In the event of a fuel spill, one could expect hydrogen to form combustible mixtures more rapidly than methane because hydrogen has a higher buoyant velocity and a slightly lower flammable limit. Again, gasoline would be orders of magnitude slower than hydrogen or methane in forming combustible mixtures in air. In some fuel applications these relative mixing times may be important while in others they are meaningless, e.g., an instantaneous fire hazard exists for the impact rupture of an auto fuel tank irrespective of the type of fuel carried.

Because of their higher buoyant velocities, hydrogen and methane can also be expected to disperse more rapidly than gasoline and thus shorten the duration of the flammable hazard. Even though the upper flammable limit (UFL) of hydrogen is much higher than that of methane, the higher buoyant velocity of hydrogen permits it to disperse to concentrations below the lower flammable limit (LFL) more rapidly²⁸² than methane. Thus, one could expect a fire hazard to exist more readily with hydrogen, methane, and gasoline respectively, and to persist in the inverse order.

Some caution must be exercised in analyzing fuel mixing and dispersion rates by comparing relative buoyant and diffusion velocities of the NTP fuel gases. In large cryogenic liquid fuel spills, the vaporization of liquid and warming of the vapor can cool large masses of air. In addition, NBP hydrogen vapor density approaches that of NTP air while NBP methane vapor density is greater than the density of NTP air. Consequently, for some finite period of time these cold vapor-air mixtures are nonbuoyant and may extend to appreciable distances from the spill. Therefore, both the range and duration of the fire hazard may be extended somewhat when cryogenic liquid fuels are spilled. More definitive experimental data are needed in this area to supplement existing knowledge.^{249, 250, 320}

3.2.14. MAXIMUM EXPERIMENTAL SAFE GAP

(MESG) IN NTP AIR^{255, 256, 276}

The MESG is defined as the maximum permissible clearance, between flat parallel steel surfaces, that prevents the propagation of dangerous flames or sparks through the gap. The MESG is measured by igniting a combustible fuel-air mixture inside of a test enclosure and observing a similar combustible mixture surrounding the enclosure to detect its ignition. The MESG is the largest gap size that does not permit ignition outside of the test enclosure. The MESG is dependent upon the test gap flange width, composition of combustible mixtures inside of and surrounding the test enclosure, the initial pressure and temperature of the mixture, location of the ignition source and enclosure geometry.^{255, 276} The hydrogen and gasoline MESG data recorded in Table 28 were obtained using parallel steel flanges that were 1.905 cm wide.

and 10.16 cm long. The methane MESG data were obtained using an 8 liter chamber with equatorial flanges that were 2.54 cm wide. MESG data are of vital importance to the design and manufacture of explosion-proof equipment.

3.2.15. QUENCHING GAP IN NTP AIR^{240,257,277,287}

The quenching gap is defined as the spark gap between two flat parallel plate electrodes at which ignition of combustible fuel-air mixtures is suppressed, i.e., smaller gaps have the effect of totally suppressing spark ignition.^{240,257} Other types of electrode geometries are also used in laboratory measurements^{240,257} of quenching distance. The experimental data^{240,257,277} are dependent upon the temperature, pressure, and composition of the combustible gas mixture and electrode configuration. Experiments have shown that the quenching distance is relatively independent of the mode of ignition. The quenching distance is sometimes determined by measuring the smallest diameter tube through which flame will propagate in a flammable NTP mixture of fuel-air that fills the tube. Similarly, quenching distances can be obtained by measuring the gap required to quench propagation of flame between flanges or plates that form a narrow channel and are filled with a flammable fuel-air mixture at NTP. In the latter two experiments the explosive gas mixture is ignited at one end of a long tube or channel by a pilot flame.

In general, faster-burning gases have smaller quenching gaps and flame arresters for faster-burning gases must have smaller apertures.²⁸⁷ The quenching gap is the passage gap dimension required to prevent propagation of an open flame through a flammable fuel-air mixture that fills the passage and it is clearly distinguishable from the MESG. The latter is the maximum

permissible clearance between flanges to assure that an explosion does not propagate from within an enclosure to a flammable mixture surrounding the enclosure. Because of the high explosion pressures the MESG is always smaller than the quenching distance.

3.2.16. DETONATION INDUCTION DISTANCE IN NTP AIR^{242, 259, 260, 278}

The detonation induction distance is the distance required for a deflagration to transit to a detonation in a detonable fuel-air mixture. This distance is usually experimentally determined in a long cylindrical tube with a spark or hot wire ignitor on one end of the tube. The tube is instrumented along its length to sense the velocity of the flame front as it propagates through the detonable mixture of gases. The distance from the ignitor to the axial position in the tube where the flame front first attains the detonation velocity is reported as the induction distance. This distance is dependent upon the combustible mixture constituents, the pressure, temperature, and concentration of the gaseous mixture, the enclosure geometry²⁷⁸ and strength of the ignition source.²⁴² A deflagration is a low order explosion resulting from subsonic flame speed, relative to the unburned gas. It is conventionally defined as a propagating reaction in which the energy transfer from the reaction zone to the unreacted zone is achieved through ordinary rate-limiting transport processes such as heat and mass transfer. A detonation is a high order explosion resulting from supersonic flame speed, relative to the unburned gas. It may be defined as a propagating reaction in which energy is transferred from the reaction zone to the unreacted zone on a reactive shock wave.

3.2.17. LIMITING OXYGEN INDEX^{238,258}

The limiting oxygen index is the minimum concentration of oxygen that will support flame propagation in an unknown mixture of fuel, air, and nitrogen, e.g., no mixture of hydrogen, air, and nitrogen at NTP conditions will propagate flame if the mixture contains less than 5.0 volume percent oxygen.²³⁸ Use of diluents other than nitrogen results in different values for the limiting oxygen index of each fuel.^{238,258} The low values of limiting oxygen index reflects the high value of the upper flammable limit (UFL) for hydrogen-air mixtures.

3.2.18. VAPORIZATION RATES OF LIQUID POOLS WITHOUT BURNING²⁵⁰

The vaporization rate of a liquid pool (in the absence of burning) is determined by the rate at which the liquid level decreases after a pool of liquid fuel has been formed by spilling fuel onto a warm surface such as sand or soil. These evaporation rates are measured after subsidence of the violent boiling that accompanies the initial liquid spill. Vaporization rates of the cryogenic fuels can be expected to vary widely with the conductivity and heat capacity of the soil or other material confining the spilled liquid fuel. In the case of gasoline, vaporization rates will vary with the volatility of constituents (blend), age, fuel temperature, ground surface texture, and temperature, etc. Wind velocity influences the vaporization rate of all fuels considered herein.

3.2.19. BURNING RATES OF SPILLED LIQUID POOLS^{249, 250, 342}

The burning rate is the rate at which the liquid level decreases after a pool of liquid fuel has been formed by spilling fuel onto a warm surface and the resultant vapor-air mixture has been ignited. Again, these burning rates are measured after the initial-spill violent boiling has subsided and the vapor is mixing and burning in air above the pool of spilled fuel. These burning rates may also be obtained by adding the vaporization rate (without burning) and the liquid level regression rate attributable to the burning of vapors in the open air over liquid fuels that are contained in open-mouthed insulated vessels. Steady state burning rates increase with liquid pool diameter while vaporization rates continuously decrease with time, irrespective of pool size. Burning rates can be expected to vary with pool diameter and wind velocity.

As indicated in Table 28, the volumetric vaporization rates and burning rates are highest for hydrogen, methane, and gasoline, respectively. Consequently, for a given liquid spillage volume, gasoline fires will last the longest and hydrogen fires the shortest while all of the fuels burn at about the same flame temperature. The thermal energy radiated from these pool-fed fires may be computed by multiplying the appropriate (burning rate) X (NBP liquid density) X (high heat of combustion) X (percentage of thermal energy radiated from the flame to its surroundings). The radiated thermal energy should not exceed 276 W/cm² of pool liquid-vapor surface area for hydrogen, 155 W/cm² for methane, or 212 W/cm² for gasoline. Then, the scene of a hydrogen fire may be hotter than that of a hydrocarbon fire, but the hydrocarbon fires will last five to ten times longer than hydrogen fires (for equivalent fuel spillage volumes).

3.2.20. FLASH POINT^{232, 279}

The flash point is the minimum liquid fuel temperature required to provide a fuel vapor-air mixture above the surface of the liquid that will propagate a flame. The liquid fuel is heated in an open or closed cup²⁷⁹ until the vaporization rate is sufficient to form a mixture of fuel vapor and air that is within the flammable limits near the liquid surface. Ignition is accomplished with an open flame near the surface of the liquid.

3.2.21. ENERGY OF EXPLOSION^{290, 298, 309, 320}

The energy of explosion is the theoretical maximum energy available from a chemical explosion. This maximum energy release is determined by computing the isothermal decrease in the Helmholtz free-energy function. Explosive energies listed in Table 28 are expressed in terms of equivalent quantities of TNT (symmetrical trinitrotoluene) and may be converted directly to energy units by multiplying by 4602 J/(g TNT). Note that hydrogen is the most potent on a mass basis and the least potent on a volumetric basis. The explosive potential per kJ of stored heating value (based on the high heat of combustion) is 0.17 (g TNT)/kJ for hydrogen, 0.19 (g TNT)/kJ for methane, and 0.21 (g TNT)/kJ for gasoline. Thus, for equivalent energy storage, hydrogen has the least theoretical explosive potential of the three fuels.

It must be emphasized that only a fraction of this theoretical explosive yield can be realized in an actual open-air mishap because it is virtually impossible to spill or release a large quantity of fuel and have all of it mixed in proper proportions with air prior to ignition. Experimental data and computations indicate that the fraction^{290, 309, 320} of fuel within the combustible range at any time following a massive or continuous fuel spillage

will be less than 10 percent of the quantity spilled. Such explosive yield data are meager for all three fuels; however, the vapor or gas phase mixing limitations are equally applicable to all fuels. Hydrogen disperses much more rapidly than methane or gasoline, but it also has much wider flammable and detonable limits, etc. Thus, in the absence of more definitive experimental data it is impossible to accurately assess the probable explosive yield attributable to accidental release and ignition of hydrogen, methane, or gasoline in air. The 'energy of explosion' values listed in Table 28 should be considered theoretical maximums and yield factors of 10 percent are considered reasonable for fuel-air explosions. Higher yield factors are possible in liquid bipropellant explosions.²⁹⁸

3.2.22. TOXICITY^{261-263, 280, 281}

Although not a combustion property, the toxicity of a fuel is an important factor in safety studies. Toxicity is the quality or condition of being harmful, destructive, deadly, or poisonous to living organisms. The toxicity of a fuel can only be described in terms of its effects on living organisms and specifically in terms of its effects on humans.²⁸⁰ Toxicity ratings²⁸⁰ are (of necessity) relative values and threshold limit values for exposure to toxic substances are published annually (see Reference 281).

3.3 DATA GRAPHS

3.3.1. DISCUSSION OF THE FIGURES

Personnel safety criteria and hydrogen storage standards have been developed by combining the properties data in Table 28 with certain technical formulae and experimental results. These safety and storage criteria are

summarized on Figures 45-47. The derivation and use of data shown on these figures are fully discussed in summary documents^{225, 290} treating the explosive hazards of hydrogen and only a brief summary of these figures is given here.

Figures 45 and 46 summarize much of the fire and explosive hazard data for experimental areas and illustrate the variation in conservatism of various authorities that generate safety criteria. Obviously, when in doubt, the more conservative criteria should be used. The overpressure band on Figure 45 corresponds to breakage of ordinary window glass (3.5 to 7 kPa) and the overpressure band on Figure 46 relates to the estimated external pressure capability of liquid hydrogen storage dewars. Note that the data on both of these figures specify safe unbarriered distances. Safe barricaded distances for TNT and fuel-air explosions may also be estimated from data made available in References 290, 298, and 308.

Unbarriered distances required for the protection of personnel in inhabited buildings that are exposed to shrapnel from TNT explosions are indicated by curve 6 on Figure 45. These data also predict the maximum observed fragment distances for space vehicle explosions²⁹⁸ and are more restrictive than the unbarriered distances required for shrapnel protection of personnel on roadways (see curve 2 on Figure 45).

A single series of documents²⁹⁸ offers comprehensive treatment of overpressure, impulse, fireballs, shrapnel, barricades, structural response, and physiological effects, as they relate to propellant explosions. These documents are believed to be applicable to fuel-air explosions where the TNT equivalent is properly estimated.

Figure 47 provides a ready comparison of industrially accepted fuel storage standards for hydrogen, liquefied natural gas (LNG), and gasoline. By

comparing curves 1 and 4 on Figure 47 with the data given on Figures 45 and 46, we find that the industrial quantity-distance standards (Figure 47) for hydrogen are less demanding than those suggested for experimental areas (Figures 45 and 46). Also, by comparing curves 1, 2, 3 and curves 4, 5, 6 on Figure 47, we observe that industrial storage standards are more restrictive for hydrogen, methane, and gasoline, respectively.

Curve 3 on Figure 47 represents the minimal distance for separation of two adjacent above-ground gasoline storage tanks. The distance³⁴¹ between such tanks shall not be less than 0.9 m (three feet) and not less than one-sixth the sum of the diameters of two adjacent tanks. When the diameter of one tank is less than one-half the diameter of the adjacent tank, the distance³⁴¹ between the two tanks shall not be less than one-half the diameter of the smaller tank.

Curves 6A and 6B on Figure 47 represent the variation in quantity-distance standards for the protection of personnel in buildings adjacent to gasoline storage tanks. These curves bound standards³⁴¹ that vary with type of tank construction, fire control measures and protection for exposures, tank operating pressure, and emergency venting equipment.

The distance³⁴¹ from any part of an underground tank (storing gasoline) to the nearest wall of any basement or pit shall be not less than 0.3 m (one foot), and not less than 0.9 m (three feet) from inhabited buildings.

It is apparent that industrial storage standards are least restrictive for gasoline; however, the industrial storage standards for LNG and hydrogen fuels are not prohibitive and should not limit their use.

CHAPTER FOUR

MISCELLANEOUS PROPERTIES OF HYDROGEN

Jesse Hord, Robert D. McCarty, and Hans M. Roder

4.1. INTRODUCTION

This chapter collects many of the properties, of interest to scientists and engineers, that are not readily categorized and treated in one of the previous chapters.

4.2. DISCUSSION OF THE PROPERTIES

4.2.1. RADIATIVE PROPERTIES

No references to the emissivity of hydrogen were found in the literature; see Subsection 4.2.2. for spectral absorption.

4.2.2. INFRARED ABSORPTION³⁴⁴⁻³⁵⁰

Definition - The absorption coefficient, k , of a material is a measure of the loss in intensity, I , of radiation which is passed through a unit length of a homogeneous region of the material, i.e., if Z is the axis of propagation, then $dI/I = -kdZ$ or in integral form $I = I_0 e^{-kZ}$.

Absorption Bands - k is for most gases a strong function of frequency, being zero over large ranges of frequency and sharply peaked in certain other regions. It is difficult to summarize this subject because so many transitions are possible for hydrogen, i.e., rotational, vibrational, Raman, ultraviolet, infrared, and far infrared spectra have all been investigated. An extensive survey of induced transitions in liquid and solid hydrogen up to about 1965 is given by Colpa.³⁴⁸ More recent data for solid hydrogen includes Raman spectra at the lambda transition³⁷⁰ and both infrared and Raman spectra at pressures up to 1500 MPa (15 kbar).³⁷¹ As with other gases, the absorption

coefficient k is density dependent, varying roughly as the density squared (see Figure 48); in the particular case of hydrogen, k is significantly dependent upon the ortho-para composition (see Figures 49 and 50). For an estimate of importance to heat transfer problems, see Reference 349.

Figure - 48, Raman; ³⁴⁶ 49, far infrared (rotational); ³⁴⁴ 50, far infrared (translational); ³⁴⁴ 51, far infrared (rotational); ³⁴⁵ 52, ultraviolet. ³⁴⁷

Uncertainty - The uncertainty varies with frequency but a typical conservative estimate is 5%. Note: Differences of 30 to 40% for the peak absorption between Jones^{344, 350} and others have not been explained.

4.2.3. ISOTOPES¹⁹

Definition - An isotope is an atom of an element having a different nuclear mass and atomic weight from other atoms of the same element.

Discussion - Hydrogen has two such isotopes, deuterium with an atomic weight of 2 and tritium with an atomic weight of 3. The three different kinds of hydrogen atoms may combine in six different ways to form a molecule, i.e., H₂, D₂, T₂, HD, HT, and DT. There are some data in the literature for D₂ but very little for any of the tritium-containing molecules. The isotopes are beyond the scope of this work, and the reader is referred to Reference 19 for data on the hydrogen isotopes. Also, isotope data pertinent to magnetic fusion applications are being compiled at the Lawrence Livermore Laboratory.¹³⁹

4.2.4. MIXTURE PROPERTIES³⁵¹⁻³⁵⁹

Thermodynamic Properties - A review by Hiza et al.³⁵³ lists experimental data for fluid mixtures properties of cryogenic interest; included are data

for hydrogen systems. In addition to the above review, two reviews^{354, 355} give experimental data and some theoretical discussion of solid-vapor equilibria. For liquid-vapor equilibria, a bibliography by Oellrich et al.³⁵⁶ gives references for both experimental and theoretical studies; this review includes all components with normal boiling points below 350 K. Also, the liquid-vapor section of the review by Hiza et al. has been published.³⁵⁷ Figure 53 can be used to obtain a rough estimate of the solubility of hydrogen in various solvents as a function of temperature and pressure. To estimate hydrogen solubility use

$$X(P,T) = \frac{X(100,T)}{100 - p_0(T)} \cdot P$$

where $X(P,T)$ is the mole percent H_2 in the solvent at the desired pressure P , in atmospheres, and temperature T , in Kelvin; $X(100,T)$ is the mole percent in the solvent at 100 atm and T which is obtained from Figure 53; $p_0(T)$ is the solvent's vapor pressure at T . It is recommended that the above equation be used only for pressures of 10.1325 MPa (100 atm) or less and that the curves not be extrapolated to higher temperature; one should refer to the original data (see References 351, 352, 360-368) for higher temperatures or pressures. To estimate the vapor phase composition one can use $y = 100 X p_0(T)/P$, where y is the mole percent of the solvent in the vapor phase; however, this estimate will always be too low, especially if the pressure is more than 1.01325 MPa (10 atm) above the vapor pressure. For additional information on thermodynamic properties of mixtures, see References 351 to 359. Solubility references differ from liquid-vapor equilibria references in that they consider only liquid phase compositions, whereas the liquid-vapor references consider both phases. Mixture data on isotopes pertinent to magnetic fusion applications are being compiled

at the Lawrence Livermore Laboratory.¹³⁹ The influence of helium and neon impurities on freezing of hydrogen isotopes is treated in Reference 369.

Transport Properties of Mixtures - This subsection considers only viscosity and thermal conductivity. For dilute gas mixtures, Wilke's correlation can be used to estimate the viscosity³⁵⁸ and thermal conductivity.³⁵⁹ To our knowledge, no reliable technique exists for estimating the effect of hydrogen concentration on the viscosity or thermal conductivity in the liquid phase.

4.2.5. METALLIC HYDROGEN^{170, 207, 372-380}

Definition - Solid hydrogen under extreme pressure (about 2 to 3×10^5 MPa) is thought to undergo a phase transition to the metallic state and may be superconducting. The subject of metallic hydrogen is beyond the scope of this work, but References 372 to 380 will serve as a starting point for those who wish to pursue the subject further. These citations include surveys and summaries,³⁷⁴⁻³⁷⁷ Russian static press efforts,³⁷⁸ Japanese static press efforts,³⁷⁹ a metallic hydrogen phase diagram,²⁰⁷ and observations³⁸⁰ of a new solid phase transition at pressures below those where the metallic phase transition occurs.

4.2.6. ORTHO-PARA MODIFICATIONS^{17, 19, 110, 381, 382}

Definition - The hydrogen atom is composed of a nucleus of one proton and an electron orbiting around the nucleus. The hydrogen molecule is composed of two hydrogen atoms; however, there are two modifications of hydrogen molecules called orthohydrogen and parahydrogen. The differentiating feature of these molecules is the relative orientation of the nuclear spin of the individual atoms. The nuclear spin is a rotational motion of the nucleus about an axis perpendicular to the molecular axis. It is therefore possible to have two

relative orientations of these nuclear spins, i.e., the spins may be in the same direction or they may be in opposite directions. These orientations are commonly called parallel and antiparallel, respectively. The nuclear spin is a quantized motion; therefore, only certain motions are allowed. Associated with this quantization are quantum numbers for the spin and the corresponding energy levels. The molecules with antiparallel nuclear spins, called parahydrogen, have even quantum numbers and are in the lowest energy state. Conversely, the molecules with parallel nuclear spins, called orthohydrogen, have odd quantum numbers and are in a higher energy level.

Discussion - Fluid hydrogen may be thought of as a binary mixture of two different species of molecules differing from each other in physical properties. These differences are easily detectable on a macroscopic scale and in some cases are of great importance in design problems. The percentage of the ortho-para concentrations in the mixture is temperature dependent. The term equilibrium hydrogen is, as the name implies, the equilibrium concentration at a given temperature. For example, at a temperature of about 80 K, the equilibrium concentration of ortho and para is 50% for each. Near ambient temperature the composition is 75% ortho and 25% para. This 25-75 composition is called normal hydrogen. See also Subsection 2.2.19.

Tables of Values - These tables are from Reference 110.

Units	Range of table	Table location
% Para	0 - 500 K	29

Figure - 54

Equation - None

Range of Values -

Units	20 K	300 K
% Para	99.821	25.072

Uncertainty - These values are estimated to be uncertain by less than 1%.

Heat of Conversion¹¹⁰

Definition - The conversion of orthohydrogen to parahydrogen is an exothermic process. The amount of heat given off in the conversion is temperature dependent.

Table - Values taken from Reference 110.

Units	Range of tables	Table location
cal/mol*	10 - 300 K	30

Figure - 55

Equation - None

Range of Values -

Units	10 K	300 K
J/g	527.14	27.56
(cal/mol)	(253.99)	(13.28)

Uncertainty - The uncertainty of the heats of conversion is estimated to be less than 0.1%.

Conversion Rates

Since the percentage of the ortho-para composition is temperature dependent, the rate of conversion is of interest in a variety of problems. The conversion of a nonequilibrium ortho-para composition to an equilibrium composition is a very slow process in the absence of a catalyst. This mode of conversion (no catalyst present) is called self-conversion. In general, the self-conversion rate is also a function of temperature. For example, at liquid air temperatures the half-life of the conversion is greater than 1 year, while at 923 K and 0.0067 MPa (50 mmHg) pressure the half-life is on the order of 10 min. The "half-life period" is defined as the amount of time required to convert 1/2 of the excess ortho or para composition present at the starting time.

* (cal/mol) x 2.0755 = J/g.

Catalysis increases liquefaction energy requirements by approximately 15 percent. If normal hydrogen is liquefied and not converted by catalyst to the equilibrium concentration at 20 K, a portion of the liquid will boil away due to ortho-para conversion. Figure 56 shows the fraction of liquid hydrogen boiled off as a function of storage time and initial ortho content. This boil-off is due to the ortho-para heat of conversion only.

Tables of Values - None

Figure - 56

Catalytic Conversion Rates³⁸²

The ortho-para conversion process is greatly enhanced by catalysis; since many substances as well as magnetic and radiation fields will speed up the conversion, only a typical example of conversion will be given here. Weitzel et al.,¹⁷ using 1.5 liters of unsupported hydrous ferric oxide granules, converted liquid normal hydrogen to 90 to 95% equilibrium H₂ at an average rate of 235 L/h.

Tables of Values - None

Figure - None

Equation - None

Property Differences - In general, the larger differences in the properties of ortho and parahydrogen will occur in the derived properties where heat is important. Properties like enthalpy, specific heat capacity, and thermal conductivity show large differences. On the other hand, the density of ortho-para mixtures will vary very little. The difference in density between normal and parahydrogen is probably less than about 0.3%, with normal hydrogen having the larger density. For differences in a particular property, the reader should consult Chapter One for a description of the property and see the figures listed below.

Figure - 57, density differences between normal and parahydrogen; 58, specific heat (heat capacity) differences between normal and parahydrogen; 59, thermal conductivity differences between normal and parahydrogen.

4.2.7. THERMAL TRANSPIRATION³⁸³

Definition - Thermal transpiration is the phenomenon of the flow of a gas at very low pressures through a capillary due to a temperature gradient. In a closed system, with a constant temperature gradient, a steady state pressure difference will occur between the ends of the capillary, provided the mean free path of the gas is about equal to, or larger than, the diameter of the tube.

Thermomolecular Pressure Difference

If, at the steady state, the pressure at the ends of the tube are P_H and P_C , corresponding to temperatures of T_H and T_C , then

$$\frac{P_H}{P_C} = \frac{T_H}{T_C}$$

where the subscripts H and C refer to hot and cold, respectively. The equation is only valid in the limit of $P \rightarrow 0$. At higher pressures, correction terms must be added. However, it must be remembered that thermal transpiration is an apparatus effect; therefore, correction terms to the equation should not be added for a particular gas but rather for a particular apparatus.

4.2.8. HEAT TRANSFER AND PRESSURIZATION PARAMETERS^{4, 7, 8, 384}

A number of thermodynamic expressions have become convenient for the engineer to use in dealing with the storage and transfer of liquefied gases. Tabulations for four such parameters for hydrogen have been included in this subsection.

Specific heat input
(commonly symbolized by θ)

$$V \left(\frac{\partial H}{\partial V} \right)_P = \rho C_P \left[\left(\frac{\partial P}{\partial \rho} \right)_T / \left(\frac{\partial P}{\partial T} \right)_V \right]$$

Energy derivative
(commonly symbolized by Φ)

$$V \left(\frac{\partial P}{\partial U} \right)_V = \frac{V}{C_V} \left(\frac{\partial P}{\partial T} \right)_V$$

Isothermal bulk modulus
(commonly symbolized by α)

$$V \left(\frac{\partial P}{\partial V} \right)_T = -\rho \left(\frac{\partial P}{\partial \rho} \right)_T$$

Volume expansivity
(commonly symbolized by β)

$$\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P = \frac{1}{\rho} \left(\frac{\partial P}{\partial T} \right)_P / \left(\frac{\partial P}{\partial \rho} \right)_T$$

Specific Heat Input, θ - This parameter is sometimes referred to as dQ/dM , heat input per increment of mass. It is frequently expressed in terms of density instead of specific volume, i.e., $\rho(\partial H/\partial \rho)_P$. It is the amount of heat required to expel a unit mass of fluid from a storage vessel. The units are the same as those for enthalpy: J/g.

Energy Derivative, Φ - This quantity is also frequently expressed in density by substituting $1/\rho$ for V . Typical units are MPa-cm³/J. This parameter is often used in conjunction with the specific heat input, θ , to determine expulsion rates from rigid containers.

Isothermal Bulk Modulus, α - Likewise, this parameter is frequently expressed in density; $-\rho(\partial P/\partial \rho)_T$ with the usual units of MPa. It is the reciprocal of isothermal compressibility $-(\partial V/\partial P)_T/V$ and is a convenient factor to use in certain engineering calculations.

Volume Expansivity, β - Often called simply expansivity or constant pressure expansion, it is separately described in Subsection 1.2.29. Units are K⁻¹. A related expression is the constant pressure expansion coefficient,

$T(\partial V/\partial T)_P/V$, but values for this latter expression have not been tabulated and are not as widely used.

Tables of Values - These parameters are tabulated in Tables 2, 3, 8, and 9 as follows:

Parameter	Units	Range of tables		Table location
$\theta = V(\partial H/\partial V)_P$	J/g	13.8 - 3000 K Saturation boundary	0.01 - 100 MPa	2, 8
$\phi = V(\partial P/\partial U)_V$	MPa-m ³ /kJ			
$\alpha = -V(\partial P/\partial V)_T$	MPa		0.01 - 1.3 MPa	3, 9
$\beta = (\partial V/\partial T)_P/V$	K ⁻¹			

Figure - 60, 61

Equations - None except as shown above

Range of Values -

Parameter	Units	Triple point		Boiling point		Critical point	STP
		Liquid	Vapor	Liquid	Vapor		
Para							
θ	J/g	a	a	a	a	a	4455
ϕ	MPa-m ³ /kJ	a	a	a	a	0b	0.0385
α	MPa	a	a	a	a	0	a
β	K ⁻¹	a	a	a	a	∞	a
Normal							
θ	J/g	622.6	139.8	587.9	189.1	199.0	4295
ϕ	(MPa-m ³ /kJ)x10 ²	0.2565	0.0668	0.2018	0.0667	0b	0.0405
α	MPa	90.34	0.0069	50.21	0.0903	0	0.101
β	K ⁻¹	0.0102	0.0752	0.0164	0.0642	∞	0.0033

aValues the same as normal table.

bNot conclusive; may be finite but small value instead of 0.

Uncertainty - The uncertainties for each parameter are estimated as follows:

Parameter	Compressed liquid, %	Gas and supercritical, %
θ	3 - 5	3
Φ	3	2
α	3 - 5	2
β	3 - 5	2

4.2.9. SLUSH HYDROGEN TECHNOLOGY³⁸⁵⁻³⁹³

Definition - Slush hydrogen is a homogeneous mixture of coexisting liquid and solid hydrogen. Slush hydrogen is more dense and has a greater heat capacity than liquid hydrogen; therefore, it offers certain advantages in volume-restricted aerospace missions, e.g. deep space probes. The high density of slush allows more fuel to be carried within a prescribed tankage volume and the increased heat capacity increases non-venting storage times, thereby decreasing overboard vent losses and/or increasing mission duration. The density of slush that is 0.5 solid (by mass) hydrogen is 15.5% greater than that of normal boiling liquid hydrogen. Similarly 0.5 solid fraction slush hydrogen has 18.3% more heat capacity than normal boiling liquid. Slush heat capacity and density relationships are plotted on Figure 62.

Production - There are two recognized methods of producing slush hydrogen. One is the auger method³⁸⁶ and the other is the freeze-thaw method.³⁸⁵

The auger method simply uses an auger rotating inside of an externally-insulated refrigerated cylinder that is submerged in liquid hydrogen. Hydrogen freezes on the internal walls of the cylinder and is continuously shaved or scraped off by the auger.³⁸⁶ Commercial ice-makers operate on a similar

principle. Solid fraction is adjusted by the rate of outflow of slush and equivalent inflow of liquid. The auger method can be used in a continuous production mode and produces slush hydrogen at super-atmospheric pressures so that the slush can be pressure-transferred to storage containers. The auger method has been successfully used to produce small quantities³⁸⁶ of slush hydrogen and should be practical for large scale production.

The freeze-thaw method has been used to generate small³⁸⁵ and relatively large³⁹² quantities of slush hydrogen. This production technique requires that the ullage over a fixed volume of liquid be vacuum pumped until a solid layer forms at the liquid-vapor interface. The vacuum pumping is then stopped and the solid layer melts (thaws) and settles into the liquid. This cycle is repeated until the desired solid content has been formed. The solid is then mixed with the liquid by stirring to form a homogeneous mixture of solid and liquid. The porosity of the solid formed in this manner is a function of the pumping rate. Low pumping rates produce dense solid which when broken forms large particles of solid and will not form a homogeneous mixture with the liquid. Higher pumping rates produce a porous solid which is easily broken into much smaller particles and is easily mixed with the liquid to form a homogeneous mixture which may be defined as slush. This batch method is capable of producing slush in large quantities. Disadvantages of the method are: 1) A safety hazard exists because the required low ullage pressures (~ 0.0061 MPa) invite air leakage into the slush container, and 2) transfer of slush into a storage container requires ullage pressurization or pump-transfer. Maximum solid fractions achieved to date are ~ 0.6 with 0.4 to 0.5 solid content being practical and easily accomplished.

Storage - The latent heat of fusion of the solid makes slush hydrogen more storable than subcooled liquid, i.e., the slush can absorb more energy (heat

leak) and reduce boil-off losses; however, the solid particles settle and tend to agglomerate in the absence of agitation. In low gravity environments this settling is of little concern and in one-g and high-g fields it can be overcome by using mixers.³⁹³

Some very interesting aging effects have been observed³⁸⁵ in slush hydrogen. Although the change in the particle size was insignificant, the structure changed dramatically during aging. The solid particles were observed to change from particles with irregular rough edges to particles with smooth edges. The smaller particles would tend to combine with the larger particles to form a particle of higher density.

The rate of pressure-rise in slush filled vessels can be predicted if the storage vessel heat load distribution and heat transfer rates³⁸⁸ are known. Idealized calculations³⁹¹, for uniformly distributed heat load, have been performed. These thermodynamic calculations assume that an insulated storage tank is filled at some specified fluid state (known solid fraction when fill is complete) and then sealed off. Its contents are allowed to warm up until the fluid pressure rises to the predetermined tank vent pressure. Both liquid and solid-liquid mixtures expand when warmed; therefore, the designer must specify an appropriate ullage (an unfilled portion of the vessel) to accommodate the fluid when it expands. Thus, calculational input parameters are tank volume, tank ullage, vent pressure, heat load (and distribution), heat transfer rates, and fresh-fill fluid state condition.

Handling - Slush hydrogen can be pressure transferred³⁸⁵ through pipelines, orifices, flow devices, etc., using helium or hydrogen as a pressurant. In general, slush behaves as a conventional Newtonian fluid and pipeline pressure losses can be predicted³⁸⁵ using the Fanning equation. Slush with 0.3 or less solid was found to have transfer losses of 10% less than those of the triple

point liquid when the Reynolds number was $\gtrsim 7 \times 10^5$. Slush can also be pumped³⁹⁰ using conventional liquid hydrogen pumps. Slush with solid content of up to 0.6 may be pumped with losses similar to that of liquid hydrogen at its triple point.

Instrumentation - Commercial sensors are available to measure temperature, pressure, quantity, and flow of slush hydrogen in practical applications.³⁸⁷ Germanium, platinum, and carbon thermometers are useful in measuring temperature.

Pressure can be measured using a cold flush-mounted pressure transducer or a remote transducer coupled via transmitting tubes. Care must be taken to avoid thermal-acoustic oscillations in these transmitting tubes and preventive measures include: Establishing a low-flow bleed rate through the tube; roughing the tube interior wall at its entrance (sensing or tap end); restricting flow in the tube by using small bore tubing or packing the bore with a wire or string; damping the oscillations by using a stepped diameter transmitting tube or by attaching a resonant cavity to the transmitting tube.

Volumetric flow can be measured with standard head-meter (orifice, nozzle, venturi) devices and microwave Doppler meters, and thermal boundary layer meters have been used³⁸⁷ to determine mass flow. Fluid level gauging can be accomplished with rod-to-blade capacitance gauges,³⁸⁷ carbon resistance point-sensor rakes, time-domain reflectometry (RF pulsed cable), and head-difference pressure gauges. Mass gauging has been accomplished using RF cavity mode analysis.³⁸⁹ This technique uses a small antennae inside the metal tank to generate electromagnetic standing waves. These standing waves occur at resonant frequencies and resonance decreases with increasing quantities of dielectric fluid within the cavity (tank); i.e., the fluid slows propagation of the electromagnetic wave and mass content of the tank can be determined by measuring resonant frequencies.

Density or solid fraction can be determined by using Beta-ray or Gamma-ray attenuation,³⁸⁷ capacitance methods, and the RF gauging technique. The capacitance techniques are currently considered the most dependable--the bulls-eye ring capacitor for point density measurements and the rod-to-blade capacitance for average zone density determinations.

Problems - Most of the difficulties expected with slush hydrogen applications have been exposed herein. Production should not be a safety problem if the auger method is adapted. Thermal acoustic oscillations in pressure-sensing lines and other plumbing (fill lines, relief tees, vent lines, etc.) will always be a problem but it can be solved by appropriate design and handling procedures. Likewise, the settling-aging-agglomeration and need-for-mixing problem will stay with us and can be overcome with existing technology. Mass flow and mass gauging measurements need to be improved. The thermal performance of aerospace propellant systems (insulated tanks, transfer lines, vents, etc.) must be improved to take full advantage of the high density and heat capacity of 0.5 solid fraction slush hydrogen. There are no known insurmountable problems that exclude the use of slush hydrogen; on the contrary, the use of slush hydrogen in properly engineered systems appears practical and in some cases very desirable.

Thermophysical Properties - See Subsection 2.2.23 and Figure 62.

4.2.10. OTHER MISCELLANEOUS PROPERTIES

Included in this subsection are properties that have not been discussed in the preceding pages and their corresponding references.

Property	Reference
Birefringence	394
Creep	395
Cryopumping	185, 396-404
Dispersion	405-411
Electrical properties (miscellaneous)	47, 50
Electron diffraction	145, 187
Electron drift	412-415
Emissivity-reflectance	416-418
Fusion power (microsphere targets, etc.)	419-423
Hydrogen gel	424
Ionization potential	425-429
Irradiation	430-436
Isotopic phase separation	437, 438
Magnetic susceptibility	439-442
Magneto optics	443
Magneto resistance	444
Nuclear magnetic resonance (NMR)	445-466
Nuclear spin relaxation	452, 457, 462 464-477
Neutron diffraction	188, 432, 478
Neutron scattering	479-487, 514
Neutron spectra	480, 487-489
Opacity	490
Optical susceptibilities	491
Ortho-para absorption	492
Plastic deformation (solid)	493-494
Relaxation time (electron spin)	495

Property	Reference
Scattering	443, 480, 488, 489 496-500
Specific impulse	501
Surface energy	502-507
Thermomagnetism (Senftleben effect)	508, 509
X-ray diffraction	186, 510-513
<hr/>	
Cryogenic hydrogen instrumentation	319
Cryogenic hydrogen materials	319
Economics of hydrogen systems	312, 319
Hydrogen fuel literature	319

CHAPTER FIVE

DATA FIGURES

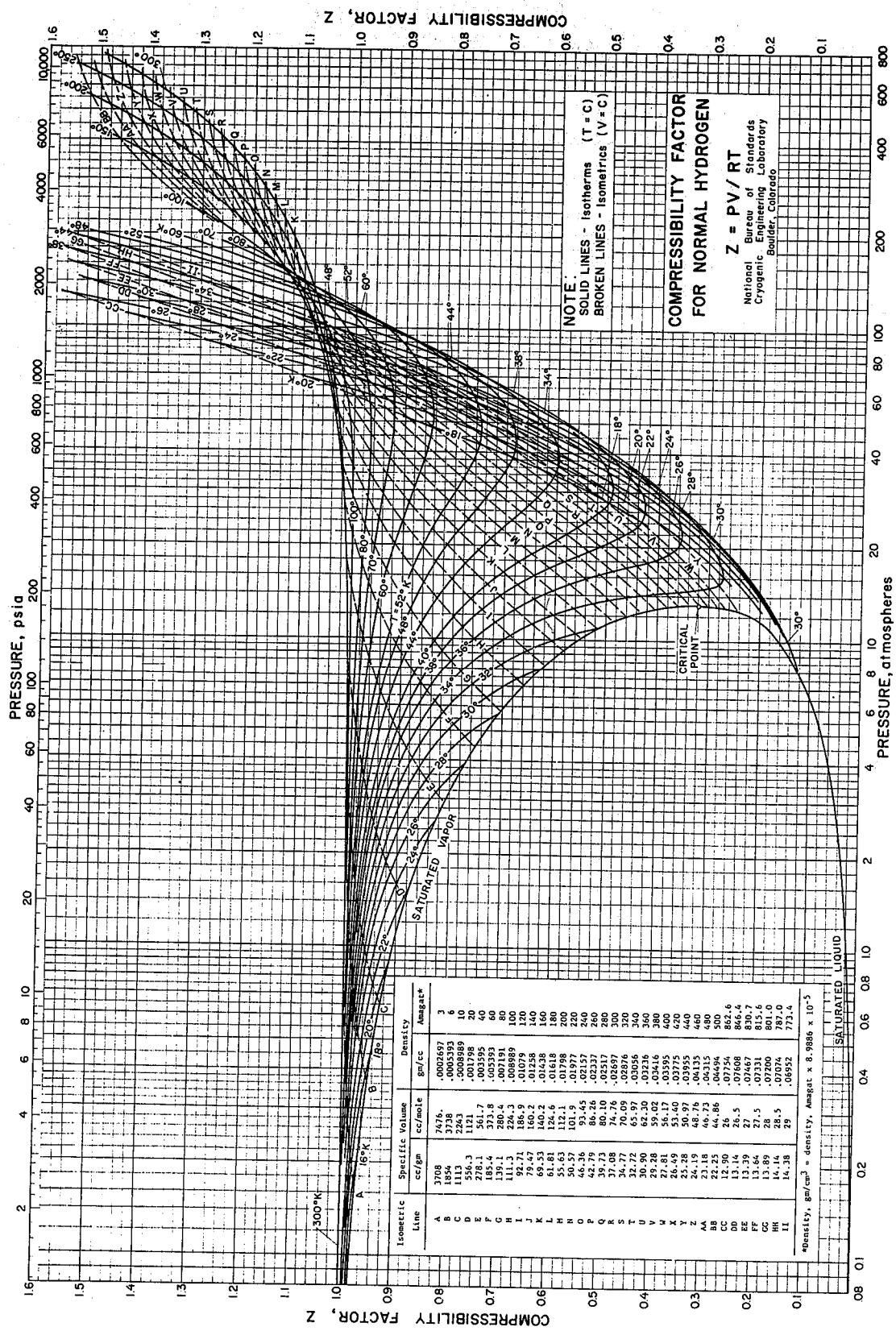


FIGURE 1. Compressibility factor for normal hydrogen.

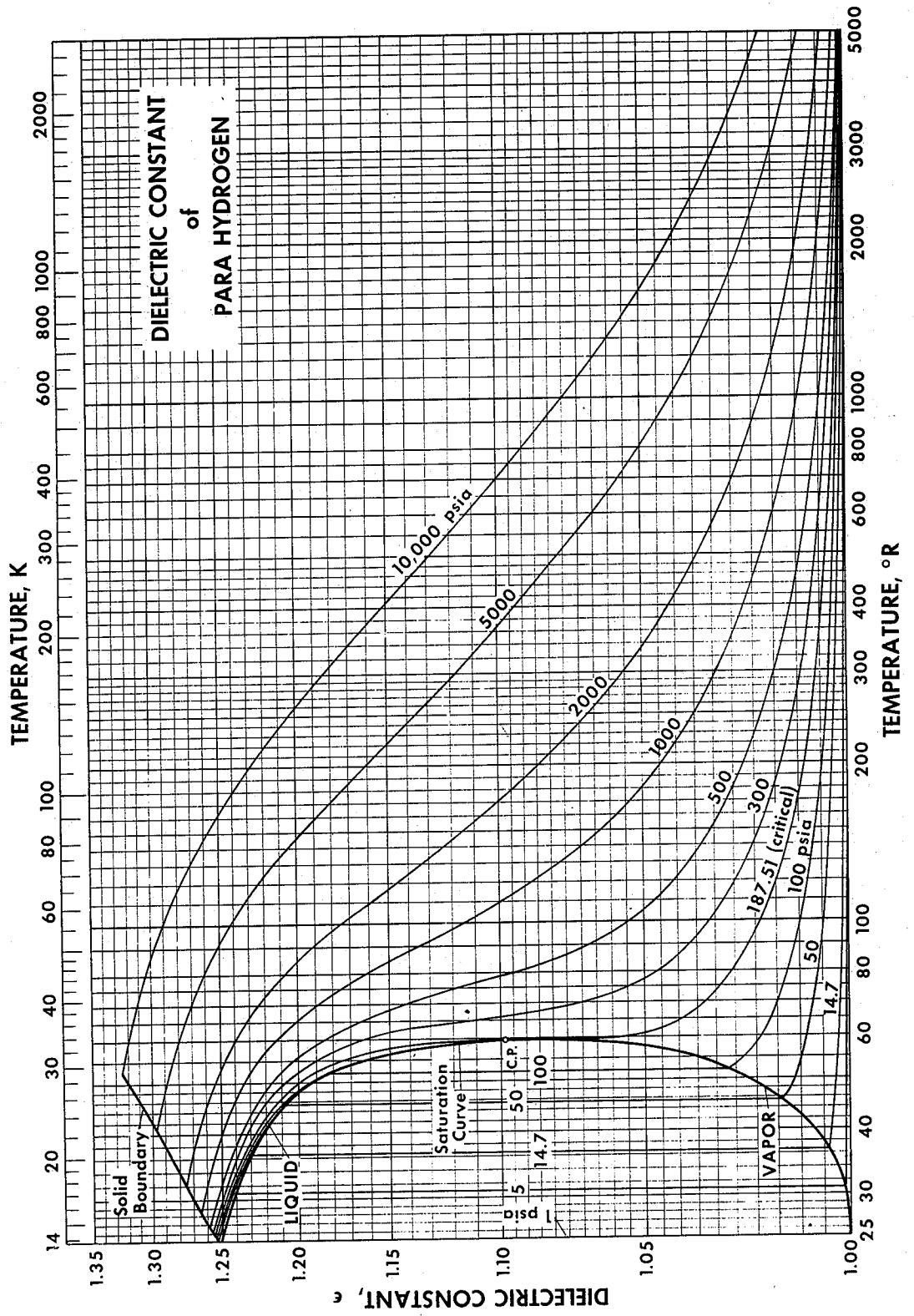


FIGURE 2. Dielectric constant of parahydrogen.

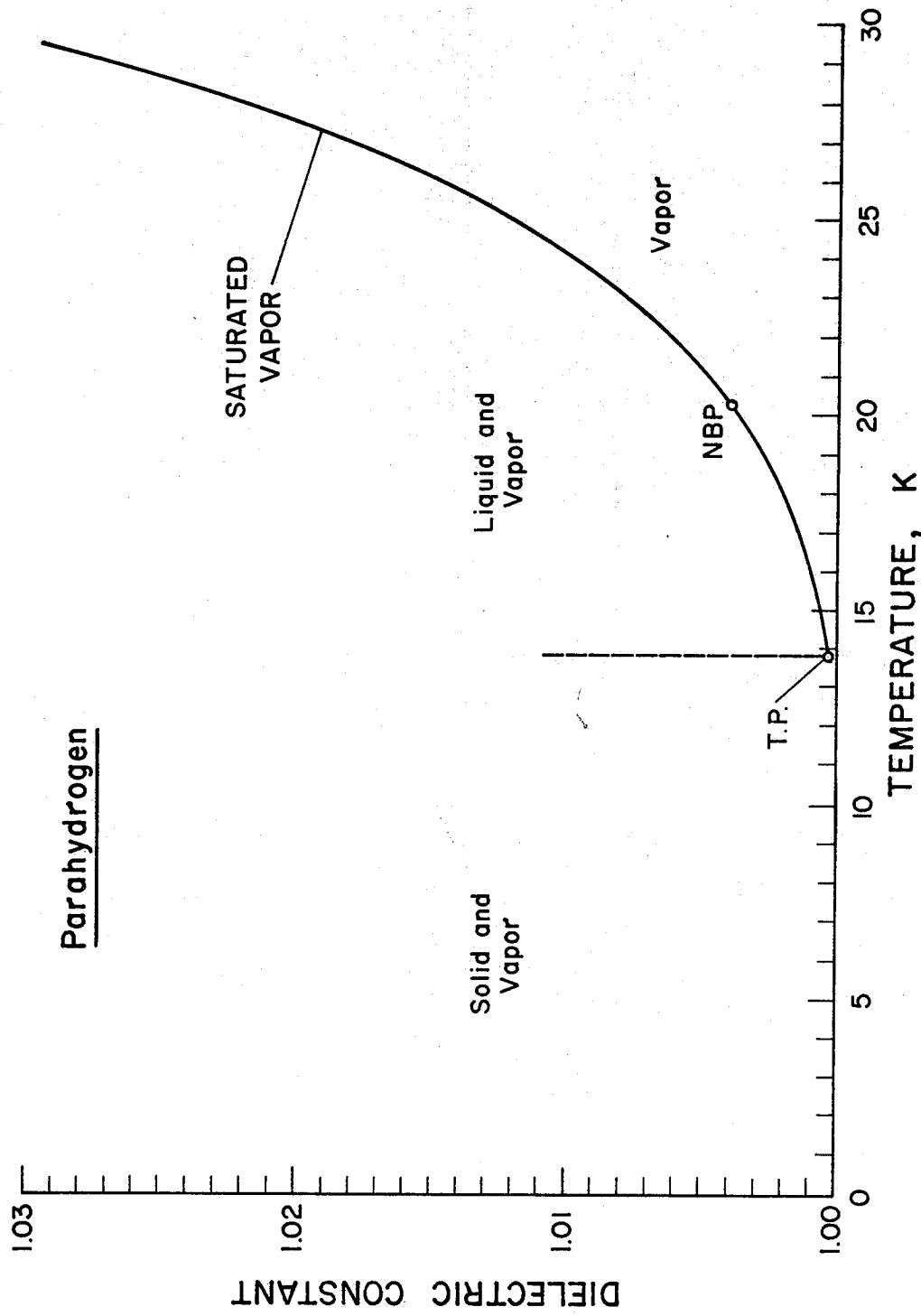


FIGURE 3. Dielectric constant of saturated parahydrogen vapor.

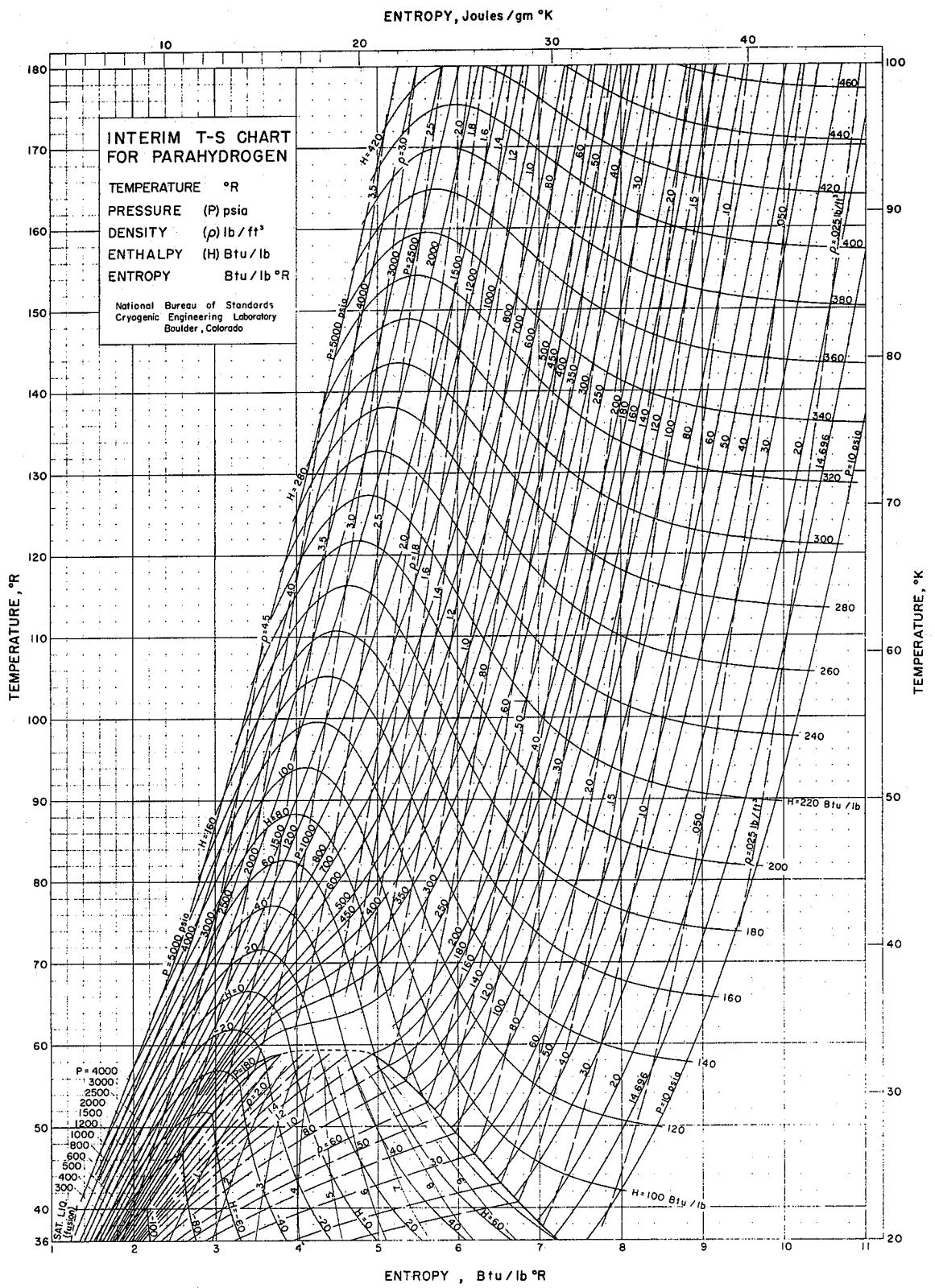


FIGURE 4. Parahydrogen temperature-entropy chart (20 to 100 K).

