

PROPERTIES OF UNDISSOCIATED NITROGEN, OXYGEN, AIR  
AND ARGON AT PRESSURES UP TO 1,000 ATMOSPHERES

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
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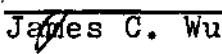
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## NOMENCLATURE

English  
Notation

A	=	molar (atomic) refractivity
B(T)	=	second virial coefficient, function of temperature only
B'(T)	=	B(T)/RT, function of temperature only
B*	=	B(T)/b <sub>0</sub> , reduced second virial coefficient
b <sub>0</sub>	=	2/3 πN̄σ <sup>3</sup>
c	=	velocity of light in vacuum
C(T)	=	third virial coefficient, function of temperature only
C'(T)	=	[C(T) - B(T) <sup>2</sup> ]/RT <sup>2</sup>
C*	=	C/b <sub>0</sub> <sup>2</sup> , reduced third virial coefficient
C <sub>p</sub>	=	molar specific heat at constant pressure for real gas
C <sub>p</sub> <sup>o</sup>	=	molar specific heat at constant pressure for ideal gas
C <sub>v</sub>	=	molar specific heat at constant volume for real gas
C <sub>v</sub> <sup>o</sup>	=	molar specific heat at constant volume for ideal gas
D(T)	=	fourth virial coefficient, function of temperature only
E	=	electric field intensity
e <sub>i</sub>	=	charge of i <sup>th</sup> particle in molecule
f( ρ̄ )	=	Mayer function = exp[-βϵ <sub>2</sub> ( ρ̄ )]-1
f <sub>i</sub>	=	oscillator strength
H	=	molar enthalpy for real gas
H'	=	Hamiltonian

$H^0$	=	molar enthalpy for ideal gas
$h$	=	Planck's constant
$k$	=	Boltzmann constant $\approx 1.3804 \times 10^{-16}$ erg/ $^{\circ}$ K
$k_i$	=	force constant of $i^{\text{th}}$ particle in molecule
$M$	=	molecular weight
$m_i$	=	mass of $i^{\text{th}}$ particle in molecule
$N$	=	the number of molecules per unit volume
$\bar{N}$	=	Avogadro's number
$n'$	=	total number of particles
$n$	=	index of refraction
$p$	=	pressure, momentum vector $p_1 \dots p_n$
$Q_n$	=	configurational partition function of a system comprised of $n$ particles
$Q_n^{(1)}$	=	first approximation to configurational partition function
$Q_n^{(2)}$	=	second approximation to configurational partition function
$r$	=	coordinate vectors $r_1 \dots r_n$ ; intermolecular separation
$\delta r_i$	=	displacement of $i^{\text{th}}$ particle in molecule from its equilibrium position
$r^*$	=	$r/\sigma$ , reduced intermolecular separation
$S$	=	molar entropy for real gas
$S^0$	=	molar entropy for ideal gas
$T$	=	absolute temperature
$T^*$	=	$kT/\epsilon$ , reduced temperature
$t$	=	time
$U$	=	molar internal energy for real gas

$U^{\circ}$	=	molar internal energy for ideal gas
$V$	=	molar volume
$v$	=	specific volume
$V^*$	=	$V/b_0$ , reduced molar volume
$\chi^{(e)}$	=	electric susceptibility
$Z'$	=	partition function for a collection of particles;
$Z$	=	compressibility factor

Greek  
Notation

$\alpha$	=	mean polarizability
$\beta$	=	$(kT)^{-1}$
$\rho$	=	density
$\sigma$	=	intermolecular potential constant
$e/k$	=	force constant
$\phi(r)$	=	intermolecular potential energy
$\Phi$	=	$\Phi$ -function [ $= \exp(-\beta\epsilon_2)$ ]
$\nu_0$	=	frequency of incident light
$\nu_i$	=	frequency of $i^{\text{th}}$ particle in molecule
$\lambda_0$	=	wavelength of incident light
$\mu$	=	induced dipole moment
$\epsilon$	=	dielectric constant
$\epsilon_2$	=	intermolecular potential energy (pair potential)

## SUMMARY

The thermodynamic properties and index of refraction for nitrogen, oxygen, air and argon have been calculated over a temperature range of 273 to 2,500°K for pressures ranging from 1 to 1,000 atmospheres. The calculated properties include density, internal energy, entropy, specific heats at constant pressure and constant volume, and index of refraction. Results are presented in tabular and graphical form. The results are found to agree within a few percent with the results of more rigorous calculations and are thus considered to be suitable for engineering purposes.

The theories and the equations used for determining the thermodynamic properties and the index of refraction are discussed in Chapter III. The reduced virial coefficients utilized for the computations of nitrogen, oxygen, air and argon properties are given in Appendix A, B, C, and D, respectively. The results are shown in the tables and figures of Chapter IV.

## CHAPTER I

### INTRODUCTION

Recent advances in engineering technology, connected with re-entry studies, high intensity radiation sources, high power circuit breakers, and magneto-hydrodynamic energy conversion systems (MHD) have produced a need for thermodynamic data for nitrogen, oxygen, air and argon over a wider range of temperatures and pressures than those provided by previous calculations and experiments.

In simulation and re-entry studies, gas is heated to plasma temperatures by an electrical arc discharge operation at pressure levels up to 200 atmospheres. Stagnation pressures up to 1,200 atmospheres are observed at leading edges of re-entry vehicles and the temperature in the plasma in front of the stagnation point is up to 10,000°K. In radiation sources used for laser pumping and other applications, pressure levels up to 50 atmospheres are applied, while system studies indicate a favorable effect of high pressure levels ( $p < 100 \text{ atm}$ ) in magneto-hydrodynamic energy conversion systems.

In all the previously mentioned systems, the plasma is contained in a gas blanket with temperatures reaching from high levels (plasma temperatures) close to the core to low values (wall temperature) at the boundaries of the device.

On the other hand, the energy transfer by conduction, convection and radiation from the plasma to the boundaries takes place through

this cold gas blanket. In this way, the cold gas thermodynamic properties are needed to establish the boundary conditions for the plasma. In addition, optical diagnostic takes place through this "cold" gas. At high pressures and low temperatures, the index of refraction shows a substantial deviation from unity. For side-on spectroscopic observations of the plasma, it is therefore necessary