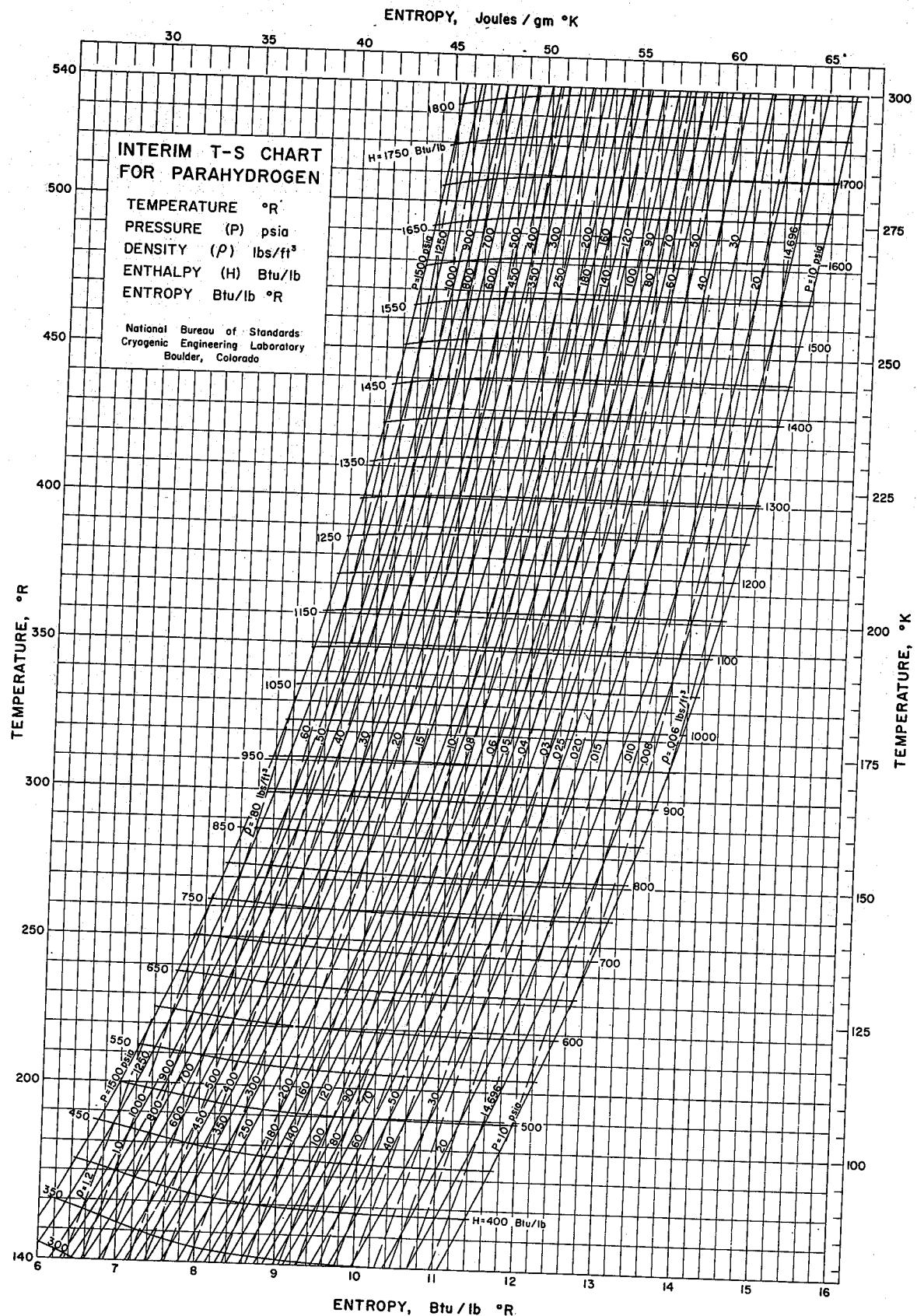


FIGURE 5. Parahydrogen temperature-entropy chart (80 to 300 K).

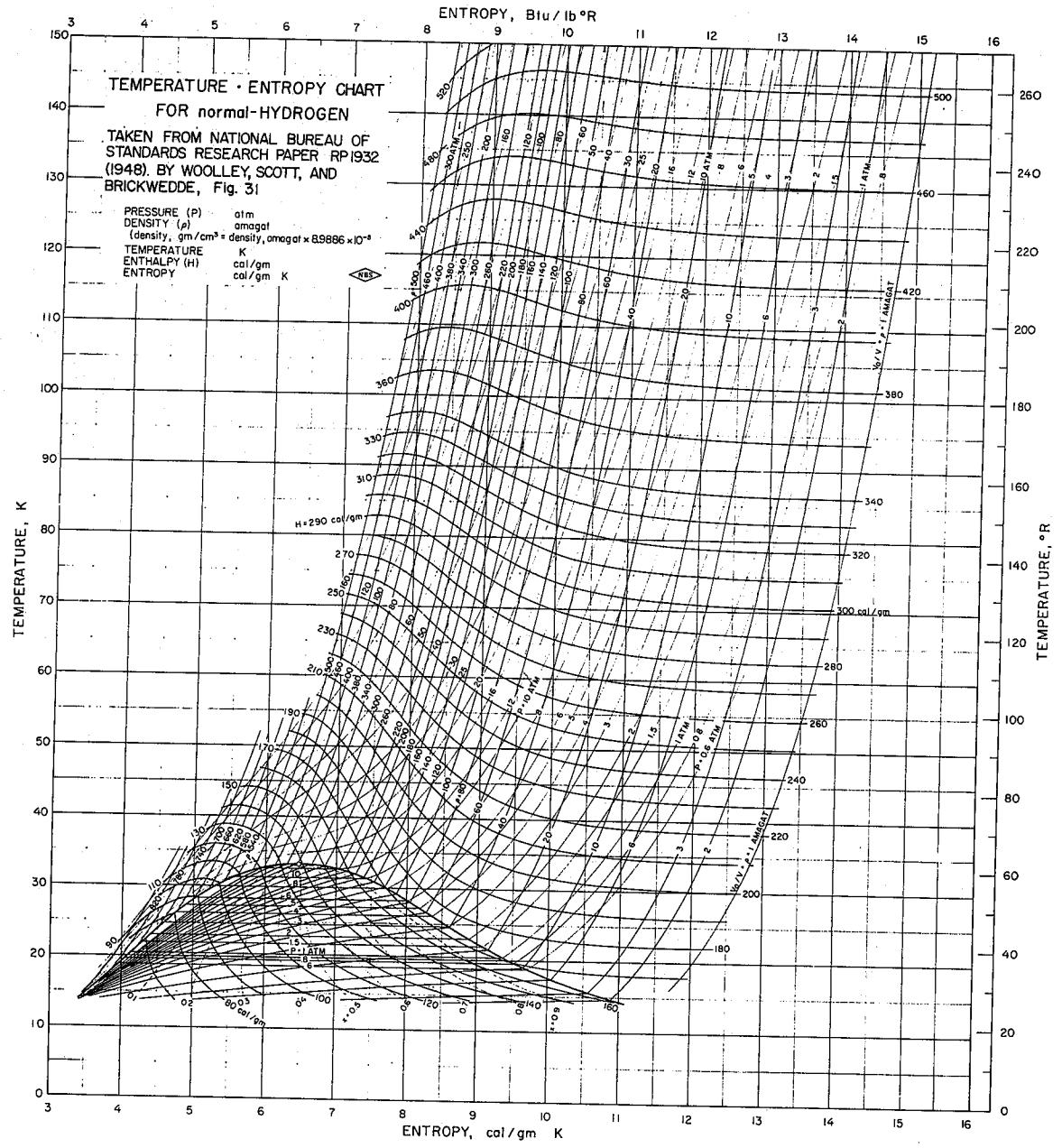


FIGURE 6. Normal hydrogen temperature-entropy chart (15 to 150 K).

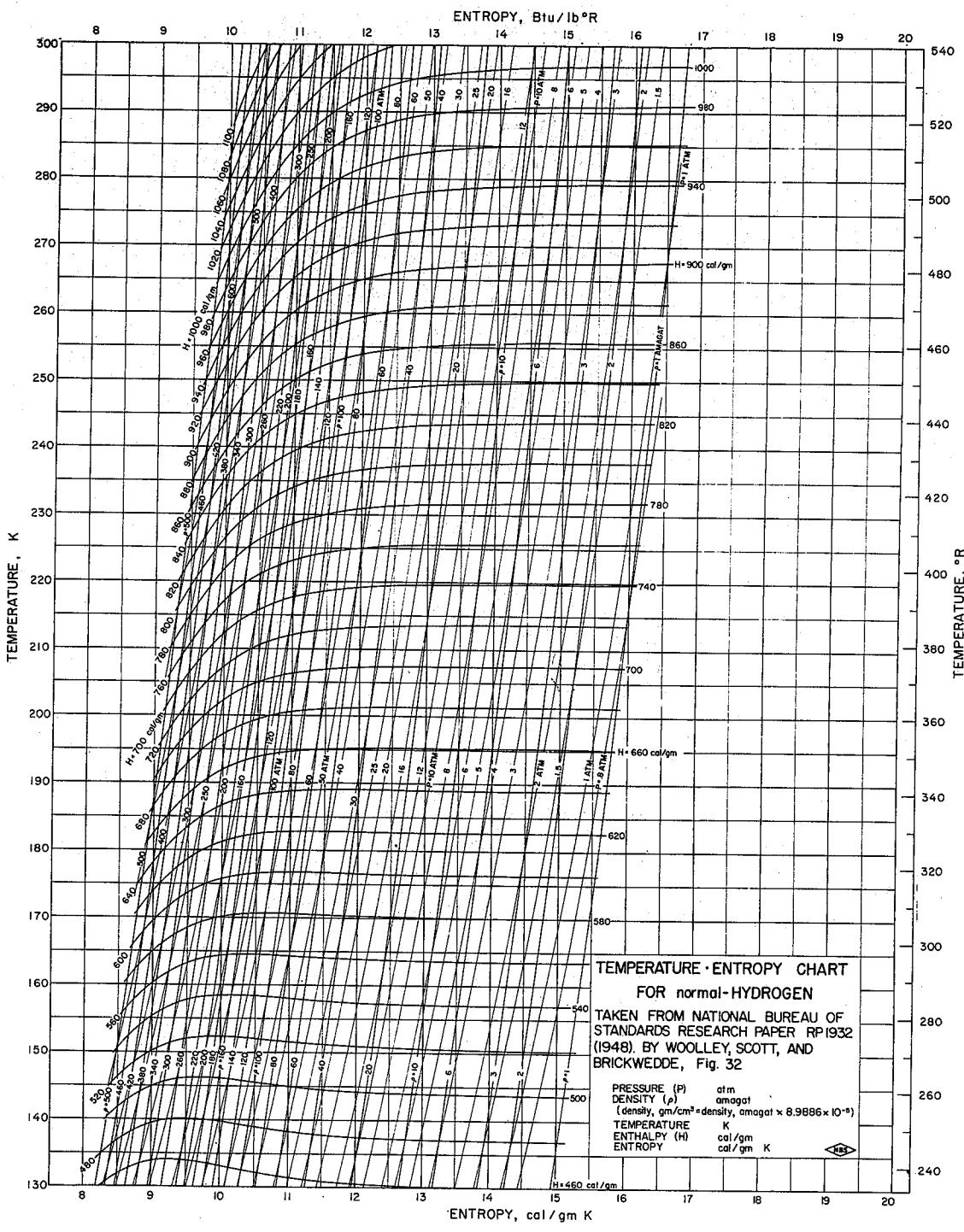


FIGURE 7. Normal hydrogen temperature-entropy chart (130 to 300 K).

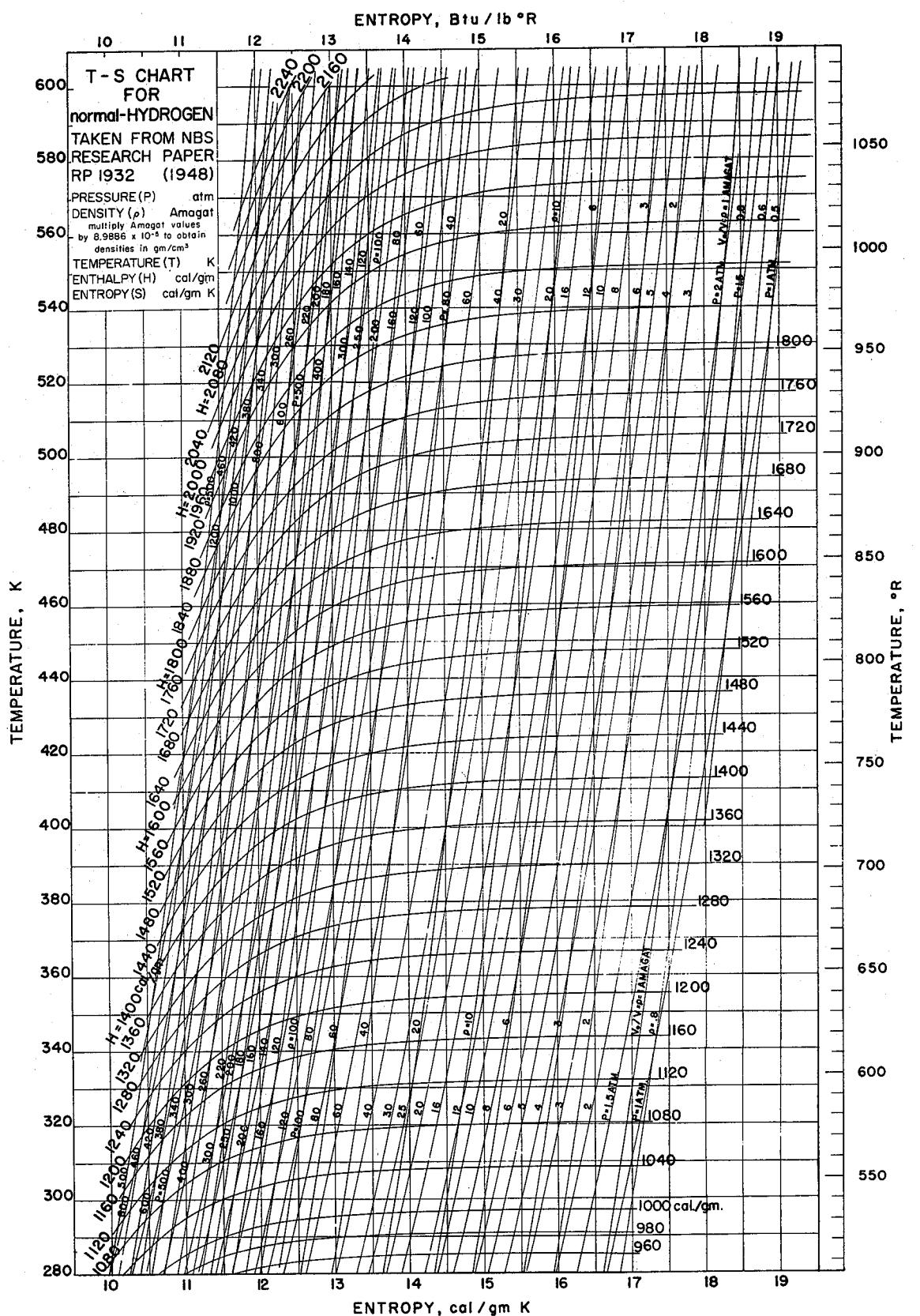


FIGURE 8. Normal hydrogen temperature-entropy chart (280 to 600 K).

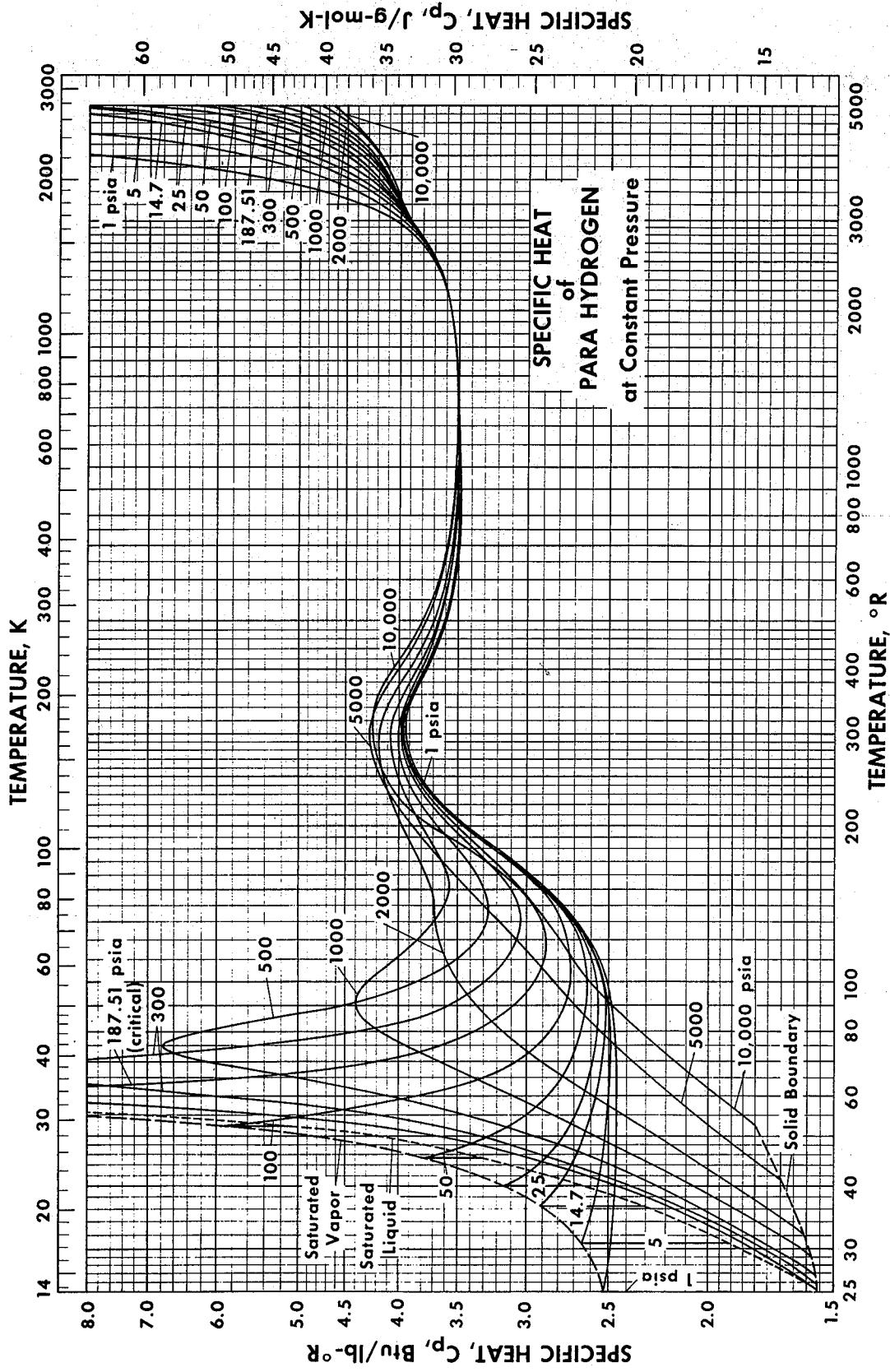


FIGURE 9. Specific heat (heat capacity) of parahydrogen at constant pressure.

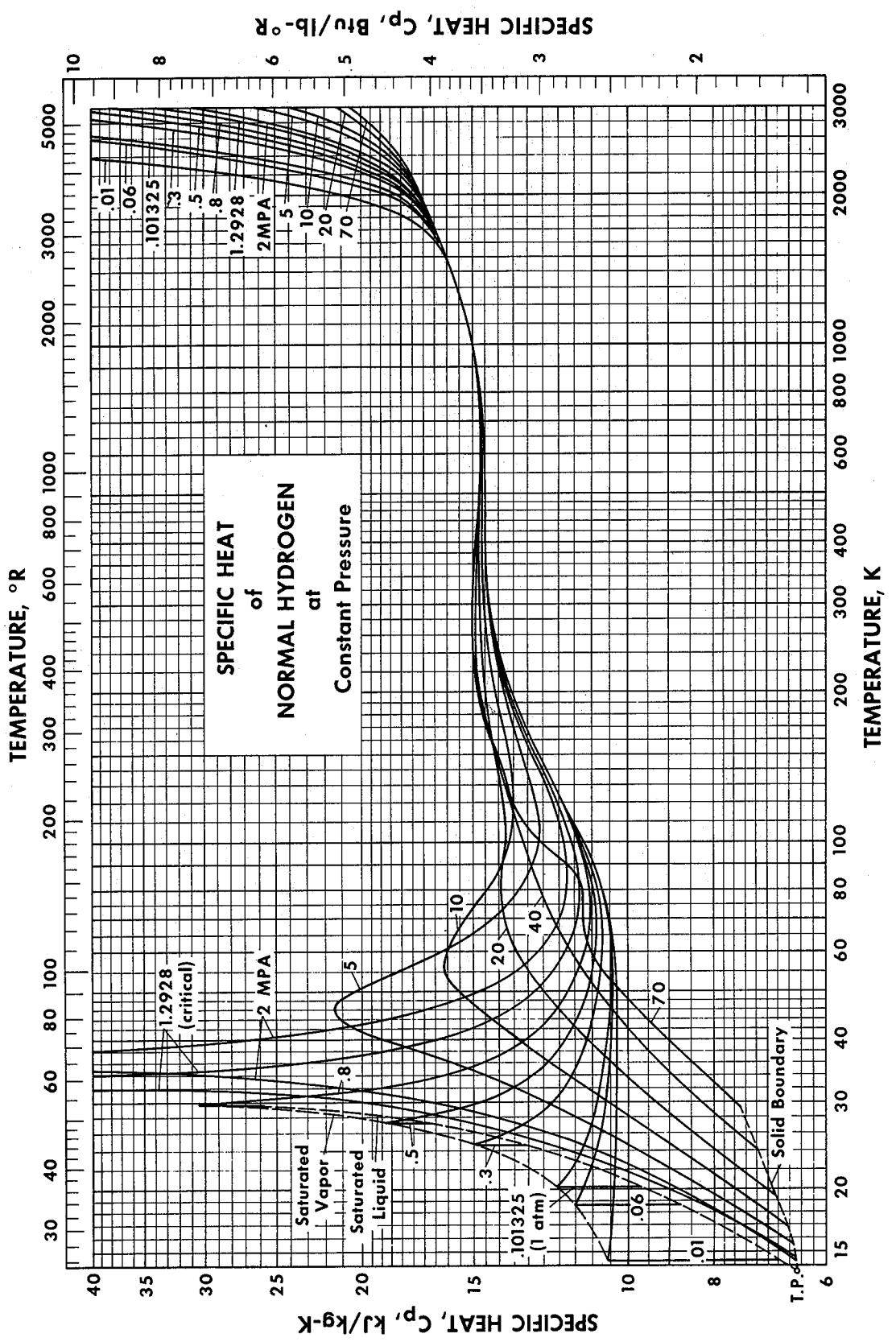


FIGURE 10. Specific heat (heat capacity) of normal hydrogen at constant pressure.

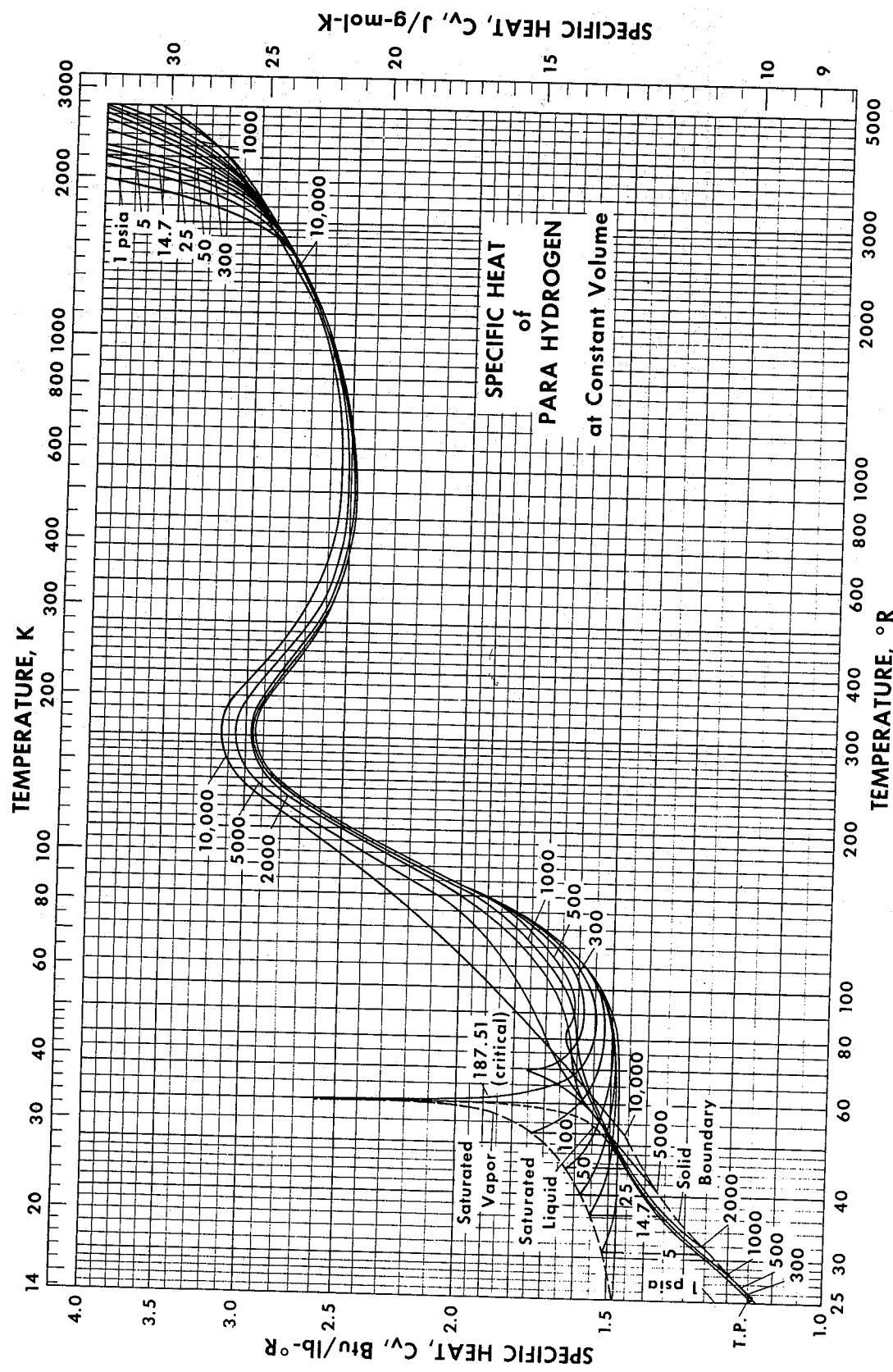


FIGURE 11. Specific heat (heat capacity) of parahydrogen at constant volume.

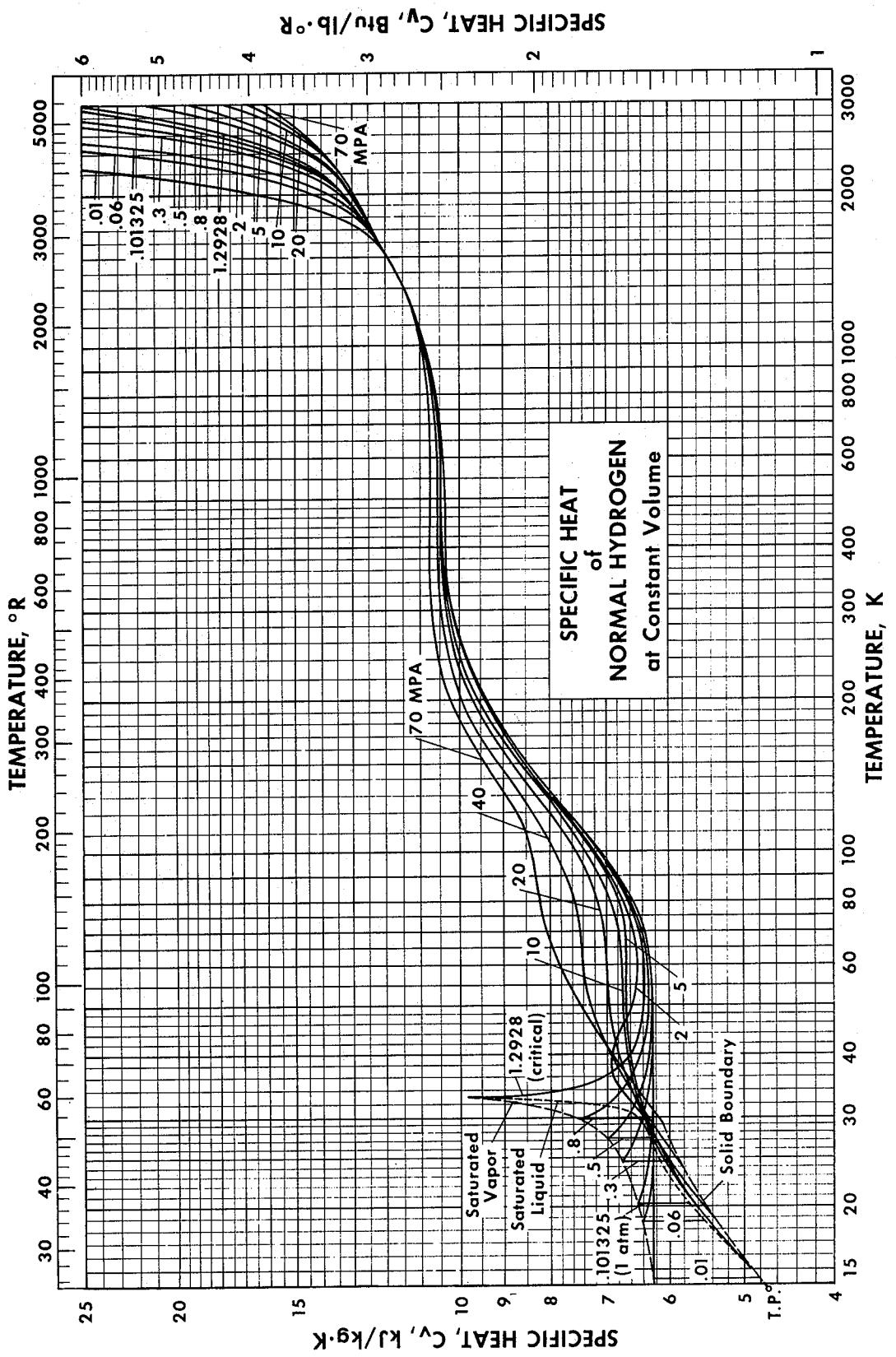


FIGURE 12. Specific heat (heat capacity) of normal hydrogen at constant volume.

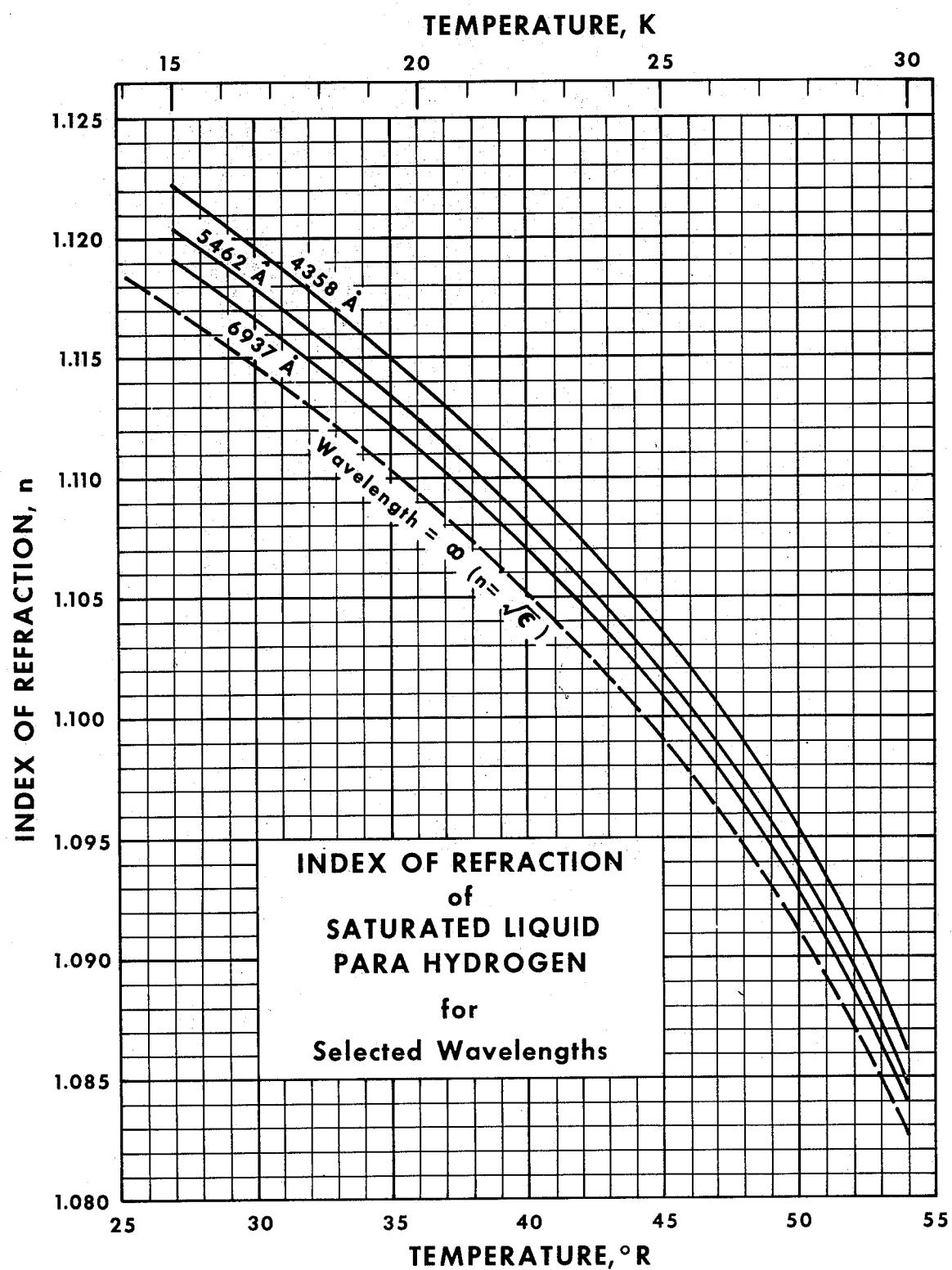


FIGURE 13. Index of refraction of saturated liquid parahydrogen.

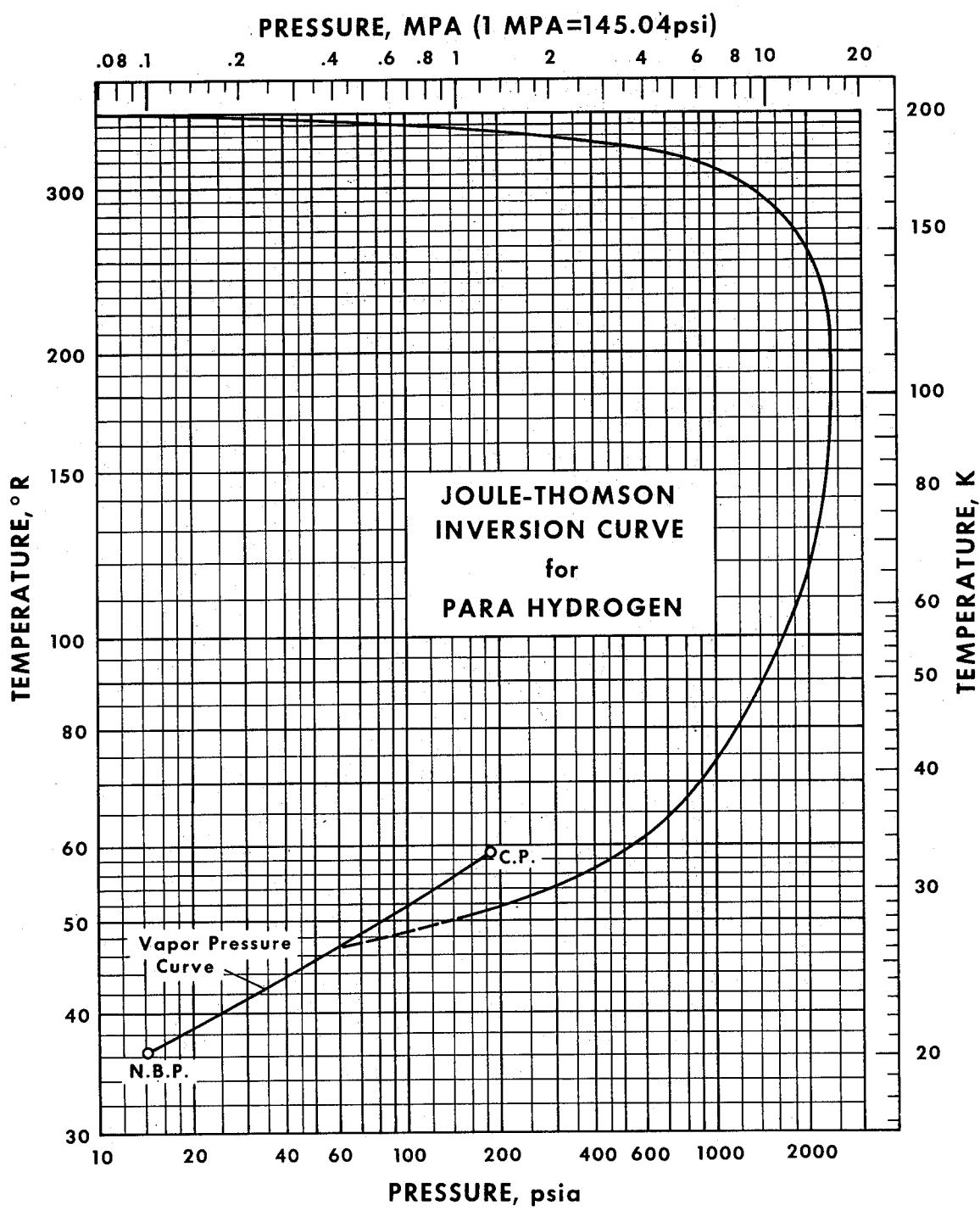


Figure 14. Joule-Thomson inversion curve for parahydrogen.

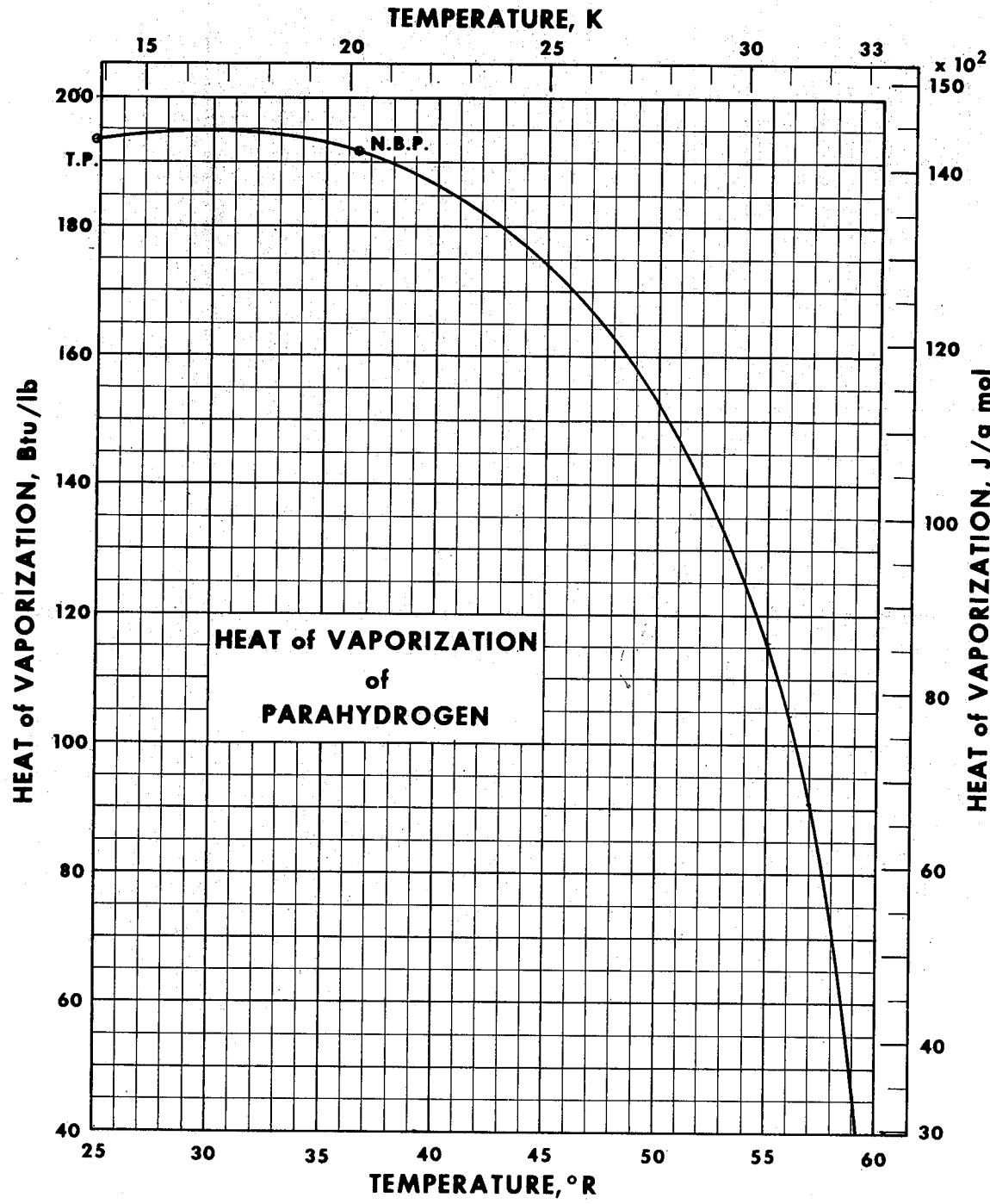


FIGURE 15. Latent heat of vaporization of parahydrogen.

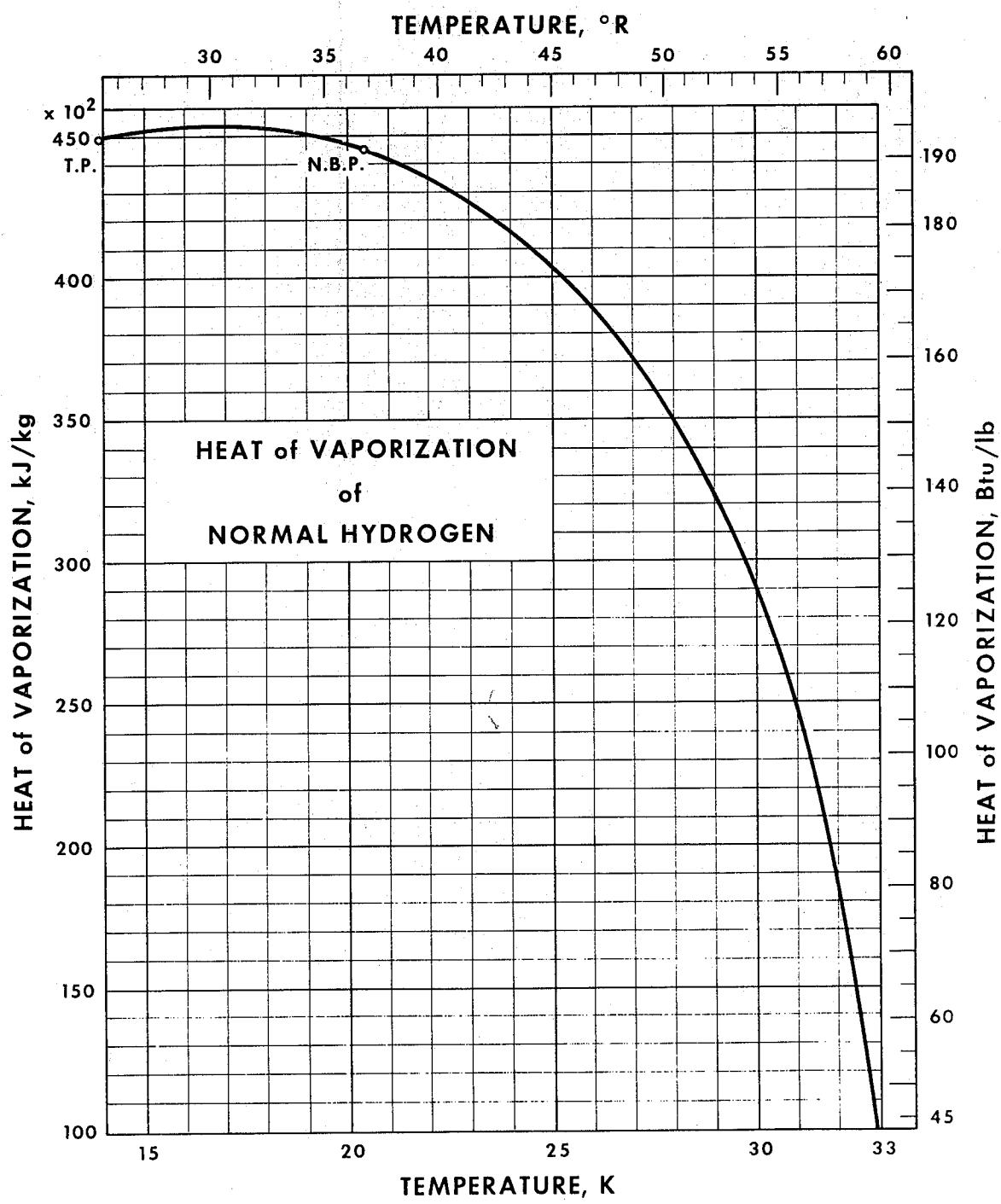


FIGURE 16. Latent heat of vaporization of normal hydrogen.

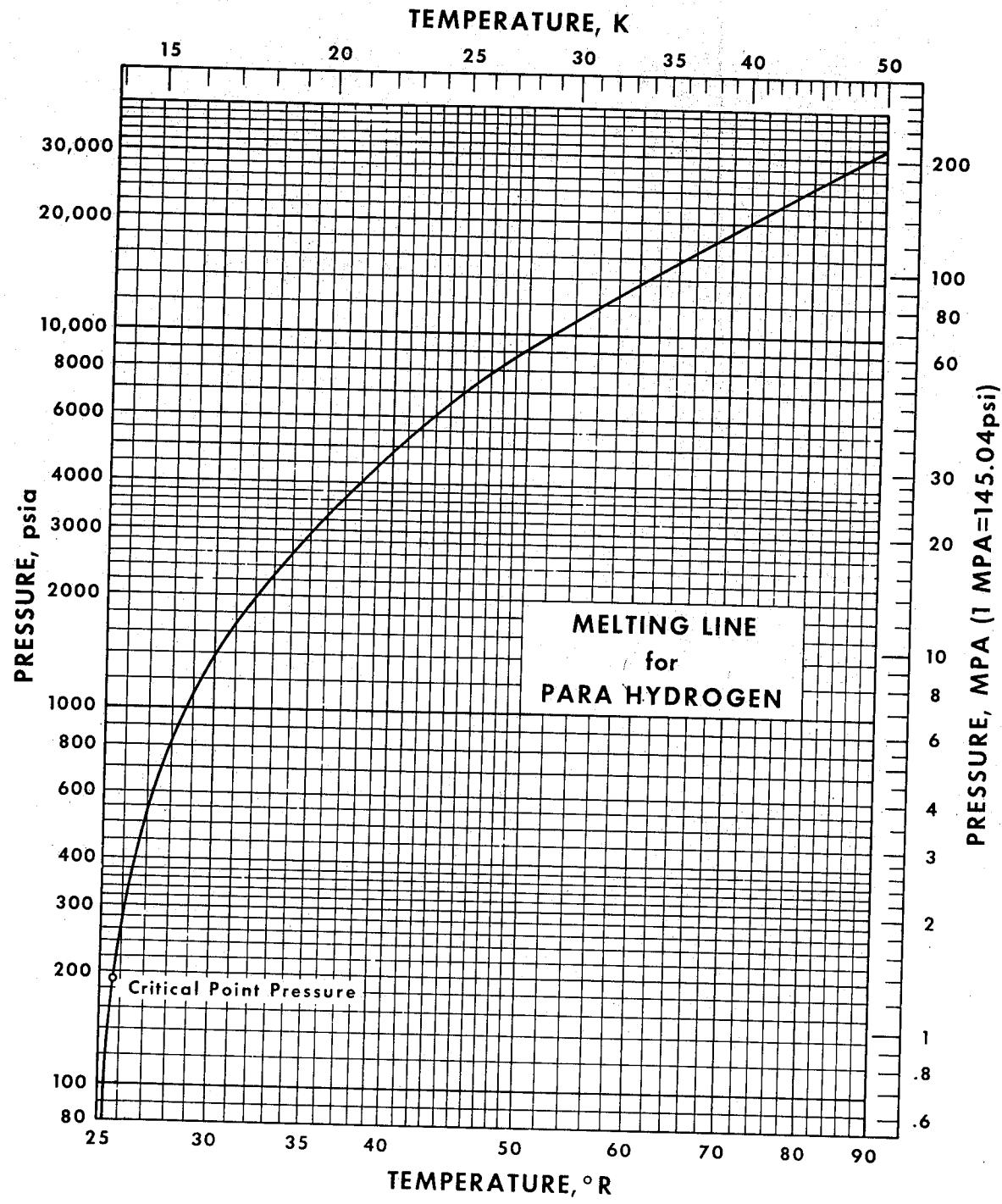


FIGURE 17. Melting line for parahydrogen (0.6 to 200 MPa).

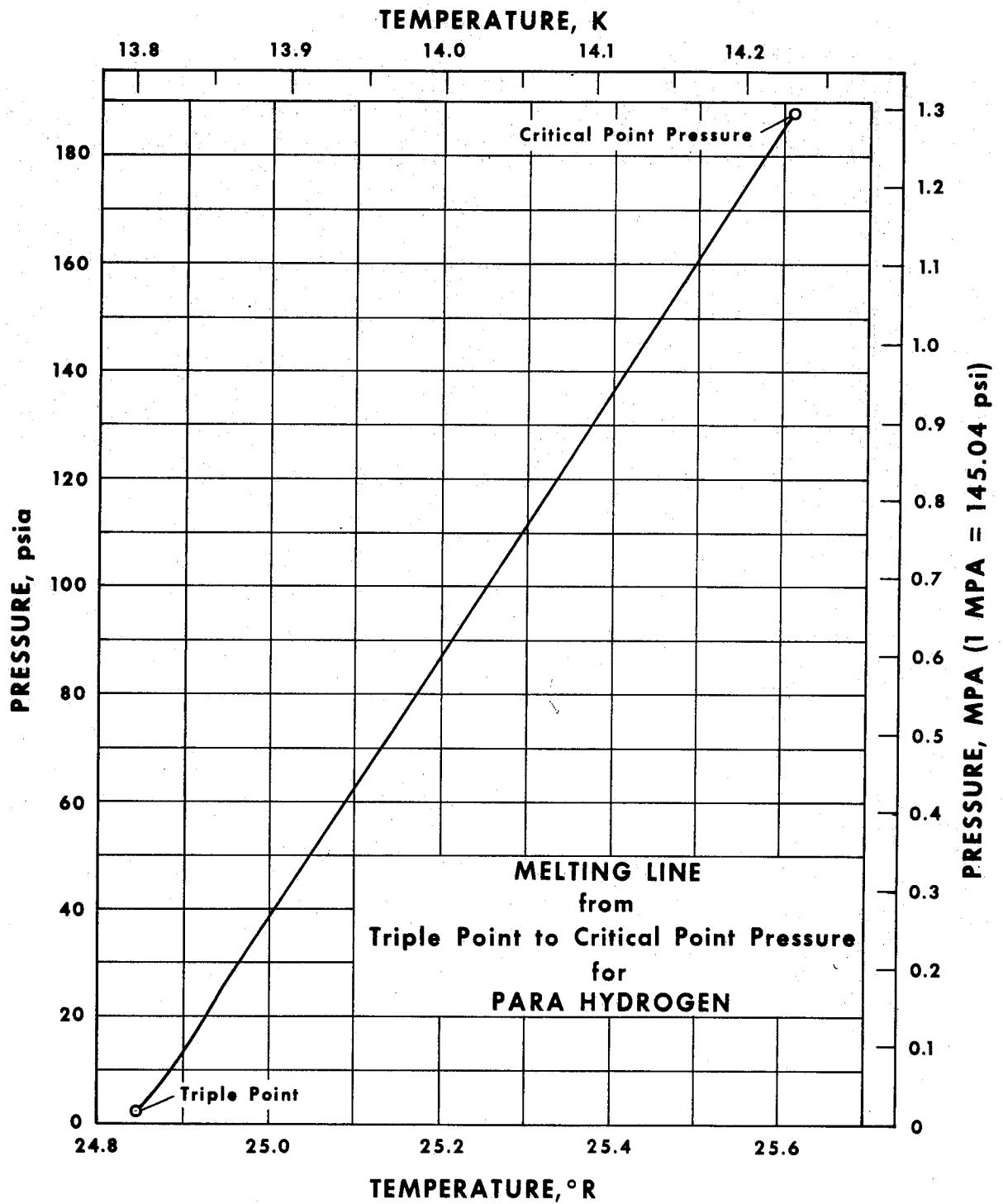


FIGURE 18. Melting line from triple point to critical point pressure for parahydrogen.

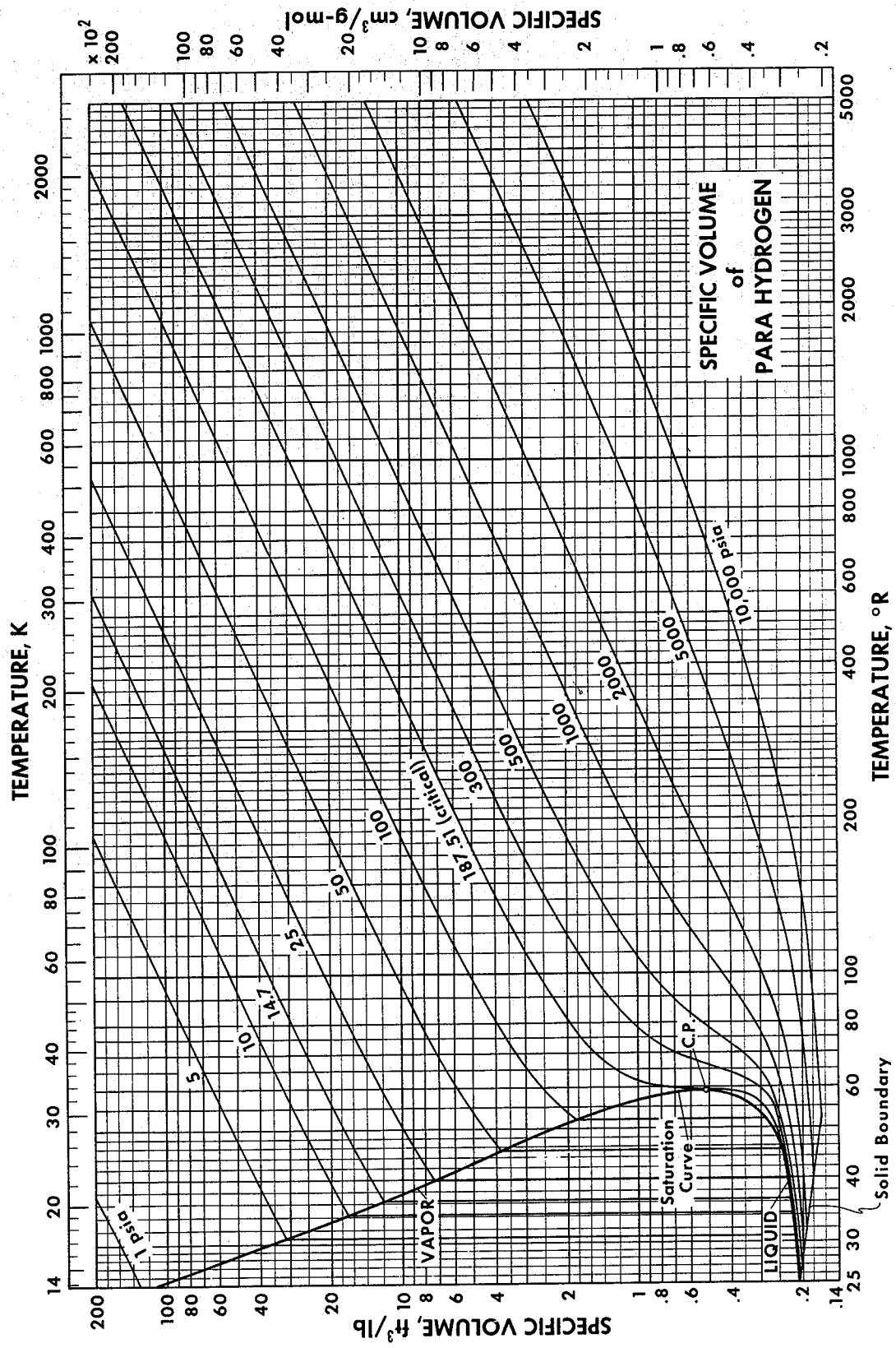


FIGURE 19. Specific volume (PVT) of parahydrogen.

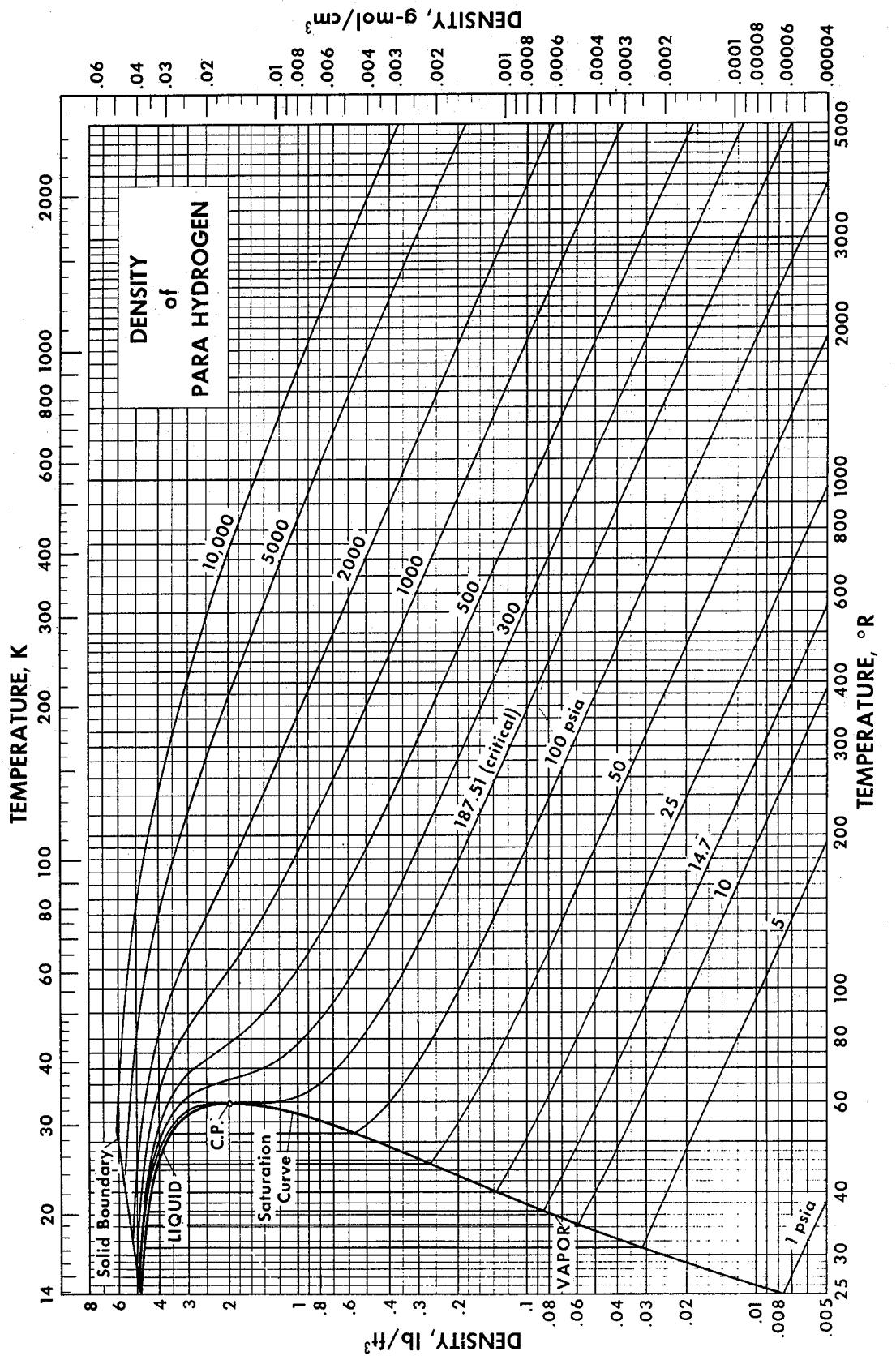


FIGURE 20. Density ($P-\rho-T$) of parahydrogen.

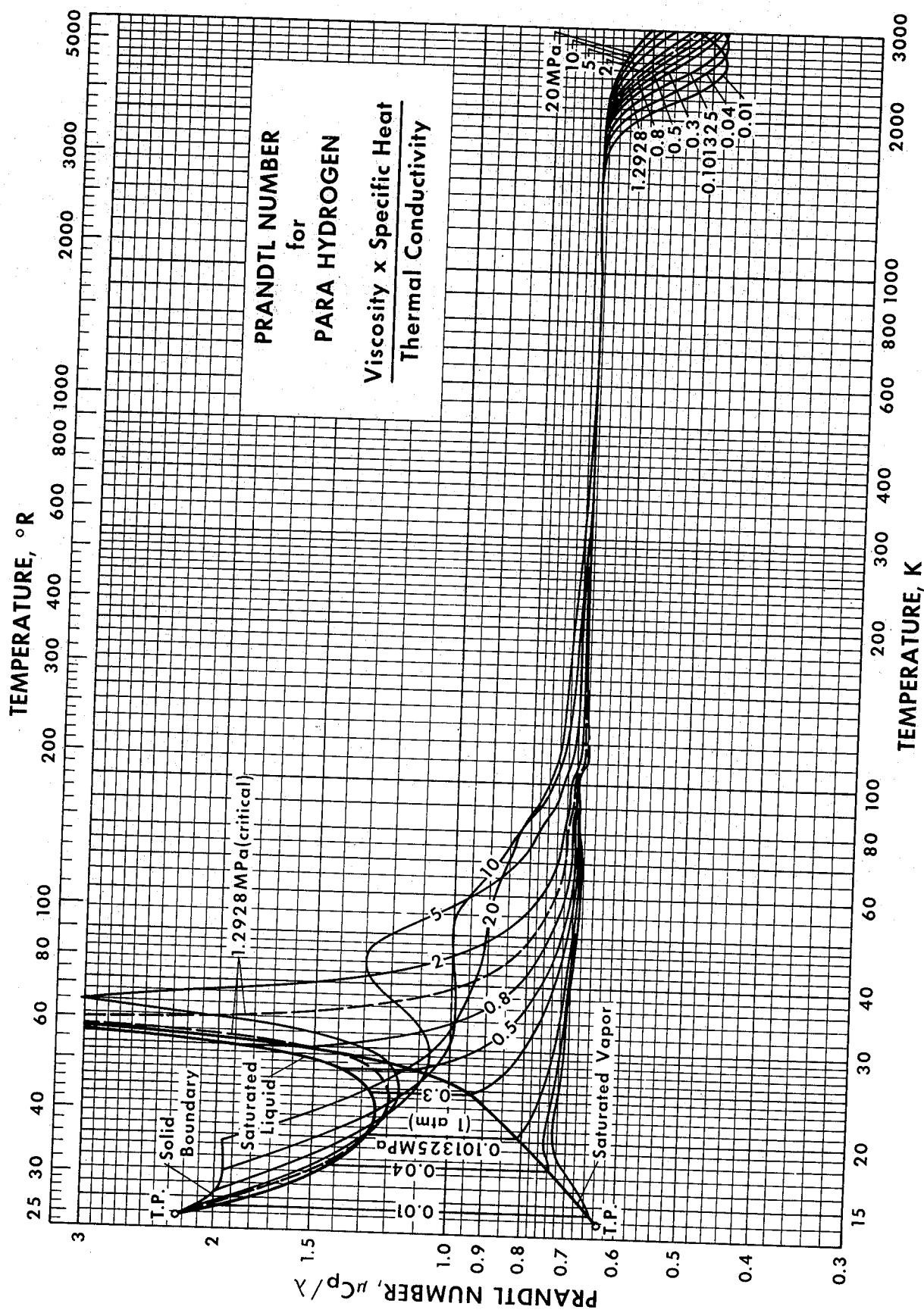


FIGURE 21. Prandtl number for parahydrogen.

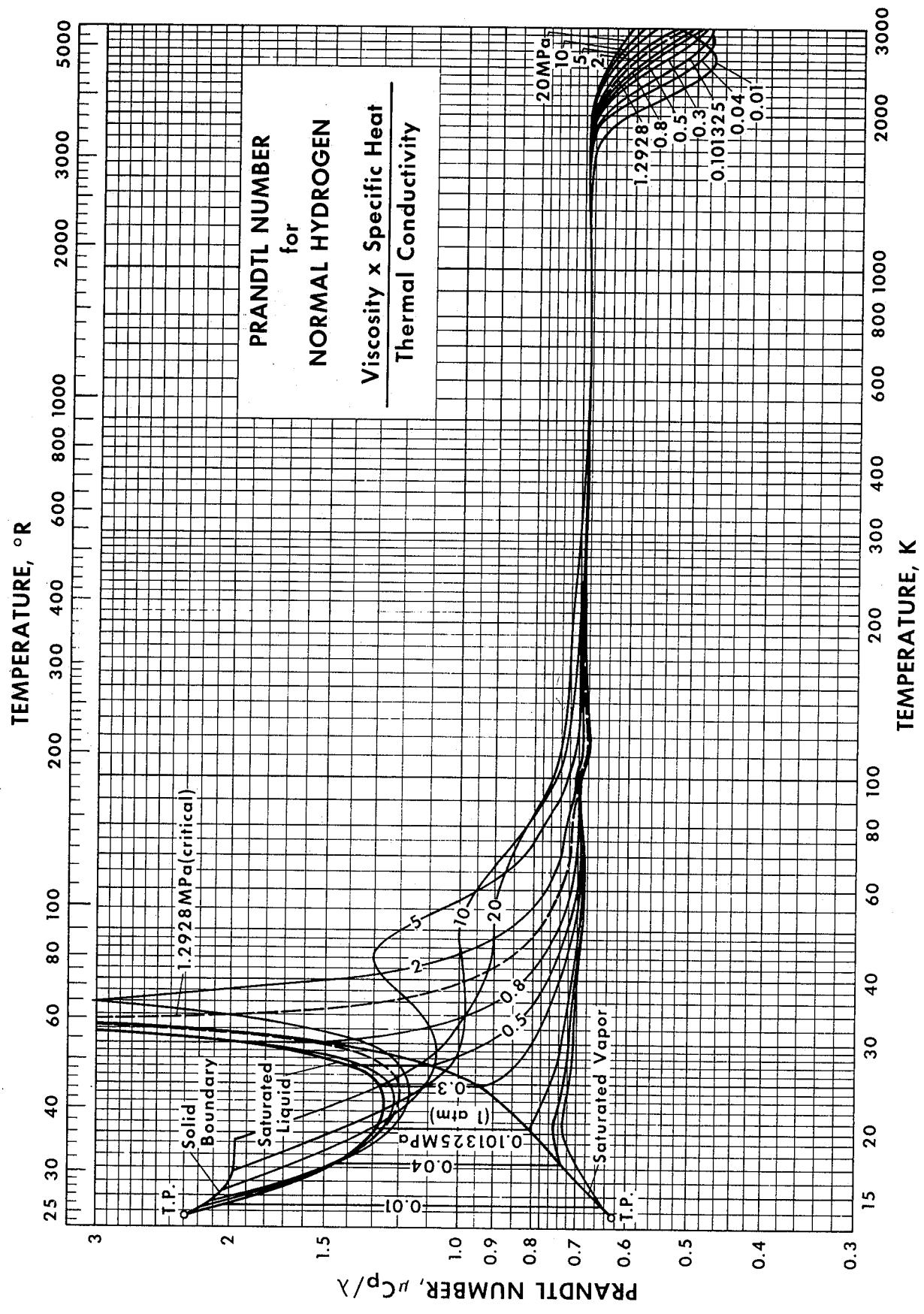


FIGURE 22. Prandtl number for normal hydrogen.

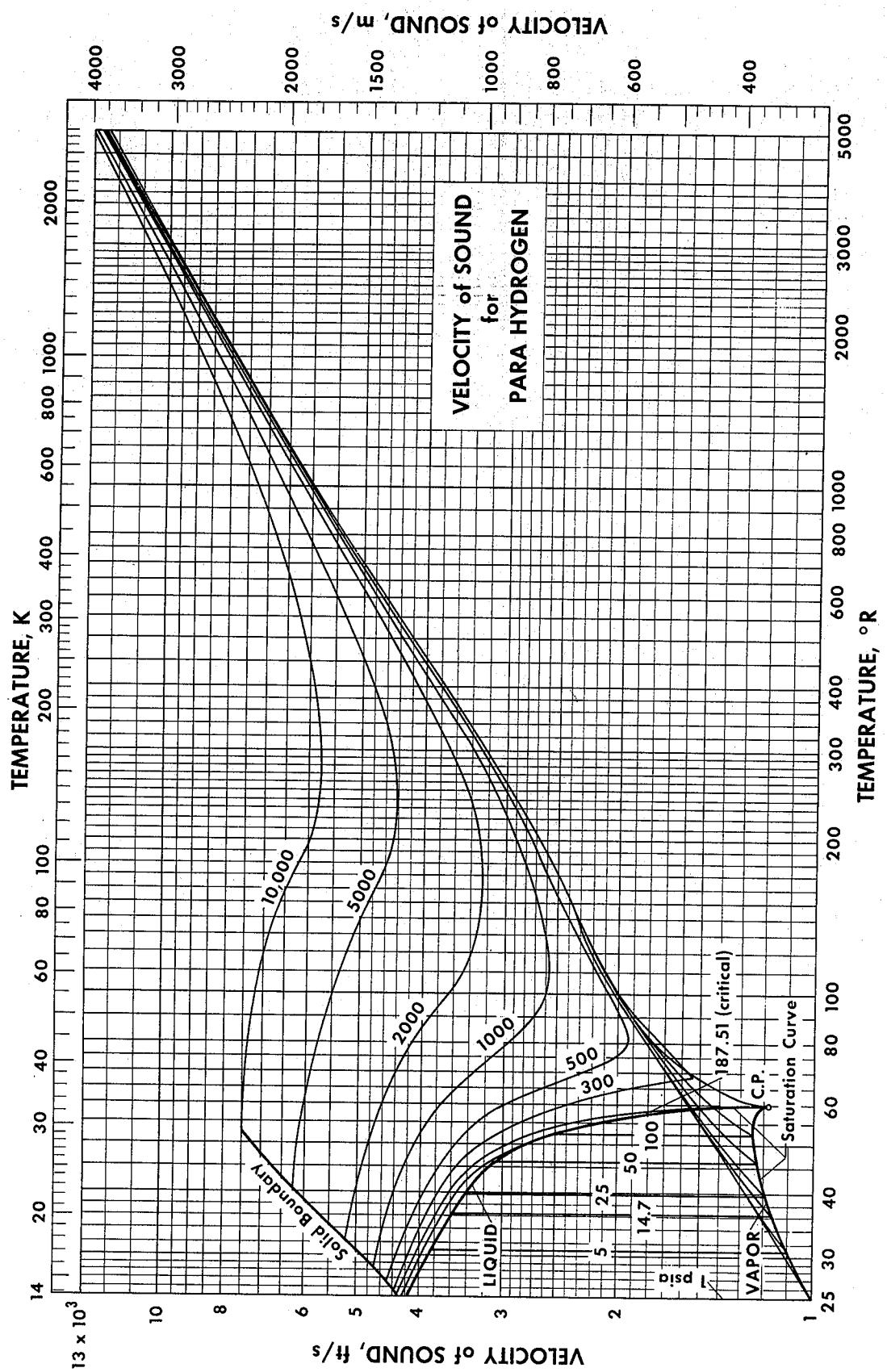


FIGURE 23. Velocity of sound for parahydrogen.

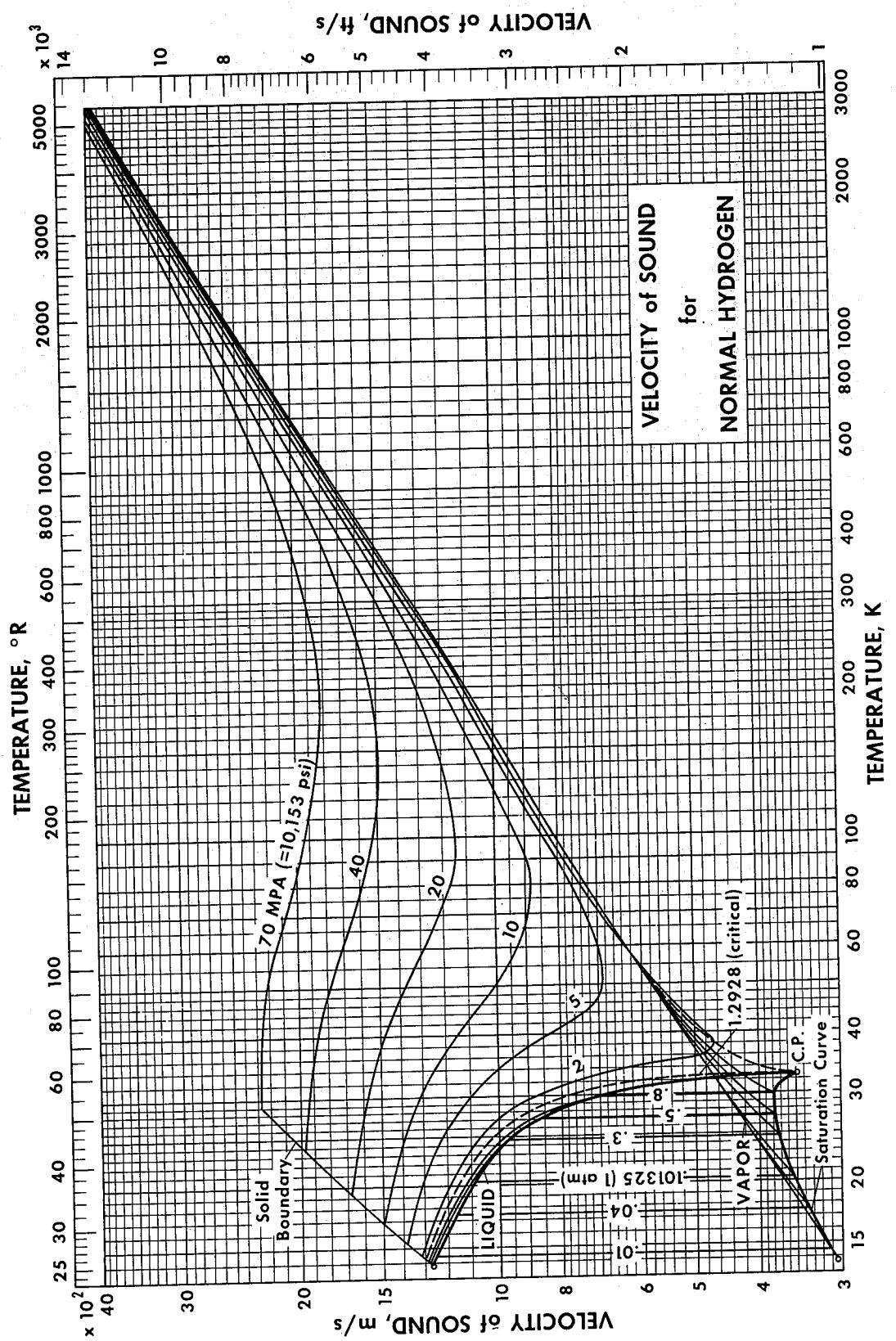


FIGURE 24. Velocity of sound for normal hydrogen.

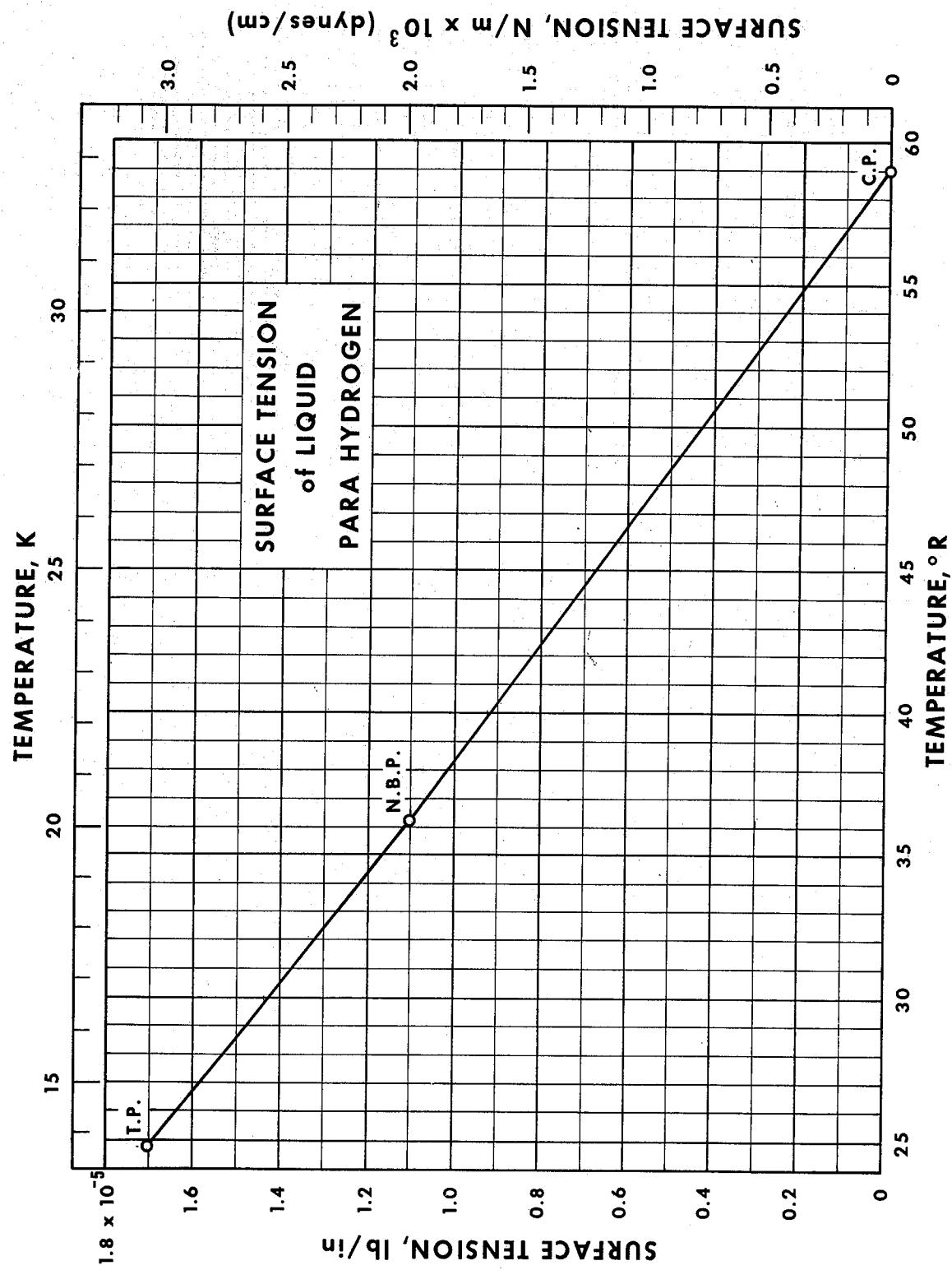


FIGURE 25. Surface tension of liquid parahydrogen.

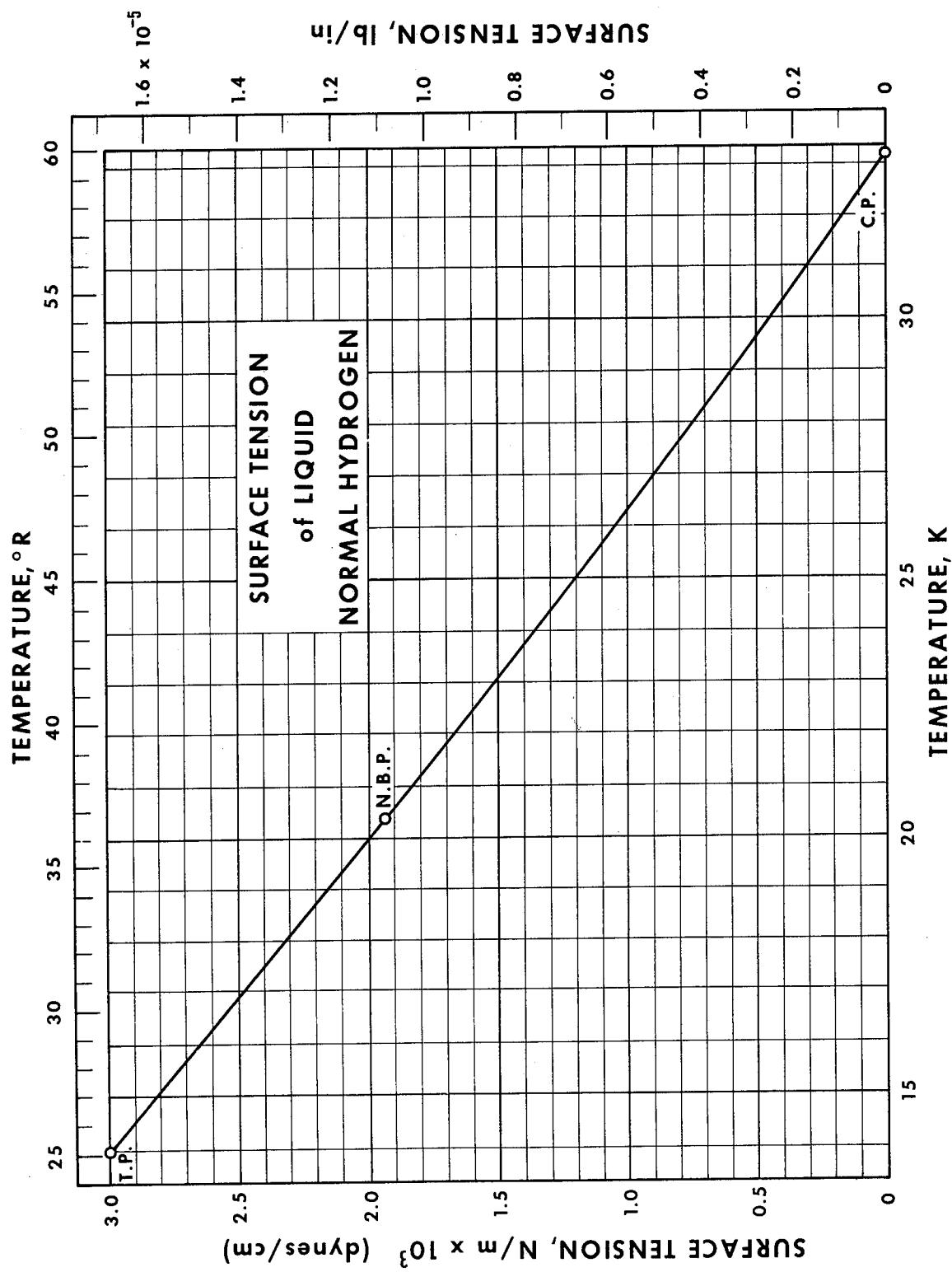


FIGURE 26. Surface tension of liquid normal hydrogen.

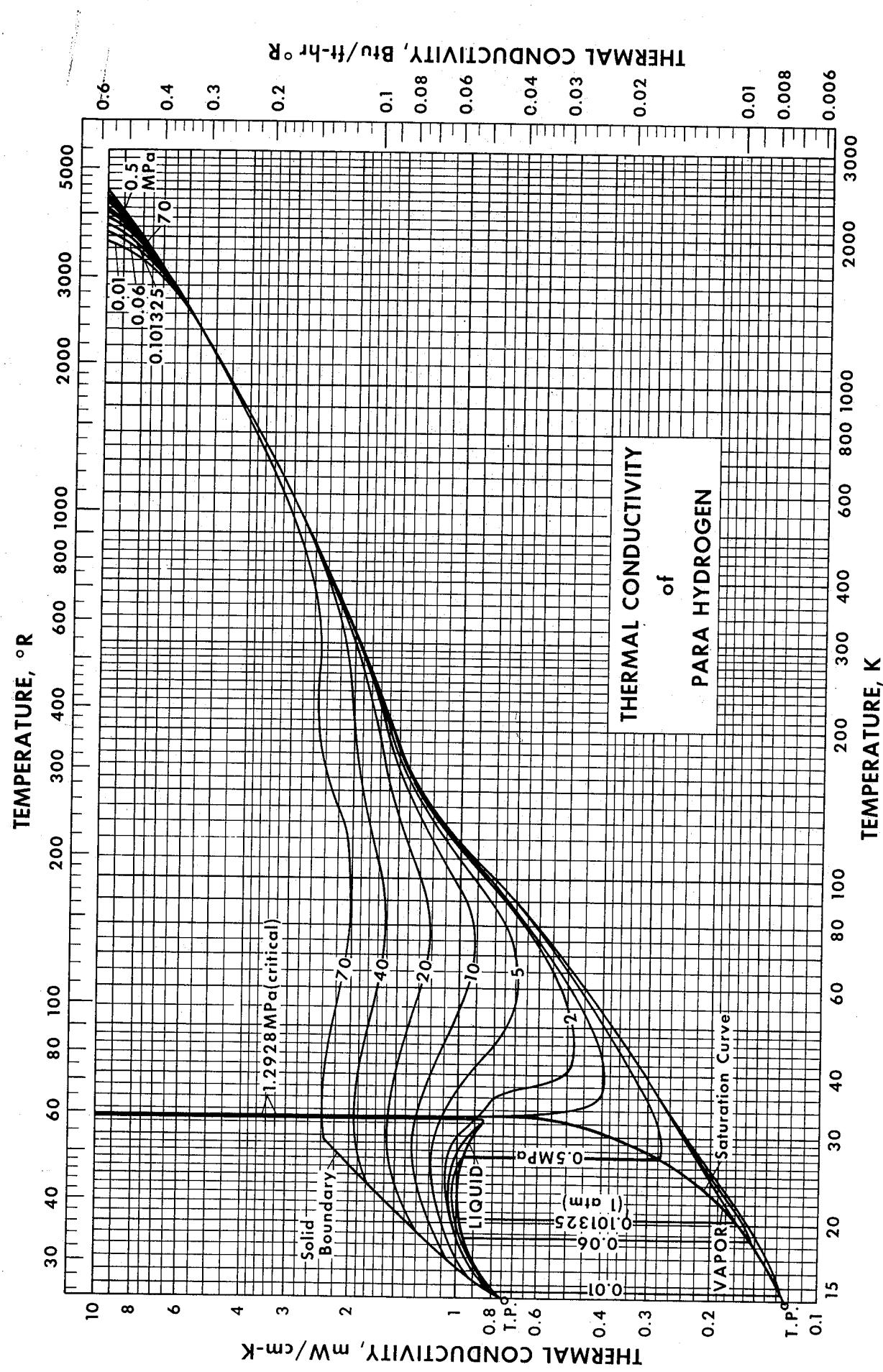


FIGURE 27. Thermal conductivity of parahydrogen.

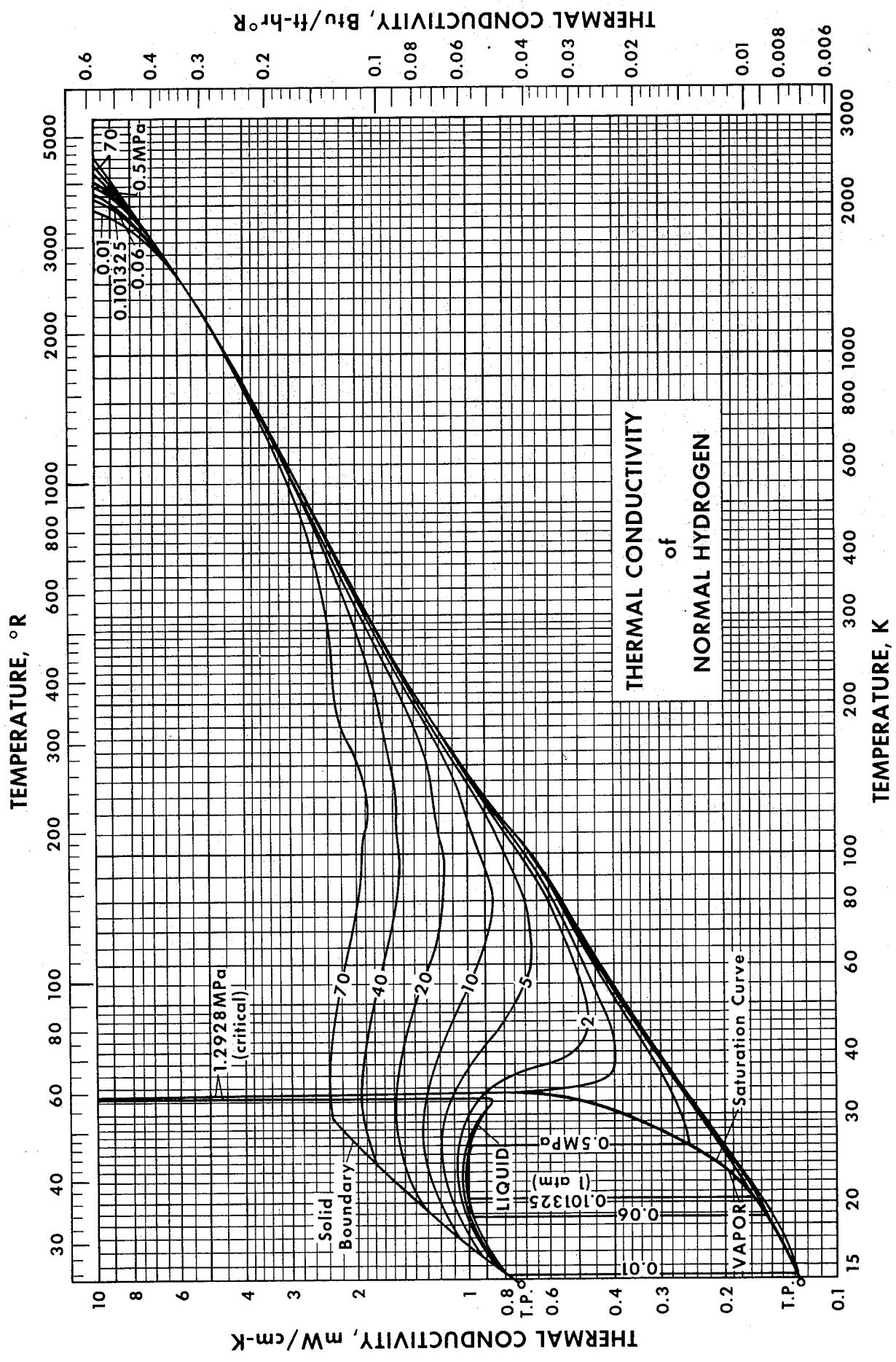
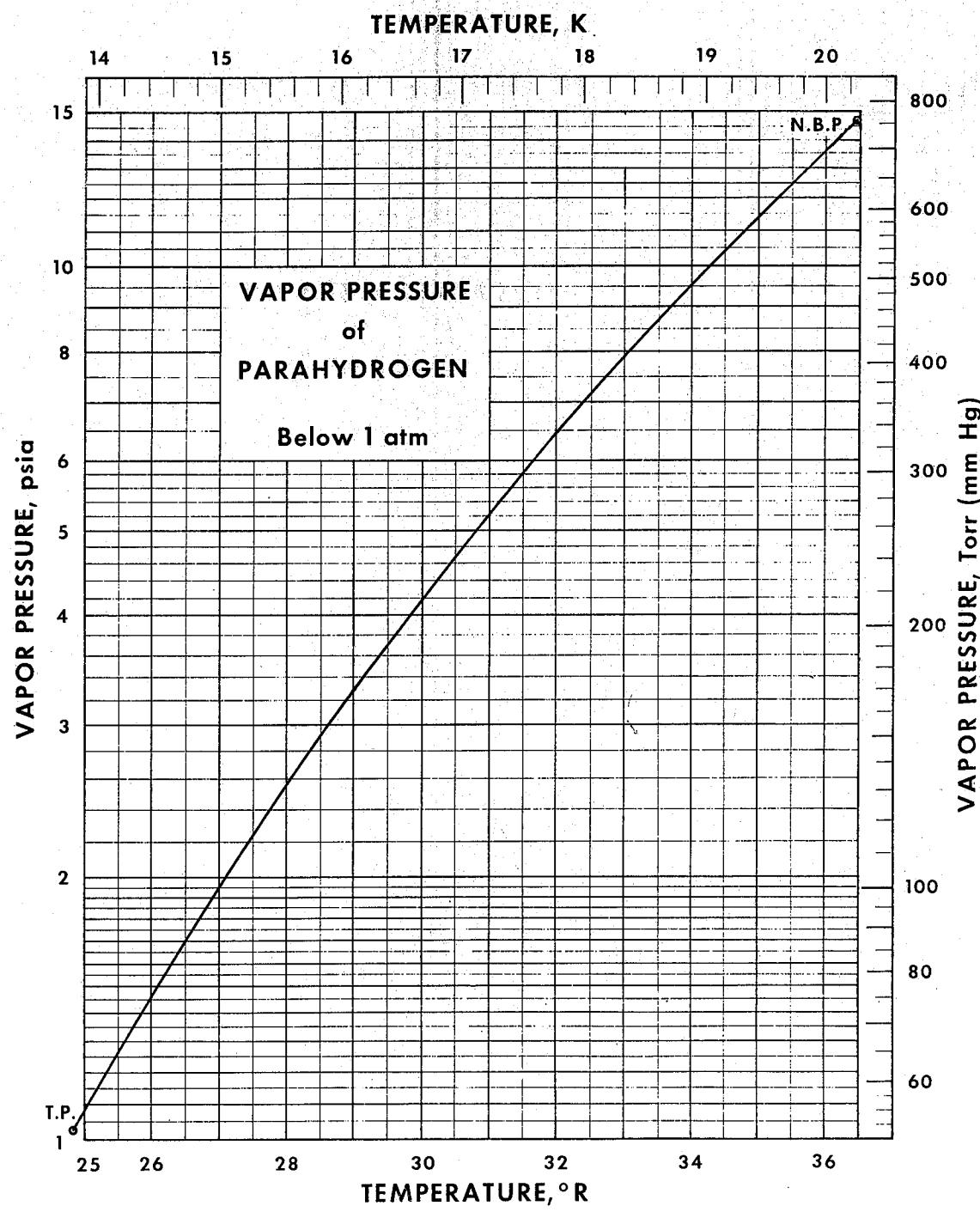


FIGURE 28. Thermal conductivity of normal hydrogen.



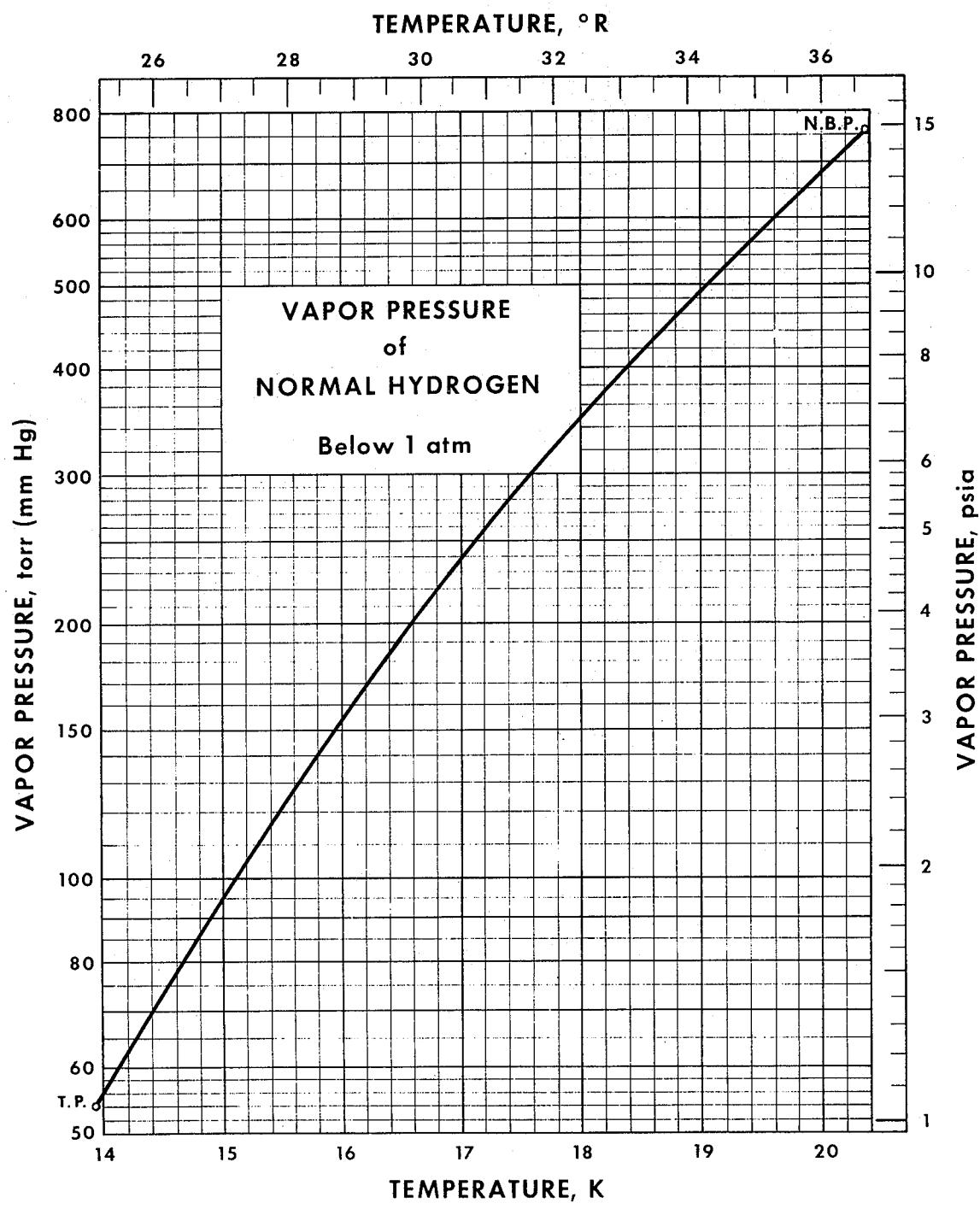


FIGURE 30. Vapor pressure of normal hydrogen
below 0.101325 MPa (1 atm).

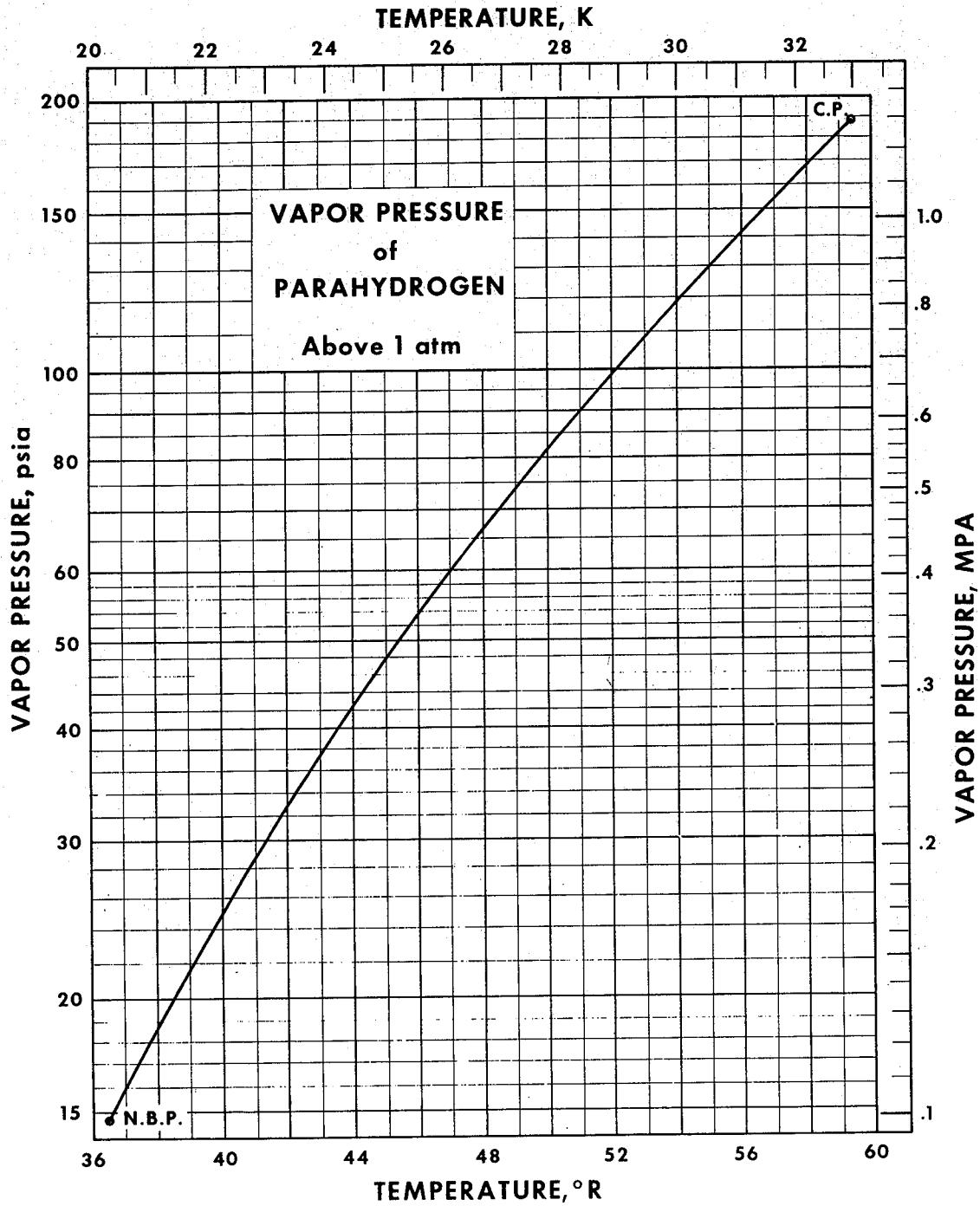


FIGURE 31. Vapor pressure of parahydrogen
above 0.101325 MPa (1 atm).

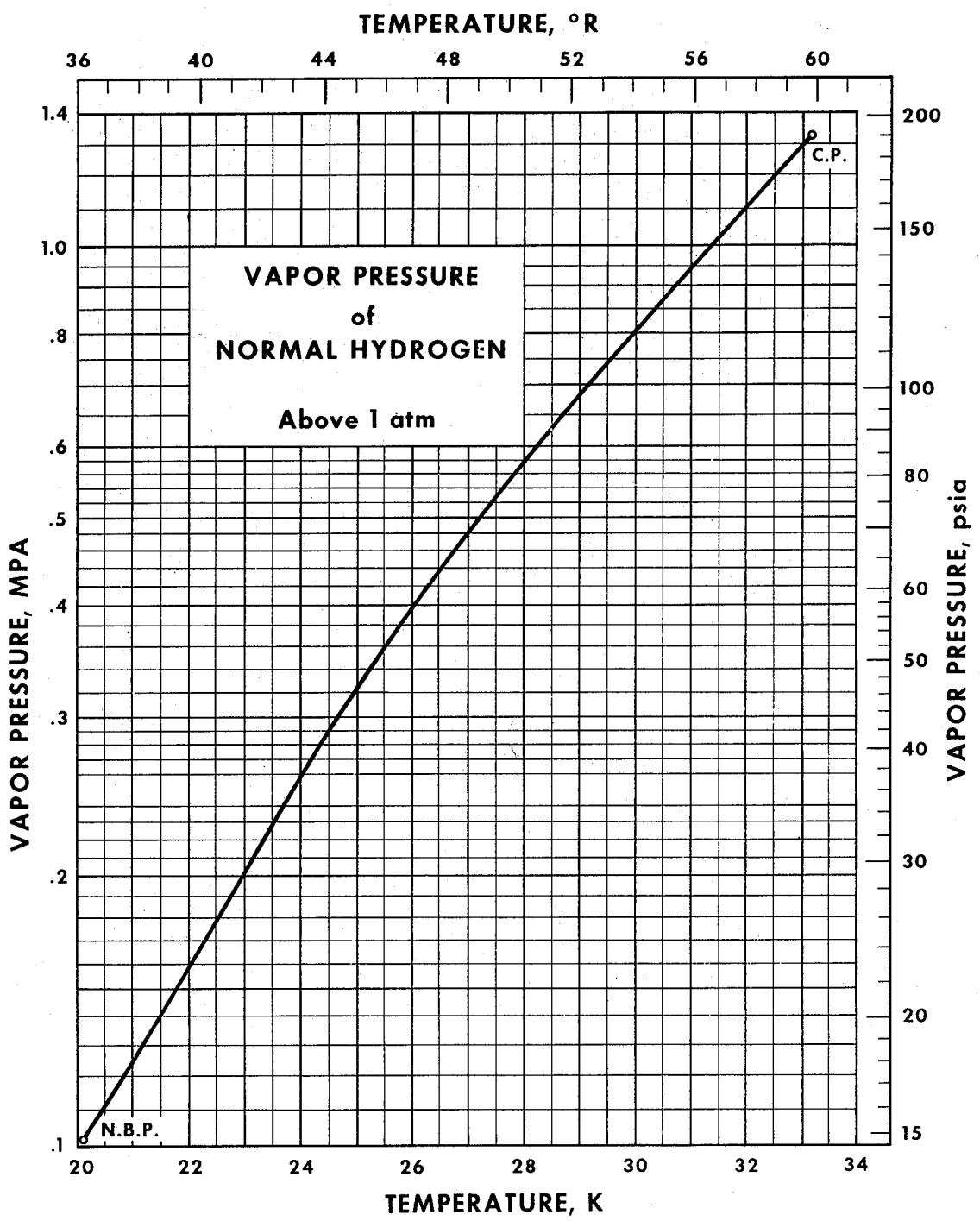


FIGURE 32. Vapor pressure of normal hydrogen
above 0.101325 MPa (1 atm).

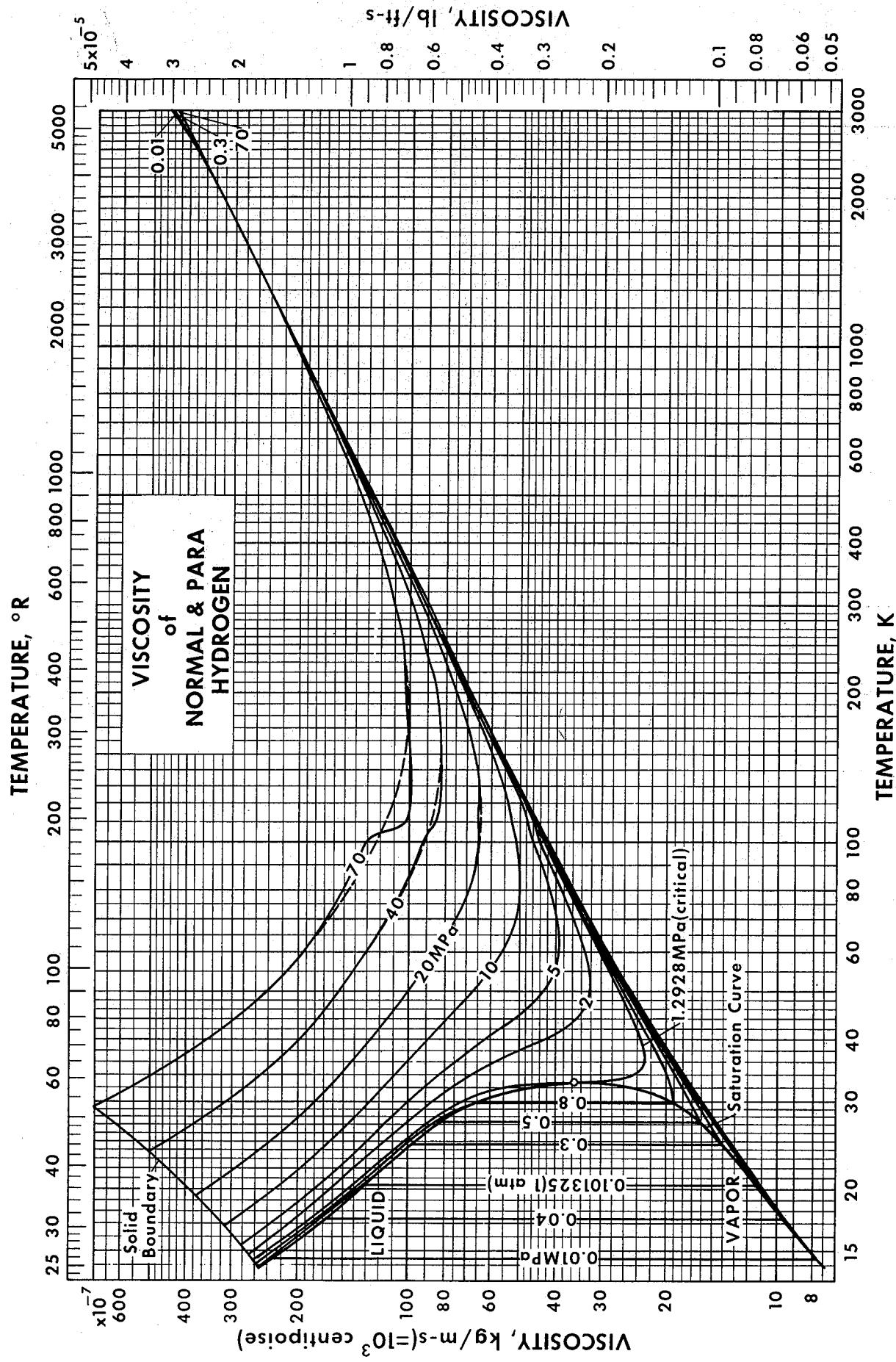


FIGURE 33. Viscosity of normal and parahydrogen.

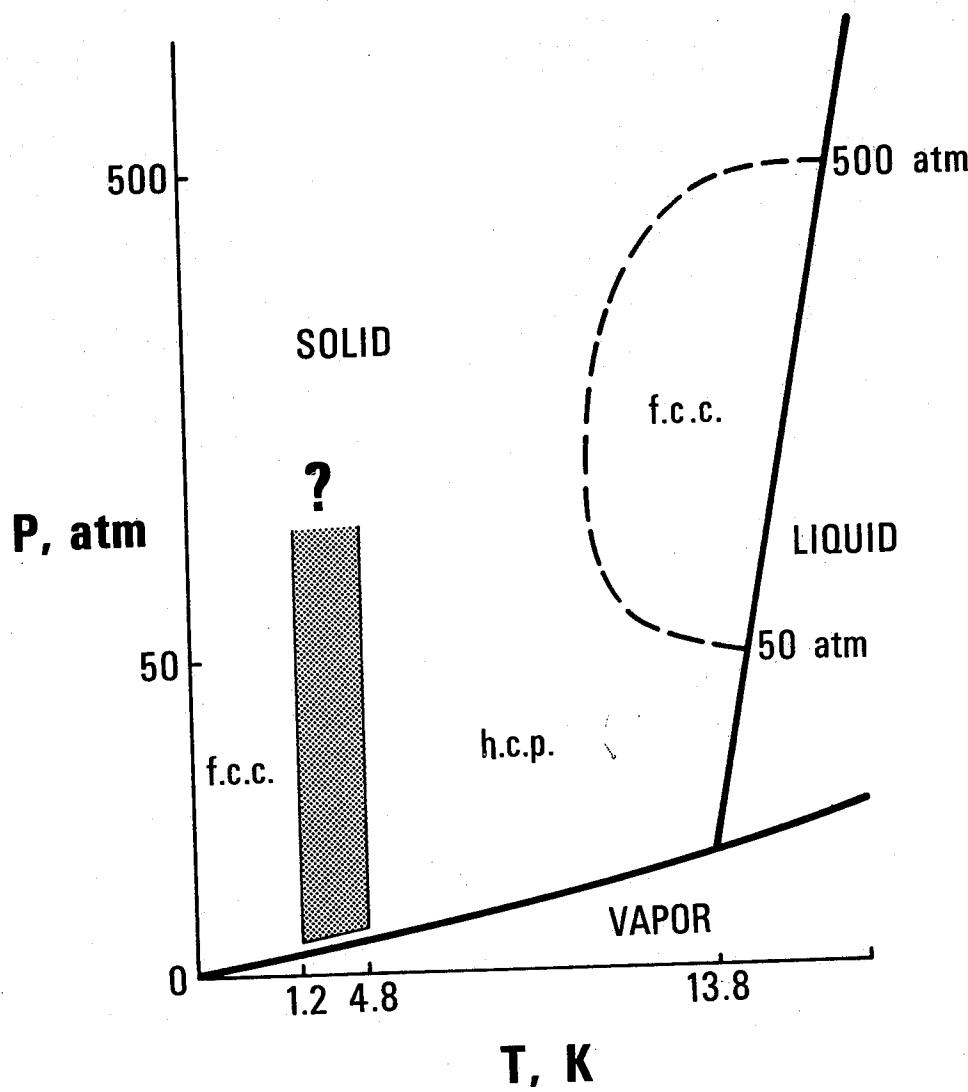


FIGURE 34a. Location of the different crystal structures in the solid hydrogen P-T plane.

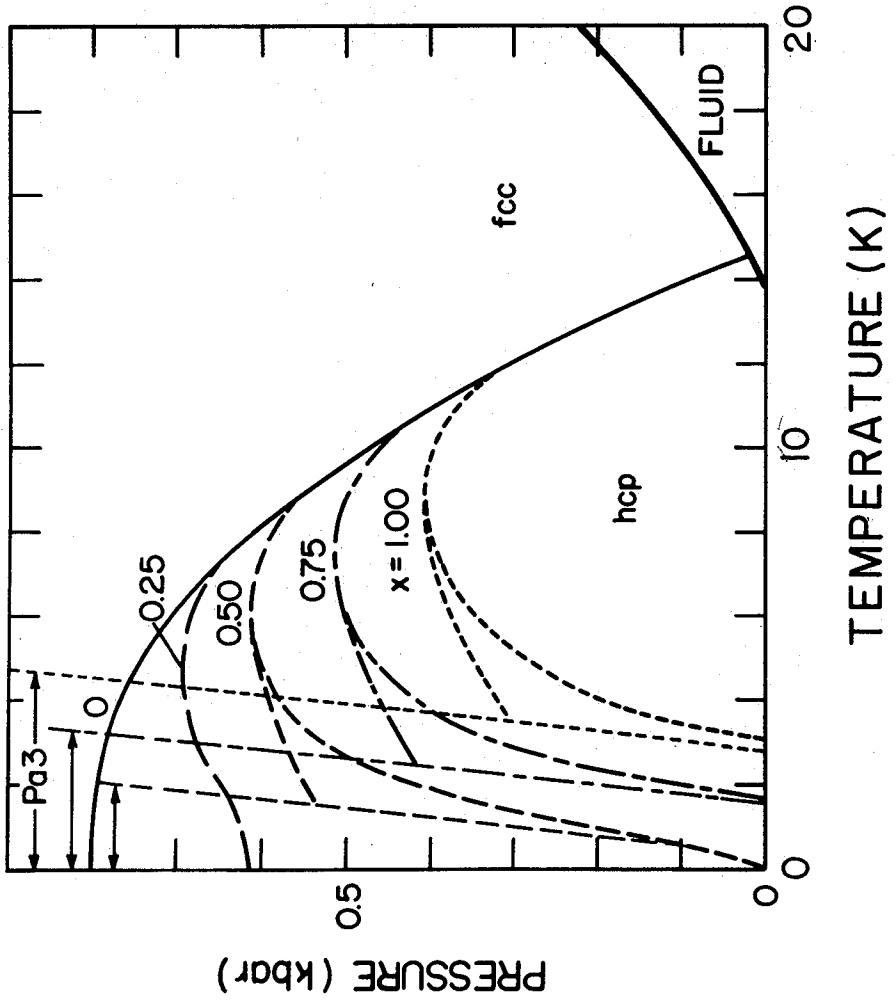


FIGURE 34b. Proposed phase diagram (P-T plane) for solid hydrogen.

Shown on a common temperature scale at various ortho mole fractions x . Solid line, $x = 0$; long-dash line, $x = 0.25$; short-dash line, $x = 0.50$; dash-dot line, $x = 0.75$; dotted line, $x = 1$. Alternate branches are shown for hcp-fcc transition. Heavy solid line is melting curve.

With permission from Mills, R. L., Journ. Low Temp. Phys., 31 (3-4), 423, 1978 [Ref. 159].

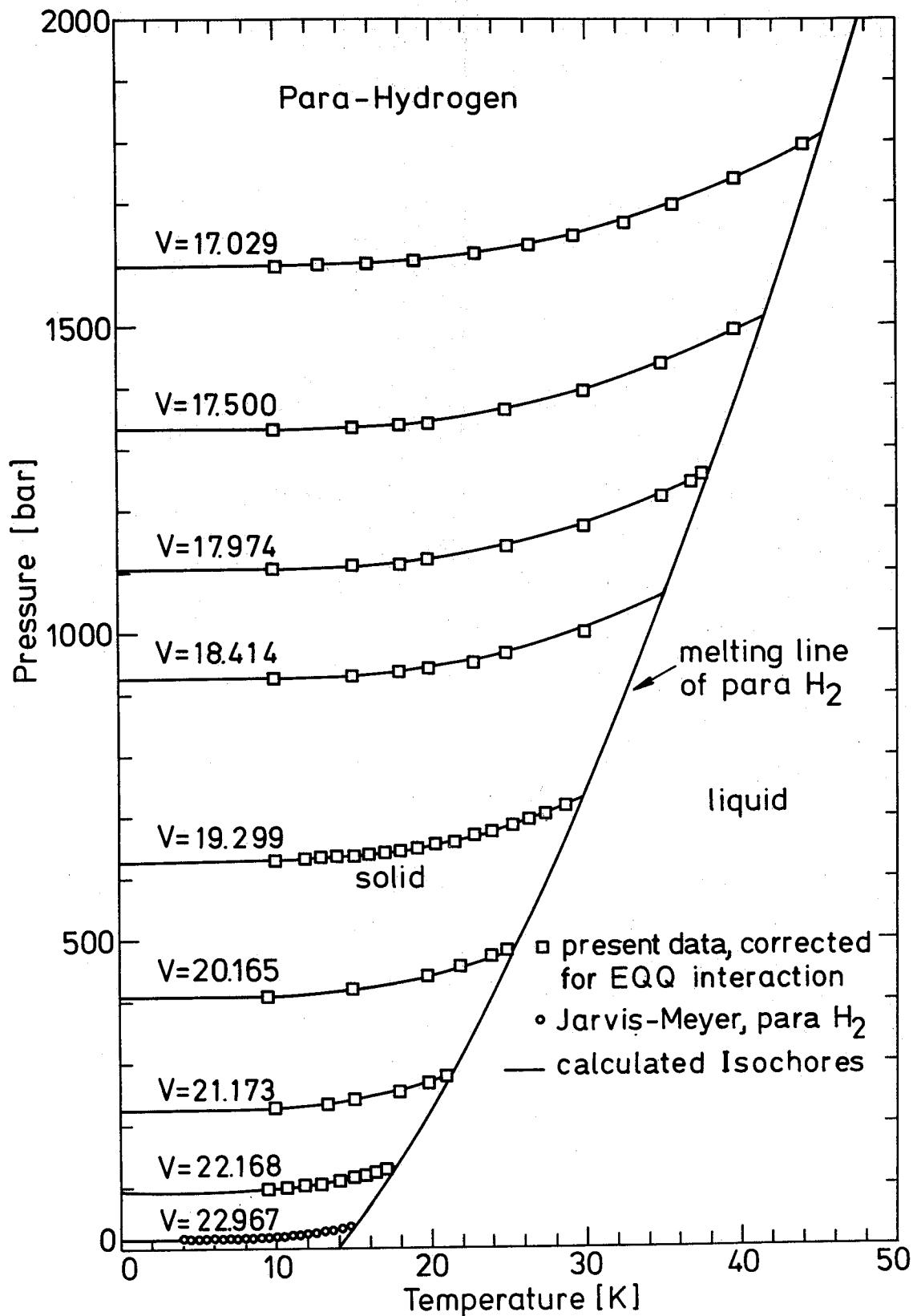


FIGURE 34c. Isochores of solid parahydrogen in the P-T plane.

With permission from Silvera, I. F., Phys. Lett., A68(2), 207, 1978 [Ref. 160].

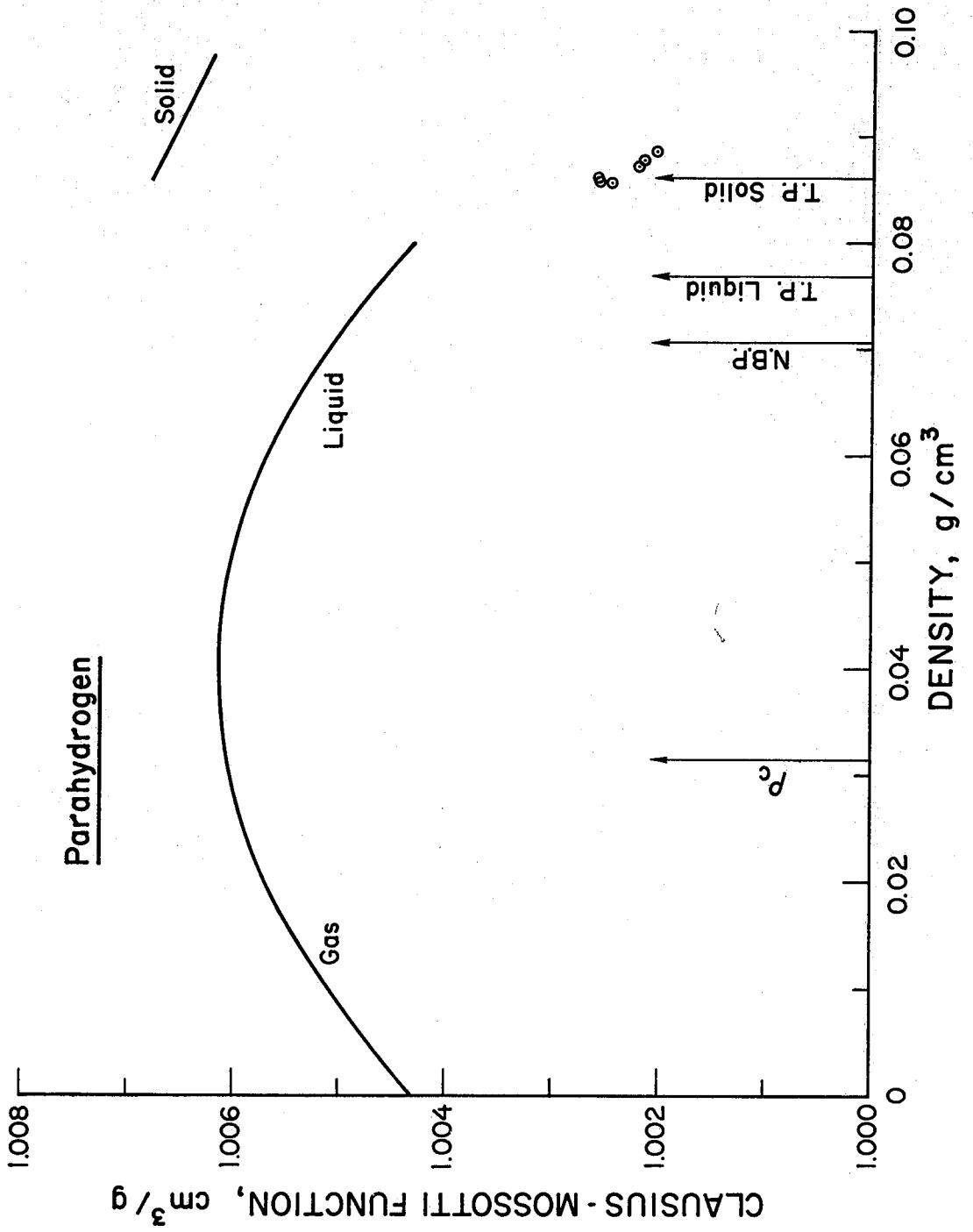


FIGURE 35. Clausius-Mossotti function for parahydrogen.

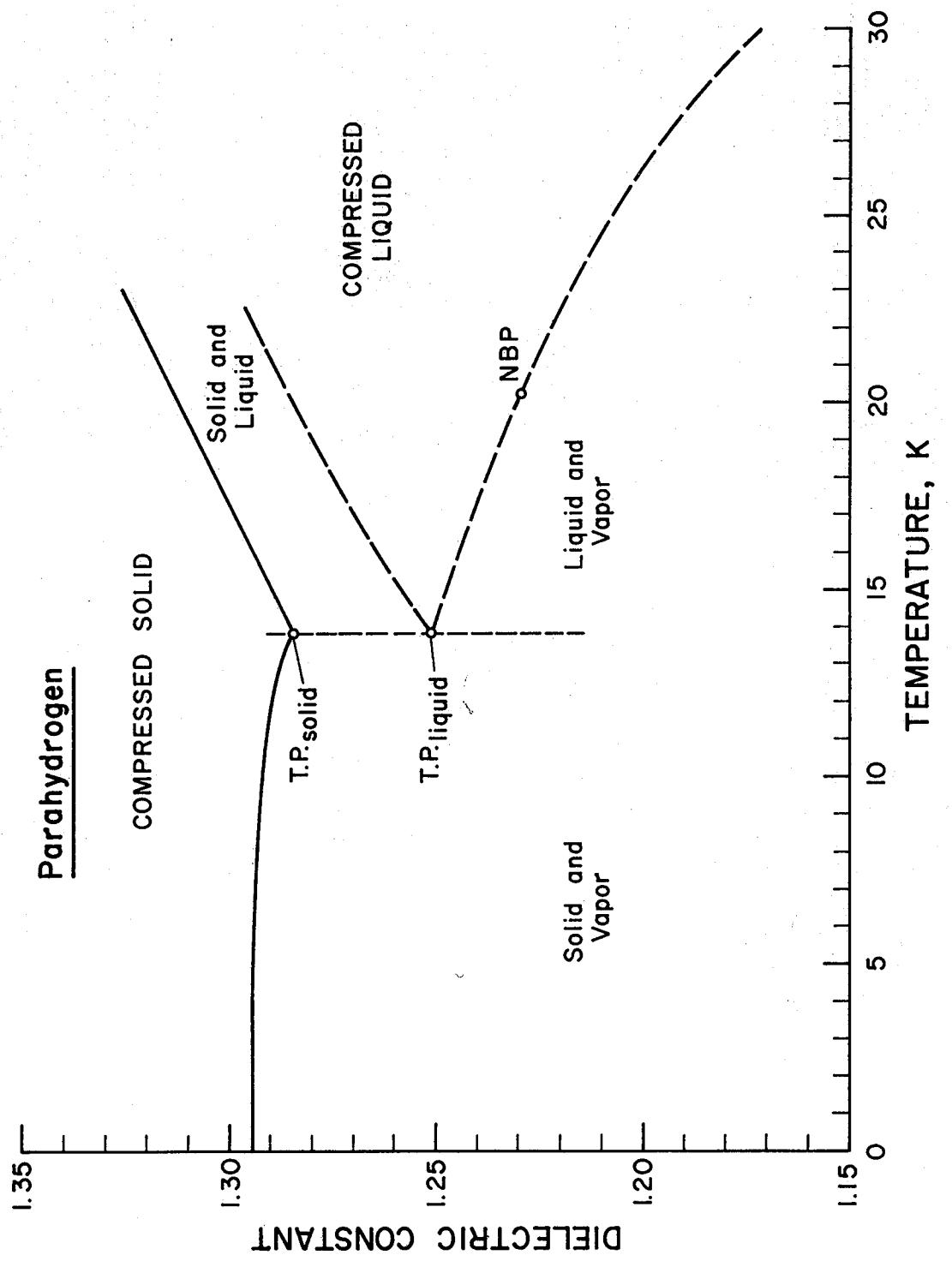


FIGURE 36. Dielectric constant of saturated liquid and solid parahydrogen.

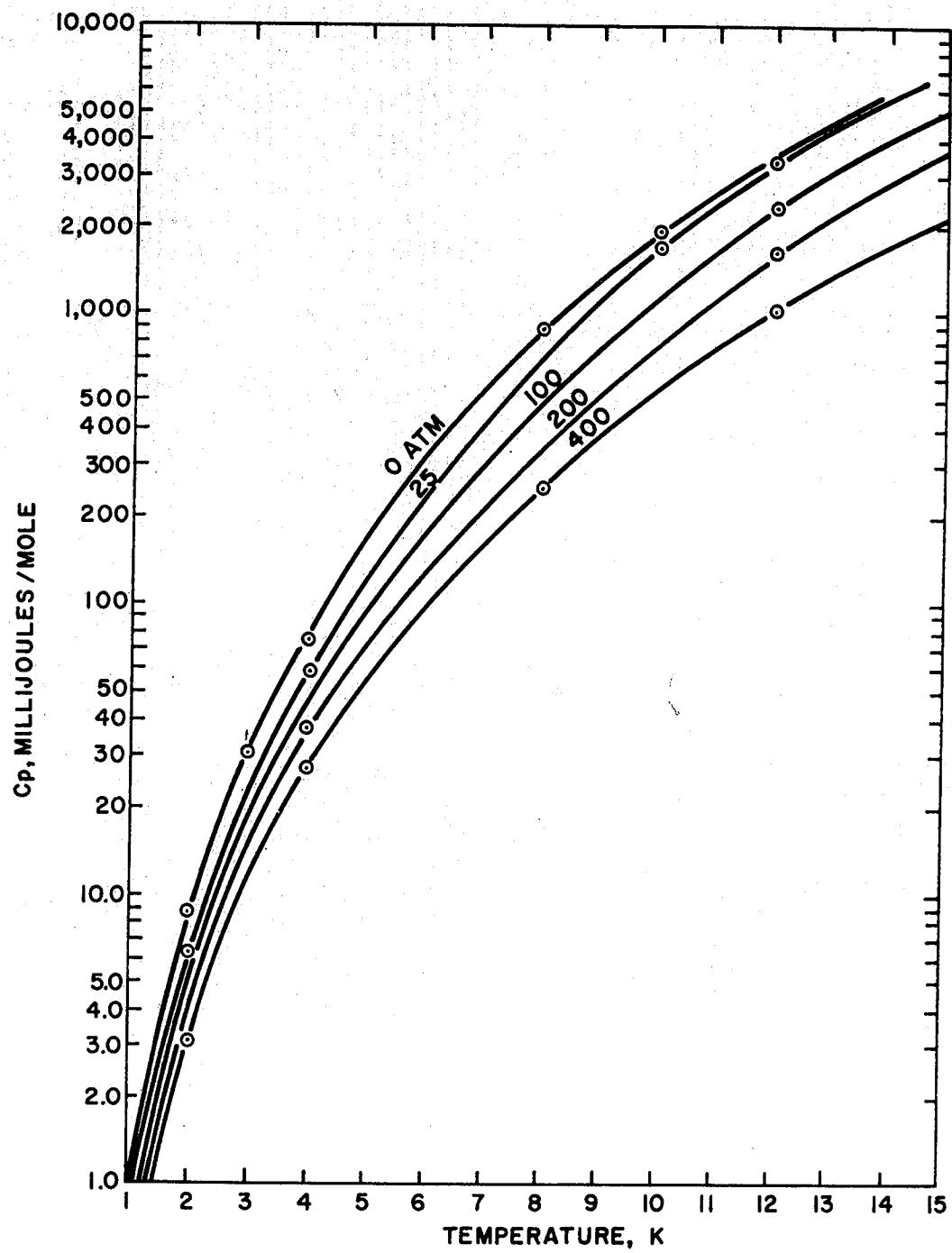


FIGURE 37. Isobars of C_p for compressed solid parahydrogen.

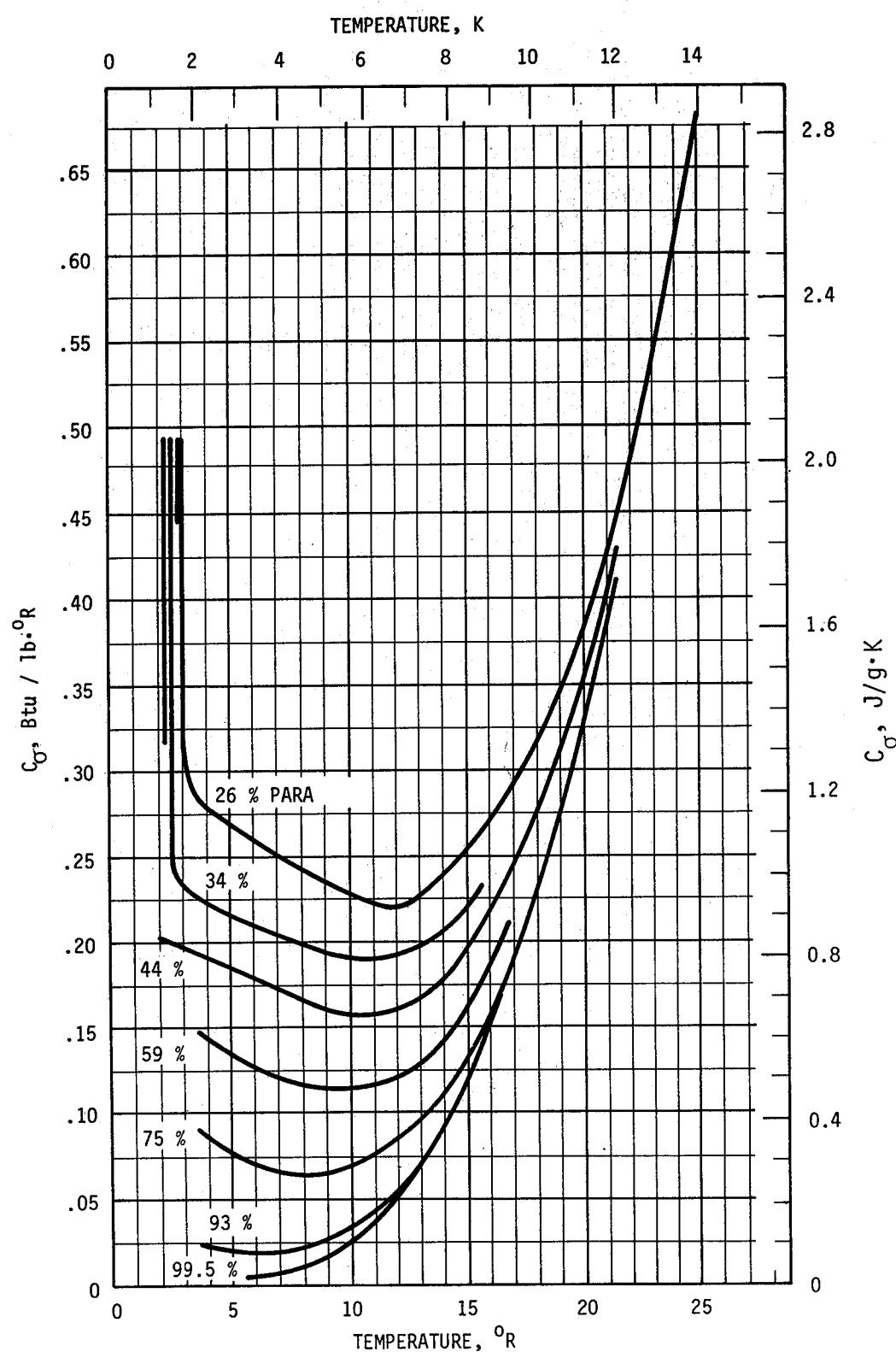


FIGURE 38. Specific heat (heat capacity) of saturated solid hydrogen.

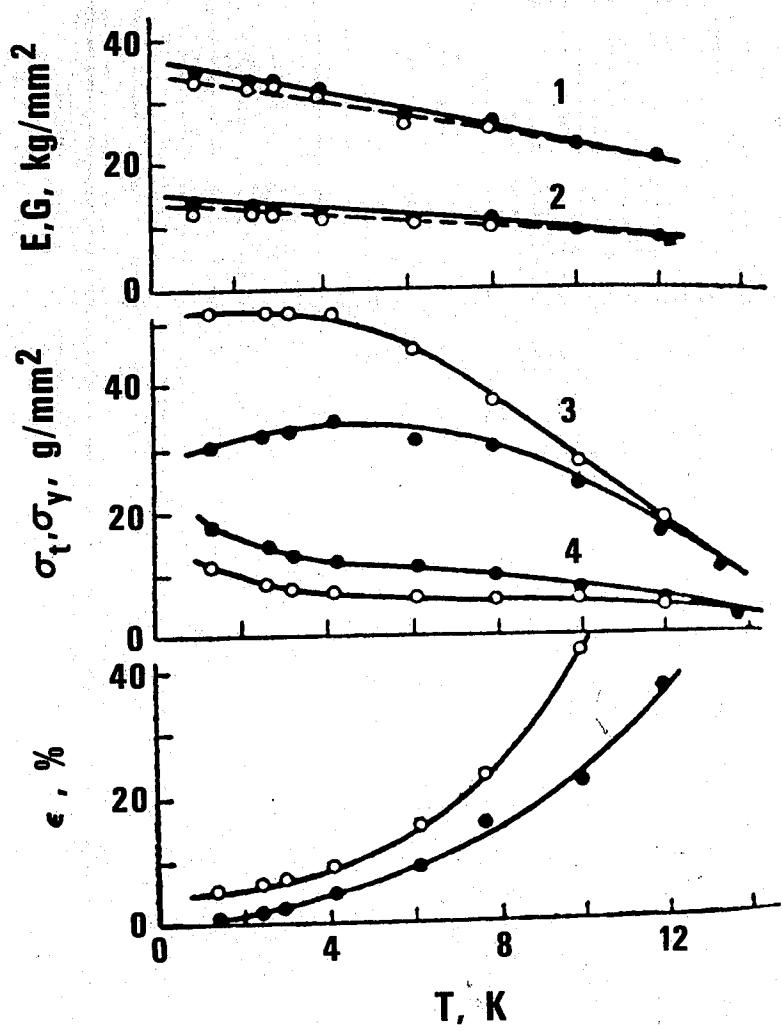


FIGURE 39. Temperature dependencies of the mechanical properties of normal and parahydrogen.

1 - is Young's modulus (E), 2 - the shear modulus (G), 3 - tensile strength (σ_t),
 4 - nominal yield stress (σ_y), ϵ - relative elongation.

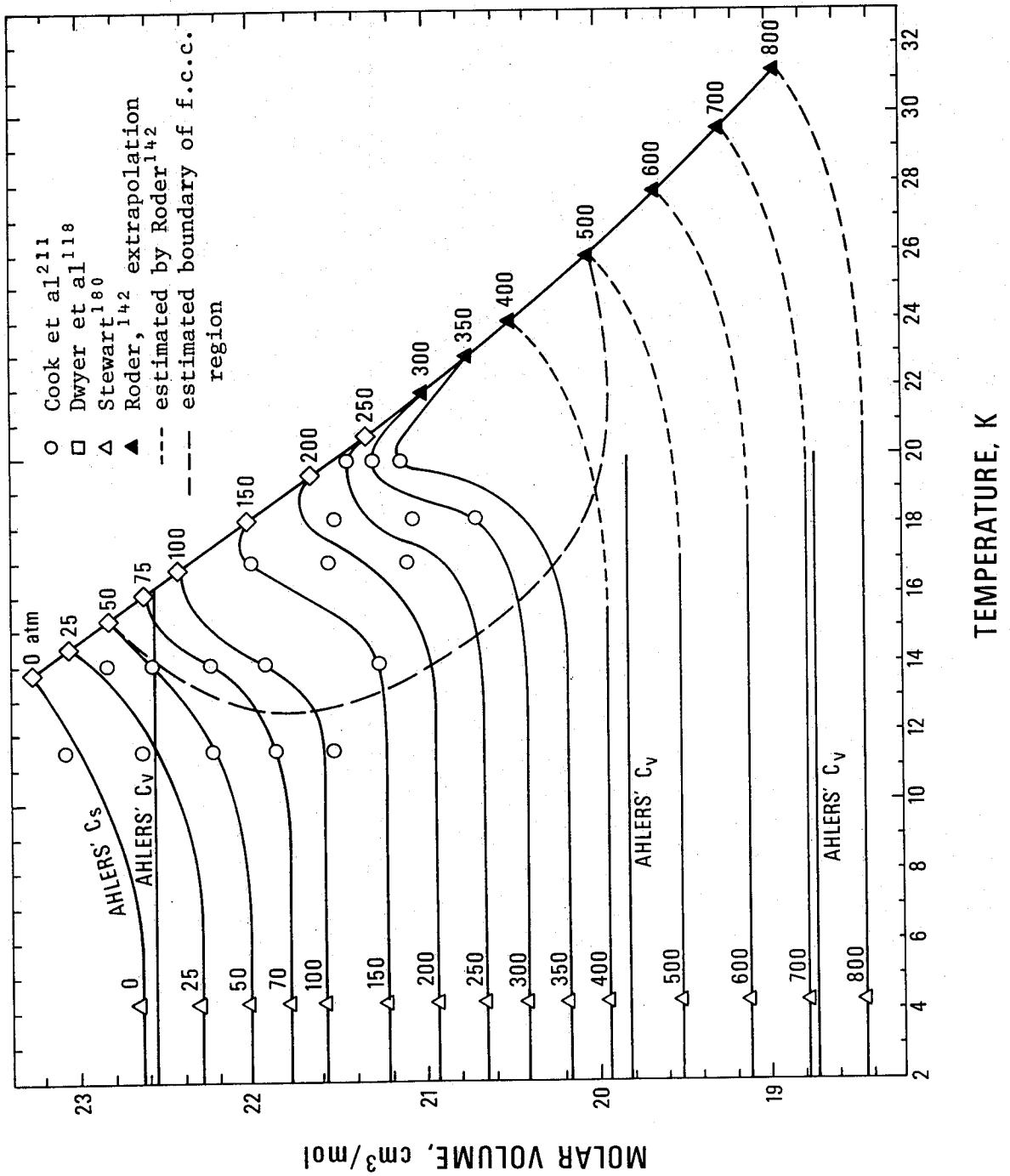


FIGURE 40a. PVT diagram for compressed solid parahydrogen at low pressures.

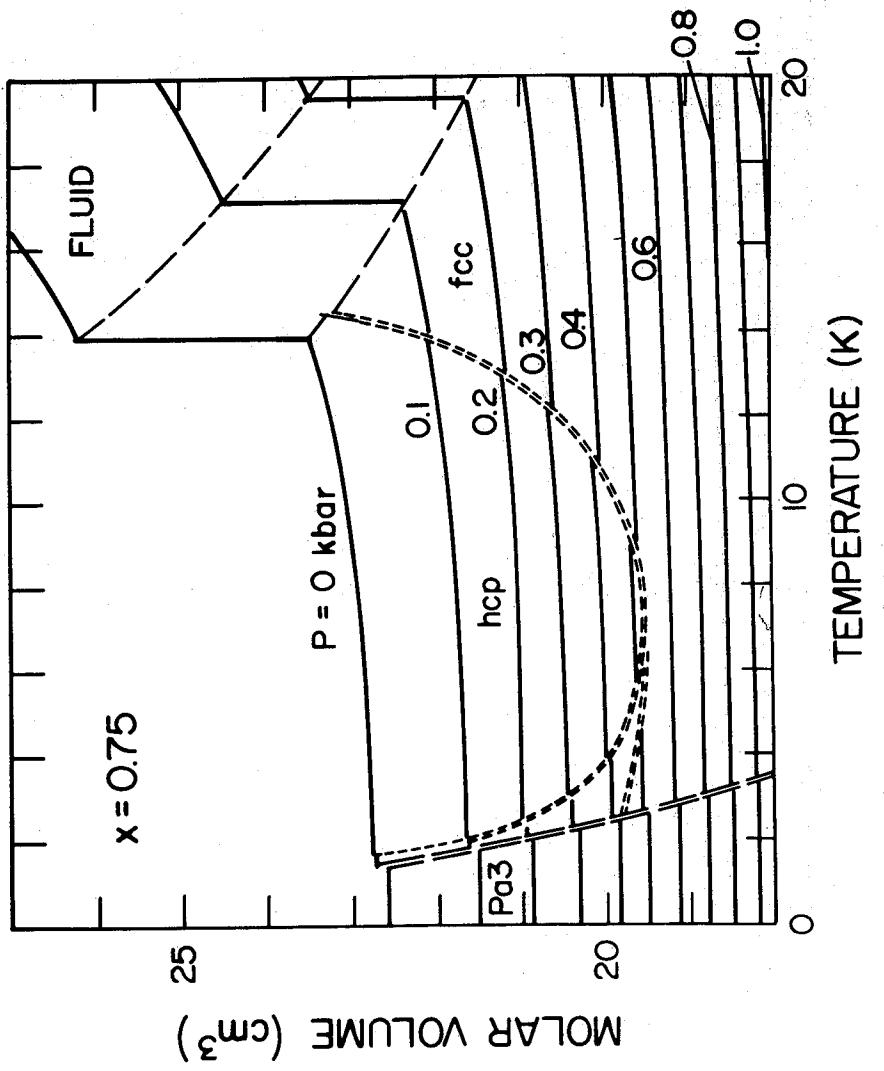


FIGURE 40b. Proposed phase diagram for solid normal hydrogen.
 $V-T$ plane for $n\text{-H}_2$ ($x = 0.75$). Dashed lines indicate alternate
 branches for hcp-fcc transition curve.

With permission from Mills, R. L., Journ. Low Temp. Phys., 31 (3-4), 423, 1978 [Ref. 159].

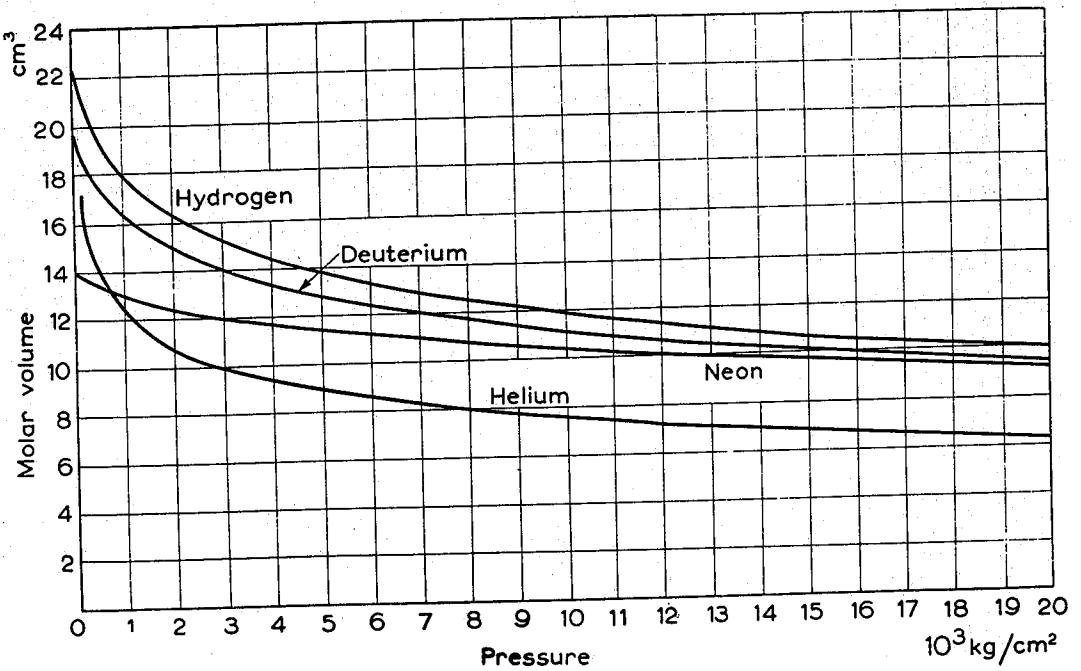


FIGURE 41. PVT diagram for compressed solid hydrogen at high pressures and 4K.

With permission from Stewart, J. W., Phys. Chem. Solids, 1, 146, 1956 [Ref. 180].

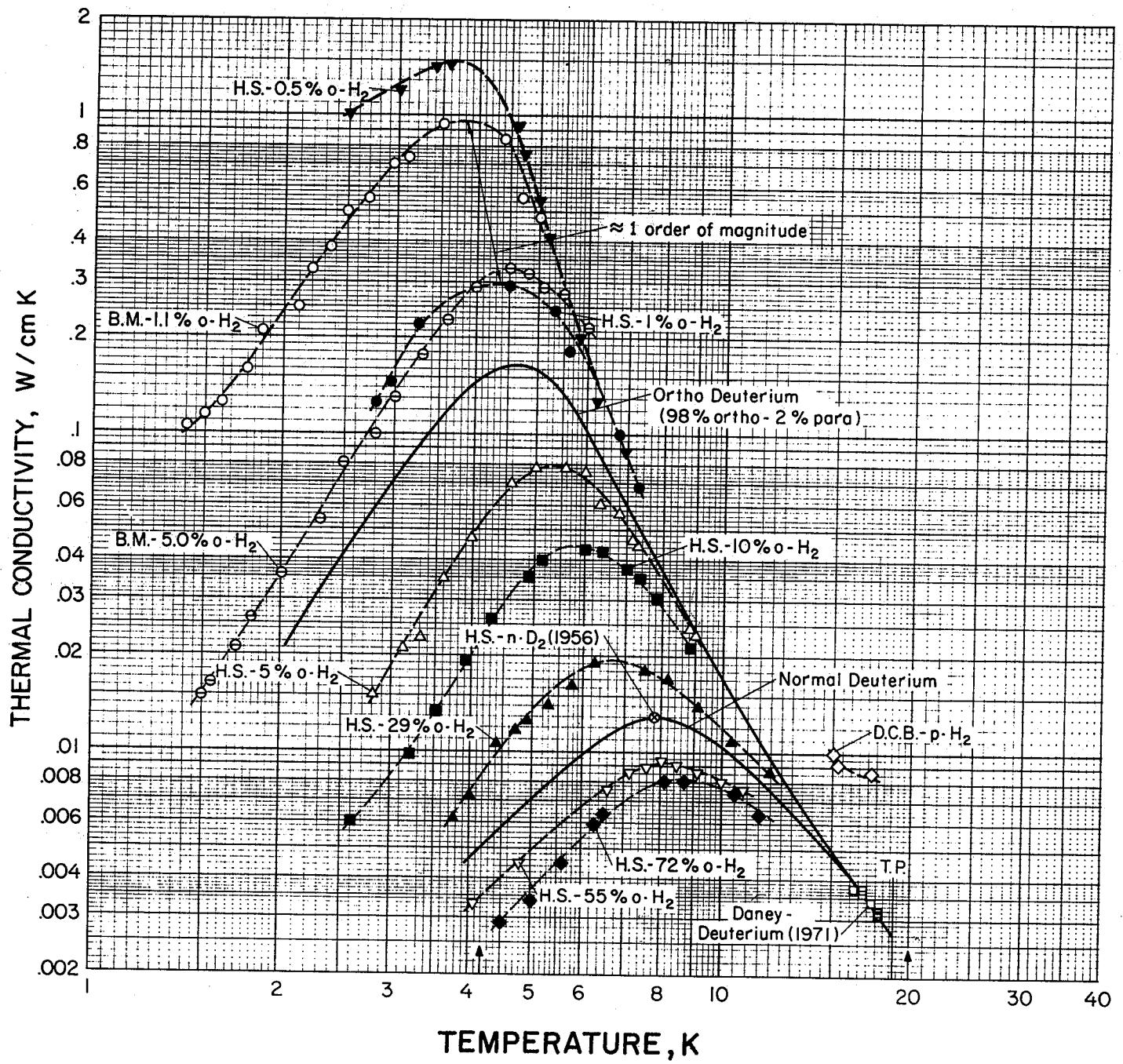


FIGURE 42. Thermal conductivity of solid hydrogen.

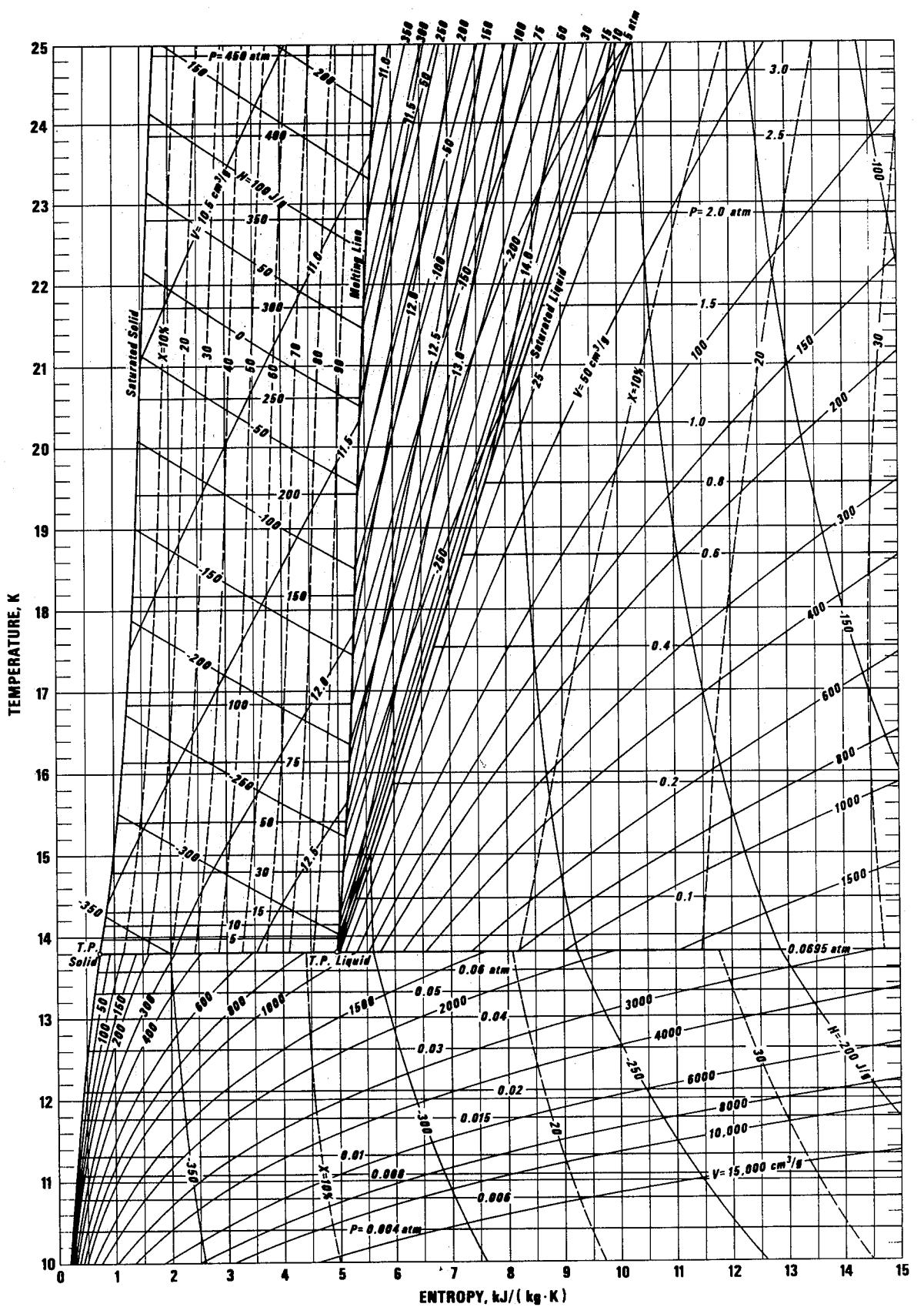


FIGURE 43. Parahydrogen, temperature-entropy diagram (10 to 25 K).

VAPOR PRESSURE, atm

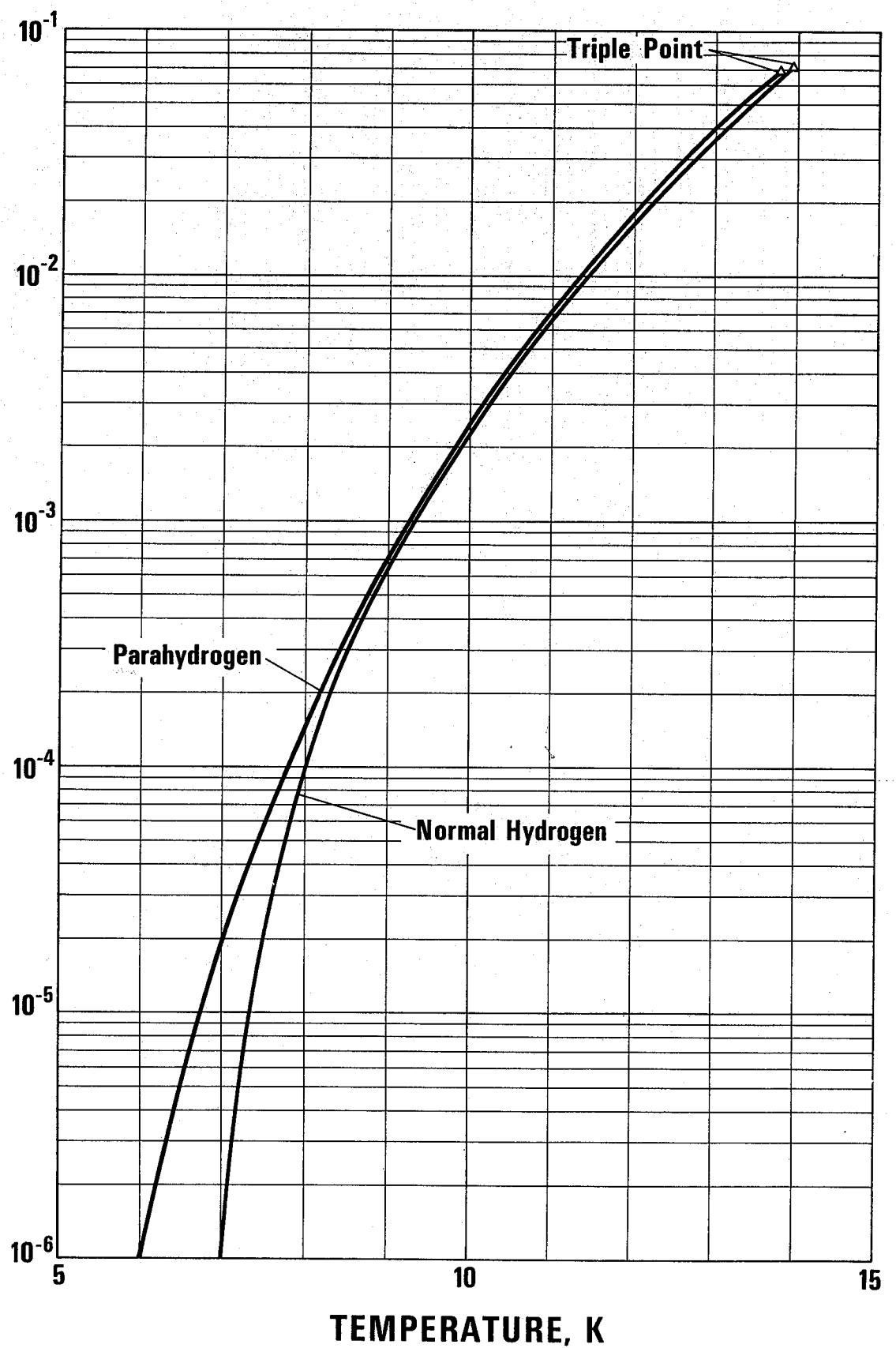


FIGURE 44. Vapor pressures of hydrogen below the triple point.

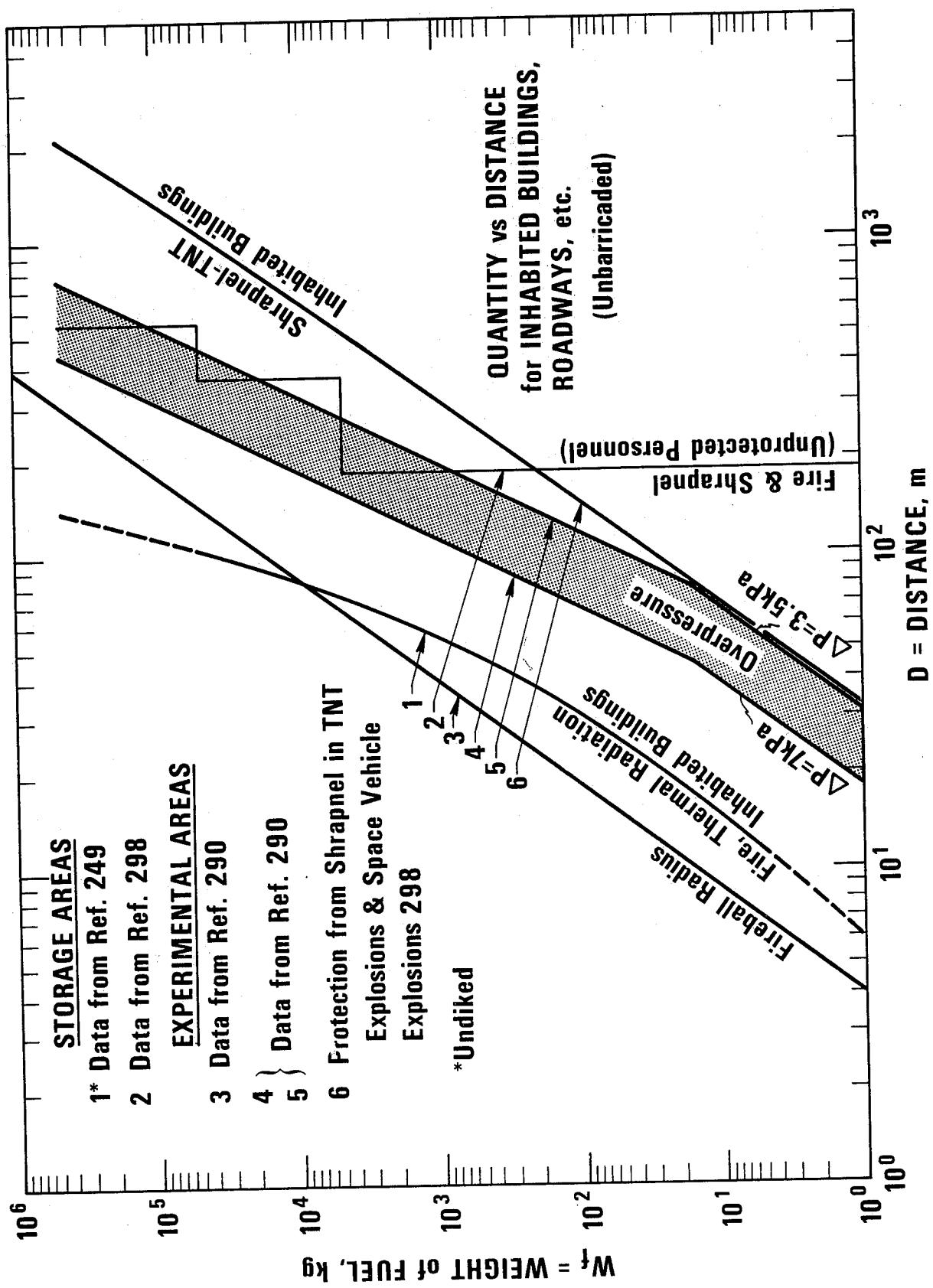


FIGURE 45. Quantity-distance relationships for the protection of personnel near liquid hydrogen storage and experimental areas (unbarricaded).

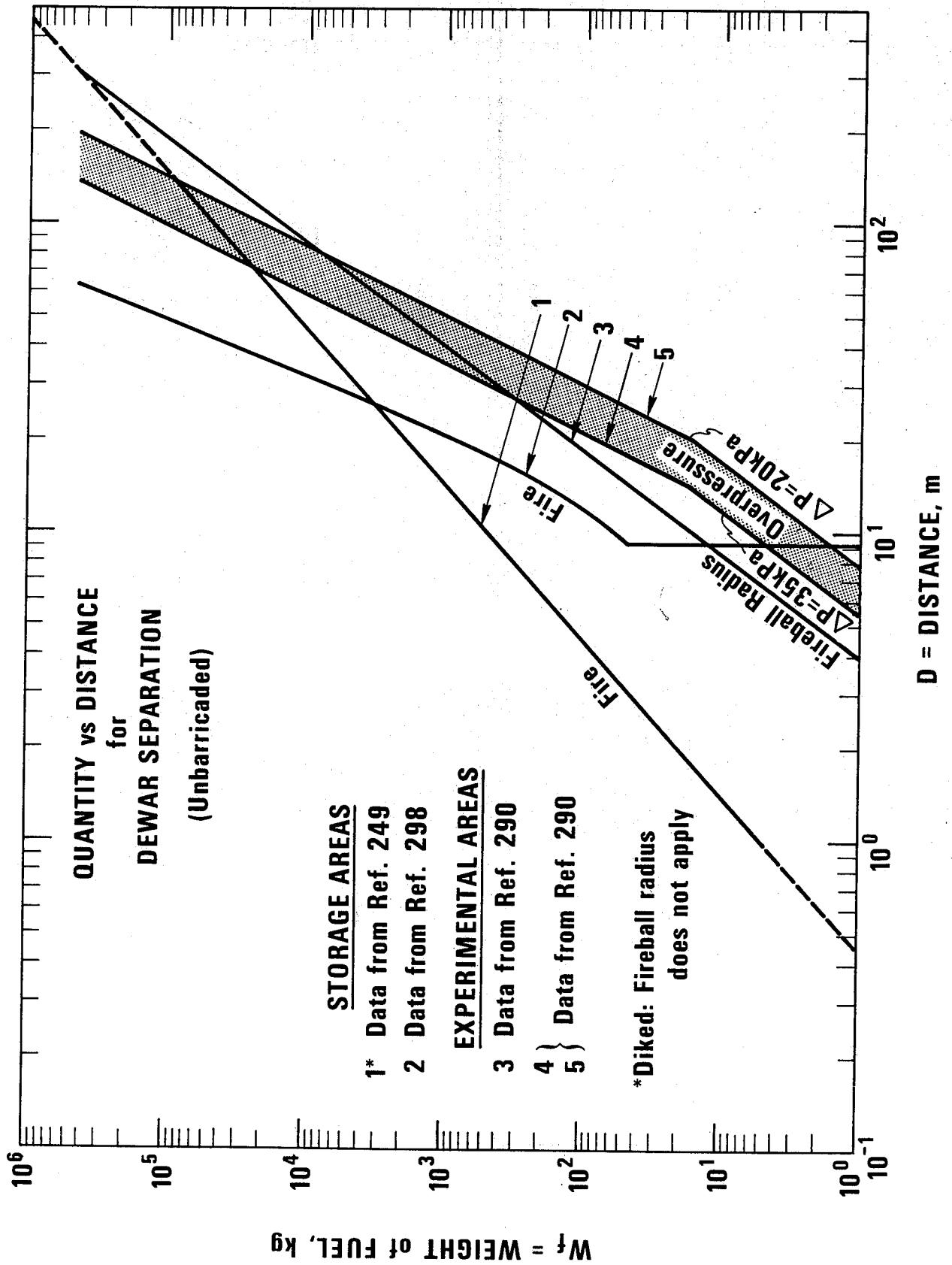


Figure 46. Quantity-distance relationships for liquid hydrogen dewar separation in storage and experimental areas (unbarricaded).

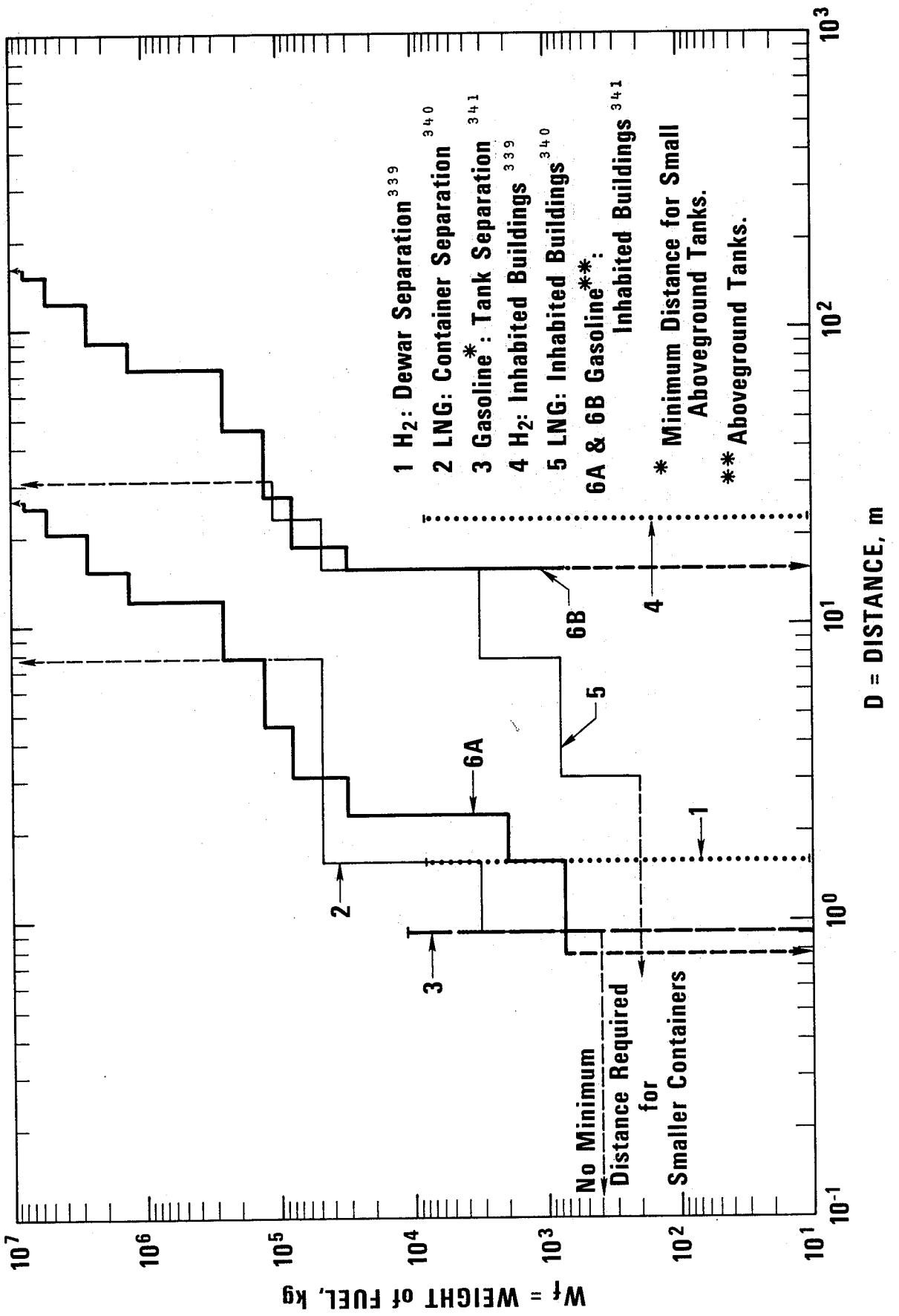


FIGURE 47. Industrial storage standards (quantity-distance) for hydrogen, liquefied natural gas (LNG), and gasoline.

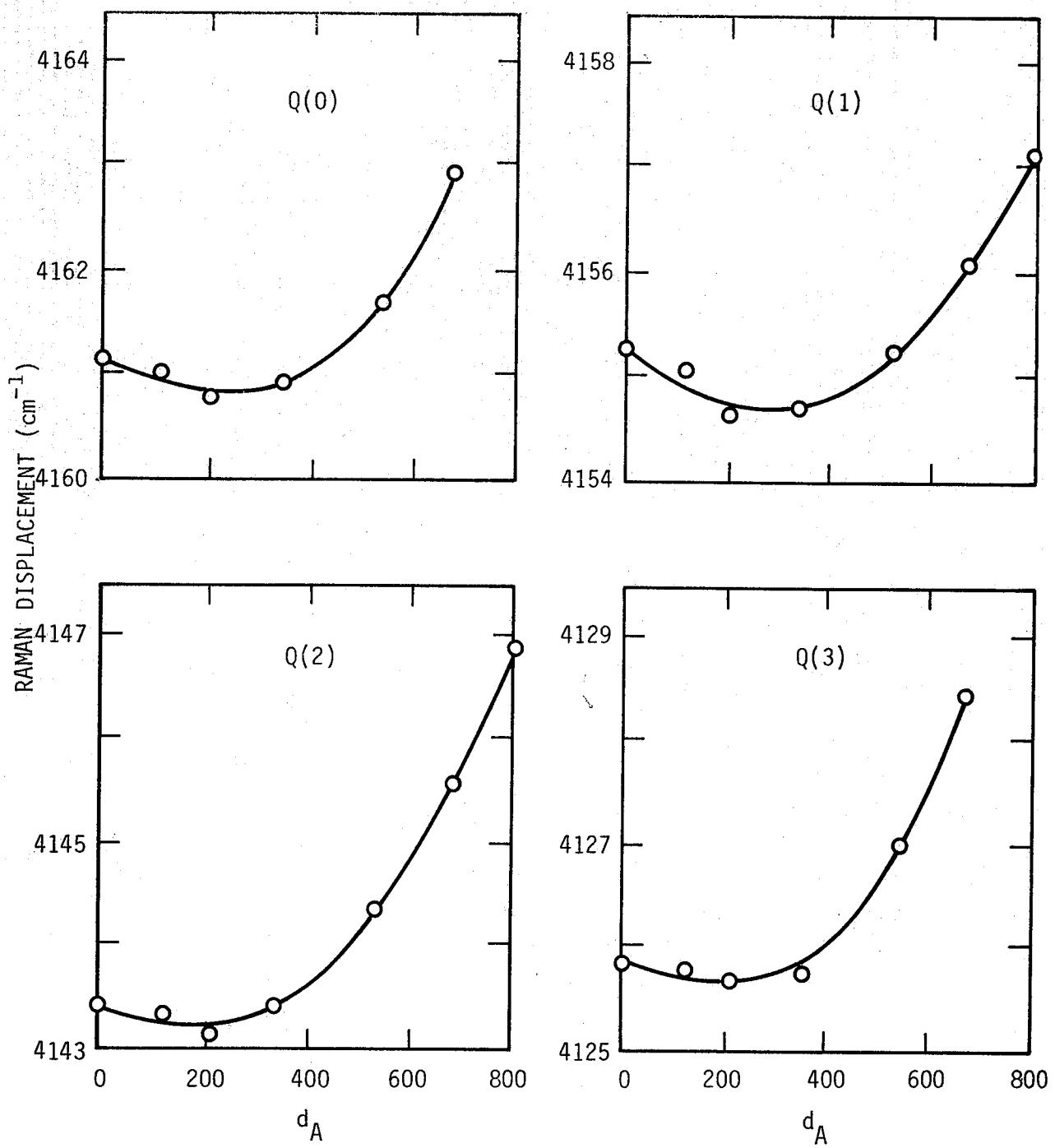


FIGURE 48. Raman displacement. Note: d_A = density in Amagats and $\text{Amagats} \times 0.089881 = \text{kg/m}^3$. See Chapter 7 for density conversions.

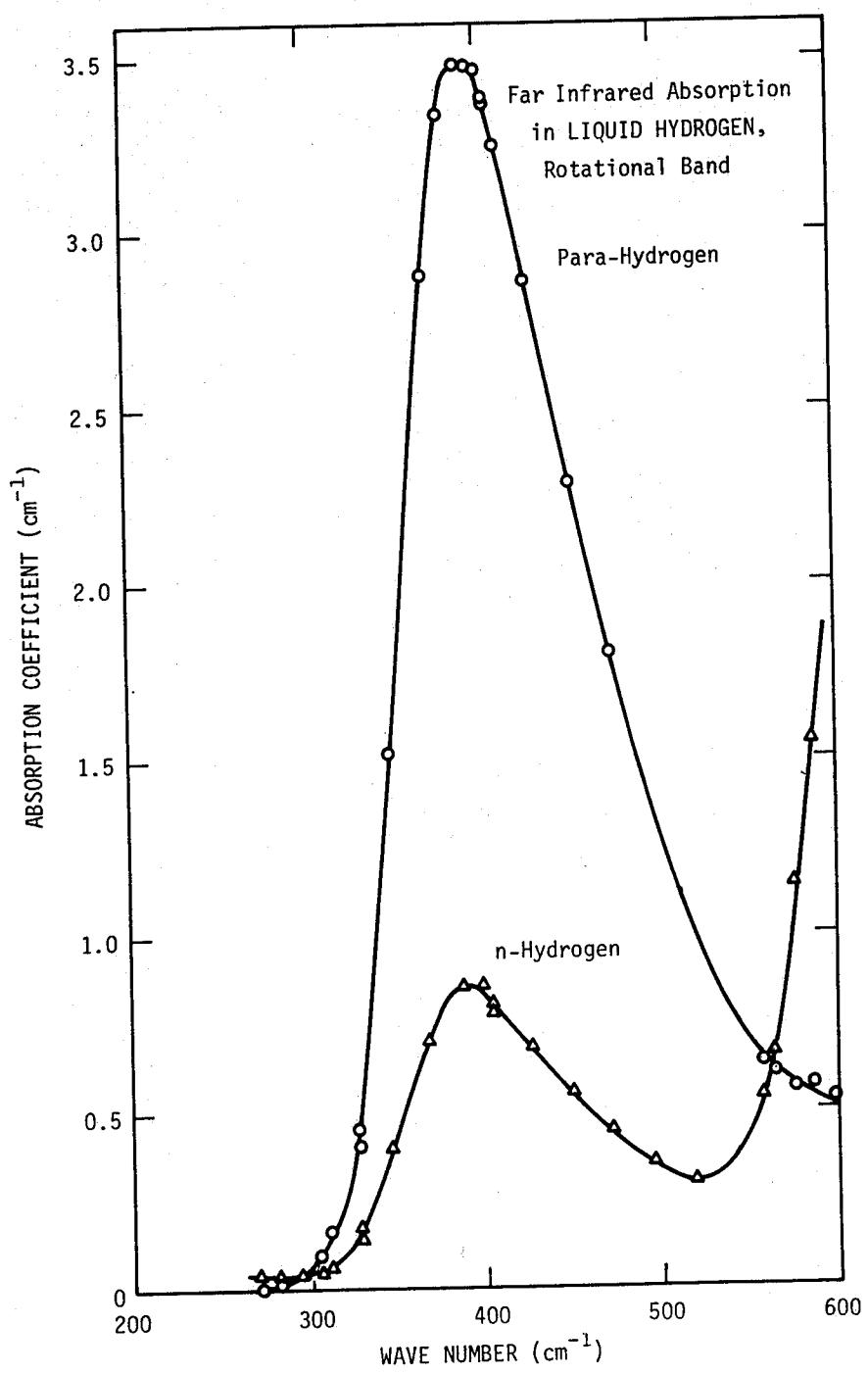


FIGURE 49. Far infrared absorption in liquid hydrogen (rotational band).

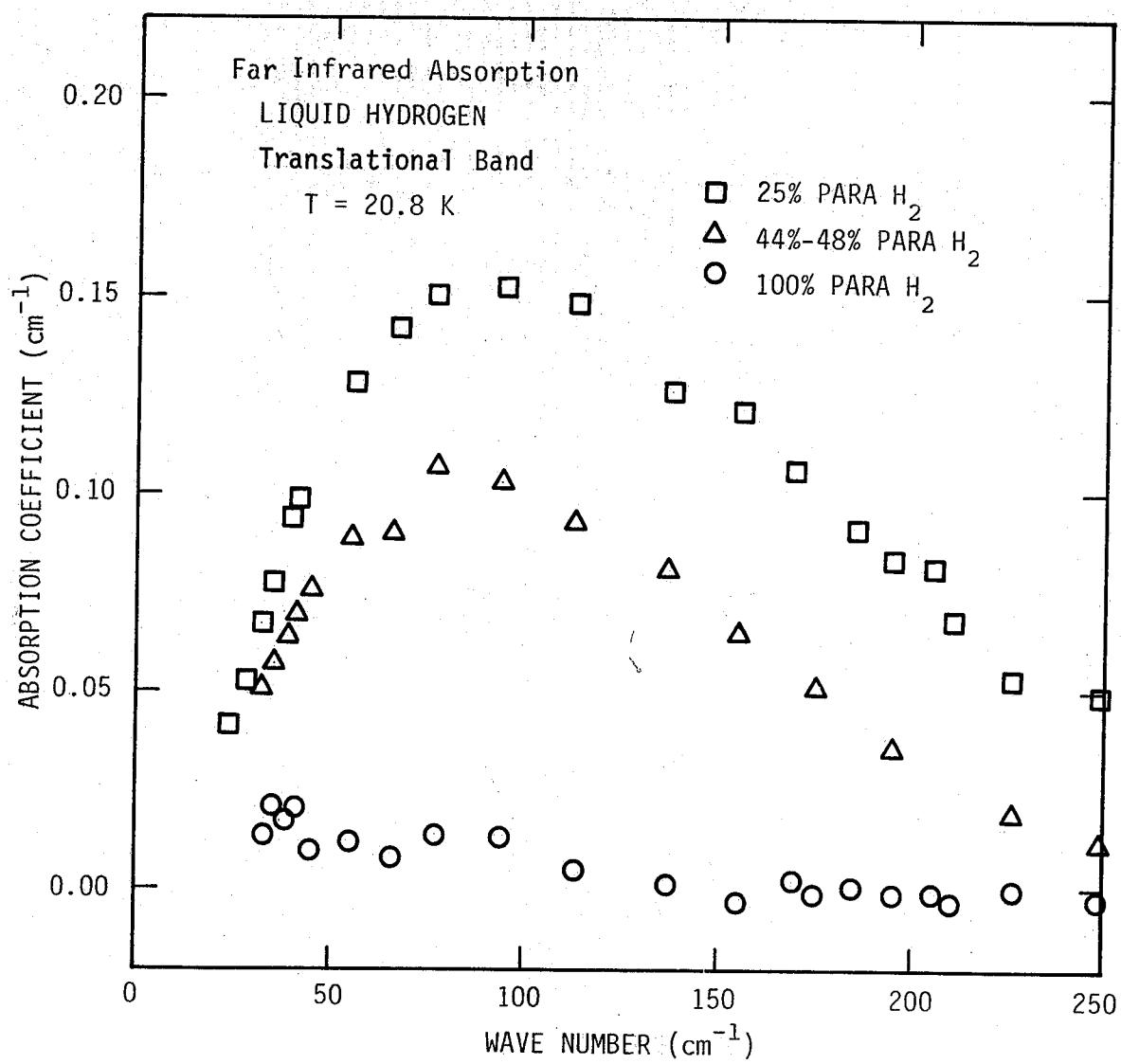


FIGURE 50. Far infrared absorption in liquid hydrogen (translational band).

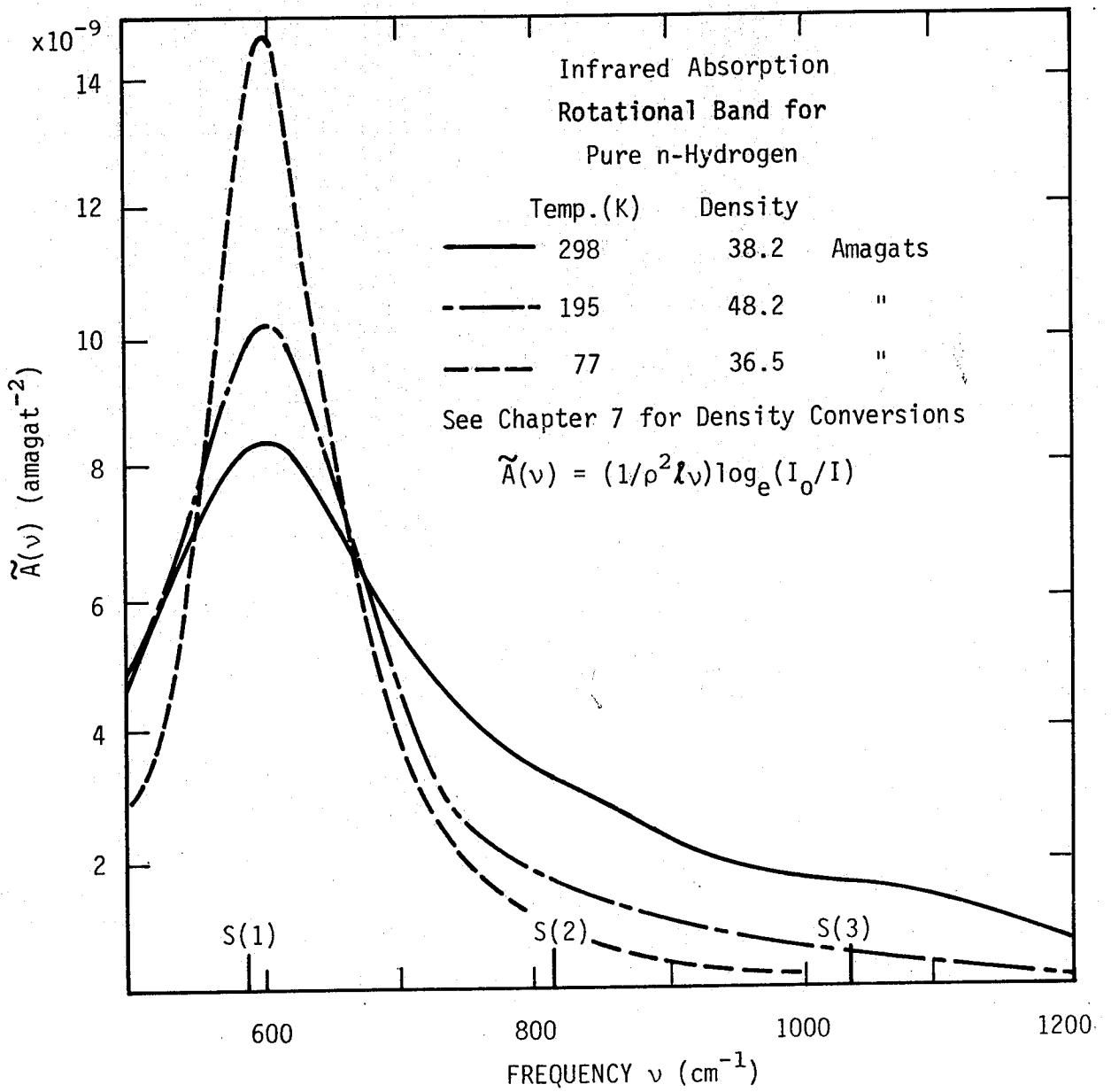


FIGURE 51. Infrared absorption (rotational band) for normal hydrogen.

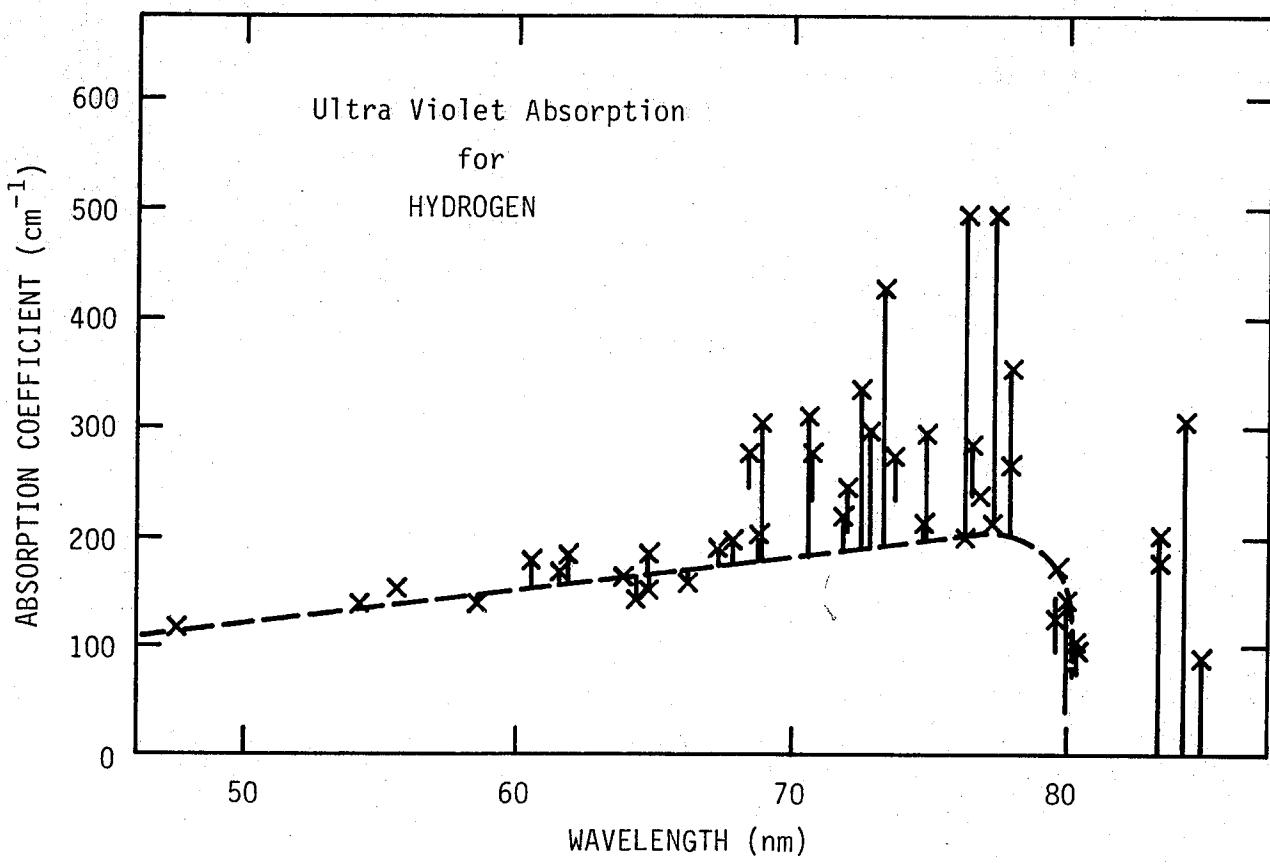


FIGURE 52. Ultraviolet absorption for hydrogen.

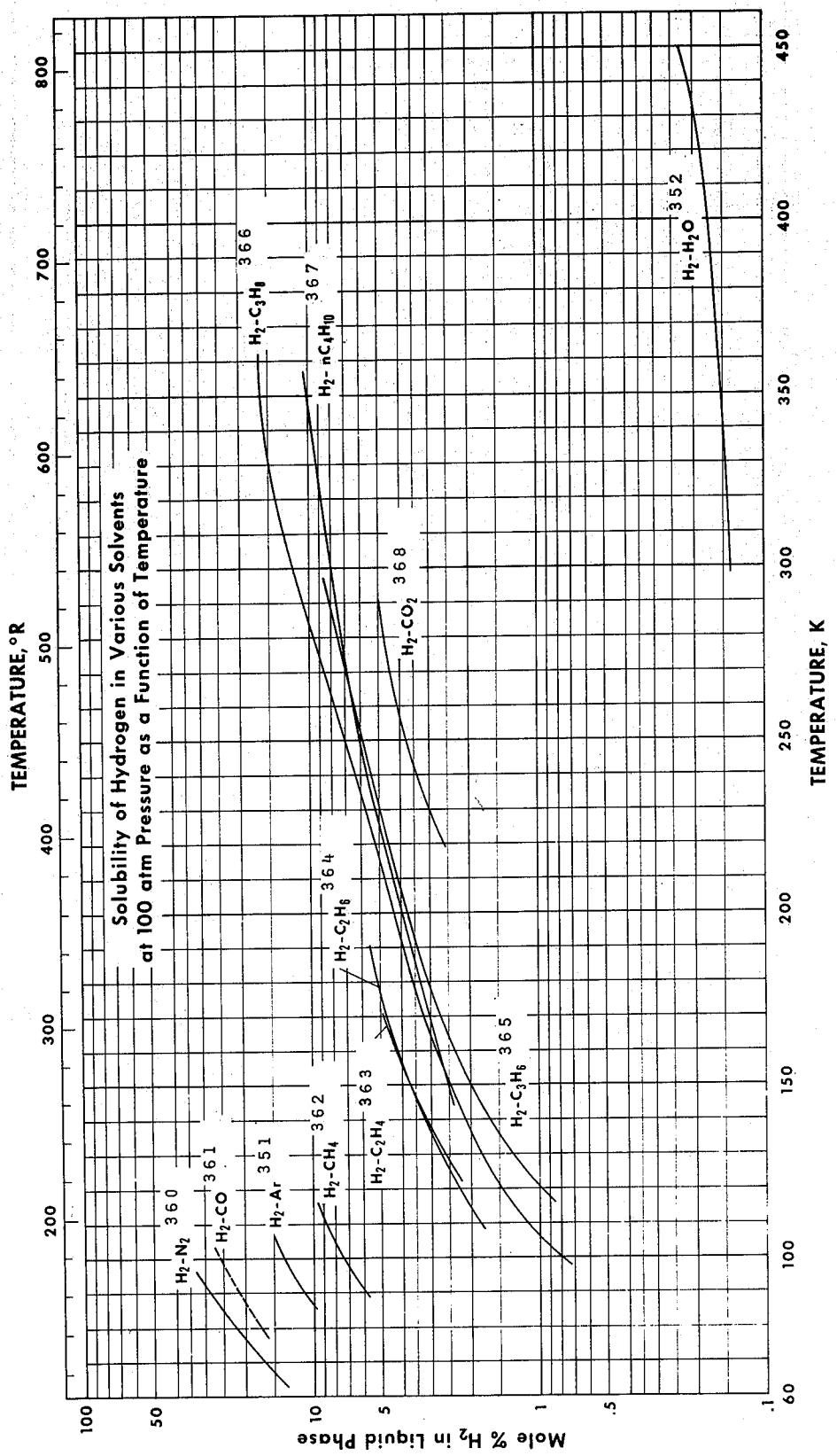


FIGURE 53. Solubility of hydrogen in various solvents at 10.1325 MPa (100 atm)

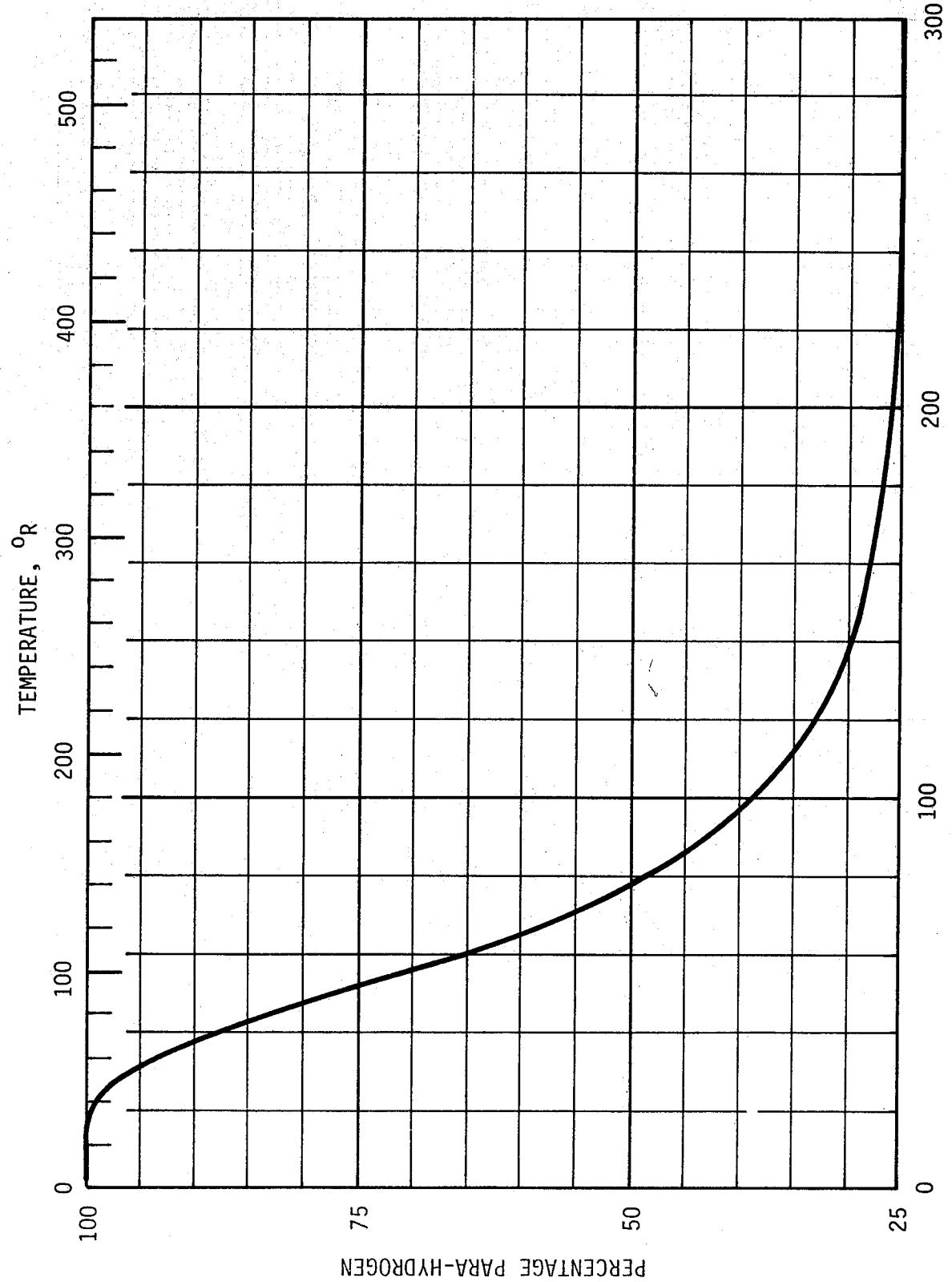


FIGURE 54. Equilibrium percentage of parahydrogen.

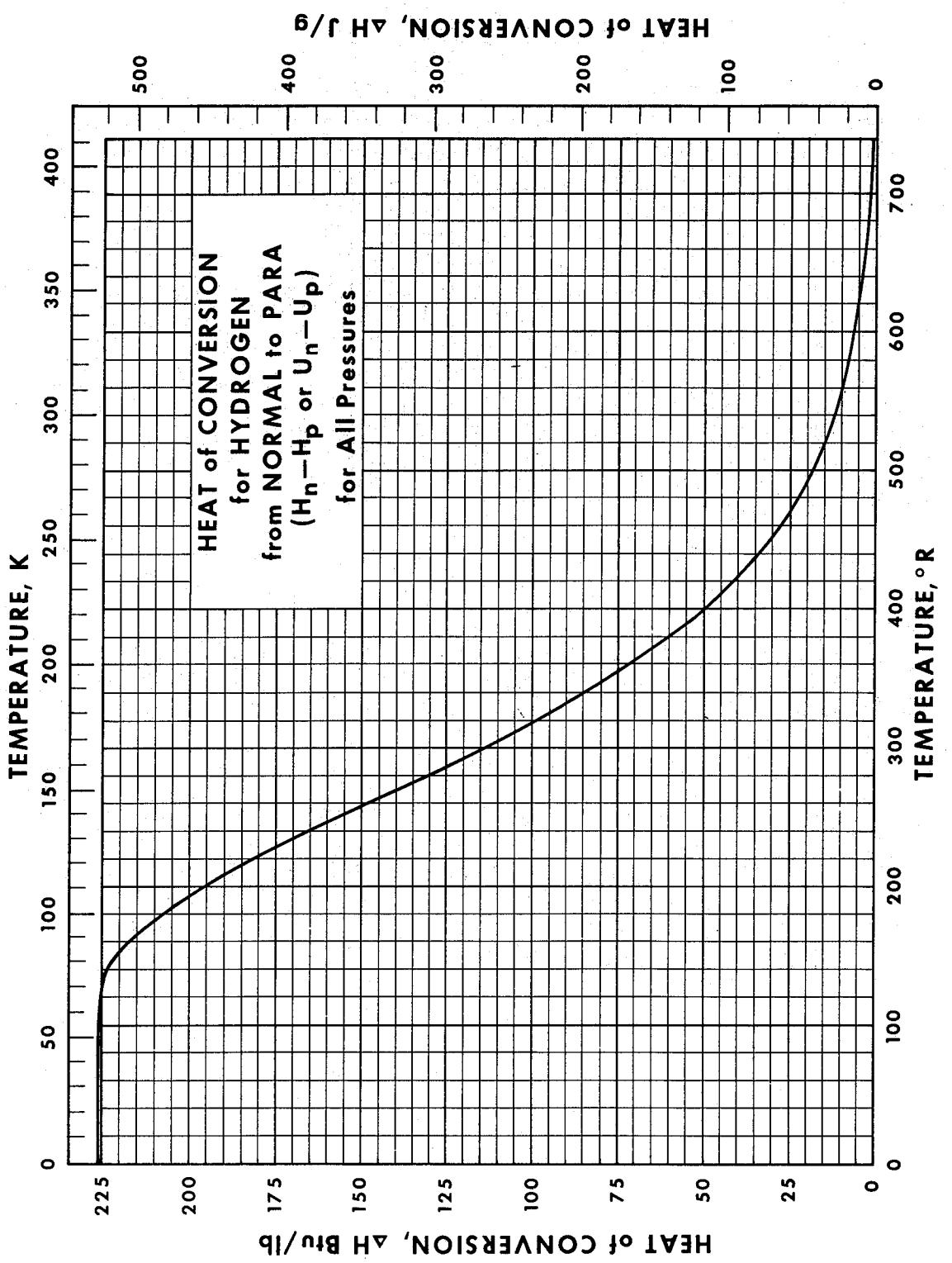


FIGURE 55. Heat of conversion for hydrogen from normal to para.

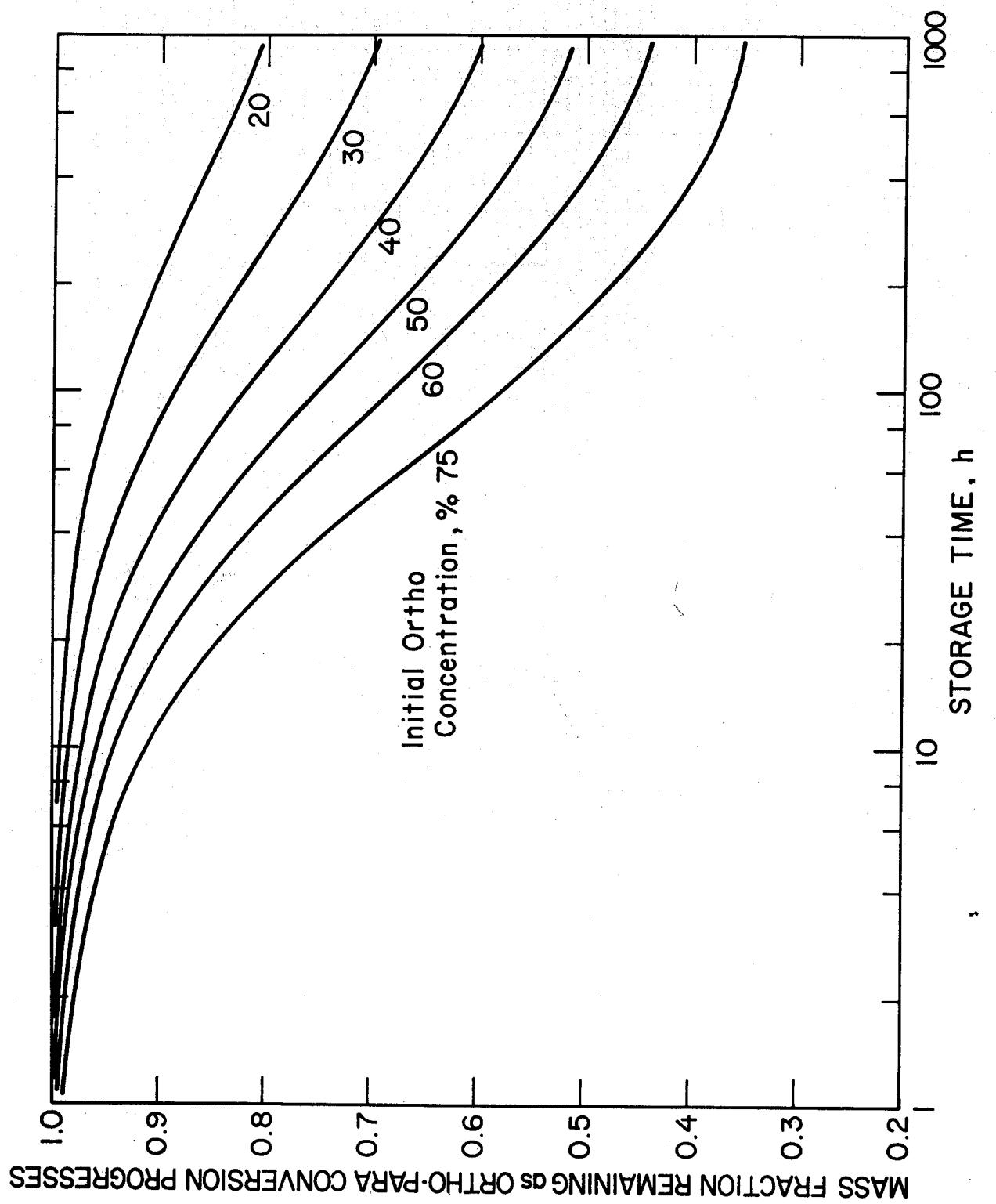


FIGURE 56. Fraction of liquid hydrogen boiled off, due to ortho-para conversion, as a function of time.

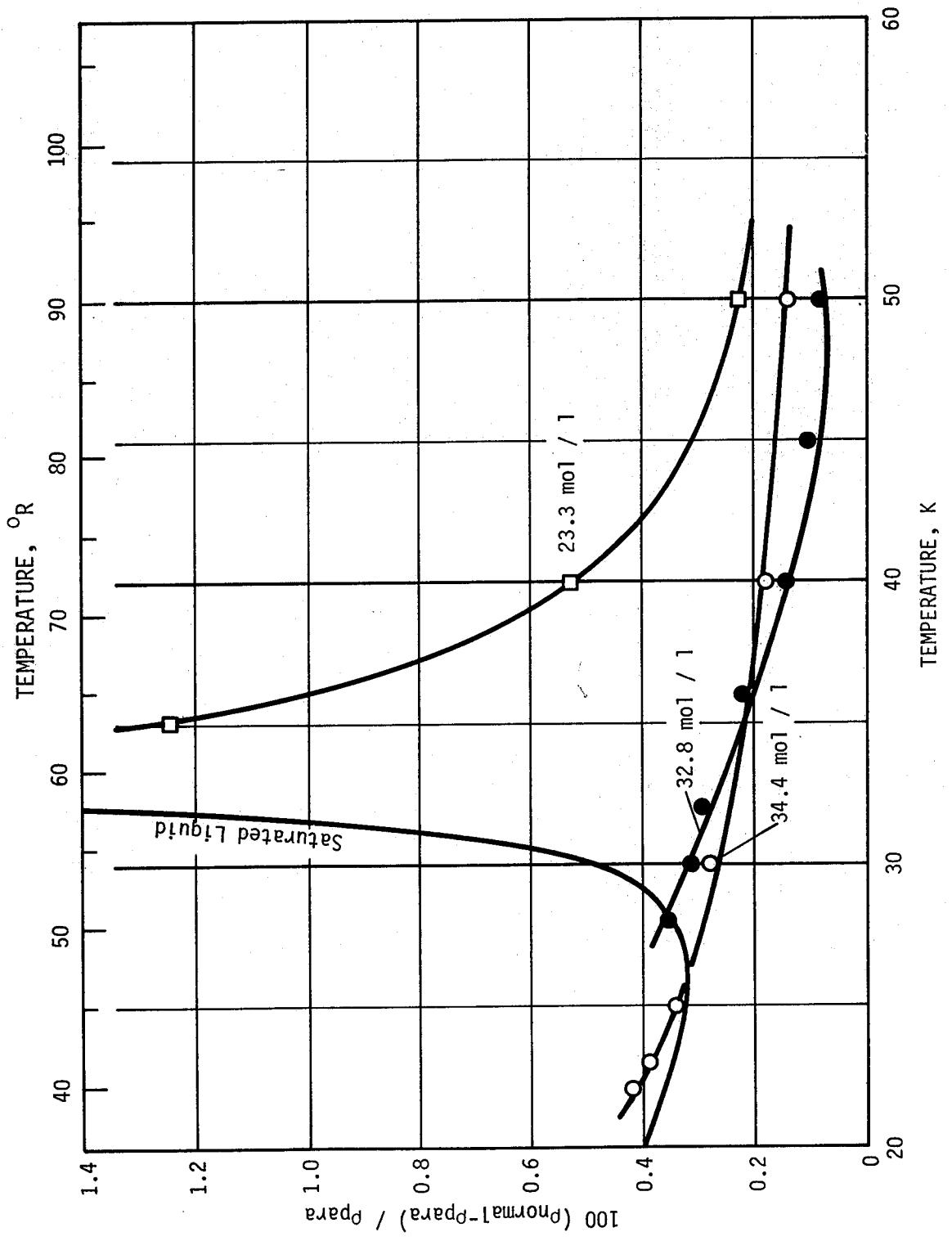


FIGURE 57. Density differences between normal and parahydrogen.

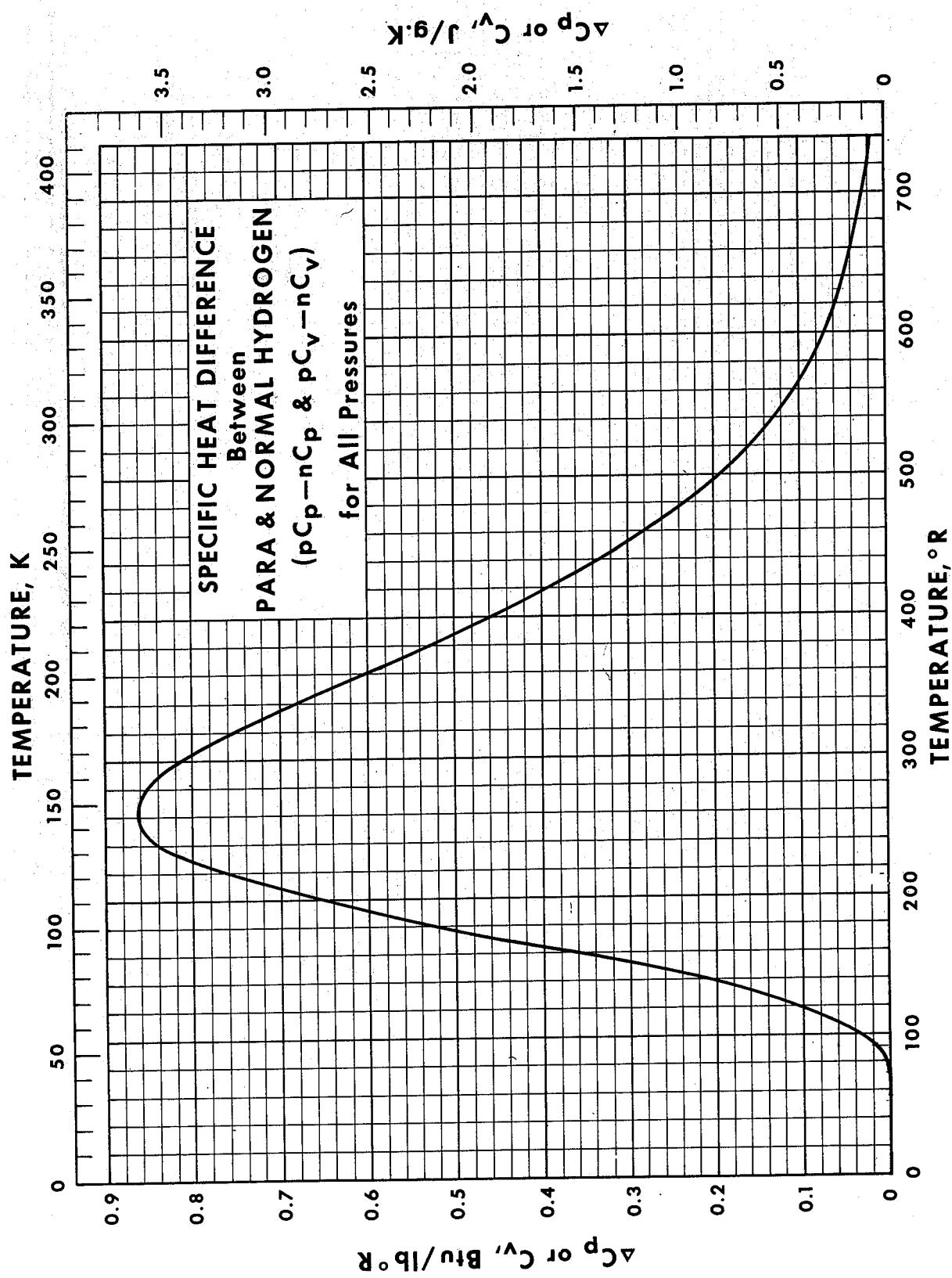


FIGURE 58. Differences in specific heat (heat capacity) between para and normal hydrogen.

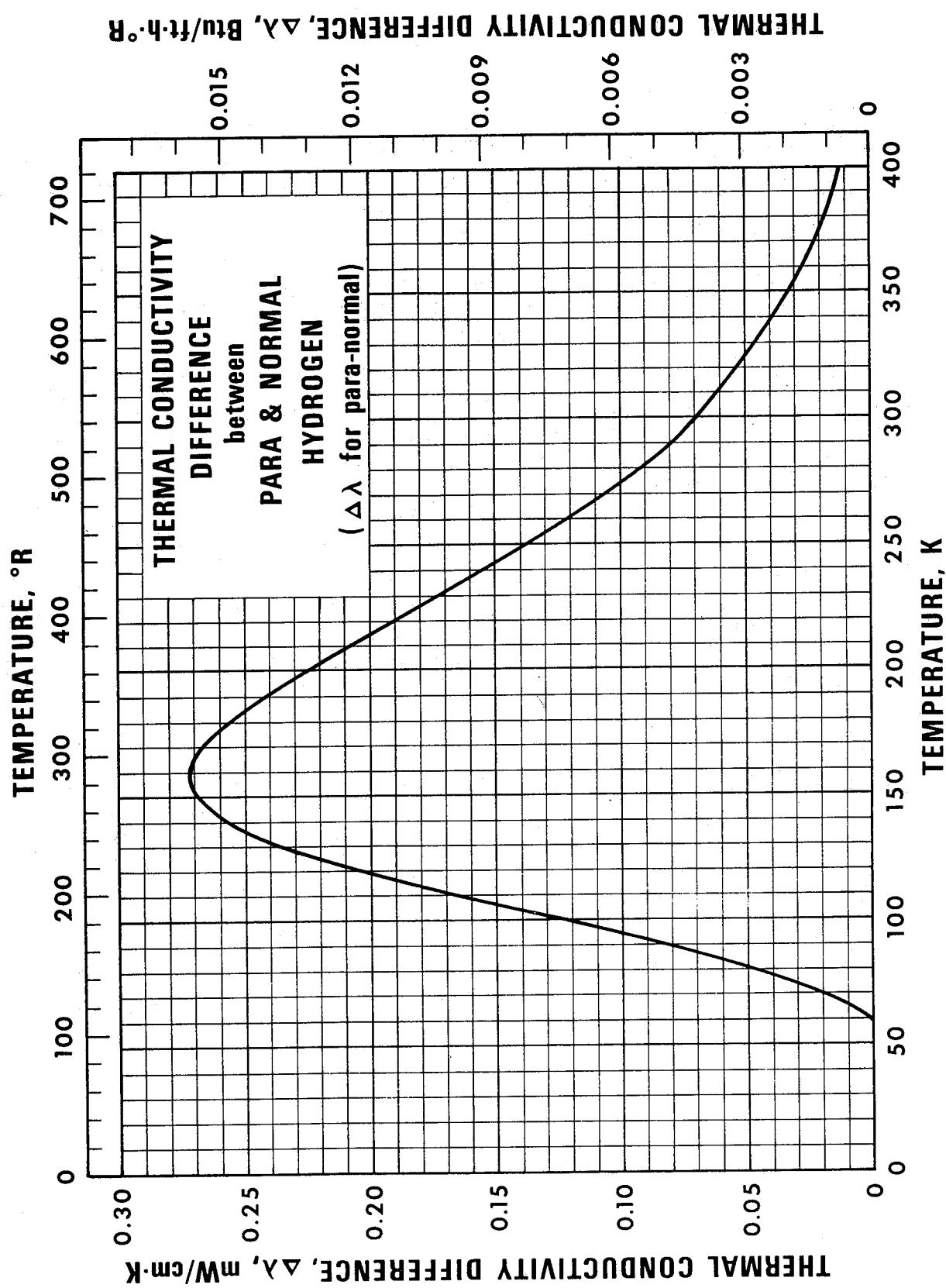


FIGURE 59. Differences in thermal conductivity between para and normal hydrogen (invariant with pressure).

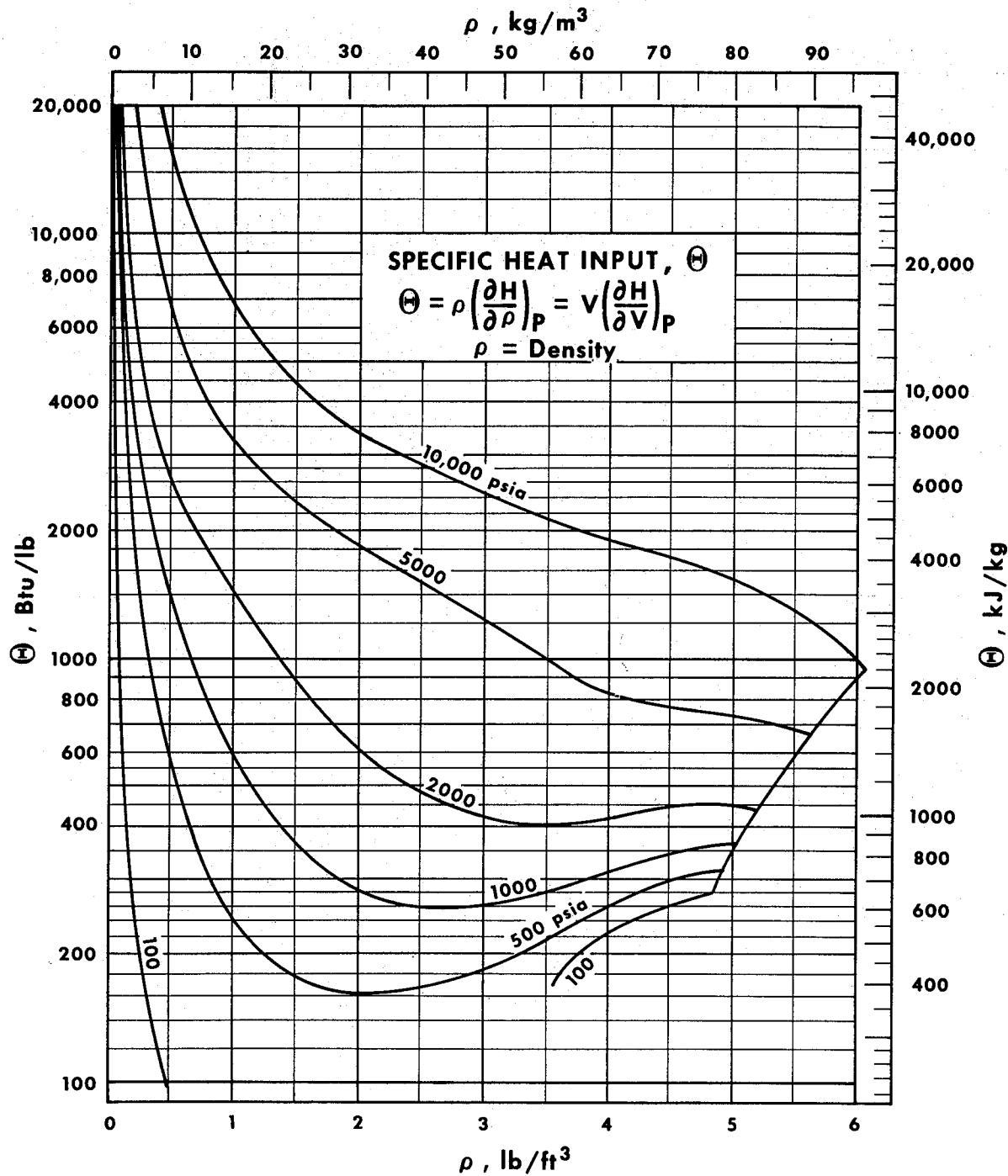


FIGURE 60. Specific heat input function for hydrogen.

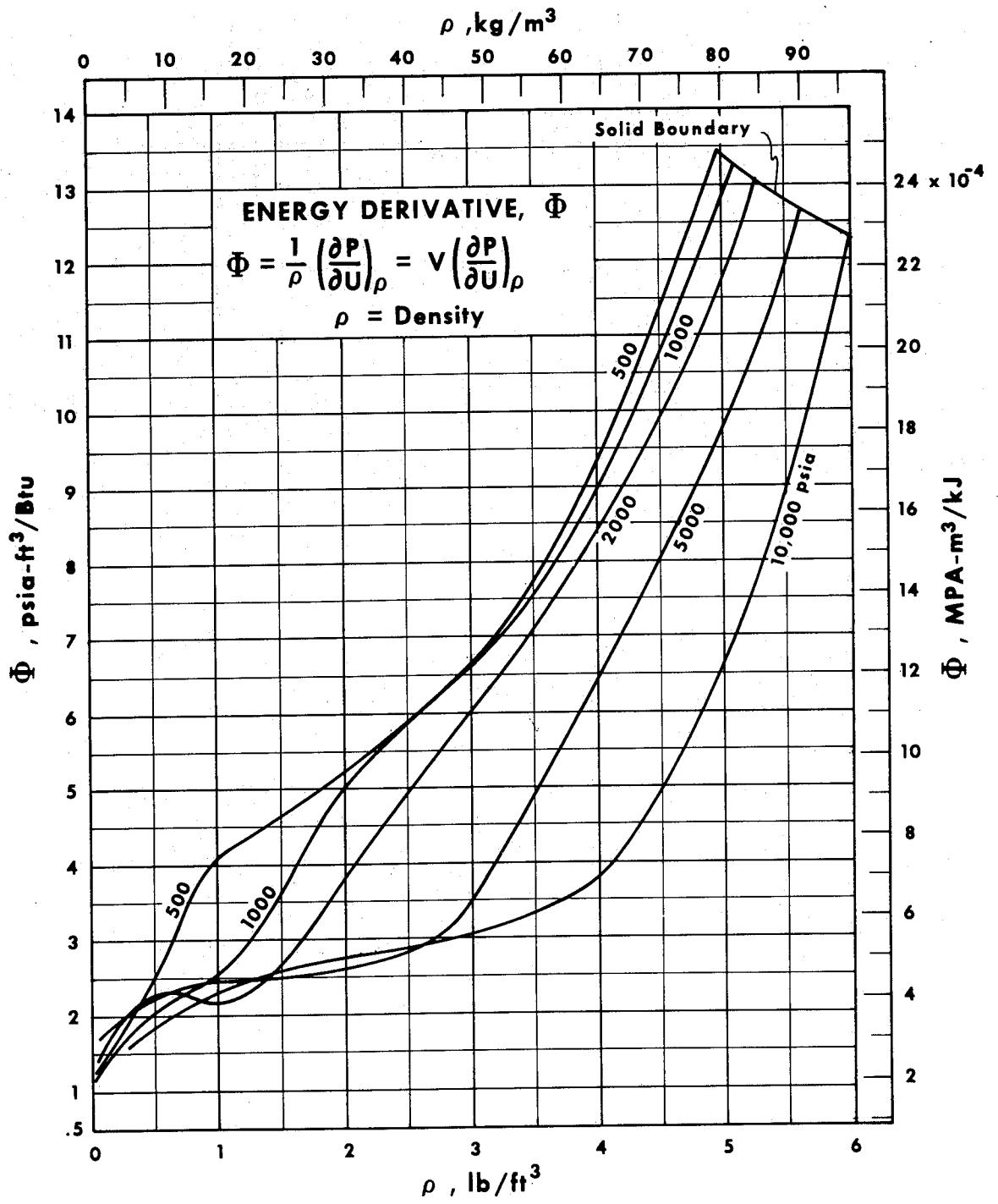


FIGURE 61. Energy derivative function for hydrogen.

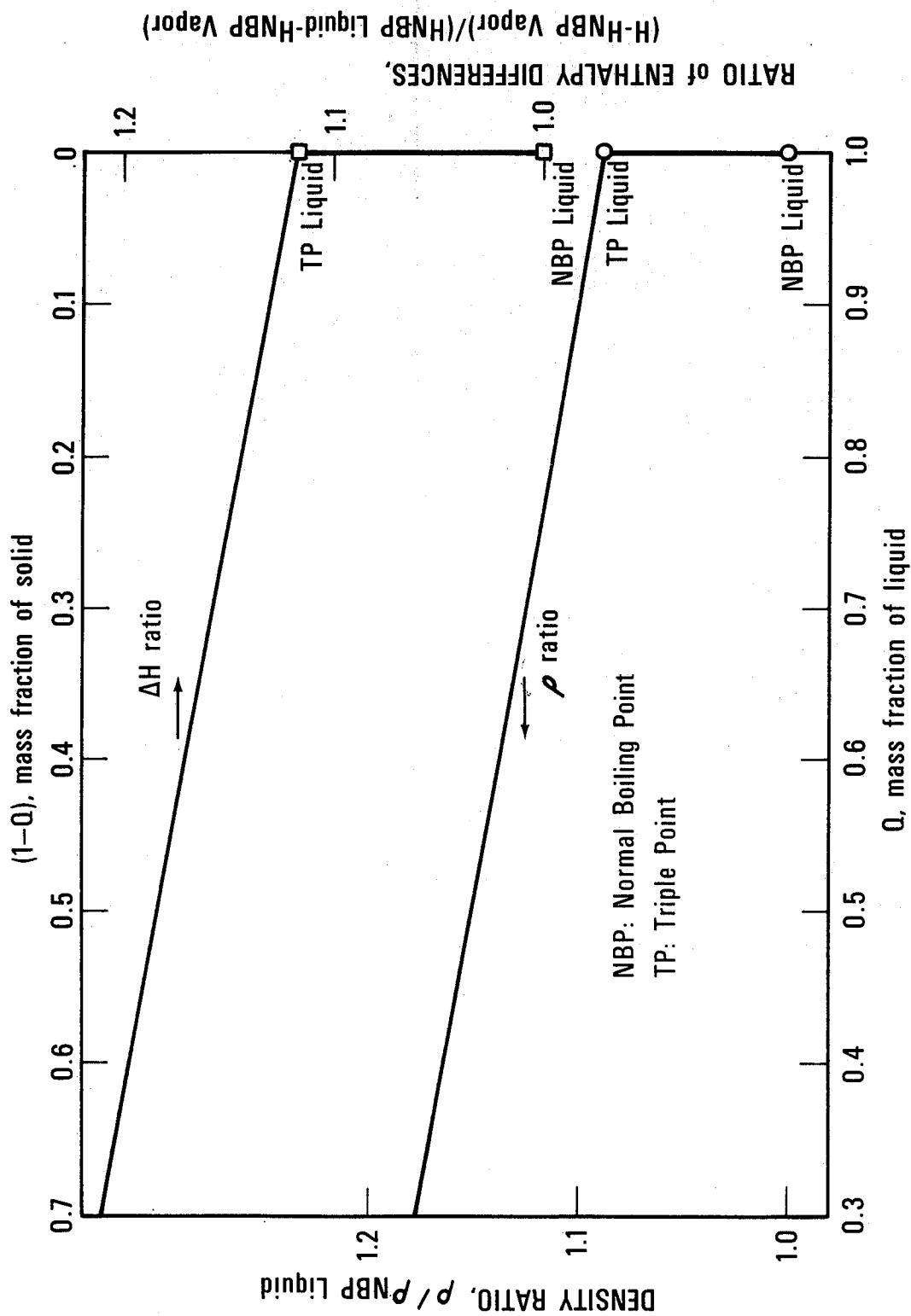


FIGURE 62. Comparison of densities and bulk fluid heat capacities for slush, triple-point liquid, and normal boiling liquid parahydrogen.

CHAPTER SIX

DATA TABLES

Table 1
MAJOR COMPUTER PROGRAMS FOR HYDROGEN FLUID PROPERTIES

Program name	Type	P-T range	List of properties	Accuracy	Continuous	Modifications	Input
Tab Code ²	Linear interpolation	0-35 MPa 14-3300 K	$P, T, \rho, H, S, \lambda, \eta, \omega$ C_p, C_v	1% average	NBS Cryogenic Data Center	No	Para and equilibrium
H_2 Props ^{1,04,1,05}	33-term MBWR	0-83 MPa 14-1100 K	P, T, ρ, H, S C_p, C_v, ω	0.1% average	NBS Cryogenic Data Center	Yes	Para, ortho, equilibrium, and normal
H_2 Gen ^{b, 4, 7, 8}	Polynomial interpolation	0-103 MPa 14-3300 K	$P, T, \rho, H, S, \lambda, \eta, \omega$ $C_p, C_v, E, \gamma, R, I, \epsilon$	Better than 0.1% average	NBS Cryogenic Data Center	No	Para
GASP ⁵	20-term MBWR	0-83 MPa 14-1100 K	$P, T, \rho, H, S, \frac{\partial Y}{\partial P}$ $C_p, C_v, \omega, \frac{\partial P}{\partial T}$	0.1% average	NASA ^d	Yes	Para
							$(P, T) (\rho, T)$ $(T, \rho) (H, P)$ (S, P)

aNumbers refer to Column explanations in text.

bThis program was used to produce the tables in Chapter 6 and to generate tabular data in Reference 6. Also, Reference 4 is an updated modification of Reference 3.

cCryogenic Data Center, Thermophysical Properties Division, National Bureau of Standards, Boulder, Colorado 80303.

dLewis Research Center, National Aeronautics and Space Administration, 21000 Brookpark Road, Cleveland, Ohio 44135.

TABLE 2
Thermodynamic Properties of Parahydrogen
(Isobars, SI Units)

0.01 to 100 MPa Isobars
13.8 to 3000 K

TABLE 2
THERMODYNAMIC PROPERTIES OF PARAHYDROGEN (ISOBARS, SI UNITS)

.01 MPa ISOBAR

TEMPERATURE	VOLUME	ISOTHERM DERIVATIVE	ISOCHORE DERIVATIVE	INTERNAL ENERGY	ENTHALPY	ENTROPY	CV	CP	VELOCITY OF SOUND
K	CU M/KG	CU M-MPA/KG	MPA/K	KJ/KG-K	KJ/KG	KJ/KG-K	KJ / KG-K	KG-K	M/S
* 13.804	.01298	1.1628	.9233	-308.9	-308.8	4.966	4.67	6.38	1260.
14.	.01301	1.1302	.9233	-307.6	-307.5	5.059	4.72	6.50	1248.
* 14.430	.01307	1.1173	.9196	-304.8	-304.7	5.259	4.80	6.57	1245.
* 14.430	5.63386	.0571	.0007	87.7	146.0	36.498	6.22	10.59	312.
15.	6.07554	.0596	.0007	91.3	152.1	36.907	6.22	10.56	318.
16.	6.49795	.0640	.0006	97.6	162.6	37.587	6.21	10.52	329.
17.	6.91887	.0683	.0006	103.9	173.1	38.224	6.20	10.49	340.
18.	7.33861	.0725	.0006	110.2	183.6	38.822	6.20	10.46	350.
19.	7.75743	.0768	.0005	116.4	194.0	39.388	6.20	10.44	360.
20.	8.17550	.0810	.0005	122.7	204.5	39.923	6.20	10.43	369.
21.	8.59295	.0852	.0005	128.9	214.9	40.431	6.20	10.42	379.
22.	9.00988	.0895	.0005	135.2	225.3	40.916	6.20	10.41	388.
23.	9.42636	.0937	.0004	141.4	235.7	41.378	6.20	10.40	396.
24.	9.84245	.0979	.0004	147.7	246.1	41.820	6.19	10.39	405.
25.	10.25822	.1021	.0004	153.9	256.5	42.244	6.19	10.38	414.
26.	10.67369	.1062	.0004	160.1	266.8	42.651	6.19	10.38	422.
27.	11.08891	.1104	.0004	166.3	277.2	43.043	6.19	10.37	430.
28.	11.50391	.1146	.0004	172.6	287.6	43.420	6.19	10.37	438.
29.	11.91870	.1188	.0003	178.8	298.0	43.784	6.19	10.36	446.
30.	12.33332	.1229	.0003	185.0	308.3	44.135	6.19	10.36	453.
31.	12.74778	.1271	.0003	191.2	318.7	44.475	6.19	10.36	461.
32.	13.16210	.1313	.0003	197.4	329.0	44.803	6.19	10.35	468.
33.	13.57629	.1354	.0003	203.6	339.4	45.122	6.19	10.35	476.
34.	13.99036	.1396	.0003	209.8	349.7	45.431	6.19	10.35	483.
36.	14.81819	.1479	.0003	222.2	370.4	46.022	6.19	10.34	497.
38.	15.64568	.1562	.0003	234.7	391.1	46.581	6.20	10.34	511.
40.	16.47288	.1645	.0003	247.1	411.8	47.112	6.20	10.35	524.
42.	17.29983	.1728	.0002	259.5	432.5	47.617	6.21	10.35	537.
44.	18.12657	.1811	.0002	271.9	453.2	48.099	6.21	10.36	549.
46.	18.95313	.1893	.0002	284.4	473.9	48.559	6.23	10.37	561.
48.	19.77953	.1976	.0002	296.9	494.7	49.001	6.25	10.38	573.
50.	20.60580	.2059	.0002	309.4	515.5	49.425	6.27	10.41	585.
52.	21.43196	.2142	.0002	322.0	536.3	49.834	6.30	10.43	596.
56.	23.08396	.2307	.0002	347.4	578.2	50.610	6.38	10.51	617.
60.	24.73564	.2472	.0002	373.1	620.5	51.339	6.49	10.62	636.
65.	26.79987	.2679	.0002	406.0	674.0	52.196	6.58	10.82	658.
70.	28.86380	.2886	.0001	440.1	728.7	53.007	6.93	11.07	679.
75.	30.92747	.3092	.0001	475.5	784.8	53.780	7.24	11.37	697.
80.	32.99095	.3299	.0001	512.6	842.5	54.525	7.59	11.72	714.
90.	37.11746	.3711	.0001	592.5	963.7	55.952	8.41	12.53	744.
100.	41.24353	.4124	.0001	680.9	1093.4	57.317	9.27	13.40	772.
110.	45.36928	.4537	.0001	777.8	1231.5	58.630	10.10	14.23	799.
120.	49.49480	.4950	.0001	882.6	1377.5	59.901	10.83	14.35	827.
130.	53.62013	.5362	.0001	993.8	1530.0	61.121	11.40	15.53	855.
140.	57.74534	.5775	.0001	1110.1	1687.5	62.288	11.82	15.94	883.
160.	65.99544	.6600	.0001	1351.2	2011.2	64.449	12.21	16.34	940.
180.	74.24525	.7425	.0001	1595.7	2338.2	66.375	12.19	16.31	997.
200.	82.49487	.8250	.0001	1837.2	2662.2	68.081	11.94	16.07	1053.
220.	90.74635	.9075	.0000	2073.0	2980.5	69.598	11.63	15.76	1109.
240.	98.99373	.9900	.0000	2302.5	3292.5	70.955	11.33	15.45	1162.
260.	107.24303	1.0725	.0000	2526.5	3598.9	72.182	11.07	15.20	1213.
280.	115.49227	1.1550	.0000	2745.8	3900.7	73.301	10.87	15.00	1262.
300.	123.73215	1.2374	.0000	2961.7	4199.0	74.330	10.72	14.84	1309.
350.	144.35340	1.4436	.0000	3491.6	4935.1	76.598	10.51	14.63	1418.
400.	164.97452	1.6498	.0000	4014.6	5664.3	78.547	10.42	14.55	1517.
450.	185.59556	1.8560	.0000	4534.8	6390.8	80.260	10.40	14.53	1610.
500.	206.21654	2.0622	.0000	5055.1	7117.3	81.789	10.40	14.52	1697.
550.	226.83749	2.2685	.0000	5575.1	7843.5	83.174	10.41	14.53	1780.
600.	247.45841	2.4747	.0000	6096.1	8570.6	84.437	10.42	14.55	1858.
700.	288.70020	2.8871	.0000	7141.0	10028.0	86.685	10.48	14.61	2006.
800.	329.94195	3.2995	.0000	8193.4	11492.9	88.640	10.57	14.70	2142.
900.	371.18367	3.7119	.0000	9256.8	12968.6	90.376	10.70	14.82	2268.
1000.	412.42538	4.1243	.0000	10334.0	14458.2	91.949	10.86	14.98	2386.
1200.	494.90891	4.9492	.0000	12544.2	17493.3	94.702	11.24	15.37	2601.
1400.	577.39658	5.7740	.0000	14838.3	20612.3	97.110	11.70	15.83	2795.
1600.	659.93251	6.5988	.0000	17233.3	23832.7	99.237	12.28	16.42	2970.
1800.	742.78144	7.4237	.0000	19799.6	27227.4	101.197	13.45	17.66	3121.
2000.	826.97486	8.2485	.0000	22778.4	31048.1	103.273	16.49	20.91	3235.
2200.	915.44934	9.0733	.0000	26764.6	35919.1	106.261	23.62	28.72	3322.
2400.	1014.83413	9.8982	.0000	32969.2	43117.5	110.429	38.05	44.31	3417.
2600.	1137.61448	10.7230	.0000	43400.4	54776.5	116.383	63.16	74.13	3545.
2800.	1303.75995	11.5478	.0000	60877.2	73914.8	124.850	100.49	120.06	3710.
3000.	1538.60332	12.3727	.0000	88375.8	103761.9	136.424	145.32	179.51	3904.

* TWO-PHASE BOUNDARY

TABLE 2
THERMODYNAMIC PROPERTIES OF PARAHYDROGEN. (ISOBARS, SI UNITS)

.01 MPa ISOBAR

TEMPERATURE	DENSITY	$V(DH/DV)_P$	$V(DP/DV)_V$	$-V(DP/DV)_T$	$(DV/DT)_V$	Thermal Conductivity	VISCOSITY	Thermal Diffusivity	Dielectric Constant	Prandtl Number
K	KG/CU M	KJ/KG	MPA-CU M/KJ	MPA	1/K	W/K-M X 10 ³	KG/M-S X 10 ³	SQ M/HR X 10 ⁷		
* 13.804	77.0167	648.8	.25650	89.5531	.01031	72.63	254.83	.00053	1.25158	2.2385
14.	76.8435	611.8	.25478	86.8501	.01063	74.61	247.76	.00054	1.25097	2.1598
* 14.430	76.4900	620.0	.25021	85.4586	.01076	78.59	234.09	.00055	1.24972	1.9873
* 14.430	.1714	145.5	.06684	.0098	.07279	12.77	7.74	.02532	1.00052	.6420
15.	.1646	151.5	.06684	.0098	.06968	13.01	8.07	.02656	1.00050	.6546
16.	.1539	162.1	.06684	.0098	.06488	13.45	8.64	.02992	1.00046	.6756
17.	.1445	172.6	.06683	.0099	.06074	13.89	9.21	.03300	1.00044	.6949
18.	.1363	183.1	.06681	.0099	.05713	14.40	9.77	.03635	1.00041	.7099
19.	.1289	193.6	.06680	.0099	.05394	14.99	10.32	.03985	1.00039	.7235
20.	.1223	204.1	.06679	.0099	.05109	15.53	10.87	.04382	1.00037	.7303
21.	.1164	214.6	.06678	.0099	.04855	16.32	11.41	.04846	1.00035	.7286
22.	.1110	225.0	.06677	.0099	.04625	17.11	11.95	.05334	1.00033	.7267
23.	.1061	235.4	.06676	.0099	.04416	17.91	12.48	.05844	1.00032	.7247
24.	.1016	245.9	.06675	.0099	.04226	18.70	13.01	.06378	1.00031	.7225
25.	.0975	256.3	.06675	.0099	.04051	19.49	13.52	.06934	1.00029	.7202
26.	.0937	266.7	.06674	.0100	.03891	20.28	14.04	.07510	1.00028	.7181
27.	.0902	277.1	.06674	.0100	.03743	21.07	14.54	.08109	1.00027	.7159
28.	.0869	287.4	.06673	.0100	.03506	21.85	15.04	.08730	1.00026	.7136
29.	.0839	297.8	.06673	.0100	.03479	22.64	15.54	.09374	1.00025	.7112
30.	.0811	308.2	.06672	.0100	.03361	23.42	16.03	.10040	1.00024	.7088
31.	.0784	318.6	.06672	.0100	.03251	24.12	16.51	.10690	1.00024	.7089
32.	.0760	328.9	.06671	.0100	.03147	24.82	16.99	.11359	1.00023	.7088
33.	.0737	339.3	.06671	.0100	.03050	25.51	17.47	.12049	1.00022	.7085
34.	.0715	349.7	.06670	.0100	.02959	26.22	17.93	.12761	1.00022	.7078
36.	.0675	370.4	.06668	.0100	.02793	27.63	18.86	.14247	1.00020	.7061
38.	.0639	391.2	.06665	.0100	.02644	29.04	19.76	.15812	1.00019	.7041
40.	.0607	412.1	.06660	.0100	.02510	30.45	20.65	.17454	1.00018	.7017
42.	.0578	433.1	.06653	.0100	.02390	31.85	21.53	.19166	1.00017	.6394
44.	.0552	454.2	.06643	.0100	.02280	33.25	22.38	.20950	1.00017	.6971
46.	.0528	475.5	.06628	.0100	.02180	34.65	23.22	.22802	1.00016	.6949
48.	.0506	497.1	.06609	.0100	.02089	36.05	24.05	.24720	1.00015	.6927
50.	.0485	519.1	.06585	.0100	.02005	37.45	24.86	.26696	1.00015	.6938
52.	.0467	541.4	.06554	.0100	.01927	38.85	25.66	.28725	1.00014	.6893
56.	.0433	587.7	.06471	.0100	.01789	41.65	27.22	.32922	1.00013	.6872
60.	.0404	636.5	.06387	.0100	.01669	44.51	28.74	.37306	1.00012	.6851
65.	.0373	702.2	.06174	.0100	.01540	48.38	30.58	.43162	1.00011	.6836
70.	.0346	773.8	.05950	.0100	.01430	52.26	32.36	.49076	1.00010	.6852
75.	.0323	852.1	.05699	.0100	.01334	56.13	34.09	.54968	1.00010	.6905
80.	.0303	937.2	.05433	.0100	.01251	60.04	35.77	.60829	1.00009	.6985
90.	.0269	1127.4	.04909	.0100	.01112	69.96	39.01	.74586	1.00008	.6988
100.	.0242	1339.5	.04450	.0100	.01000	79.87	42.10	.88510	1.00007	.7062
110.	.0220	1564.7	.04084	.0100	.00909	92.12	44.74	.105750	1.00007	.6910
120.	.0202	1793.9	.03811	.0100	.00833	102.77	47.58	.122467	1.00006	.6922
130.	.0186	2018.2	.03618	.0100	.00769	112.82	50.33	.140262	1.00006	.6926
140.	.0173	2231.9	.03491	.0100	.00714	121.77	53.00	.158779	1.00005	.6939
160.	.0152	2613.6	.03378	.0100	.00625	136.35	58.14	.198308	1.00005	.6965
180.	.0135	2935.8	.03385	.0100	.00556	147.52	63.06	.241750	1.00004	.6972
200.	.0121	3213.9	.03453	.0100	.00500	156.62	67.80	.289449	1.00004	.6956
220.	.0110	3466.4	.03546	.0100	.00455	164.59	72.38	.341274	1.00003	.6928
240.	.0101	3708.8	.03641	.0100	.00417	172.05	76.82	.395798	1.00003	.6900
260.	.0093	3951.5	.03725	.0100	.00385	179.32	81.15	.455552	1.00003	.6877
280.	.0087	4199.1	.03794	.0100	.00357	186.57	85.36	.517287	1.00003	.6861
300.	.0081	4453.3	.03848	.0100	.00333	193.88	89.48	.581800	1.00002	.6851
350.	.0069	5121.4	.03925	.0100	.00286	212.50	99.40	.754703	1.00002	.6844
400.	.0061	5819.8	.03956	.0100	.00250	231.39	108.86	.944559	1.00002	.6845
450.	.0054	6538.4	.03964	.0100	.00222	250.24	117.95	.1150740	1.00002	.6848
500.	.0048	7262.3	.03966	.0100	.00200	268.83	126.70	.1374060	1.00001	.6845
550.	.0044	7993.3	.03962	.0100	.00182	287.08	135.18	.1613138	1.00001	.6843
600.	.0040	8729.7	.03956	.0100	.00167	305.01	143.40	.1867624	1.00001	.6840
700.	.0035	10223.8	.03935	.0100	.00143	340.16	159.23	.2420609	1.00001	.6837
800.	.0030	11757.5	.03901	.0100	.00125	374.85	174.35	.3029554	1.00001	.6836
900.	.0027	13341.4	.03855	.0100	.00111	409.59	188.89	.3692235	1.00001	.6836
1000.	.0024	14983.1	.03798	.0100	.00100	444.68	202.95	.4406646	1.00001	.6838
1200.	.0020	18442.2	.03668	.0100	.00083	511.19	229.87	.5926340	1.00001	.6911
1400.	.0017	22156.4	.03525	.0100	.00071	584.62	255.49	.7673658	1.00001	.6916
1600.	.0015	26269.7	.03358	.0100	.00063	668.03	280.05	.9645688	1.00000	.6883
1800.	.0013	31767.5	.03065	.0100	.00056	800.59	303.70	.12123303	1.00000	.6699
2000.	.0012	41718.6	.02508	.0100	.00050	1099.16	326.65	.15647369	1.00000	.6215
2200.	.0011	62633.3	.01762	.0099	.00046	1809.21	345.83	.20757597	1.00000	.5491
2400.	.0010	105137.6	.01111	.0098	.00043	3327.26	369.24	.27064373	1.00000	.4984
2600.	.0009	181673.2	.00693	.0094	.00041	6112.35	394.59	.33768331	1.00000	.4786
2800.	.0008	297765.7	.00463	.0089	.00040	10361.10	421.87	.40503496	1.00000	.4389
3000.	.0006	433048.8	.00353	.0080	.00041	15311.58	447.27	.47246613	1.00000	.5244

TABLE 2
THERMODYNAMIC PROPERTIES OF PARAHYDROGEN (ISOBARS, SI UNITS)

100.00 MPA ISOBAR

TEMPERATURE	VOLUME	ISOHERM DERIVATIVE	ISOCHORE DERIVATIVE	INTERNAL ENERGY	ENTHALPY	ENTROPY	CV	CP	VELOCITY OF SOUND
K	CU M/KG	CU M-MPA/KG	MPA/K	KJ/KG-K	KJ/KG	KJ/KG-K	KJ	KG-K	M/S
* 34.169	.00977	5.2095	1.542	-166.3	810.4	6.279	6.60	8.08	2527.
35.	.00979	5.1881	1.535	-161.9	817.2	6.474	6.66	8.18	2525.
36.	.00982	5.1618	1.526	-156.5	825.4	6.706	6.73	8.30	2522.
37.	.00985	5.1350	1.517	-151.0	833.8	6.935	6.81	8.41	2520.
38.	.00988	5.1078	1.508	-145.4	842.2	7.161	6.87	8.52	2517.
39.	.00990	5.0801	1.499	-139.7	850.8	7.384	6.93	8.62	2514.
40.	.00993	5.0520	1.490	-133.9	859.5	7.603	6.98	8.72	2511.
42.	.00999	4.9948	1.472	-122.1	877.1	8.033	7.09	8.90	2505.
44.	.01005	4.9365	1.453	-110.1	895.1	8.452	7.19	9.09	2498.
46.	.01011	4.8773	1.434	-98.2	913.0	8.848	7.32	9.31	2490.
48.	.01017	4.8175	1.415	-85.4	931.8	9.249	7.44	9.51	2481.
50.	.01023	4.7573	1.396	-72.3	951.0	9.641	7.55	9.70	2472.
52.	.01029	4.6971	1.377	-58.9	970.6	10.025	7.66	9.88	2462.
54.	.01036	4.6369	1.359	-45.2	990.5	10.401	7.76	10.06	2453.
56.	.01042	4.5771	1.340	-31.0	1011.1	10.775	7.85	10.23	2443.
58.	.01048	4.5178	1.321	-16.7	1031.7	11.137	7.93	10.40	2433.
60.	.01055	4.4591	1.302	-2.2	1052.7	11.493	8.02	10.56	2423.
65.	.01071	4.3169	1.255	35.2	1106.5	12.355	8.26	10.99	2396.
70.	.01088	4.1826	1.209	74.3	1162.6	13.185	8.54	11.44	2367.
75.	.01106	4.0581	1.162	115.4	1221.0	13.991	8.87	11.92	2336.
80.	.01123	3.9448	1.116	156.5	1281.8	14.776	9.23	12.41	2304.
85.	.01141	3.8431	1.070	203.9	1345.1	15.543	9.62	12.91	2272.
90.	.01160	3.7530	1.024	251.4	1411.0	16.296	10.03	13.41	2240.
95.	.01178	3.6737	.9796	301.2	1479.2	17.034	10.44	13.89	2210.
100.	.01197	3.6035	.9357	353.3	1549.8	17.758	10.86	14.34	2181.
110.	.01234	3.4819	.8522	465.2	1698.9	19.178	11.72	15.21	2126.
120.	.01276	3.3346	.8066	584.0	1860.0	20.580	12.38	16.19	2088.
130.	.01315	3.2230	.7503	709.2	2024.5	21.896	12.91	16.83	2050.
140.	.01355	3.1987	.7030	839.3	2194.3	23.155	13.28	17.25	2039.
160.	.01437	3.1972	.6180	1107.5	2544.5	25.493	13.59	17.53	2031.
180.	.01517	3.1143	.5439	1377.3	2893.9	27.551	13.49	17.42	2005.
200.	.01597	2.9502	.4914	1642.2	3239.6	29.372	13.18	17.36	1971.
220.	.01684	2.9419	.4488	1900.6	3584.7	31.017	12.82	17.09	1981.
240.	.01768	3.0865	.4119	2152.3	3920.5	32.478	12.48	16.60	2026.
260.	.01852	3.1323	.3779	2397.5	4249.2	33.794	12.20	16.26	2044.
280.	.01934	3.1686	.3488	2637.2	4571.2	34.988	11.97	15.99	2057.
300.	.02024	3.2500	.3354	2847.0	4870.5	35.991	11.42	15.67	2112.
350.	.02234	3.3883	.2846	3409.3	5643.3	38.373	11.10	15.28	2159.
400.	.02443	3.5426	.2470	3958.2	6400.9	40.398	10.94	15.05	2208.
450.	.02650	3.7063	.2182	4499.3	7149.3	42.162	10.86	14.92	2257.
500.	.02856	3.8759	.1955	5036.7	7892.9	43.728	10.80	14.82	2306.
550.	.03061	4.0497	.1771	5570.9	8632.3	45.137	10.77	14.77	2356.
600.	.03266	4.2264	.1620	6103.7	9369.9	46.419	10.76	14.73	2406.
700.	.03674	4.5866	.1385	7167.4	10841.7	48.690	10.77	14.72	2504.
800.	.04082	4.9536	.1210	8233.9	12315.4	50.656	10.82	14.76	2599.
900.	.04488	5.3261	.1076	9308.1	13796.5	52.399	10.93	14.86	2692.
1000.	.04895	5.7030	.0968	10393.9	15289.2	53.974	11.06	15.01	2781.
1200.	.05710	6.4678	.0808	12616.8	18326.5	56.730	11.42	15.37	2951.
1400.	.06525	7.2439	.0694	14918.2	21443.4	59.136	11.83	15.80	3110.
1600.	.07342	8.0286	.0609	17302.8	24644.6	61.251	12.23	16.21	3262.
1800.	.08160	8.8200	.0542	19770.4	27930.0	63.148	12.59	16.58	3408.
2000.	.08978	9.6165	.0489	22320.2	31298.6	64.988	12.96	16.96	3548.
2200.	.09798	10.4171	.0445	24943.7	34742.1	67.301	13.35	17.37	3682.
2400.	.10620	11.2210	.0408	27651.8	38272.3	69.883	13.79	17.84	3809.
2600.	.11446	12.0275	.0377	30460.2	41905.8	72.641	14.34	18.42	3931.
2800.	.12276	12.8363	.0351	33394.0	45670.1	75.432	15.03	19.17	4046.
3000.	.13115	13.6469	.0328	36488.4	49603.8	78.089	15.91	20.14	4156.

* TWO-PHASE BOUNDARY

TABLE 2
THERMODYNAMIC PROPERTIES OF PARAHYDROGEN (ISOBARS, SI UNITS)

100.00 MPa ISOBAR

TEMPERATURE K	DENSITY KG/CU M	V(DH/DV) _P KJ/KG	V(DP/DV) _V MPA-CU M/KJ X 10 ²	-V(DP/DV) _T MPA	(DV/DT)/V 1/K	THERMAL CONDUCTIVITY W/K-M X 10 ³	VISCOSITY KG/M-S X 10 ⁷	THERMAL DIFFUSIVITY SQ M/HR	DIELECTRIC CONSTANT	PRANDTL NUMBER
* 34.169	102.3875	2796.3	.22830	533.3893	.00289	276.26	937.81	.00120	1.34287	2.7436
35.	102.1417	2825.5	.22560	529.9203	.00290	276.34	870.98	.00119	1.34197	2.5791
36.	101.8460	2859.4	.22250	525.7090	.00290	276.25	800.91	.00118	1.34088	2.4065
37.	101.5504	2891.7	.21955	521.4625	.00291	275.96	740.27	.00116	1.33980	2.2570
38.	101.2550	2921.8	.21602	517.1855	.00292	275.51	687.46	.00115	1.33871	2.1263
39.	100.9598	2949.0	.21436	512.8820	.00292	274.92	641.22	.00114	1.33763	2.0108
40.	100.6647	2974.8	.21203	508.5564	.00293	274.20	600.50	.00112	1.33655	1.9090
42.	100.0751	3024.3	.20754	499.8546	.00294	272.38	532.43	.00110	1.33439	1.7406
44.	99.4861	3072.7	.20314	491.1104	.00296	270.25	478.19	.00108	1.33223	1.6036
46.	98.8978	3130.6	.19798	482.3525	.00297	267.90	434.26	.00105	1.33008	1.5088
48.	98.3099	3181.3	.19345	473.6076	.00299	265.41	398.20	.00102	1.32793	1.4263
50.	97.7226	3228.6	.18922	464.9006	.00300	262.83	368.22	.00100	1.32578	1.3586
52.	97.1359	3273.1	.18524	456.2550	.00302	260.20	343.02	.00098	1.32364	1.3028
54.	96.5496	3315.5	.18144	447.6927	.00303	257.54	321.63	.00095	1.32151	1.2565
56.	95.9639	3355.2	.17786	439.2340	.00305	254.90	303.31	.00093	1.31937	1.2178
58.	95.3788	3391.6	.17454	430.8979	.00307	252.29	287.50	.00092	1.31725	1.1849
60.	94.7943	3428.5	.17122	422.7017	.00308	250.06	273.74	.00090	1.31512	1.1563
65.	93.3370	3526.6	.16276	402.9244	.00312	245.78	246.24	.00086	1.30984	1.1009
70.	91.8870	3637.2	.15398	384.3249	.00315	241.67	225.80	.00083	1.30459	1.0690
75.	90.4480	3763.4	.14496	367.0497	.00317	237.86	210.14	.00079	1.29940	1.0529
80.	89.0241	3905.9	.13589	351.1813	.00318	234.58	197.82	.00076	1.29428	1.0468
85.	87.6203	4064.2	.12700	336.7366	.00318	235.54	187.92	.00075	1.28924	1.0304
90.	86.2414	4236.7	.11848	323.6679	.00317	236.46	179.81	.00074	1.28430	1.0197
95.	84.8920	4421.2	.11049	311.8664	.00314	237.48	173.06	.00073	1.27948	1.0120
100.	83.5760	4614.4	.10311	301.1690	.00311	238.70	167.36	.00072	1.27479	1.0052
110.	81.0536	5037.1	.08973	292.2177	.00302	226.67	109.58	.00066	1.26583	.7353
120.	78.3682	5246.8	.08312	261.3250	.00309	226.49	110.23	.00064	1.25634	.7881
130.	76.0329	5498.1	.07646	245.0524	.00306	236.40	111.17	.00066	1.24812	.7916
140.	73.7994	5791.3	.07176	236.0605	.00298	250.00	112.16	.00071	1.24029	.7738
150.	69.5909	6312.1	.06535	222.4929	.00278	278.17	113.90	.00082	1.22563	.7178
160.	65.9363	6578.4	.06114	205.3481	.00265	300.77	115.24	.00094	1.21299	.6675
200.	62.6024	6524.4	.05955	184.6887	.00266	315.25	116.31	.00104	1.20154	.6406
220.	59.3817	6650.9	.05898	174.6977	.00257	322.23	117.30	.00114	1.19054	.6221
240.	56.5559	7036.2	.05836	174.5602	.00236	323.62	118.33	.00124	1.18095	.6071
260.	54.0061	7278.9	.05737	169.1637	.00223	321.52	119.47	.00132	1.17234	.6042
280.	51.7071	7513.4	.05633	163.8406	.00213	317.67	120.77	.00138	1.16461	.6080
300.	49.4193	7504.2	.05944	160.6133	.00209	313.32	122.22	.00146	1.15695	.6113
350.	44.7643	8142.5	.05726	151.6740	.00188	304.64	126.54	.00160	1.14148	.6345
400.	40.9388	8836.4	.05515	145.0297	.00170	301.82	131.66	.00176	1.12888	.6564
450.	37.7361	9561.1	.05326	139.8609	.00156	304.57	137.36	.00195	1.11840	.6727
500.	35.0120	10291.3	.05168	135.7041	.00144	311.45	143.44	.00216	1.10953	.6828
550.	32.6639	11028.1	.05033	132.2775	.00134	321.15	149.78	.00240	1.10193	.6887
600.	30.6169	11768.7	.04918	129.3991	.00125	332.75	156.27	.00266	1.09534	.6918
700.	27.2161	13268.3	.04725	124.8291	.00111	359.51	169.47	.00323	1.08444	.6938
800.	24.5007	14806.7	.04564	121.3674	.00100	389.16	182.74	.00387	1.07580	.6933
900.	22.2795	16397.7	.04419	118.6628	.00091	420.67	195.92	.00457	1.05876	.6923
1000.	20.2477	18050.0	.04285	116.4995	.00083	453.59	208.95	.00533	1.05292	.6912
1200.	17.5141	21538.1	.04043	113.2774	.00071	511.13	234.43	.00684	1.05378	.7049
1400.	15.3253	25260.6	.03829	111.0148	.00063	583.30	259.11	.00867	1.04695	.7017
1600.	13.6206	29121.1	.03654	109.3547	.00056	655.28	283.01	.01069	1.04165	.7000
1800.	12.2556	33076.7	.03512	108.0935	.00050	726.59	306.15	.01287	1.03742	.6988
2000.	11.1379	37185.9	.03385	107.1068	.00046	799.20	328.54	.01523	1.03397	.6973
2200.	10.2057	41507.8	.03266	106.3132	.00042	875.57	344.88	.01778	1.03109	.6840
2400.	9.4158	46155.9	.03144	105.6544	.00039	960.03	366.19	.02058	1.02866	.6803
2600.	8.7370	51297.3	.03012	105.0844	.00036	1058.86	387.03	.02369	1.02657	.6732
2800.	8.1459	57149.9	.02865	104.5631	.00034	1180.19	407.47	.02721	1.02476	.6618
3000.	7.6246	63967.6	.02702	104.0528	.00031	1333.50	427.63	.03126	1.02316	.6460

* TWO-PHASE BOUNDARY

Table 3
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID PARAHYDROGEN

Temperature, K	Density, kg/m ³	V(∂H/∂V) _P , kJ/kg	V(∂P/∂V) _T , MPa·m ³ /kJ × 10 ³	-V(∂P/∂V) _T , MPa × 10 ³	(∂V/∂T) _P /V, 1/K	Thermal conductivity, W/K·m × 10 ³	Viscosity, kg/m·s × 10 ⁷	Thermal diffusivity, m ² /h	Dielectric constant	Prandtl number
13.800 ^a	77.0235 0.1254	622.6 139.8	0.25654 0.06684	90.3401 0.0069	0.01022 0.07523	72.59 12.43	255.05 7.36	0.00053 0.03395	1.25160 1.00038	2.2359 0.6230
14	76.8554 0.1388	619.2 141.6	0.25480 0.06684	88.3211 0.0077	0.01046 0.07441	74.62 12.54	248.01 7.48	0.00054 0.03084	1.25101 1.00042	2.1517 0.6291
15	75.9963 0.2228	621.9 150.5	0.24237 0.06683	81.5880 0.0131	0.01111 0.07089	83.02 13.08	217.84 8.08	0.00057 0.01981	1.24799 1.00067	1.8128 0.6591
16	75.1030 0.3385	623.0 159.1	0.23130 0.06680	75.3083 0.0208	0.01181 0.06820	88.86 13.66	194.15 8.68	0.00058 0.01339	1.24486 1.00102	1.6074 0.6891
17	74.1710 0.4922	613.1 167.1	0.22244 0.06674	68.0612 0.0313	0.01286 0.06624	92.71 14.27	175.07 9.28	0.00057 0.00943	1.24159 1.00148	1.4884 0.7197
18	73.1950 0.6902	604.3 174.6	0.21509 0.06659	61.7874 0.0452	0.01394 0.06495	95.43 14.97	159.34 9.88	0.00056 0.00689	1.23818 1.00208	1.4063 0.7484
19	72.1693 0.9395	601.0 181.4	0.20874 0.06665	56.9619 0.0626	0.01486 0.06427	97.00 15.72	146.10 10.49	0.00054 0.00517	1.23460 1.00283	1.3451 0.7783
20	71.0870 1.2474	596.1 187.6	0.20314 0.06666	52.3516 0.0840	0.01585 0.06420	98.40 16.64	134.76 11.11	0.00053 0.00399	1.23083 1.00376	1.2942 0.8042
20.268 ^a	70.7864 1.3378	587.9 189.1	0.20176 0.06667	50.2079 0.0903	0.01644 0.06424	98.92 16.94	131.98 11.28	0.00052 0.00375	1.22978 1.00404	1.2893 0.8091
21	69.9403 1.6189	577.8 193.0	0.19814 0.06672	46.2935 0.1093	0.01754 0.06471	100.05 17.79	124.87 11.74	0.00051 0.00317	1.22684 1.00489	1.2648 0.8241
22	68.7200 2.0711	563.1 197.5	0.19347 0.06686	41.1835 0.1388	0.01921 0.06597	100.95 19.02	116.11 12.38	0.00049 0.00254	1.22261 1.00625	1.2444 0.8481
23	67.4149 2.6119	540.5 201.2	0.18882 0.06708	35.4854 0.1719	0.02162 0.06804	101.20 20.36	108.22 13.04	0.00046 0.00205	1.21810 1.00789	1.2499 0.8769

^a Two-phase boundary.

Table 3 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID PARAHYDROGEN

Temperature, K	Density, kg/m ³	$V(\partial H/\partial V)_P, \text{ kJ/kg}$	$V(\partial P/\partial V)_V, \text{ MPa} \cdot \text{m}^3/\text{kJ} \times 10^2$	$-V(\partial P/\partial T)_T, \text{ MPa}$	$(\partial V/\partial T)_P/V, 1/\text{K}$	Thermal conductivity, W/K·m × 10 ³	Viscosity, kg/m·s × 10 ⁷	Thermal diffusivity, m ² /h	Dielectric constant	Prandtl number
			$V(\partial P/\partial U)_U, \text{ MPa} \cdot \text{m}^3/\text{kJ}$	$(\partial V/\partial T)_P/V, 1/\text{K}$						
24	66.0112 3.2548	523.0 203.9	0.18378 0.06739	30.8574 0.2081	0.02394 0.07108	100.84 21.81	101.01 13.73	0.00044 0.00166	1.21325 1.00984	1.2543 0.9123
25	64.4917 4.0171	504.2 205.8	0.17820 0.06777	26.4945 0.2460	0.02665 0.07540	99.93 23.43	94.32 14.44	0.00042 0.00135	1.20802 1.01216	1.2682 0.9567
26	62.8337 4.9215	475.1 206.9	0.17151 0.06822	21.4244 0.2842	0.03116 0.08144	98.43 25.24	88.03 15.19	0.00038 0.00110	1.20233 1.01491	1.3240 1.0145
27	61.0065 5.9999	451.1 207.3	0.16381 0.06868	17.4346 0.3201	0.03585 0.09002	96.38 27.36	82.02 16.00	0.00035 0.00088	1.19608 1.01820	1.3764 1.0916
28	58.9665 7.2979	418.4 207.1	0.15535 0.06912	13.1188 0.3498	0.04417 0.10259	93.78 29.91	76.19 16.89	0.00031 0.00069	1.18913 1.02216	1.5012 1.1997
29	56.6460 8.8866	382.6 206.2	0.14600 0.06947	9.1967 0.3676	0.05763 0.12220	90.55 33.18	70.42 17.91	0.00026 0.00053	1.18125 1.02703	1.7146 1.3601
30	53.9303 10.8872	350.6 204.7	0.13555 0.06965	6.2743 0.3638	0.07585 0.15631	86.57 37.87	64.57 19.17	0.00022 0.00039	1.17208 1.03319	1.9834 1.6195
31	50.5892 13.5411	310.8 202.6	0.12320 0.06952	3.5282 0.3205	0.11759 0.22979	85.85 46.48	58.40 20.89	0.00017 0.00027	1.16087 1.04140	2.4889 2.0930
32	45.9927 17.4983	265.8 199.1	0.10744 0.06952	1.3886 0.2258	0.24599 0.43710	91.46 66.77	51.31 23.79	0.00011 0.00016	1.14555 1.05373	3.6672 3.1004
32.976 ^a	31.4285	199.0					35.43			1.09795

^a Two-phase boundary.

Table 3 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID PARAHYDROGEN

Temperature, K	Pressure, MPa	Isotherm derivative, $m^3\text{-MPa}/\text{kg}$	Isochore derivative, MPa/K	Internal energy, $\text{kJ}/\text{kg}\cdot\text{K}$	Enthalpy, kJ/kg	Entropy, $\text{kJ}/\text{kg}\cdot\text{K}$	C_V , $\text{kJ}/\text{kg}\cdot\text{K}$	C_p , $\text{kJ}/\text{kg}\cdot\text{K}$	Velocity of sound, m/s	Surface tension, $\text{N/m} \times 10^3$
13.800 ^a	0.0070	1.1729	0.9234	-309.0	-308.9	4.964	4.67	6.36	1264	2.9910
	0.0070	0.0552	0.0005	84.2	140.3	37.520	6.21	10.52	306	
14	0.0079	1.1492	0.9234	-307.6	-307.5	5.057	4.72	6.47	1256	2.9578
	0.0079	0.0558	0.0006	85.3	142.1	37.135	6.21	10.54	308	
15	0.0134	1.0736	0.9064	-300.9	-300.7	5.525	4.92	6.91	1228	2.7921
	0.0134	0.0588	0.0009	90.7	151.1	35.648	6.24	10.67	317	
16	0.0216	1.0027	0.8893	-293.7	-293.4	5.989	5.12	7.36	1200	2.6270
	0.0216	0.0615	0.0014	95.9	159.6	34.303	6.27	10.85	326	
17	0.0329	0.9176	0.8750	-286.0	-285.6	6.453	5.30	7.88	1168	2.4625
	0.0329	0.0637	0.0021	100.7	167.6	33.111	6.32	11.07	334	
18	0.0482	0.8441	0.8612	-277.9	-277.3	6.917	5.47	8.42	1140	2.2987
	0.0482	0.0654	0.0029	105.1	175.0	32.042	6.37	11.34	341	
19	0.0682	0.7893	0.8465	-269.3	-268.4	7.382	5.62	8.93	1120	2.1356
	0.0682	0.0667	0.0040	109.1	181.7	31.073	6.43	11.66	348	
20	0.0935	0.7364	0.8300	-260.2	-258.9	7.851	5.75	9.45	1100	1.9732
	0.0935	0.0674	0.0054	112.7	187.6	30.184	6.49	12.04	354	
20.268 ^a	0.1013	0.7093	0.8253	-257.7	-256.2	7.977	5.78	9.66	1089	1.9299
	0.1013	0.0675	0.0058	113.6	189.3	29.967	6.50	12.15	355	
21	0.1250	0.6619	0.8119	-250.5	-248.8	8.323	5.86	10.13	1070	1.8117
	0.1250	0.0675	0.0071	115.8	193.0	29.369	6.55	12.49	359	
22	0.1634	0.5993	0.7913	-240.3	-237.9	8.802	5.95	10.82	1044	1.6510
	0.1634	0.0670	0.0092	118.3	197.2	28.592	6.61	13.03	363	
23	0.2096	0.5264	0.7673	-229.4	-226.3	9.287	6.03	11.69	1010	1.4913
	0.2096	0.0658	0.0117	120.2	200.5	27.855	6.68	13.69	367	

^a Two-phase boundary.

Table 3 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID PARAHYDROGEN

Temperature, K	Pressure, MPa	Isotherm derivative, m ³ /MPa/kg	Isochore derivative, MPa/K	Internal energy, kJ/kg-K	Enthalpy, kJ/kg	Entropy, kJ/kg-K	C _V , kJ/kg-K	C _P , kJ/kg-K	Velocity of sound, m/s	Surface tension, N/m × 10 ³
24	0.2645	0.4675	0.7389	-217.9	-213.8	9.783	6.09	12.52	980	1.3327
	0.2645	0.0639	0.0148	121.4	202.6	27.148	6.74	14.49	371	
25	0.3288	0.4108	0.7060	-205.5	-200.4	10.291	6.14	13.44	948	1.1751
	0.3288	0.0613	0.0186	121.7	203.6	26.461	6.81	15.52	373	
26	0.4035	0.3410	0.6676	-192.3	-185.9	10.813	6.20	14.80	903	1.0189
	0.4035	0.0578	0.0231	121.1	203.1	25.784	6.89	16.85	376	
27	0.4892	0.2858	0.6251	-178.2	-170.1	11.356	6.26	16.17	860	0.8641
	0.4892	0.0533	0.0288	119.3	200.8	25.104	6.99	18.66	377	
28	0.5871	0.2225	0.5794	-162.8	-152.8	11.926	6.33	18.48	806	0.7110
	0.5871	0.0479	0.0359	116.1	196.5	24.409	7.11	21.24	378	
29	0.6978	0.1624	0.5300	-145.9	-133.6	12.535	6.41	22.05	747	0.5599
	0.6978	0.0414	0.0449	110.9	189.5	23.680	7.28	25.19	378	
30	0.8225	0.1163	0.4759	-126.9	-111.7	13.200	6.51	26.59	689	0.4112
	0.8225	0.0334	0.0569	103.2	178.8	22.887	7.50	31.99	378	
31	0.9627	0.0697	0.4149	-104.9	-85.8	13.960	6.66	36.55	619	0.2659
	0.9627	0.0237	0.0736	91.5	162.6	21.976	7.82	46.56	375	
32	1.1198	0.0302	0.3416	-76.7	-52.4	14.917	6.91	65.37	534	0.1254
	1.1198	0.0129	0.0987	72.1	136.1	20.811	8.11	87.02	372	
32.976 ^a	1.2928		0.1898	-2.8	38.3	17.565			0.0000	

^a Two-phase boundary.

Table 4
SECOND AND THIRD VIRIAL COEFFICIENTS
FOR PARAHYDROGEN

Temperature, K	B (cm ³ / mol)	C (cm ³ / mol) ²
14	-2.372 × 10 ²	-6.713 × 10 ⁴
16	-1.992 × 10 ²	-2.265 × 10 ⁴
18	-1.698 × 10 ²	-7.121 × 10 ³
20	-1.467 × 10 ²	-1.503 × 10 ³
22	-1.281 × 10 ²	5.656 × 10 ²
24	-1.129 × 10 ²	1.323 × 10 ³
26	-1.003 × 10 ²	1.580 × 10 ³
28	-8.969 × 10 ¹	1.640 × 10 ³
30	-8.066 × 10 ¹	1.615 × 10 ³
32	-7.290 × 10 ¹	1.550 × 10 ³
34	-6.615 × 10 ¹	1.467 × 10 ³
36	-6.025 × 10 ¹	1.376 × 10 ³
38	-5.504 × 10 ¹	1.290 × 10 ³
40	-5.042 × 10 ¹	1.214 × 10 ³
45	-4.086 × 10 ¹	1.066 × 10 ³
50	-3.343 × 10 ¹	9.638 × 10 ²
60	-2.264 × 10 ¹	8.351 × 10 ²
70	-1.522 × 10 ¹	7.510 × 10 ²
80	-9.824 × 10 ⁰	6.878 × 10 ²
90	-5.725 × 10 ⁰	6.405 × 10 ²
100	-2.510 × 10 ⁰	6.085 × 10 ²
120	2.144 × 10 ⁰	5.491 × 10 ²
140	5.342 × 10 ⁰	5.063 × 10 ²
160	7.654 × 10 ⁰	4.726 × 10 ²
180	9.388 × 10 ⁰	4.449 × 10 ²
200	1.073 × 10 ¹	4.217 × 10 ²
250	1.300 × 10 ¹	3.768 × 10 ²
300	1.438 × 10 ¹	3.438 × 10 ²
400	1.589 × 10 ¹	2.976 × 10 ²
500	1.660 × 10 ¹	2.661 × 10 ²

Table 5
FIXED POINT PROPERTIES OF PARAHYDROGEN

Properties	Triple point			Normal boiling point			Standard conditions		References and notes ^b
	Solid	Liquid	Vapor	Liquid	Vapor	Critical point ^a	STP(0°C)	NTP(20°C)	
Temperature (K)	13.803	13.803	13.803	20.268	32.976	273.15	293.15	293.15	4
Pressure (mm Hg)	52.82	52.82	52.85	760	9696.8	760	760	760	4
Density (mol/cm ³) $\times 10^3$	42.91 ^{1.33}	38.207	0.0623	35.11	15.59	0.5459	0.04155	0.04155	3,4
Specific volume (cm ³ /mol) $\times 10^{-3}$	0.02330 ^{1.33}	0.026173	16.057	0.028482	1.5069	0.064144	22.425	24.069	3,4
Compressibility factor, Z = $\frac{PV}{RT}$	0.001606	0.9850	0.01712	0.9061	0.3025	1.0005	1.0006	1.0006	f
Heats of fusion and vaporization (J/mol)	117.5 ^{1.29}	905.5	898.3	0	—	—	—	—	g
Specific heat (J/mol·K)	—	—	—	—	—	—	—	—	—
$C_{\bar{Q}}$, at saturation	5.73 ^{1.10}	13.85	-46.94	18.91	-33.28	(Very large)	—	—	110.134
C_p , at constant pressure	—	13.13	21.20	19.53	24.50	(Very large)	30.35	30.02	3,4
C_v , at constant volume	—	9.50	12.52	11.57	13.11	19.7	21.87	21.70	3,4
Specific heat volume ratio, $\gamma = C_p/C_v$	—	1.382	1.693	1.688	1.869	(Large)	1.388	1.383	h
Enthalpy (J/mol)	-740.2 ^{1.29}	-622.7	282.8	-516.6	381.7	77.6	7656.6	8260.6	3,4
Internal energy (J/mol)	-740.4 ^h	-622.9	169.8	-519.5	229.0	5.7	5384.5	5822.0	3,4
Entropy (J/mol·K)	1.49 ^{1.29}	10.00	75.63	16.08	60.41	35.4	127.77	129.90	3,4
Velocity of sound (m/s)	—	1273	305	1093	355	350	1246	1294	4,7
Viscosity, μ	—	—	—	—	—	—	—	—	—
N-s/m ² $\times 10^3$	—	0.026	0.00074	0.0132	0.0011	0.0035	0.00839	0.00881	128.136,137
Centipoise ^c	—	0.026	0.00074	0.0132	0.0011	0.0035	0.00839	0.00881	128.136,137
Thermal conductivity (mW/cm-K), k	9.0 ^{1.35}	0.73	0.124	0.99	0.169	e	1.841	1.914	125,128,136
Prandtl number, N _{Pr} = $\mu C_p/k$	—	2.24	0.623	1.29	0.809	—	0.6866	0.6855	—
Dielectric constant, ϵ_d	1.286	1.252	1.00038	1.230	1.0040	1.098	1.00027	1.00026	131
Index of refraction, $n = \sqrt{\epsilon}$	1.134	1.119	1.00019	1.109	1.0020	1.048	1.00013	1.00012	114 j
Surface tension (N/m) $\times 10^3$	—	2.99	—	1.93	—	0	—	—	123 k
Equiv. vol/vol liquid at NBT	0.8181	0.9190	563.8	1	52.91	2.252	787.4	845.1	—
Note: Gas constant = R = 8.31434 J·mol ⁻¹ ·K ⁻¹ ; Molecular weight ^{1.11} = 2.01594; Mole = gram mole.									

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Values in parentheses are estimates.

Apply to all items on the line except for specific values separately referenced by superscript.

c Units for poise are g/cm-s
d Long wavelengths.
e Anomalously large.

f Compressibility factor calculated from the tabulated data using the gas constant, R, from Reference 4.

g Heats of vaporization calculated from enthalpy differences given in References 3 and 4.

h Calculated from property values given in this table.

i Base point (zero values) for enthalpy, internal energy, and entropy are 0 K for the ideal gas at 0.101325 MPa (1 atm) pressure.

j Index of refraction calculated from the dielectric constant data given in Reference 131, in good agreement with the values reported in Reference 114.

k Ratio of specific volumes reported in References 3 and 4 or 110 and 132.
 λ (mmHg) $\times 1.3332 \times 10^{-4} = \text{MPa}$.

Table 6
REFRACTIVE INDEX OF SATURATED
LIQUID PARAHYDROGEN AT THREE
WAVELENGTHS

Temperature, K	Wavelength		
	435.8 nm	546.2 nm	693.9 nm
15	1.1222	1.1204	1.1191
16	1.1208	1.1189	1.1177
17	1.1192	1.1174	1.1162
18	1.1176	1.1158	1.1146
19	1.1159	1.1141	1.1129
20	1.1141	1.1124	1.1112
21	1.1123	1.1106	1.1095
22	1.1103	1.1086	1.1075
23	1.1082	1.1065	1.1054
24	1.1059	1.1042	1.1032
25	1.1034	1.1018	1.1008
26	1.1007	1.0991	1.0981
27	1.0977	1.0962	1.0952
28	1.0944	1.0929	1.0920
29	1.0906	1.0892	1.0883
30	1.0862	1.0849	1.0840

Table 7
JOULE-THOMSON INVERSION CURVE (PARAHYDROGEN)

Temperature	Pressure			Density			
	K	R	MPa	atm	psia	mol/cm ³ × 10 ³	lb _m /ft ³
28	50.4	1.000	9.87	145.1	30.06	3.783	
29	52.2	1.525	15.05	221.2	29.90	3.763	
30	54.0	2.035	20.08	295.1	29.73	3.742	
31	55.8	2.534	25.01	367.6	29.56	3.720	
32	57.6	3.025	29.85	438.7	29.40	3.700	
34	61.2	3.968	39.16	575.5	29.05	3.656	
36	64.8	4.870	48.06	706.3	28.70	3.612	
40	72.0	6.545	64.59	949.2	27.99	3.523	
50	90.0	10.02	98.93	1454	26.16	3.292	
60	108.0	12.60	124.4	1828	24.30	3.058	
80	144.0	15.55	153.5	2256	20.58	2.590	
100	180.0	16.35	161.4	2372	17.04	2.145	
120	216.0	16.42	162.1	2353	14.12	1.777	
140	252.0	14.24	140.5	2064	10.86	1.367	
160	288.0	10.36	102.2	1502	7.176	0.9031	
180	324.0	5.165	50.97	749.1	3.321	0.4179	
200	360.0	0.0547	0.54	8.6	0.036	0.0045	

TABLE 8

Thermodynamic Properties of Normal Hydrogen
(Isobars, SI Units)

0.01 to 100 MPa Isobars
13.8 to 3000 K

TABLE 8
THERMODYNAMIC PROPERTIES OF NORMAL HYDROGEN (ISOBARS, SI UNITS)

.01 MPa ISOBAR

TEMPERATURE K	VOLUME CU M/KG	ISOTHERM DERIVATIVE CU M-MPA/KG	ISOCHORE DERIVATIVE MPA/K	INTERNAL ENERGY KJ/KG-K	ENTHALPY KJ/KG	ENTROPY KJ/KG-K	CV KJ / KG-K	CP KG-K	VELOCITY OF SOUND M/S
* 13.804	.01298	1.1628	.9233	218.2	218.4	14.081	4.67	6.38	1260.
14.	.01301	1.1302	.9233	219.5	219.7	14.175	4.72	6.50	1248.
* 14.430	.01307	1.1173	.9196	222.4	222.5	14.374	4.80	6.67	1245.
* 14.430	5.83386	.0571	.0007	614.8	673.2	45.613	6.22	10.59	312.
15.	6.07554	.0596	.0007	618.4	679.2	46.023	6.22	10.56	318.
16.	6.49796	.0640	.0006	624.8	689.7	46.703	6.21	10.52	329.
17.	6.91887	.0683	.0006	631.0	700.2	47.339	6.20	10.49	340.
18.	7.33861	.0725	.0006	637.3	710.7	47.938	6.20	10.46	350.
19.	7.75743	.0768	.0005	643.6	721.2	48.503	6.20	10.44	360.
20.	8.17550	.0810	.0005	649.8	731.6	49.038	6.20	10.43	369.
22.	9.00988	.0895	.0005	662.3	752.4	50.033	6.20	10.41	388.
24.	9.84245	.0979	.0004	674.8	773.2	50.938	6.19	10.39	405.
26.	10.67369	.1062	.0004	687.3	794.0	51.767	6.19	10.38	422.
28.	11.50391	.1146	.0004	699.7	814.7	52.535	6.19	10.37	438.
30.	12.33332	.1229	.0003	712.1	835.5	53.250	6.19	10.36	453.
32.	13.16210	.1313	.0003	724.5	856.2	53.919	6.19	10.35	468.
34.	13.99036	.1396	.0003	737.0	876.9	54.546	6.19	10.35	483.
36.	14.81819	.1479	.0003	749.4	897.6	55.138	6.19	10.34	497.
38.	15.64568	.1562	.0003	761.8	918.2	55.697	6.19	10.34	511.
40.	16.47288	.1645	.0003	774.2	938.9	56.227	6.19	10.34	524.
42.	17.29983	.1728	.0002	786.6	959.6	56.732	6.19	10.34	537.
44.	18.12657	.1811	.0002	799.0	980.3	57.212	6.20	10.34	550.
46.	18.95313	.1893	.0002	811.4	1001.0	57.672	6.20	10.34	562.
48.	19.77953	.1976	.0002	823.9	1021.6	58.112	6.20	10.34	574.
50.	20.60580	.2059	.0002	836.3	1042.3	58.534	6.21	10.35	586.
55.	22.67099	.2266	.0002	867.4	1094.1	59.521	6.23	10.37	614.
60.	24.73564	.2472	.0002	898.6	1146.0	60.425	6.27	10.40	641.
65.	26.79987	.2679	.0002	930.1	1198.1	61.258	6.31	10.45	666.
70.	28.86380	.2886	.0001	961.8	1250.5	62.035	6.38	10.51	689.
75.	30.92747	.3092	.0001	994.0	1303.2	62.763	6.46	10.59	712.
80.	32.99095	.3299	.0001	1026.5	1356.4	63.449	6.56	10.59	733.
90.	37.11746	.3711	.0001	1093.3	1464.5	64.722	6.80	10.92	772.
100.	41.24353	.4124	.0001	1162.6	1575.0	65.886	7.07	11.20	808.
110.	45.36928	.4537	.0001	1234.7	1688.4	66.963	7.35	11.49	841.
120.	49.49480	.4950	.0001	1309.8	1804.8	67.976	7.66	11.78	873.
140.	57.74534	.5775	.0001	1466.7	2046.2	69.836	8.22	12.34	931.
160.	65.99544	.6600	.0001	1638.0	2298.0	71.516	8.70	12.82	986.
180.	74.24525	.7425	.0001	1816.0	2558.4	73.049	9.09	13.21	1039.
200.	82.49487	.8250	.0001	2001.0	2826.0	74.459	9.40	13.53	1089.
220.	90.74435	.9075	.0000	2191.7	3099.1	75.760	9.65	13.78	1138.
240.	98.99373	.9900	.0000	2386.7	3376.7	76.968	9.85	13.97	1185.
260.	107.24303	1.0725	.0000	2585.2	3657.6	78.093	9.99	14.12	1231.
280.	115.49227	1.1550	.0000	2786.3	3941.2	79.143	10.10	14.23	1275.
300.	123.73215	1.2374	.0000	2989.2	4226.6	80.127	10.18	14.31	1319.
350.	144.35340	1.4436	.0000	3501.8	4945.3	82.343	10.30	14.42	1422.
400.	164.97452	1.6498	.0000	4018.3	5668.0	84.273	10.35	14.47	1519.
450.	185.59556	1.8560	.0000	4536.5	6392.5	85.980	10.37	14.49	1611.
500.	206.21654	2.0622	.0000	5055.6	7117.8	87.507	10.39	14.51	1697.
550.	226.83749	2.2685	.0000	5575.3	7843.7	88.891	10.40	14.53	1780.
600.	247.45841	2.4747	.0000	6096.1	8570.7	90.153	10.42	14.55	1858.
650.	268.07931	2.6809	.0000	6617.7	9298.5	91.315	10.45	14.57	1934.
700.	288.70020	2.8871	.0000	7141.0	1028.0	92.403	10.48	14.60	2006.
750.	309.32108	3.0933	.0000	7666.2	10759.4	93.414	10.52	14.64	2075.
800.	329.94195	3.2995	.0000	8193.5	11492.9	94.361	10.57	14.69	2142.
850.	350.56281	3.5057	.0000	8723.7	12229.3	95.253	10.63	14.75	2206.
900.	371.18367	3.7119	.0000	9256.9	12968.7	96.097	10.70	14.82	2268.
950.	391.80453	3.9181	.0000	9793.5	13711.6	96.899	10.77	14.90	2328.
1000.	412.42538	4.1243	.0000	10334.0	14458.2	97.664	10.86	14.98	2386.
1100.	453.66709	4.5368	.0000	11429.4	15966.0	99.091	11.04	15.16	2496.
1200.	494.98891	4.9492	.0000	12544.2	17493.3	100.412	11.24	15.36	2601.
1300.	536.15138	5.3616	.0000	13680.1	19041.6	101.651	11.46	15.58	2700.
1400.	577.39658	5.7740	.0000	14838.4	20612.3	102.822	11.70	15.82	2795.
1500.	618.65110	6.1864	.0000	16021.4	22207.9	103.937	11.97	16.10	2884.
1600.	659.93251	6.5988	.0000	17233.3	23832.7	104.978	12.30	16.44	2969.
1700.	701.28140	7.0113	.0000	18485.8	25498.6	105.984	12.78	16.94	3048.
1800.	742.78144	7.4237	.0000	19799.6	27227.4	106.971	13.52	17.71	3119.
2000.	826.97486	8.2485	.0000	22778.4	31048.1	108.991	16.56	20.99	3232.
2200.	915.44934	9.0733	.0000	26764.6	35919.1	111.299	23.70	28.81	3319.
2400.	1014.83413	9.8982	.0000	32969.2	43117.5	114.416	38.13	44.99	3415.
2600.	1137.61448	10.7230	.0000	43408.4	54776.5	119.066	63.23	74.19	3543.
2800.	1303.75995	11.5478	.0000	60877.2	73914.8	126.142	100.52	120.10	3709.
3000.	1538.60332	12.3727	.0000	86375.8	103761.9	136.424	145.32	179.51	3904.

* TWO-PHASE BOUNDARY

TABLE 8

THERMODYNAMIC PROPERTIES OF NORMAL HYDROGEN (ISOBARS, SI UNITS)

.01 MPa ISOBAR

TEMPERATURE K	DENSITY KG/CU M	V(DH/DV) _P KJ/KG	V(DP/DV) _V MPA-CU M/KJ X 10 ²	-V(DP/DV) _T NPA	(DV/DT) _P /V 1/K	THERMAL CONDUCTIVITY W/K-M ⁻¹ X 10 ³	VISCOSITY KG/M-S X 10 ⁴	THERMAL DIFFUSIVITY SQ M/HR	DIELECTRIC CONSTANT	PRANDTL NUMBER
* 13.804	77.0167	618.8	.25650	89.5531	.01031	72.54	254.83	.00053	1.25158	2.2412
14.	76.8435	611.8	.25478	86.8501	.01063	74.54	247.76	.00054	1.25097	2.1617
* 14.430	76.4900	620.0	.25021	85.4586	.01076	78.55	234.09	.00055	1.24972	1.9881
* 14.430	.1714	145.5	.06684	.0098	.07279	12.74	7.74	.02526	1.00052	.6435
15.	.1646	151.5	.06684	.0098	.06968	13.01	8.07	.02696	1.00050	.6547
16.	.1539	162.1	.06684	.0098	.06488	13.47	8.64	.02997	1.00046	.6745
17.	.1445	172.6	.06683	.0099	.06074	13.91	9.21	.03306	1.00044	.6938
18.	.1363	183.1	.06681	.0099	.05713	14.41	9.77	.03639	1.00041	.7092
19.	.1289	193.6	.06680	.0099	.05394	14.91	10.32	.03987	1.00039	.7231
20.	.1223	204.1	.06679	.0099	.05109	15.53	10.87	.04382	1.00037	.7302
22.	.1110	225.0	.06677	.0099	.04625	17.11	11.95	.05332	1.00033	.7270
24.	.1016	245.9	.06675	.0099	.04226	18.69	13.01	.06376	1.00031	.7227
26.	.0937	266.7	.06674	.0100	.03891	20.28	14.04	.07509	1.00028	.7182
28.	.0869	287.4	.06673	.0100	.03606	21.85	15.04	.08730	1.00026	.7136
30.	.0811	308.2	.06672	.0100	.03361	23.43	16.03	.10041	1.00024	.7087
32.	.0760	328.9	.06672	.0100	.03147	24.82	16.99	.11363	1.00023	.7085
34.	.0715	349.6	.06672	.0100	.02959	26.23	17.93	.12767	1.00022	.7075
36.	.0675	370.4	.06670	.0100	.02793	27.64	18.86	.14254	1.00020	.7058
38.	.0639	391.1	.06669	.0100	.02644	29.04	19.76	.15820	1.00019	.7037
40.	.0607	411.9	.06667	.0100	.02510	30.45	20.65	.17464	1.00018	.7013
42.	.0578	432.6	.06665	.0100	.02390	31.83	21.53	.19178	1.00017	.6990
44.	.0552	453.4	.06662	.0100	.02280	33.21	22.38	.20963	1.00017	.6967
46.	.0528	474.2	.06659	.0100	.02180	34.57	23.22	.22817	1.00016	.6944
48.	.0506	495.1	.06655	.0100	.02089	35.92	24.05	.24734	1.00015	.6923
50.	.0485	516.1	.06649	.0100	.02005	37.25	24.86	.25709	1.00015	.6905
55.	.0441	569.0	.06624	.0100	.01822	40.47	26.84	.31862	1.00013	.6875
60.	.0404	623.0	.06587	.0100	.01669	43.55	28.74	.37298	1.00012	.6862
65.	.0373	678.2	.06535	.0100	.01540	46.73	30.58	.43156	1.00011	.6837
70.	.0346	735.0	.06467	.0100	.01430	49.65	32.36	.49083	1.00010	.6851
75.	.0323	793.7	.06385	.0100	.01334	52.63	34.09	.55322	1.00010	.6861
80.	.0303	854.4	.06291	.0100	.01251	55.18	35.77	.61322	1.00009	.6928
90.	.0269	982.7	.06070	.0100	.01112	61.76	39.01	.75544	1.00008	.6900
100.	.0242	1119.3	.05835	.0100	.01000	67.78	42.10	.89873	1.00007	.6955
110.	.0220	1263.4	.05604	.0100	.00909	76.26	44.74	.108415	1.00007	.6740
120.	.0202	1413.9	.05387	.0100	.00833	82.86	47.58	.125287	1.00006	.6766
140.	.0173	1728.1	.05019	.0100	.00714	96.08	53.00	.161795	1.00005	.6809
160.	.0152	2051.4	.04743	.0100	.00625	109.16	58.14	.202283	1.00005	.6828
180.	.0135	2378.4	.04539	.0100	.00556	121.88	63.06	.246548	1.00004	.6836
200.	.0121	2705.4	.04387	.0100	.00500	134.09	67.80	.294392	1.00004	.6839
220.	.0110	3031.2	.04273	.0100	.00455	145.72	72.38	.345508	1.00003	.6843
240.	.0101	3353.1	.04189	.0100	.00417	156.78	76.82	.399933	1.00003	.6846
260.	.0093	3670.9	.04127	.0100	.00385	167.31	81.15	.457538	1.00003	.6847
280.	.0087	3984.0	.04082	.0100	.00357	177.36	85.36	.518288	1.00003	.6848
300.	.0081	4292.7	.04050	.0100	.00333	186.98	89.48	.582079	1.00002	.6847
350.	.0069	5048.8	.04004	.0100	.00286	209.48	99.40	.754673	1.00002	.6845
400.	.0061	5790.0	.03985	.0100	.00250	230.29	108.86	.944925	1.00002	.6842
450.	.0054	6522.9	.03977	.0100	.00222	249.93	117.95	.1152072	1.00002	.6840
500.	.0048	7257.1	.03970	.0100	.00200	268.76	126.70	.1374702	1.00001	.6842
550.	.0044	7990.6	.03964	.0100	.00182	287.02	135.18	.1613349	1.00001	.6842
600.	.0040	8726.4	.03957	.0100	.00167	304.90	143.40	.1867226	1.00001	.6842
650.	.0037	9470.6	.03948	.0100	.00154	322.54	151.41	.2136436	1.00001	.6840
700.	.0035	10222.3	.03936	.0100	.00143	340.01	159.23	.2419941	1.00001	.6838
750.	.0032	10982.8	.03921	.0100	.00133	357.41	166.86	.2717932	1.00001	.6837
800.	.0030	11754.6	.03902	.0100	.00125	374.78	174.35	.3029753	1.00001	.6835
850.	.0029	12539.5	.03881	.0100	.00118	392.16	181.68	.3354945	1.00001	.6834
900.	.0027	13338.6	.03856	.0100	.00111	409.59	188.89	.3693071	1.00001	.6835
950.	.0026	14152.9	.03828	.0100	.00105	427.10	195.97	.4043739	1.00001	.6836
1000.	.0024	14983.1	.03798	.0100	.00100	444.68	202.95	.4406624	1.00001	.6838
1100.	.0022	16680.4	.03736	.0100	.00091	475.57	216.59	.5122083	1.00001	.6906
1200.	.0020	18437.5	.03669	.0100	.00083	511.07	229.87	.5923423	1.00001	.6911
1300.	.0019	20257.4	.03600	.0100	.00077	547.21	242.83	.6778122	1.00001	.6915
1400.	.0017	22150.2	.03526	.0100	.00071	584.47	255.49	.7678772	1.00001	.6916
1500.	.0016	24146.2	.03446	.0100	.00067	624.14	267.89	.8635098	1.00000	.6909
1600.	.0015	26303.1	.03352	.0100	.00063	668.83	280.05	.9664986	1.00000	.6884
1700.	.0014	28785.3	.03228	.0100	.00059	724.87	291.98	.10805260	1.00000	.6822
1800.	.0013	31869.2	.03053	.0100	.00056	802.94	303.70	.12120117	1.00000	.6700
2000.	.0012	41867.6	.02497	.0100	.00050	1102.50	326.65	.15638992	1.00000	.6218
2200.	.0011	62819.1	.01756	.0099	.00046	1813.25	345.83	.20742375	1.00000	.5495
2400.	.0010	105323.9	.01109	.0098	.00043	3331.19	369.24	.27048414	1.00000	.4987
2600.	.0009	181821.4	.00692	.0094	.00041	6115.38	394.59	.3375737	1.00000	.4787
2800.	.0008	297845.5	.00463	.0089	.00040	10362.66	421.87	.40498758	1.00000	.4889
3000.	.0006	433048.8	.00353	.0080	.00041	15311.58	447.27	.47246613	1.00000	.5244

* TWO-PHASE BOUNDARY

TABLE 8
THERMODYNAMIC PROPERTIES OF NORMAL HYDROGEN (ISOBARS, SI UNITS)

100.00 MPa ISOBAR

TEMPERATURE K	VOLUME CU M/KG	ISOHERM DERIVATIVE CU M-MPA/KG	ISOCHORE DERIVATIVE MPA/K	INTERNAL ENERGY KJ/KG-K	ENTHALPY KJ/KG	ENTROPY KJ/KG-K	CV KJ / KG-K	CP KG-K	VELOCITY OF SOUND M/S
* 34.169	.00977	5.2095	1.542	360.9	1337.6	15.394	6.59	6.08	2527.
36.	.00982	5.1618	1.526	370.7	1352.6	15.822	6.73	8.30	2522.
38.	.00988	5.1078	1.508	381.8	1369.4	16.277	6.87	8.52	2517.
40.	.00993	5.0520	1.490	393.2	1386.6	16.719	6.98	8.71	2512.
42.	.00999	4.9948	1.472	405.0	1404.2	17.148	7.07	8.89	2506.
44.	.01005	4.9365	1.453	417.0	1422.2	17.566	7.17	9.07	2499.
46.	.01011	4.8773	1.434	428.9	1440.0	17.961	7.30	9.28	2491.
48.	.01017	4.8175	1.415	441.6	1458.8	18.360	7.40	9.46	2482.
50.	.01023	4.7573	1.396	454.5	1477.8	18.750	7.49	9.64	2474.
52.	.01029	4.6971	1.377	467.8	1497.3	19.131	7.57	9.80	2465.
54.	.01036	4.6369	1.359	481.3	1517.0	19.504	7.65	9.95	2457.
56.	.01042	4.5771	1.340	495.3	1537.3	19.874	7.71	10.09	2448.
58.	.01048	4.5178	1.321	509.2	1557.6	20.231	7.75	10.22	2440.
60.	.01055	4.4591	1.302	523.3	1578.2	20.579	7.80	10.34	2431.
65.	.01071	4.3169	1.255	559.2	1630.6	21.416	7.89	10.62	2410.
70.	.01088	4.1826	1.209	596.1	1684.4	22.214	7.99	10.89	2387.
75.	.01106	4.0581	1.162	633.8	1739.4	22.973	8.09	11.14	2364.
80.	.01123	3.9448	1.116	672.5	1795.8	23.700	8.19	11.38	2341.
85.	.01141	3.8431	1.070	711.9	1853.2	24.397	8.30	11.60	2317.
90.	.01160	3.7530	1.024	752.2	1911.7	25.067	8.42	11.80	2294.
95.	.01178	3.6737	.9796	793.2	1971.2	25.709	8.53	11.98	2271.
100.	.01197	3.6035	.9357	834.9	2031.5	26.327	8.66	12.13	2248.
110.	.01234	3.4819	.8522	922.1	2155.8	27.511	8.98	12.47	2199.
120.	.01276	3.3346	.8066	1011.2	2287.3	28.656	9.22	13.03	2171.
140.	.01355	3.1987	.7030	1198.0	2553.0	30.703	9.68	13.65	2124.
160.	.01437	3.1972	.6180	1394.3	2831.2	32.560	10.07	14.02	2109.
180.	.01517	3.1143	.5439	1597.5	3114.2	34.226	10.39	14.33	2072.
200.	.01597	2.9502	.4914	1806.0	3403.4	35.749	10.64	14.62	2027.
220.	.01684	2.9419	.4488	2019.3	3703.3	37.179	10.84	15.11	2025.
240.	.01768	3.0865	.4119	2236.5	4004.7	38.491	11.00	15.12	2060.
260.	.01852	3.1323	.3779	2456.3	4307.9	39.705	11.12	15.18	2068.
280.	.01934	3.1686	.3488	2677.7	4611.7	40.831	11.21	15.23	2075.
300.	.02024	3.2500	.3354	2874.6	4898.1	41.788	10.88	15.14	2126.
350.	.02234	3.3883	.2846	3419.5	5653.5	44.118	10.89	15.07	2165.
400.	.02443	3.5426	.2470	3961.9	6404.6	46.124	10.86	14.97	2210.
450.	.02650	3.7063	.2182	4501.0	7151.0	47.882	10.82	14.88	2257.
500.	.02856	3.8759	.1955	5037.2	7893.4	49.446	10.79	14.81	2306.
550.	.03061	4.0497	.1771	5571.1	8632.6	50.855	10.77	14.76	2356.
600.	.03266	4.2264	.1620	6103.8	9369.9	52.135	10.76	14.73	2406.
650.	.03470	4.4055	.1493	6635.5	10105.9	53.310	10.75	14.71	2455.
700.	.03674	4.5866	.1385	7167.4	10841.7	54.407	10.76	14.72	2504.
750.	.03878	4.7694	.1291	7700.1	11578.1	55.425	10.79	14.73	2552.
800.	.04082	4.9536	.1210	8234.0	12315.5	56.377	10.82	14.76	2599.
850.	.04285	5.1393	.1139	8769.9	13054.9	57.273	10.87	14.80	2646.
900.	.04488	5.3261	.1076	9308.2	13796.6	58.120	10.92	14.86	2692.
950.	.04692	5.5140	.1019	9849.4	14544.2	59.924	10.99	14.93	2737.
1000.	.04895	5.7030	.0968	10393.9	15289.2	59.690	11.06	15.01	2781.
1100.	.05302	6.0838	.0881	11496.2	16798.6	61.118	11.23	15.17	2867.
1200.	.05710	6.4678	.0808	12616.8	18326.5	62.440	11.41	15.37	2951.
1300.	.06117	6.8546	.0747	13757.2	19874.4	63.678	11.61	15.57	3032.
1400.	.06525	7.2439	.0694	14918.2	21443.4	64.848	11.83	15.79	3110.
1500.	.06933	7.6353	.0649	16100.4	23033.8	65.959	12.04	16.01	3186.
1600.	.07342	8.0286	.0609	17302.8	24644.6	66.992	12.25	16.23	3261.
1700.	.07751	8.4236	.0573	18526.2	25276.8	67.977	12.45	16.44	3335.
1800.	.08160	8.8200	.0542	19770.4	27930.0	68.921	12.65	16.64	3406.
2000.	.08978	9.6165	.0489	22320.2	31298.6	70.706	13.03	17.04	3546.
2200.	.09798	10.4171	.0445	24943.7	34742.1	72.339	13.43	17.45	3679.
2400.	.10620	11.2210	.0408	27651.8	38272.3	73.870	13.87	17.91	3807.
2600.	.11446	12.0275	.0377	30460.2	41905.8	75.323	14.40	18.48	3929.
2800.	.12276	12.8363	.0351	33394.0	45670.1	76.723	15.06	19.20	4045.
3000.	.13115	13.6469	.0328	36488.4	49603.8	78.089	15.91	20.14	4156.

* TWO-PHASE BOUNDARY

TABLE 8
THERMODYNAMIC PROPERTIES OF NORMAL HYDROGEN (ISOBARS, SI UNITS)

100.00 MPa ISOBAR

TEMPERATURE K	DENSITY KG/CU M	V(DH/DV) _P KJ/KG	V(DP/DV) _V MPA-CU M/KJ X 10 ²	-V(DP/DV) _T MPA	(DV/DT)/V 1/K	THERMAL CONDUCTIVITY W/K-M X 10 ³	VISCOSITY KG/M-S X 10 ⁷	THERMAL DIFFUSIVITY SQ M/HR	DIELECTRIC CONSTANT	PRANDTL NUMBER
* 34.169	102.3875	2795.8	.22835	533.3893	.00289	276.26	937.81	.00120	1.34287	2.7431
36.	101.8460	2858.7	.22256	525.7090	.00290	276.26	800.91	.00118	1.34088	2.4058
38.	101.2550	2920.6	.21694	517.1055	.00292	275.52	687.46	.00115	1.33871	2.1254
40.	100.6647	2972.7	.21222	508.5564	.00293	274.20	600.50	.00113	1.33655	1.9077
42.	100.0751	3020.5	.20787	499.8546	.00294	272.37	532.43	.00110	1.33439	1.7385
44.	99.4861	3066.5	.20366	491.1104	.00296	270.22	478.19	.00108	1.33223	1.6055
46.	98.8978	3120.9	.19876	482.3525	.00297	267.84	434.26	.00105	1.33008	1.5045
48.	98.3099	3167.1	.19456	473.6076	.00299	265.30	398.20	.00103	1.32793	1.4205
50.	97.7226	3208.6	.19074	464.9006	.00300	262.66	368.22	.00100	1.32578	1.3511
52.	97.1359	3246.1	.18723	456.2550	.00302	259.94	343.02	.00098	1.32364	1.2933
54.	96.5496	3279.6	.18402	447.6927	.00303	257.18	321.63	.00096	1.32151	1.2447
56.	95.9639	3308.8	.18113	439.2340	.00305	254.40	303.31	.00095	1.31937	1.2034
58.	95.3788	3332.7	.17861	430.8979	.00307	251.62	287.50	.00093	1.31725	1.1674
60.	94.7943	3355.1	.17619	422.7017	.00308	249.19	273.74	.00092	1.31512	1.1354
65.	93.3370	3408.0	.17038	402.9244	.00312	244.27	246.24	.00089	1.30984	1.0705
70.	91.8870	3461.0	.16466	384.3249	.00315	239.28	225.80	.00086	1.30459	1.0273
75.	90.4480	3517.6	.15891	367.0497	.00317	234.35	210.14	.00084	1.29940	.9989
80.	89.0241	3580.0	.15308	351.1813	.00318	229.72	197.82	.00082	1.29428	.9798
85.	87.6203	3650.1	.14713	336.7366	.00318	229.10	187.92	.00081	1.28924	.9514
90.	86.2414	3728.6	.14112	323.6679	.00317	228.27	179.81	.00081	1.28430	.9296
95.	84.8920	3813.3	.13521	311.8664	.00314	227.38	173.06	.00081	1.27948	.9116
100.	83.5760	3905.6	.12934	301.1690	.00311	226.60	167.36	.00080	1.27479	.8962
110.	81.0536	4129.9	.11711	282.2177	.00302	210.81	109.58	.00075	1.26583	.6483
120.	78.3682	4220.7	.11169	261.3250	.00309	206.59	110.23	.00073	1.25634	.6951
140.	73.7994	4582.8	.09844	236.0605	.00298	224.30	112.16	.00080	1.24029	.6825
160.	69.5909	5047.0	.08617	222.4929	.00278	250.99	113.90	.00093	1.22563	.6361
180.	65.9363	5409.2	.07936	205.3481	.00265	275.13	115.24	.00105	1.21299	.6000
200.	62.6024	5569.0	.07378	184.6887	.00266	292.72	116.31	.00114	1.20154	.5888
220.	59.3817	5881.1	.06974	174.6977	.00257	303.35	117.30	.00122	1.19054	.5843
240.	56.5559	6408.2	.06623	174.5602	.00236	308.35	118.33	.00130	1.18095	.5803
260.	54.0061	6795.8	.06294	169.1637	.00223	309.51	119.47	.00136	1.17234	.5860
280.	51.7071	7152.7	.06019	163.8406	.00213	308.46	120.77	.00141	1.16461	.5961
300.	49.4193	7247.8	.05626	160.6133	.00209	306.42	122.22	.00147	1.15695	.6038
350.	44.7643	8031.9	.05835	151.6740	.00188	301.62	126.54	.00161	1.14148	.6322
400.	40.9388	8792.6	.05553	145.0297	.00170	300.72	131.66	.00177	1.12888	.6555
450.	37.7361	9539.0	.05343	139.8609	.00156	304.27	137.36	.00195	1.11840	.6718
500.	35.0120	10284.1	.05173	135.7041	.00144	311.38	143.44	.00216	1.10953	.6824
550.	32.6639	11024.5	.05036	132.2775	.00134	321.09	149.78	.00240	1.10193	.6886
600.	30.6169	11767.1	.04919	129.3991	.00125	332.64	156.27	.00266	1.09534	.6920
650.	28.8152	12512.1	.04818	126.9455	.00118	345.52	162.85	.00293	1.08956	.6934
700.	27.2161	13266.4	.04726	124.8291	.00111	349.37	169.47	.00323	1.08444	.6939
750.	25.7866	14028.9	.04643	122.9859	.00105	373.95	176.11	.00354	1.07989	.6938
800.	24.5007	14803.2	.04565	121.3674	.00100	389.09	182.74	.00387	1.07580	.6933
850.	23.3373	15591.1	.04491	119.9362	.00095	404.69	189.35	.00422	1.07211	.6927
900.	22.2795	16394.3	.04420	118.6628	.00091	420.68	195.92	.00457	1.06876	.6921
950.	21.3135	17213.7	.04352	117.5236	.00087	436.99	202.46	.00494	1.06571	.6916
1000.	20.4277	18050.0	.04285	116.4995	.00083	453.58	208.95	.00533	1.06292	.6912
1100.	18.8595	19760.5	.04161	114.7366	.00077	475.56	221.79	.00598	1.05799	.7077
1200.	17.5141	21532.6	.04044	113.2774	.00071	511.00	234.43	.00684	1.05378	.7049
1300.	16.3472	23364.8	.03934	112.0534	.00067	546.88	246.87	.00773	1.05013	.7030
1400.	15.3253	25253.6	.03830	111.0148	.00063	583.15	259.11	.00867	1.04695	.7017
1500.	14.4231	27193.1	.03734	110.1246	.00059	619.71	271.16	.00966	1.04414	.7007
1600.	13.6206	29158.7	.03648	109.3547	.00056	656.08	283.01	.01069	1.04165	.7000
1700.	12.9023	31158.4	.03569	108.6833	.00053	692.48	294.67	.01176	1.03942	.6994
1800.	12.2556	33189.5	.03496	108.0935	.00050	728.94	306.15	.01287	1.03742	.6984
2000.	11.1379	37349.7	.03366	107.1068	.00046	802.55	328.54	.01523	1.03397	.6974
2200.	10.2057	41711.4	.03245	106.3132	.00042	879.65	344.88	.01778	1.03109	.6842
2400.	9.4158	46361.9	.03126	105.6544	.00039	964.08	366.19	.02058	1.02866	.6805
2600.	8.7370	51465.7	.02999	105.0844	.00036	1062.11	387.03	.02368	1.02657	.6734
2800.	8.1459	57245.9	.02859	104.5631	.00034	1182.01	407.47	.02721	1.02476	.6619
3000.	7.6246	63967.6	.02702	104.0528	.00031	1333.50	427.63	.03126	1.02316	.6460

* TWO-PHASE BOUNDARY

Table 9
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID NORMAL HYDROGEN

Temperature, K	Density, kg/m ³	V@H/∂V _P , kJ/kg	V@P/∂V _P , MPa·m ³ /kJ × 10 ²	-V@P/∂(V _T) MPa	θV/∂T _P /V, 1/K	θV/∂T _P /V, W/K·m · × 10 ³	Thermal conductivity W/K·m ·	Viscosity, kg/m·s × 10 ⁷	Thermal diffusivity, m ² /h	Dielectric constant	Prandtl number
13.950 ^a	77.0235	622.6	0.25654	90.3401	0.01022	72.59	255.05	0.00053	1.25160	2.2359	
	0.1254	139.8	0.06684	0.0069	0.07523	12.43	7.36	0.03395	1.00038	0.6230	
14	76.8554	619.2	0.25480	88.3211	0.01046	74.62	248.01	0.00054	1.25101	2.1517	
	0.1388	141.6	0.06684	0.0077	0.07441	12.54	7.48	0.03084	1.00042	0.6291	
15	75.9963	621.9	0.24237	81.5880	0.01111	83.02	217.84	0.00057	1.24799	1.8128	
	0.2228	150.5	0.06683	0.0131	0.07089	13.08	8.08	0.01981	1.00067	0.6591	
16	75.1030	623.0	0.23130	75.3083	0.01181	88.86	194.15	0.00058	1.24486	1.6074	
	0.3385	159.1	0.06680	0.0208	0.06820	13.66	8.68	0.01339	1.00102	0.6691	
17	74.1710	613.1	0.22244	68.0612	0.01286	92.71	175.07	0.00057	1.24159	1.4884	
	0.4922	167.1	0.06674	0.0313	0.06624	14.27	9.28	0.00943	1.00148	0.7197	
18	73.1950	604.3	0.21509	61.7874	0.01394	95.43	159.34	0.00056	1.23818	1.4063	
	0.6902	174.6	0.06669	0.0452	0.06495	14.97	9.88	0.00689	1.00208	0.7484	
19	72.1693	601.0	0.20874	56.9619	0.01486	97.00	146.10	0.00054	1.23460	1.3451	
	0.9395	181.4	0.06665	0.0626	0.06427	15.72	10.49	0.00517	1.00283	0.7783	
20	71.0870	596.1	0.20314	52.3516	0.01585	98.40	134.76	0.00053	1.23083	1.2942	
	1.2474	187.6	0.06666	0.0840	0.06420	16.64	11.11	0.00399	1.00376	0.8042	
20.390 ^a	70.7864	587.9	0.20176	50.2079	0.01644	98.92	131.98	0.00052	1.22978	1.2893	
	1.3378	189.1	0.06667	0.0903	0.06424	16.94	11.29	0.00375	1.00404	0.8091	
21	69.9403	577.8	0.19814	46.2935	0.01754	100.05	124.87	0.00051	1.22684	1.2648	
	1.6189	193.0	0.06672	0.1093	0.06471	17.79	11.28	0.00317	1.00489	0.8241	
22	68.7200	563.1	0.19347	41.1835	0.01921	100.95	116.11	0.00049	1.22261	1.2444	
	2.0711	197.5	0.06686	0.1388	0.06597	19.02	12.38	0.00254	1.00625	0.8481	
23	67.4149	540.5	0.18882	35.4854	0.02162	101.20	108.22	0.00046	1.21810	1.2499	
	2.6119	201.2	0.06708	0.1719	0.06804	20.36	13.04	0.00205	1.00789	0.8769	

^a Two-phase boundary.

Table 9 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID NORMAL HYDROGEN

Temperature, K	Density, kg/m ³	$V(\partial H/\partial V)_P$, kJ/kg	$V(\partial P/\partial V)_V$, MPa·m ³ /kJ $\times 10^2$	$-V(\partial P/\partial V)_T$, MPa	$(\partial V/\partial T)_P/V$, 1/K	Thermal conductivity $W/K\cdot m$ $\times 10^3$	Viscosity, kg/m·s $\times 10^7$	Thermal diffusivity, m ² /h	Dielectric constant	Prandtl number
24	66.0112 3.2548	523.0 203.9	0.18378 0.06739	30.8574 0.2081	0.02394 0.07108	100.84 21.81	101.01 13.73	0.00044 0.00166	1.21325 1.00984	1.2543 0.9123
25	64.4917 4.0171	504.2 205.8	0.17820 0.06777	26.4945 0.2460	0.02665 0.07540	99.93 23.43	94.32 14.44	0.00042 0.00135	1.20802 1.01216	1.2682 0.9567
26	62.8337 4.9215	475.1 206.9	0.17151 0.06822	21.4244 0.2842	0.03116 0.08144	98.43 25.24	88.03 15.19	0.00038 0.00110	1.20233 1.01491	1.3240 1.0145
27	61.0065 5.9999	451.1 207.3	0.16381 0.06868	17.4346 0.3201	0.03585 0.09002	96.38 27.36	82.02 16.00	0.00035 0.00088	1.19608 1.01820	1.3764 1.0916
28	58.9665 7.2979	418.4 207.1	0.15535 0.06912	13.1188 0.3498	0.04416 0.10259	93.78 29.91	76.19 16.89	0.00031 0.00069	1.18913 1.02216	1.5012 1.1997
29	56.6460 8.8866	382.6 206.2	0.14600 0.06947	9.1967 0.3676	0.05763 0.12220	90.55 33.18	70.42 17.91	0.00026 0.00053	1.18125 1.02703	1.7146 1.3601
30	53.9303 10.8872	350.6 204.7	0.13555 0.06965	6.2743 0.3638	0.07585 0.15631	86.57 37.87	64.57 19.17	0.00022 0.00039	1.17208 1.03319	1.9834 1.6195
31	50.5892 13.5411	310.8 202.6	0.12321 0.06952	3.5282 0.3205	0.11759 0.22979	85.85 46.48	58.40 20.89	0.00017 0.00027	1.16087 1.04140	2.4864 2.0930
32	45.9927 17.4983	265.8 199.1	0.10745 0.06953	1.3886 0.2258	0.24599 0.43710	91.46 66.77	51.31 23.79	0.00011 0.00016	1.14555 1.05373	3.6672 3.1004
	33.180 ^a	314.285					35.43			1.09795

^a Two-phase boundary.

Table 9 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID NORMAL HYDROGEN

Temperature, K	Pressure, MPa	Isotherm derivative, $m^3\text{-MPa}/\text{kg}$	Isochore derivative, MPa/K	Internal energy, $\text{kJ}/\text{kg}\cdot\text{K}$	Enthalpy, kJ/kg	Entropy, $\text{kJ}/\text{kg}\cdot\text{K}$	C_V , $\text{kJ}/\text{kg}\cdot\text{K}$	C_p , $\text{kJ}/\text{kg}\cdot\text{K}$	Velocity of sound, m/s	Surface tension, $\text{N/m} \times 10^3$
13.950 ^a	0.0072	1.1729	0.9234	218.2	218.3	14.079	4.67	6.36	1264	3.0033
	0.0072	0.0552	0.0005	611.4	667.4	46.635	6.21	10.52	306	
14	0.0074	1.1492	0.9234	219.5	219.6	14.173	4.72	6.47	1256	2.9950
	0.0074	0.0558	0.0006	612.5	669.3	46.301	6.21	10.54	308	
15	0.0127	1.0736	0.9064	226.3	226.4	14.640	4.92	6.91	1228	2.8290
	0.0127	0.0588	0.0009	617.9	678.2	44.763	6.24	10.67	317	
16	0.0204	1.0027	0.8893	233.5	233.8	15.104	5.12	7.36	1200	2.6635
	0.0204	0.0615	0.0014	623.0	686.7	43.418	6.27	10.85	326	
17	0.0314	0.9176	0.8750	241.1	241.6	15.568	5.30	7.88	1168	2.4987
	0.0314	0.0637	0.0021	627.8	694.7	42.227	6.32	11.07	334	
18	0.0461	0.8441	0.8612	249.2	249.9	16.032	5.47	8.42	1140	2.3346
	0.0461	0.0654	0.0029	632.2	702.1	41.158	6.37	11.34	341	
19	0.0654	0.7893	0.8465	257.8	258.8	16.498	5.62	8.93	1120	2.1712
	0.0654	0.0667	0.0040	636.3	708.8	40.188	6.43	11.66	348	
20	0.0901	0.7364	0.8300	266.9	268.3	16.966	5.75	9.45	1100	2.0085
	0.0901	0.0674	0.0054	639.8	714.8	39.299	6.49	12.04	354	
20.390 ^a	0.1013	0.7093	0.8253	269.5	270.9	17.093	5.78	9.66	1089	1.9453
	0.1013	0.0675	0.0058	640.7	716.5	39.083	6.50	12.15	355	
21	0.1208	0.6619	0.8119	276.6	278.4	17.440	5.86	10.13	1070	1.8466
	0.1208	0.0675	0.0071	643.0	720.2	38.485	6.55	12.49	359	
22	0.1585	0.5993	0.7913	286.8	289.2	17.919	5.95	10.82	1044	1.6856
	0.1585	0.0670	0.0092	645.5	724.4	37.710	6.61	13.03	363	
23	0.2039	0.5264	0.7673	297.7	300.8	18.405	6.03	11.69	1010	1.5255
	0.2039	0.0658	0.0117	647.4	727.6	36.973	6.68	13.69	367	

^a Two-phase boundary.

Table 9 (continued)
THERMODYNAMIC PROPERTIES OF COEXISTING GASEOUS AND LIQUID NORMAL HYDROGEN

Temperature, K	Pressure, MPa	Isotherm derivative, $\text{m}^3 \cdot \text{MPa}/\text{kg}$	Isochore derivative, MPa/K	Internal energy, $\text{kJ}/\text{kg}\cdot\text{K}$	Enthalpy, kJ/kg	Entropy, $\text{kJ}/\text{kg}\cdot\text{K}$	C_V , $\text{kJ}/\text{kg}\cdot\text{K}$	C_P , $\text{kJ}/\text{kg}\cdot\text{K}$	Velocity of sound, m/s	Surface tension, $\text{N}/\text{m} \times 10^3$
24	0.2579	0.4675	0.7389	309.3	313.3	18.901	6.09	12.52	980	1.3664
	0.2579	0.0639	0.0148	648.5	729.8	36.266	6.74	14.49	371	1.2085
25	0.3213	0.4108	0.7060	321.6	326.7	19.408	6.14	13.44	948	373
	0.3213	0.0613	0.0186	648.9	730.7	35.579	6.81	15.52	372	1.0518
26	0.3950	0.3410	0.6676	334.8	341.2	19.929	6.20	14.80	903	376
	0.3950	0.0578	0.0231	648.2	730.2	34.900	6.89	16.85	376	0.8965
27	0.4800	0.2858	0.6251	349.0	357.0	20.473	6.26	16.17	860	377
	0.4800	0.0533	0.0288	646.5	728.0	34.221	6.99	18.66	377	0.7429
28	0.5770	0.2225	0.5794	364.4	374.3	21.041	6.33	18.48	806	378
	0.5770	0.0479	0.0359	643.2	723.7	33.524	7.11	21.24	378	0.5912
29	0.6872	0.1624	0.5300	381.2	393.6	21.650	6.41	22.05	747	378
	0.6872	0.0414	0.0449	638.1	716.6	32.795	7.28	25.19	378	0.4418
30	0.8116	0.1163	0.4759	400.2	415.4	22.315	6.51	26.59	689	378
	0.8116	0.0334	0.0569	630.4	705.9	32.002	7.50	31.99	378	0.2955
31	0.9510	0.0697	0.4149	422.3	441.3	23.075	6.66	36.55	619	375
	0.9510	0.0237	0.0736	618.6	689.7	31.091	7.82	46.56	372	0.1537
32	1.1068	0.0302	0.3416	450.4	474.7	24.032	6.91	65.37	534	372
	1.1068	0.0129	0.0987	599.2	663.2	29.926	8.11	87.02	372	0.0000
33.180 ^a	1.3130		0.1898	524.3	565.4	26.680				

^a Two-phase boundary.

Table 10
FIXED POINT PROPERTIES OF NORMAL HYDROGEN

Properties	Triple point			Normal boiling point			Critical point ^a			Standard conditions		References and notes
	Solid	Liquid	Vapor	Liquid	Vapor	Critical point ^a	STP(0°C)	NTP(20°C)	STP(0°C)	NTP(20°C)		
Temperature (K)	13.957 ^c	13.957 ^c	13.957 ^c	20.390 ^c	20.390 ^c	33.19 ^c	273.15	293.15	-	-	-	
Pressure (mm Hg) ^m	54.04	54.04	54.04	760	9865	760	760	760	110	110	-	
Density (mol/cm ³) × 10 ³	43.01 ^{1.3} ₃	38.30	0.0644	35.20	0.6604	14.94	0.04460	0.04155	110	110	-	
Specific volume (cm ³ /mol) × 10 ⁻³	0.02325 ^{1.3} ₃	0.026108	15.519	0.028409	1.5143	0.06949	22.423	24.066	110,132	110,132	-	
Compressibility factor, Z = $\frac{PV}{RT}$	-	0.001621	0.9635	0.01698	0.9051	0.3191	1.00042	1.00049	d	1.00049	-	
Heats of fusion and vaporization (J/mol)	117.1	911.3	899.1	0	0	-	-	-	-	-	129 ^e	
Heats of fusion and vaporization (J/mol-K)	-	-	-	-	-	-	-	-	-	-	-	
C _v , at saturation	5.73	13.85	-46.94	18.91	-33.28	(Very large)	-	-	-	-	-	
C _p , at constant pressure	-	13.23	21.22	19.70	24.60	(Very large)	-	-	-	-	110,134	
C _v , at constant volume	-	9.53	12.52	11.60	13.2	(Very large)	28.59	28.89	110,132,134	-	-	
Specific heat ratio, $\gamma = C_p/C_v$	-	1.388	1.695	1.698	1.863	(Large)	-	-	-	-	-	
Enthalpy (J/mol)	-	438.7	1350.0	548.3	1447.4	1164	1.408	20.40	110,132,134, f	-	-	
Internal energy (J/mol)	321.6	435.0	1234.8	545.7	1294.0	-	7749.2	8324.1	110,132 ^g	-	-	
Entropy (J/mol-K)	317.9 ^f	20.3	28.7	93.6	34.92	78.94	54.77.1	5885.4	110,132 ^g	-	-	
Velocity of sound (m/s)	-	1282	307	1101	357	-	139.59	141.62	110,132 ^g	-	-	
Viscosity, μ	N-s/m ² × 10 ³	-	-	-	-	-	1246	1294	134,138	-	-	
Centipoise ^h	-	0.026	0.00074	0.0132	0.0011	(0.0035)	0.00839	0.00881	138	138	-	
Thermal conductivity (mW/cm-K), k	9.0 ^{1.3} ₅	0.026	0.00074	0.0132	0.0011	(0.0035)	0.00839	0.00881	138	138	-	
Prandtl number, N _{Pr} = $\mu C_p/k$	0.73	0.124	0.99	0.169	1.740	1.740	1.838	1.838	-	-	-	
Dielectric constant, ϵ	2.24	0.623	1.29	0.809	-	-	0.6849	0.6848	134,136	-	-	
Index of refraction, n = $\sqrt{\epsilon}$	1.287	1.253	1.00039	1.231	1.0040	1.0937	1.000271	1.000253	131	131	-	
Surface tension (N/m) × 10 ³	1.134	1.119	1.000196	1.1093	1.0020	1.0458	1.000136	1.000126	k	k	-	
Equiv. vol./vol. liquid at NBT	0.8184	3.00	-	1.94	0	0	-	-	-	-	-	
Note: Gas constant = R = 8.31434 J·mol ⁻¹ ·K ⁻¹ ; Molecular weight = 1.11 = 2.01594; Mole = gram mole.				53.30	2.357	789.3	847.1	847.1	-	-	-	
a Values in parentheses are estimates.												
b Apply to all items on the line except for specific values separately referenced by superscript.												
c These temperatures given in Reference 110 are based on the IPTS-1968 temperature scale. To compare with the corresponding temperatures given in Reference 4 for parahydrogen which are based on the NBS-1955 temperature scale, 0.01 K should be subtracted, i.e., use 13.947, 20.380, and 33.18 respectively for the triple point, normal boiling point, and critical point when determining property differences between normal and parahydrogen.												
d Compressibility factor calculated from the tabulated data using the gas constant, R, from Reference 4.												
e Heats of fusion and vaporization calculated from enthalpy differences and as reported in References 110, 129, 132.												
f Calculated from property values given in this table.												
g Base point (zero values) for enthalpy, internal energy, and entropy are 0 K for the ideal gas at 0.101325 MPa (1 atm) pressure.												
h Units for poise are g/cm-s.												
i Anomalous large.												
j Long wavelengths.												
k Index of refraction calculated from the dielectric constant data given in Reference 131, in good agreement with the values reported in Reference 114.												
l Ratio of specific volumes reported in References 3 and 4 or 110 and 132.												
m (mmHg) × 1.3332 × 10 ⁻⁴ = MPa.												

Table 11
 VAPOR PRESSURE OF COEXISTING GASEOUS
 AND LIQUID NORMAL HYDROGEN¹²⁷

Temperature, K	Pressure, MPa
20.560	0.1064887
21	0.1207211
22	0.1581615
23	0.2033624
24	0.2571729
25	0.3204464
26	0.3940357
27	0.4787904
28	0.5755541
29	0.6851619
30	0.8084393
31	0.9462002
32	1.0992464
32.270	1.1432921

TABLE 12. THERMODYNAMIC PROPERTIES OF THE HYDROGEN SOLID-VAPOR TWO-PHASE REGION^a

PRESS.	TEMP.	V-SOL.	D-SOL.	H-SOL.	S-SOL.	U-SOL.	C-SAT.	G-P ^b	ΔH _{SUB.}	V-VAP.	D-VAP.	H-VAP.	S-VAP.	U-VAP.
ATM	K	CC/MOL	MOL/L	J/MOL	J/MOL-K	J/MOL	J/MOL-K	J/MOL	J/MOL-K	OC/MOL	OC/MOL	J/MOL	J/MOL-K	J/MOL
.06950	13.8	23.30	42.911	-740.2	1.500	-740.4	5.634	5.640	1022.1	16030.	.06238	281.9	75.57	
.06955	13.7	23.29	42.931	-740.8	1.559	-740.9	5.502	5.508	1021.0	17015.	.05877	280.2	75.58	
.06964	13.6	23.28	42.950	-741.3	1.420	-741.5	5.371	5.377	1019.8	18074.	.05533	278.5	75.98	
.06965	13.5	23.27	42.969	-741.8	1.380	-742.0	5.243	5.248	1018.5	19213.	.05205	276.7	76.40	
.05318	13.4	23.26	42.989	-742.4	1.342	-742.5	5.117	5.122	1017.3	20441.	.04892	274.9	76.83	
.04951	13.3	23.25	43.007	-742.9	1.304	-743.0	4.992	4.997	1016.0	21765.	.04594	273.1	77.26	
.04954	13.2	23.24	43.026	-743.4	1.267	-743.5	4.870	4.874	1014.6	23194.	.04311	271.3	77.69	
.04956	13.1	23.23	43.045	-743.8	1.224	-743.9	4.750	4.754	1013.3	24738.	.04042	269.5	78.33	
.03996	13.0	23.22	43.063	-744.3	1.194	-744.4	4.631	4.635	1011.9	26407.	.03707	267.6	78.58	
.03713	12.9	23.21	43.082	-744.8	1.159	-744.8	4.514	4.518	1010.5	2825.5	.03544	265.7	79.13	
.03447	12.8	23.20	43.100	-745.3	1.124	-745.3	4.400	4.403	1009.0	30173.	.03314	263.8	79.49	
.03197	12.7	23.19	43.118	-745.6	1.090	-745.7	4.287	4.290	1007.6	3228.	.03096	261.9	79.6	
.02962	12.6	23.18	43.136	-746.1	1.057	-746.1	4.176	4.179	1006.1	34616.	.02890	261.0	80.43	
.02741	12.5	23.17	43.153	-746.5	1.024	-746.5	4.067	4.070	1004.5	37114.	.02694	258.1	80.90	
.02534	12.4	23.16	43.170	-746.9	.992	-746.9	3.956	3.963	1003.0	39845.	.0250	256.1	81.39	
.02340	12.3	23.15	43.188	-747.3	.960	-747.3	3.855	3.858	1001.4	42021.	.02335	254.2	81.88	
.02158	12.2	23.15	43.205	-747.6	.929	-747.6	3.751	3.753	999.6	45687.	.02171	252.2	82.38	
.01988	12.1	23.14	43.222	-748.0	.899	-748.1	3.650	3.652	998.2	49613.	.02016	250.2	82.68	
.01830	12.0	23.13	43.238	-748.4	.869	-748.4	3.550	3.552	996.5	53491.	.01869	248.2	83.92	
.01681	11.9	23.12	43.255	-748.7	.839	-748.8	3.452	3.454	994.9	57738.	.01732	246.2	84.45	
.01543	11.8	23.11	43.271	-749.1	.811	-749.1	3.356	3.358	993.2	62395.	.01603	244.2	84.98	
.01415	11.7	23.10	43.287	-749.4	.783	-749.4	3.261	3.263	991.5	67509.	.01481	242.1	85.53	
.01295	11.6	23.09	43.303	-749.7	.755	-749.8	3.169	3.170	989.8	73131.	.01367	240.1	85.16	
.01184	11.5	23.08	43.319	-750.0	.728	-750.1	3.078	3.078	987.9	79321.	.01261	238.1	86.09	
.01081	11.4	23.08	43.335	-750.3	.701	-750.4	2.989	2.990	986.3	86146.	.01161	236.0	86.65	
.00986	11.3	23.07	43.350	-750.6	.676	-750.7	2.901	2.902	984.6	93682.	.01067	233.9	87.22	
.00895	11.2	23.06	43.366	-750.9	.650	-750.9	2.815	2.816	982.8	102017.	.00980	231.9	87.81	
.00816	11.1	23.05	43.381	-751.2	.625	-751.2	2.731	2.732	981.0	11248.	.00884	229.8	88.40	
.00741	11.0	23.04	43.396	-751.5	.601	-751.5	2.649	2.650	979.2	121489.	.00823	227.2	89.00	
.00671	10.9	23.04	43.411	-751.7	.577	-751.7	2.568	2.569	977.3	132869.	.00753	225.6	89.62	
.00617	10.8	23.03	43.425	-752.0	.554	-752.0	2.489	2.490	975.5	145535.	.00687	223.5	90.24	
.00559	10.7	23.02	43.440	-752.2	.531	-752.2	2.412	2.412	973.6	159656.	.00626	221.4	91.88	
.00495	10.6	23.01	43.454	-752.5	.509	-752.5	2.336	2.336	971.8	175429.	.00570	219.3	91.52	
.00445	10.5	23.01	43.468	-752.7	.487	-752.7	2.262	2.262	969.9	193077.	.00518	217.1	92.18	
.00400	10.4	23.00	43.482	-752.9	.466	-752.9	2.189	2.189	966.0	212861.	.00474	215.1	92.86	
.00359	10.3	22.99	43.496	-753.1	.445	-753.1	2.118	2.118	964.1	235082.	.00425	213.0	93.54	
.00321	10.2	22.98	43.509	-753.3	.424	-753.3	2.048	2.048	962.2	260087.	.00384	210.8	94.24	
.00287	10.1	22.98	43.523	-753.5	.405	-753.5	1.980	1.980	960.3	28824.	.00347	208.7	95.05	
.00256	10.0	22.97	43.536	-753.7	.385	-753.7	1.914	1.914	958.3	32046.	.00312	206.6	95.68	
MN HG	K	CC/MOL C	CAL/MOL	CAL/MOL CAL/MOL-K	CAL/MOL	Z, VAPOR d	CAL/MOL	CAL/MOL CAL/MOL-K	CAL/MOL	Z, VAPOR d	CAL/MOL	CAL/MOL CAL/MOL-K	CAL/MOL	
.1917E+01	10.0	22.873	1.4790000	1.9750000	5.751000	230.55	.99876	232.03	23.252					
.5343E+00	9.0	22.819	.9788000	1.4500000	.4280000	226.12	.9956	227.10	25.269					
.1118E+00	8.0	22.754	.6139000	.1022000	.3054000	221.53	1.00000	222.15	27.794					
.1561E+01	7.0	22.711	.3598000	.0684200	.2065000	216.82	1.00000	217.16	31.043					
.1190E+02	6.0	22.678	.0927500	.0429000	.1304000	212.02	1.00000	212.21	35.379					
.3570E+04	5.0	22.660	.0375900	.0124750	.0742000	207.15	1.00000	207.24	41.455					
.2080E+06	4.0	22.650	.0124660	.0037990	.0379900	202.24	1.00000	202.28	50.572					
.4833E+10	3.0	22.646	.0012020	.0053620	.0161300	197.30	1.00000	197.31	65.771					
.3988E+17	2.0	22.645	.0023740	.0015630	.0047490	192.34	1.00000	192.34	96.170					
.8255E+36	1.0	22.645	.0004484	.0001979	.0005936	187.37	1.00000	187.37	187.37					

^a Upper part of table from Reference 142, lower part of table from References 19, 129.^b Estimated from values and differences given in Reference 19.^c From Ahlers.¹⁶⁹ Mullins et al.¹²⁹ set this value constant.^d Z is compressibility factor.Note: atm × 0.101325 = MPa; mmHg × 1.33332 × 10⁻⁴ = MPa; (cal/mol) × 2.0755 = J/g.

TABLE 13. THERMODYNAMIC PROPERTIES OF THE HYDROGEN SOLID-LIQUID TWO-PHASE REGION

PRESS.	TEMP.	V-SOL.	O-SOL.	H-SOL.	S-SOL.	U-SOL.	$\Delta_{HFUS.}$	V-LIQ.	D-LIQ.	H-LIQ.	S-LIQ.	U-LIQ.
ATH	K	CC/MOL	MOL/L	J/MOL	J/MOL	J/MOL	J/MOL	CC/MOL	MOL/L	J/MOL	J/MOL	J/MOL
•0695	13.8	23.30	42.911	-740.2	1.500	-740.4	117.3	26.17	38.214	-622.9	10.00	-623.1
5.976	14.0	23.27	42.972	-724.9	1.595	-739.0	118.4	26.07	38.354	-606.6	10.05	-622.4
11.982	14.2	23.23	43.048	-709.5	1.685	-737.7	119.5	25.97	38.502	-590.0	10.10	-621.6
18.087	14.4	23.18	43.137	-693.9	1.771	-736.4	120.6	25.87	38.657	-573.3	10.15	-620.7
24.288	14.6	23.13	43.237	-678.1	1.854	-735.1	121.8	25.76	38.816	-556.4	10.19	-619.8
30.585	14.8	23.07	43.346	-662.2	2.008	-732.4	124.1	25.65	38.980	-539.3	10.24	-618.8
36.976	15.0	23.01	43.462	-646.2	2.079	-731.1	125.3	25.44	39.314	-504.7	10.32	-617.8
43.459	15.2	22.94	43.584	-630.0	2.145	-729.7	126.5	25.33	39.483	-487.2	10.36	-615.6
50.033	15.4	22.88	43.710	-613.8	2.208	-728.4	127.7	25.22	39.652	-469.6	10.40	-614.5
56.69	15.6	22.81	43.840	-597.4	2.267	-727.1	129.0	25.11	39.821	-451.9	10.43	-613.3
63.45	15.8	22.74	43.971	-580.9	2.321	-725.8	130.2	25.01	39.989	-434.0	10.46	-612.1
70.29	16.0	22.67	44.104	-564.3	2.386	-724.4	131.5	24.90	40.155	-416.0	10.49	-610.9
77.22	16.2	22.60	44.238	-547.6	2.439	-723.1	132.8	24.80	40.319	-397.9	10.52	-609.6
84.23	16.4	22.54	44.372	-530.8	2.4919	-721.8	134.1	24.70	40.482	-379.7	10.54	-608.3
91.33	16.6	22.47	44.506	-513.9	2.463	-721.5	135.5	24.60	40.643	-361.4	10.57	-607.0
98.51	16.8	22.40	44.639	-496.8	2.504	-720.5	136.8	24.51	40.801	-342.9	10.61	-605.6
105.78	17.0	22.34	44.772	-479.7	2.543	-719.2	138.2	24.42	40.957	-324.4	10.63	-604.3
113.13	17.2	22.27	44.903	-462.5	2.612	-716.5	139.5	24.32	41.111	-305.7	10.67	-602.8
120.56	17.4	22.21	45.034	-445.2	2.644	-715.1	140.9	24.23	41.263	-286.9	10.65	-601.4
128.07	17.6	22.14	45.163	-427.8	2.673	-713.8	142.3	24.15	41.412	-268.0	10.67	-599.9
135.66	17.8	22.08	45.292	-410.3	2.702	-712.4	143.7	24.06	41.559	-248.9	10.69	-598.4
143.33	18.0	22.02	45.419	-392.6	2.738	-711.0	145.2	23.98	41.704	-229.7	10.72	-596.8
151.07	18.2	21.96	45.545	-374.9	2.774	-709.6	146.6	23.90	41.847	-210.4	10.74	-595.2
158.90	18.4	21.90	45.670	-357.0	2.812	-708.2	148.1	23.82	41.988	-191.0	10.76	-591.8
166.80	18.6	21.84	45.793	-339.1	2.849	-706.7	149.6	23.74	42.142	-171.4	10.77	-590.1
174.78	18.8	21.78	45.916	-321.0	2.884	-705.2	151.0	23.66	42.264	-151.8	10.77	-588.3
182.83	19.0	21.72	46.037	-302.8	2.914	-703.7	152.5	23.59	42.400	-132.0	10.79	-586.5
190.96	19.2	21.66	46.158	-284.5	2.947	-702.2	154.1	23.51	42.533	-112.0	10.81	-584.6
199.17	19.4	21.61	46.277	-266.1	2.980	-700.6	155.6	23.44	42.666	-91.9	10.83	-582.7
207.44	19.6	21.55	46.396	-247.5	2.914	-699.0	157.1	23.37	42.796	-71.8	10.85	-580.7
215.79	19.8	21.50	46.514	-228.9	2.936	-697.3	158.7	23.30	42.925	-51.4	10.87	-578.7
224.22	20.0	21.45	46.631	-210.1	2.956	-695.7	160.3	23.23	43.053	-31.0	10.89	-576.6
232.71	20.2	21.39	46.747	-191.2	2.976	-694.0	161.8	23.16	43.180	-10.4	10.91	-574.5
241.28	20.4	21.34	46.863	-172.3	2.999	-692.2	163.4	23.09	43.305	10.3	10.93	-572.3
249.92	20.6	21.29	46.978	-153.2	3.020	-690.4	165.0	23.03	43.430	31.1	10.95	-570.1
258.63	20.8	21.24	47.092	-133.9	3.041	-688.6	166.7	22.96	43.553	52.0	11.00	-567.8
267.41	21.0	21.18	47.206	-114.6	3.063	-686.6	168.3	22.90	43.675	73.1	11.03	-565.5
276.26	21.2	21.13	47.319	-95.2	3.084	-684.9	169.9	22.83	43.796	94.3	11.05	-563.1
285.19	21.4	21.08	47.432	-75.6	3.106	-682.9	171.6	22.77	43.916	115.6	11.05	-560.7
294.18	21.6	21.03	47.544	-56.0	3.128	-681.0	173.3	22.71	44.036	137.1	11.08	-558.2
303.23	21.8	20.98	47.656	-36.2	3.150	-678.9	175.0	22.65	44.154	158.6	11.10	-555.7
312.36	22.0	20.93	47.768	-16.3	3.173	-676.9	176.7	22.59	44.272	180.3	11.13	-553.1
321.56	22.2	20.89	47.879	3.6	3.195	-674.8	178.4	22.53	44.389	202.1	11.16	-550.4
330.82	22.4	20.84	47.990	23.7	3.218	-672.6	180.1	22.47	44.505	224.0	11.19	-550.4
340.15	22.6	20.79	48.101	43.9								

Note: atm \times 0.101325 = MPa.

Table 14. Parahydrogen Properties in the Compressed Solid States.

Temperature K	Ahlers' 22.56 cm ³ /mol isochore			Ahlers' 19.83 cm ³ /mol isochore			Ahlers' 18.73 cm ³ /mol isochore			
	est. pressure atm	C _v mJ/mol-K	C _p mJ/mol-K	est. C J/mol	est. pressure atm	C _p = C _v mJ/mol-K	est. enthalpy J/mol	est. pressure atm	C _p = C _v mJ/mol-K	est. enthalpy J/mol
0	5.3	0	0	-758.0	427	0	-636.0	710	0	-476.0
1	5.3	0.93	0.93	-758.0	427	0.40	-636.0	710	0.29	-476.0
2	5.3	7.58	7.58	-757.9	427	3.26	-636.0	710	2.31	-476.0
3	5.3	26.4	26.4	-757.9	427	11.18	-636.0	710	7.88	-476.0
4	5.3	65.3	65.3	-757.9	427	27.1	-636.0	710	18.94	-476.0
5	5.3	134.6	134.6	-757.8	427	54.2	-635.9	710	37.5	-476.0
6	5.3	247	247	-757.6	427	96.8	-635.9	710	66.3	-475.9
7	6.5	418	455	-757.3	427	159.1	-635.7	710	107.7	-475.8
8	8.5	662	743	-756.7	427	247	-635.5	710	164.9	-475.7
9	12	990	1209	-755.8	427	367.	-635.2	710	242	-475.5
10	16	1413	1818	-754.3	427	523	-634.8	710	343	-475.2
11	22	1919	2589	-752.1	427	723	-634.2	710	471	-474.8
12	28	2499	3504	-748.9	427	968	-633.3	710	632	-474.2
13	37	3142	5112	-744.5	427	1259	-632.2	710	830	-473.5
14	50	3866	6816	-738.5	427	1597	-630.8	710	1067	-472.9
15	63	4678	8505	-731.0	427	1978	-629.0	710	1340	-471.4

Note: atm \times 0.101325 = MPa.

Table 15. Isothermal Compressibility of Solid

Parahydrogen ($x_T \times 10^5$), cm^2/kg

$P, \text{kg}/\text{cm}^2$	T, K	14.5	13.5	12.0	10.0; 8.0; 6.0
0			59.8 ^a	57.1 ^a	53.7 ^a
20			54.4 \pm 1.4	52.3 \pm 1.3	49.4 \pm 1.6
40		53.1	49.9	48.2	45.8
60		48.8	46.2	44.7	42.8
80		45.0	42.9	41.8	40.2
100		41.8	40.2	39.3	38.0
120		39.1	37.9	37.2	36.2
140		36.7	36.0	35.4	34.8
180		33.0 \pm 0.7	32.9 \pm 0.7	32.5 \pm 0.8	32.3 \pm 1.2
200					31.2 ^a

^aObtained by extrapolation.

With permission from Udovidchenko, B. G., et al., Journ. Low Temp. Phys., 3(4), 429,
 1970 [Ref. 16].

Table 16. Experimental Values of the Latent Heat of Fusion of Hydrogen

Hydrogen modification		Author (year)	Temperature K	ΔH fusion cal/mol
n-H ₂		Simon and Lange ¹⁸³ (1923)	T.P. (13. 93)	<u>28.0</u> ± 0.15 cal/mol
94% p-H ₂	Clusius and Hiller ¹⁸²	(1929)	T.P. (13. 95)	28.03 ± 0.4 cal/mol
99.8% p-H ₂	Johnston, et al. ¹¹⁶	(1950)	T.P. (13. 845)	<u>28.08</u> ^a ± 0.15 cal/mol
99.79% p-H ₂	Ahlers ¹⁶⁹	(1963)	T.P. (13. 803)	28.20 ± 0.24 cal/mol
99.79% p-H ₂	Dwyer, et al. ¹¹⁷	(1965)	T.P. (13. 803)	27.75 cal/mol
"	"	"	T.P. (13. 803)	28.00 cal/mol
"	"	"	$\left\{ \begin{array}{l} 13.808 \text{ (0.203 atm)} \\ 14.653 \text{ (25.85 atm)} \end{array} \right.$	27.87 cal/mol
"	"	"	$\left\{ \begin{array}{l} 15.535 \text{ (54.4 atm)} \\ 17.813 \text{ (136.05 atm)} \end{array} \right.$	29.37 cal/mol
"	"	"	$\left\{ \begin{array}{l} 19.481 \text{ (202.38 atm)} \\ 19.522 \text{ (204.08 atm)} \end{array} \right.$	30.80 cal/mol
"	"	"	$\left\{ \begin{array}{l} 21.186 \text{ (275.51 atm)} \\ 338.10 \text{ atm) } \end{array} \right.$	34.21 cal/mol
"	"	"	"	36.95 cal/mol
"	"	"	"	36.91 cal/mol
"	"	"	"	40.28 cal/mol
"	"	"	"	42.87 cal/mol

^a Average values for more than one run.

Note: atm × 0.101325 = MPa; (cal/mol) × 4.1840 = J/mol.

Table 17. Lattice Parameters for Hydrogen

Ranges of lattice parameters, nm

species	structure	a	c	c/a	References
p - H ₂	hcp	0.375 - 0.3761	0.6105 - 0.614	0.1623 - 0.1633	146, 188, 189
	fcc	0.524 ± 0.005	---	---	155
n - H ₂	hcp	0.376 - 0.378	0.6105 - 0.616	0.1623 - 0.1633	186-188, 190
	fcc	0.5312 - 0.5338	---	---	186-188

Table 18. Debye θ , Adiabatic Bulk Modulus and Elastic Constants for Hydrogen

	Debye θ , K	adiabatic bulk modulus ¹⁹⁷
mechanical	$\left\{ \begin{array}{l} 111, \text{ single crystal normal}^{197} \\ 113, \text{ polycrystal para}^{196} \end{array} \right.$	174 MPa (1740 bar)
calorimetric	$\left\{ \begin{array}{l} 124, \text{ para calorimetric}^{169} \\ 122, \text{ para calorimetric}^{174} \end{array} \right.$	(assuming $V = 22.87 \text{ cm}^3/\text{mol}$)

Elastic Constants/density, cm^2/s^2 (Data from Reference 197)

normal hydrogen	$\frac{c_{11}}{\rho}$	$\frac{c_{12}}{\rho}$	$\frac{c_{13}}{\rho}$	$\frac{c_{33}}{\rho}$	$\frac{c_{44}}{\rho}$
	4.10	1.35	0.45	4.99	0.94

Table 19. Shear Strength of Hydrogen at 4 K

shear strength(kg/cm ²)	29	41.6	61.4	64.6
mean applied pressure(kg/cm ²)	1050	2010	3190	3710

Table 20. Melting Pressures of Normal Hydrogen

Temperature K	Pressure MPa	Pressure atm
13.947	0.0072	0.071
14.	0.1662	1.64
15.	3.2880	32.45
16.	6.647	65.60
17.	10.22	100.9
18.	14.01	138.3
19.	18.01	177.7
20.	22.18	218.9
21.	26.54	261.9
22.	31.09	306.8
23.	35.80	353.3
24.	40.68	401.5
26.	50.94	502.7
30.	73.35	723.9
35.	104.8	1034.
40.	139.8	1380.
45.	178.5	1762
50.	220.7	2178

Table 21. Molar Volume^a of Compressed Solid Parahydrogen

Pressure (atm)	Temperature (°K)				
	11.49°	13.98°	16.89°	18.20°	19.97°
0	23.08				
25	22.63	22.83			
50	22.22	22.58			
75	21.85	22.24			
100	21.53	21.93			
150		21.26	22.00		
200			21.55	21.52	
250			21.10	21.07	21.45
300				20.70	21.30
350					21.15

^a All values of the molar volume are in cubic centimeters per mole.

With permission from Cook, G. A., et. al., Journ. Chem. Phys., 43 (4), 1313, 1965
 [Ref. 211]. Note: atm x 0.101325 = MPa.

Table 22. Compressions of Normal Hydrogen at 4 K

Pressure kg/cm ²	$\frac{\Delta V}{V_0}$	$\frac{V}{V_0}$	M.V. cm ³ /mol	$10^5 \beta_i$ cm ² /kg
P ₀ or 0	---	1.000	22.65	49
200	---	.928	21.0	31
400	---	.883	20.0	23
600	---	.847	19.2	19
1,000	---	.794	18.0	14
2,043	0	.711	16.1	8.1
3,000	.065	.667	15.1	6.1
4,000	.110	.632	14.3	4.8
6,000	.181	.583	13.2	3.5
8,000	.227	.549	12.4	2.7
10,000	.266	.523	11.8	2.3
12,000	.297	.500	11.3	1.9
16,000	.343	.467	10.6	1.4
20,000	.376	.445	10.1	1.2

With permission from Stewart, J. W., Phys. Chem. Solids, 1, 146, 1956 [Ref. 180].

Table 23. Volume Changes of Hydrogen on Fusion at Elevated Temperatures

T	Bartholome ²¹⁰ n-H ₂	Roder ¹⁴² p-H ₂	% Difference
13.96 K	2.83 cm ³ /mol	2.81 cm ³ /mol	.58
16.43	2.31	2.26	2.15
18.24	2.03	2.02	.61

Table 24. Sound Velocity in Solid Hydrogen

T, K	V cm ³ /mol	v _l m/s	v _t m/s	$\beta_s \times 10^{10}$ cm ² /dyn	"adiabatic" Poisson's ratio	$\beta_T \times 10^{10}$ cm ² /dyn	isothermal Poisson's ratio
n-hydrogen							
4.2	22.64	2190	1160	3.8	0.30	4.4	
11.49	23.08	2110	1080	3.9	0.32	4.6	
13.96	23.24	2060	1030	4.1	0.33	5.1	
p-hydrogen							
	g/cm ³						
0	0.0892	2110 ^a	1140 ^a	4.12	0.29	4.1	0.29
1	0.0892	2110 ^a	1140 ^a	4.12	0.29	4.6	0.29
2	0.0892	2110	1140	4.12	0.29	4.7	0.29
3	0.0891	2105	1140	4.15	0.29	4.8	0.26
4	0.0890	2100	1140	4.19	0.29	4.9	0.26
5	0.0889	2095	1140	4.22	0.29	5.2	0.25
6	0.0888	2090	1135	4.24	0.29	5.3	0.25
7	0.0887	2085	1130	4.26	0.29	5.3	0.25
8	0.0885	2075	1125	4.31	0.29	5.4	0.25
9	0.0883	2065	1120	4.36	0.29	5.4	0.25
10	0.0880	2050	1115	4.46	0.29	5.4	0.25
11	0.0877	2035	1105	4.53	0.29	5.6	0.25
12	0.0874	2010	1095	4.64	0.29		

^a extrapolated

Note: (cm²/dyne) $\times 10^5$ = cm²/N.

Table 25. Thermal Diffusivity of Solid Hydrogen

Parahydrogen							Normal Hydrogen						
Temperature K	Density mol/L	Heat Capacity J/mol-K	Thermal Conductivity W/cm-K	Thermal Diffusivity cm ² /s	Temperature K	Density mol/L	Heat Capacity J/mol-K	Thermal Conductivity W/cm-K	Thermal Diffusivity cm ² /s				
4.	43.98	.080	1.4	397.8	4.	43.98	2.100	.0100	.108				
5.	43.96	.169	.54	72.6	5.	43.96	1.995	.0178	.202				
6.	43.91	.319	.17	12.1	6.	43.91	1.894	.0240	.288				
7.	43.84	.550	.083	3.44	7.	43.84	1.897	.0235	.282				
8.	43.76	.881	.045	1.16	8.	43.76	2.071	.0202	.222				
9.	43.66	1.330	.0278	.478	9.	43.66	2.351	.0164	.159				
10.	43.54	1.914	.0191	.229	10.	43.54	2.717	.0131	.110				
11.	43.40	2.649	.0134	.116	11.	43.40	3.156	.0107	.0781				
12.	43.24	3.550	.0099	.0645	12.	43.24	3.905	.0086	.0509				
13.	43.06	4.631	.0074	.0371	13.	43.06	4.857	.0071	.0339				

Table 26. Thermal Expansion of Solid Parahydrogen

Temperature K	Thermal expansion coefficient, $\alpha \times 10^4$, 1/K	Temperature K	Thermal expansion coefficient, $\alpha \times 10^4$, 1/K
1	0.022	8	21.7
2	0.22	9	26.7
3	1.0	10	30.4
4	3.0	11	34.6
5	6.5	12	39.4
6	11.3	13	44.7
7	16.5	13.80	49.4

Table 27. Experimental Vapor Pressures of Normal Hydrogen
Below the Triple Point

solid		
T (K)	P(Pa)	P (mm Hg)
3.4	1.33×10^{-7}	1.0×10^{-9}
3.6	7.33×10^{-7}	5.5×10^{-9}
3.8	3.87×10^{-6}	2.9×10^{-8}
4.0	12.67×10^{-6}	9.5×10^{-8}
4.2	4.67×10^{-5}	3.5×10^{-7}
4.5	2.40×10^{-4}	1.8×10^{-6}
Reference 208		
4.71	6.03×10^{-4}	4.52×10^{-6}
4.78	7.64×10^{-4}	5.73×10^{-6}
4.85	9.71×10^{-4}	7.28×10^{-6}
4.92	1.36×10^{-3}	1.02×10^{-5}
5.01	1.83×10^{-3}	1.37×10^{-5}
5.0	2.52×10^{-3}	1.89×10^{-5}
7.43	5.36	4.02×10^{-2}
7.74	8.96	6.72×10^{-2}
8.11	17.2	1.29×10^{-1}
8.76	42.4	3.18×10^{-1}
9.29	97.6	7.32×10^{-1}
9.91	206.6	1.55
10.67	482.6	3.62
11.11	759.9	5.70
Reference 209		

Table 28. Selected Thermophysical, Chemical, and Combustion Properties of Hydrogen, Methane, and Gasoline

<u>Property</u>	<u>Hydrogen</u>	<u>Methane</u>	<u>Gasoline</u>
Molecular weight	2.016 ²²⁶	16.043 ²²⁹	~107.0 ²³¹
Triple point pressure, atm	0.0695 ²²⁶	0.1159 ²²⁹	---
Triple point temperature, K	13.803 ²²⁶	90.680 ²²⁹	180 to 220 ²³¹ ^a
Normal boiling point (NBP) temperature, K	20.268 ²²⁶	111.632 ²²⁶	310 to 478 ^{231, 232}
Critical pressure, atm	12.759 ²²⁶	45.387 ²²⁹	24.5 to 27 ²³¹
Critical temperature, K	32.976 ²²⁶	190.56 ²²⁹	540 to 569 ²³¹
Density at critical point, g/cm ³	0.0314 ²²⁶	0.1604 ²²⁹	0.23 ²³³
Density of liquid at triple point, g/cm ³	0.0770 ²²⁶	0.4516 ²²⁹	---
Density of solid at triple point, g/cm ³	0.0865 ²²⁶	0.4872 ²²⁶	---
Density of vapor at triple point, g/m ³	125.597 ²²⁶	251.53 ²²⁹	---
Density of liquid at NBP, g/cm ³	0.0708 ²²⁶	0.4226 ²²⁶	~.70 ²³¹ ^b
Density of vapor at NBP, g/cm ³	0.00134 ²²⁶	0.00182 ²²⁶	~0.0045 ²³³ ^b
Density of gas at NTP, g/m ³	83.764 ²²⁶	651.19 ²²⁶	~4400 ²³³
Density ratio: NBP liquid-to-NTP gas	845 ²²⁶	649 ²²⁶	156 ^{231, 233} ^c
Heat of fusion, J/g	58.23 ²²⁶	58.47 ²²⁶	161 ²³⁶
Heat of vaporization, J/g	445.59 ²²⁶	509.88 ²²⁶	309 ^{231, 233}
Heat of sublimation, J/g	507.39 ²²⁶	602.44 ²²⁶	---
Heat of combustion (low), kJ/g	119.93 ²²⁷	50.02 ²²⁷	44.5 ^{227, 228, 233}
Heat of combustion (high), kJ/g	141.86 ²²⁷	55.53 ²²⁷	48 ^{227, 228, 233}
Specific heat (C_p) of NTP gas, J/g-K	14.89 ²²⁶	2.22 ²²⁶	1.62 ²³³ ^b
Specific heat (C_p) of NBP liquid, J/g-K	9.69 ²²⁶	3.50 ²²⁶	2.20 ²³³ ^b
Specific heat ratio (C_p/C_v) of NTP gas	1.383 ²²⁶	1.308 ²²⁶	1.05 ²³¹ ^b
Specific heat ratio (C_p/C_v) of NBP liquid	1.688 ²²⁶	1.676 ²²⁶	---
Viscosity of NTP gas, g/cm-s	0.0000881 ²²⁶	0.000110 ²²⁶	0.000052 ²³³
Viscosity of NBP liquid, g/cm-s	0.000132 ²²⁶	0.001130 ²²⁶	0.002 ²³³
Thermal conductivity of NTP gas, mW/cm-K	1.914 ²²⁶	0.330 ²²⁶	0.112 ²³³
Thermal conductivity of NBP liquid, mW/cm-K	0.99 ²²⁶	1.86 ²²⁶	1.31 ²³³
Surface tension of NBP liquid, N/m	0.00193 ²²⁶	0.01294 ²²⁶	0.0122 ²³³
Dielectric constant of NTP gas	1.00026 ⁷	1.00079 ²²⁶	1.0035 ²³⁴ ^e
Dielectric constant of NBP liquid	1.233 ⁷	1.6227 ²²⁶	1.93 ²³³ ^d
Index of refraction of NTP gas	1.00012 ²²⁶	1.0004 ²²⁶	1.0017 ²³⁴ ^e
Index of refraction of NBP liquid	1.110	1.2739 ²²⁶	1.39 ²³³ ^d
Adiabatic sound velocity in NTP gas, m/s	1294 ²²⁶	448 ²²⁶	154
Adiabatic sound velocity in NBP liquid, m/s	1093 ²²⁶	1331 ²²⁶	1155 ²³⁶ ^f
Compressibility factor (Z) in NTP gas	1.0006 ²²⁶	1.0243 ²²⁶	1.0069
Compressibility factor (Z) in NBP liquid	0.01712 ²²⁶	0.004145 ²²⁶	0.00643 ^b
Gas constant (R), cm ³ -atm/g-K	40.7037 ²²⁶	5.11477 ²²⁶	0.77
Isothermal bulk modulus (O) of NBP liquid, MN/m ²	50.13 ⁷	456.16 ²³⁰	763 ²³⁵ ^f
Volume expansivity (β) of NBP liquid, K ⁻¹	0.01658 ⁷	0.00346 ²³⁰	0.0012 ²³³ ^b

Table 28. Selected Thermophysical, Chemical, and Combustion Properties of Hydrogen, Methane, and Gasoline (cont'd.)

<u>Property</u>	<u>Hydrogen</u>	<u>Methane</u>	<u>Gasoline</u>
Limits of flammability in air, vol. %	4.0 to 75.0 ^{237,238}	5.3 to 15.0 ^{237,238}	1.0 to 7.6 ^{232,242}
Limits of detonability in air, vol. %	18.3 to 59.0 ²³⁹	6.3 to 13.5 ²⁴³	1.1 to 3.3 ²⁴⁴
Stoichiometric composition in air, vol. %	29.53	9.48	1.76
Minimum energy for ignition in air, mJ	0.02 ²⁴⁰	0.29 ²⁴⁰	0.24 ^{240,245}
Autoignition temperature, K	858 ²⁴¹	813 ²³²	501 to 744 ^{232,242}
Hot air-jet ignition temperature, K	943 ²⁴⁶	1493 ²⁴⁶	1313 ²⁴⁶⁸
Flame temperature in air, K	2318 ²⁴⁷	2148 ²⁴⁷	2470 ²⁴⁸
Percentage of thermal energy radiated from flame to surroundings, %	17 to 25 ^{249,250}	23 to 33 ^{249,250}	30 to 42 ^{249,250}
Burning velocity in NTP air, cm/s	265 to 325 ^{251,252}	37 to 45 ^{242,243}	37 to 43 ^{242,248}
Detonation velocity in NTP air, km/s	1.48 to 2.15 ^{253,259}	1.39 to 1.64 ²⁴³	1.4 to 1.7 ^{254h}
Diffusion coefficient in NTP air, cm ² /s	0.61	0.16	0.05
Diffusion velocity in NTP air, cm/s	≤2.00	≤0.51	≤0.17
Buoyant velocity in NTP air, m/s	1.2 to 9	0.8 to 6	nonbuoyant
Maximum experimental safe gap in NTP air, cm	0.008 ²⁵⁵	0.12 ²⁵⁶	0.07 ²⁵⁵
Quenching gap in NTP air, cm	0.064 ^{240,257}	0.203 ^{240,257}	0.2 ²⁵⁷
Detonation induction distance in NTP air	L/D≈100 ^{259,260}	—	—
Limiting oxygen index, vol. %	5.0 ²⁵⁸	12.1 ²⁵⁸	11.6 ^{258f}
Vaporization rates (steady state) of liquid pools without burning, cm/min	2.5 to 5.0 ²⁵⁰	0.05 to 0.5 ²⁵⁰	0.005 to 0.02
Burning rates of spilled liquid pools, cm/min	3.0 to 6.6 ^{249,250}	0.3 to 1.2 ^{249,250}	0.2 to 0.9 ^{249,250}
Flash point, K	gaseous	gaseous	~230 ²³²
Energy ^j of explosion, (g TNT)/(g fuel)	~24	-11	~10
Energy ^j of explosion, (g TNT)/(cm ³ NBP liquid fuel)	1.71	4.56	7.04
Energy ^j of explosion, (kg TNT)/(m ³ NTP gaseous fuel)	2.02	7.03	44.22
Toxicity	nontoxic ²⁶¹ (asphyxiant)	nontoxic ²⁶² (asphyxiant)	slight ²⁶³ (asphyxiant)

NBP = Normal boiling point.

NTP = 1 atm and 20 C (293.15 K).

TNT = Symmetrical Trinitrotoluene.

Note: Thermophysical properties listed are those of parahydrogen. Gasoline property values are the arithmetic average of normal heptane and octane in those cases where "gasoline" values could not be found (unless otherwise noted). Also atm x 0.101325 = MPa.

a Freezing temperatures for gasoline @ 1 atm.

b @ 1 atm and 15.5 C.

c Density ratio @ 1 atm and 15.5 C.

d @ 1 atm and 20 C.

e @ 1 atm and 100 C.

f @ 1 atm and 25 C.

g Based on the properties of butane.

h Based on the properties of n-pentane and benzene.

i Average value for a mixture of methane, ethane, propane, benzene, butane and higher hydrocarbons.

j Theoretical explosive yields.

Table 29
 ORTHO-PARA
 CONCENTRATIONS AT
 EQUILIBRIUM

Temperature, K	Percentage in para form for H ₂
10	99.9999
20	99.821
20.39	99.789
23.57	-
30	95.034
33.10	88.727
40	77.054
50	65.569
60	55.991
70	48.537
80	42.882
90	38.620
100	32.959
120	28.603
150	25.974
200	25.264
250	25.075
298.16	25.072
300	25.019
350	25.005
400	25.000
500	-

Table 30
 HEATS OF CONVERSION FROM
 NORMAL TO PARAHYDROGEN

Temperature, K	J/g	cal/mol
10	527.139	253.9865
20	527.140	253.987
20.39	527.138	253.986
30	527.138	253.986
33.1	527.138	253.976
40	527.117	253.845
50	526.845	253.212
60	525.531	251.400
70	521.770	247.623
80	513.932	241.275
90	500.757	232.079
100	481.671	205.857
120	427.248	155.385
150	322.495	78.91
200	163.774	33.98
250	70.524	13.76
298.16	28.558	13.28
300	27.562	-

CHAPTER SEVEN

PHYSICAL CONSTANTS, UNIT CONVERSIONS, AND SYMBOLS

Jesse Hord

7.1. PHYSICAL CONSTANTS

Molecular weight = 2.01594

$$\begin{aligned}\text{Universal gas constant } (R_0) &= 8.31434 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \\ &= 8.31434 \times 10^6 \text{ N} \cdot \text{cm}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \\ &= 82.0562 \text{ atm} \cdot \text{cm}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \\ &= 10.7314 \text{ psi} \cdot \text{ft}^3 \cdot \text{mol}^{-1} \cdot {}^\circ\text{R}^{-1}\end{aligned}$$

slug = 32.174 lb

7.2. UNIT CONVERSIONS

The international system of units is described in detail in NBS Special Publication 330⁵¹⁵ and lists of physical constants and conversions factors are tabulated by Mechtly.⁵¹⁶ The American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), and Institute of Electrical and Electronics Engineers (IEEE) have published a joint standard for metric practice.⁵¹⁷ The most recent guidelines for use of the metric system are given in References 515, 517 and 518. Selected unit conversions are given in the following tables.

UNIT CONVERSION FACTORS

<u>Density</u>				
kg/m ³	g/cm ³	mol/cm ³	Amagat	lb/ft ³
16.018	0.016018	7.9458×10^{-3}	178.216	1
1	0.001	4.9605×10^{-4}	11.126	0.062428
1,000	1	0.49605	1.1126×10^4	62.428
2,015.9	2.0159	1	2.2428×10^4	125.85
0.089881	8.9881×10^{-5}	4.4586×10^{-5}	1	5.6111×10^{-3}

Specific Volume

m^3/kg (L/g)	cm^3/g	cm^3/mol	ft^3/lb
0.062428	62.428	125.85	1
1	1,000	2,015.9	16.018
0.001	1	2.0159	0.016018
4.9605×10^{-4}	0.49605	1	7.9458×10^{-3}

Pressure

MPa	atm	Torr (mm Hg)	bar	lbf/in.^2 (psi)
6.8948×10^{-3}	0.068046	51.715	6.8948×10^{-2}	1
1	9.8692	7,500.6	10.0	145.04
0.101325	1	760.0	1.01325	14.696
1.3332×10^{-4}	1.3158×10^{-3}	1	1.332×10^{-3}	0.019337
0.1	0.98692	750.06	1	14.504

Enthalpy, Heat of Vaporization, Heat of
Conversion, Specific Energies

kJ/kg (J/g)	J/mol	cal/g	Btu/lb
2.3244	4.6858	0.55556	1
1	2.0159	0.23901	0.43022
0.49605	1	0.11856	0.21341
4.1840	8.4345	1	1.8

Specific Heat, Entropy

kJ/kg-K (J/g-K)	J/mol-K	cal/mol-K	Btu/lb-°R
4.184	8.4345	2.0159	1
1	2.0159	0.48182	0.23901
0.49605	1	0.23901	0.11856
2.0755	4.184	1	0.49605

Thermal Conductivity

mW/cm-K	J/s-cm-K	cal/s-cm-K	Btu/ft-hr-°R
17.296	0.017296	0.0041338	1
1	0.001	2.3901×10^{-4}	0.057816
1,000	1	0.23901	57.816
4,184	4.184	1	241.90

Viscosity

kg/m-s (N-s/m ²)	Centipoise (10^{-2} g/cm-s)	lb-s/ft ² (slug/ft-s)	lb/ft-s
1.48816	1,488.16	0.31081	1
1	1,000	0.020885	0.67197
0.001	1	2.0885×10^{-5}	6.7197×10^{-4}
47.881	4.7881×10^4	1	32.175

Velocity of Sound

Surface Tension

m/s	ft/s	N/m	dyne/cm	lb _f /in.
0.3048	1	175.13	175.13×10^3	1
1	3.2808	1	1,000	5.7102×10^{-3}
		0.001	1	5.7102×10^{-3}

Temperature

$$T(\text{Rankine}) = 1.8T(\text{Kelvin})$$

$$T(\text{Celsius}) = T(\text{Kelvin}) - 273.15$$

$$T(\text{Fahrenheit}) = T(\text{Rankine}) - 459.67$$

$$T(\text{Fahrenheit}) = 1.8T(\text{Celsius}) + 32$$

7.3. SYMBOLS

Some of the symbols used in this compilation describe more than one property because: (1) data and accompanying symbols are gleaned from the literature and the nomenclature selected by the originating author(s) is retained and (2) the number of properties compiled far exceeds the number of available symbols. Multiple use of symbols should not result in any confusion as they are explained in the text, on the figure or table wherein they are used in context with the particular property under consideration.

7.3.1. LIST OF SYMBOLS

atm	atmosphere (pressure)
a	lattice parameter
a	accommodation coefficient
b_1, b_2, b_3 , etc.	coefficients in equations
c	lattice parameter
cal	calorie
c_i	concentration of species "i" in mixture
cm	centimeter
cP	centipoise

d_A	density in amagats
dt	derivative with respect to time
ft	foot
g	gravitational acceleration constant
g	gram
h	hour
i	used as subscript to denote "ith" element or species
j	used as subscript to denote "jth" element or species
k	thermal conductivity
k	infrared absorption coefficient
kg	kilogram
ℓ	liter
l	liter
lb	pound mass
lb_f	pound force
m	meter
n	exponent in equations
n	index of refraction, also n_λ and $n_\infty \dots$ at infinite wavelength
p	used as subscript to denote constant pressure
P_0	vapor pressure
s	second
t	time
v	specific volume
v_ℓ	longitudinal velocity of sound in the solid
v_t	transverse velocity of sound in the solid
x	quality
x	fraction of ortho hydrogen in ortho-para mixture
x_T	isothermal compressibility

A,B,C	coefficients in equations
\tilde{A}	infrared absorption parameter
B	second virial coefficient
Btu	British thermal unit
C	third virial coefficient
C	temperature in degrees Celsius
$C_{11}, C_{12}, C_{13}, C_{33}, C_{44}$	elastic constants
C_i	concentration gradient of the "i" species
C_p	specific heat at constant pressure
C_p°	molar specific heat at constant pressure
C_v	specific heat at constant volume
C_σ	specific heat at saturation
D_{ij}	diffusion coefficient
D_{ij}^T	thermal diffusion coefficient
E	Young's modulus
E	internal energy
E°	molar internal energy
F	temperature in degrees Fahrenheit
F	Helmholtz free energy
F°	molar free energy
FCC	also fcc, face centered cubic
G	shear modulus
G	Gibbs free energy
H	enthalpy
H°	molar enthalpy
HCP	also hcp, hexagonal close packed
I	intensity of radiation

J	joules = watt · second
J _i	mass flux of the "ith" species
K	absolute temperature in kelvin
L	liter
LFL	lower flammable limit
LNG	liquefied natural gas
M	molecular weight
MESG	maximum experimental safe gap
MPa	megaPascal (pressure)
N	Newton
NBP	normal boiling point
NBT	normal boiling temperature (same as NBP)
NTP	normal temperature and pressure (20°C and 1 atm)
NPr	Prandtl number
P	pressure
P	molar polarizability
Pa	Pascal (pressure)
Pr	Prandtl number
P _t	triple point pressure
Q	quality
Q	heat
R	absolute temperature in degrees Rankine
R	gas constant
R ₀	universal gas constant
RI	refractive index
RTP	room temperature and pressure (300 K and 1 atm)
S	entropy
S°	molar entropy
STP	standard temperature and pressure (0°C and 1 atm)

T	temperature
T _c	critical point temperature
T _t	triple point temperature
TNT	symmetrical trinitrotoluene
Torr	millimeter of mercury (pressure)
T _P	triple point
U	internal energy
UFL	upper flammable limit
V	volume
W	watt
W	velocity of sound
X	mole percent solubility in solvent
Z	compressibility factor ($\equiv PV/RT$)

Greek

α	parameter in equation
α	thermal diffusivity
α	isothermal bulk modulus
α	thermal expansion coefficient
β	volume expansivity
β_i	"instantaneous" compressibility (\approx isothermal)
β_s	adiabatic compressibility
β_T	isothermal compressibility
γ	specific heat ratio ($\equiv C_p/C_v$)
γ	surface tension
ϵ	dielectric constant
ϵ	relative elongation

η	viscosity
θ	Debye temperature
θ	specific heat input parameter
λ	thermal conductivity
λ	wavelength
μ	viscosity
μ	Joule-Thomson coefficient
ν	frequency
ρ	density
ρ_c	density at critical point
σ_t	tensile strength (stress)
σ_y	nominal yield strength (stress)
Φ	energy derivative parameter
ω	velocity of sound

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) The National Bureau of Standards has been engaged in the compilation, review, analytical and experimental derivation, and publication of hydrogen properties for over 20 years. The properties data presented herein are compiled largely from those accumulated data; of course, pertinent data and work of other researchers in the field are also included. The general interests of scientists and engineers engaged in energy systems studies were given top priority in choosing the properties material presented in this book. Hydrogen systems cut across many energy related fields, e.g., nuclear fusion, magnetohydrodynamics, electrolysis and thermochemical decomposition of water, coal and shale derivative fuels, solar and wind power, ocean energy, geothermal processes, etc. It is generally conceded that hydrogen could be used to satisfy virtually all fuel requirements that are currently being met with natural gas and oil. To satisfy the demand for properties data over this broad spectrum of interests, we have attempted to provide comprehensive coverage of physical properties over a wide range of pressures and temperatures. Thermophysical properties of liquid, liquid-vapor, vaporous, and gaseous hydrogen are presented in Chapter 1 and the solid-liquid, solid-vapor, and solid phase properties are compiled in Chapter 2. Ortho-para modifications of the hydrogen molecule and attendant property variations are considered in both chapters. Combustion and safety data, pertinent to hazard analysis of hydrogen systems, is collected in Chapter 3. Important miscellaneous properties are compiled in Chapter 4, data figures are compiled in Chapter 5, data tables are collected in Chapter 6, and Chapter 7 summarizes symbols, units, and conversion factors used throughout the book.				
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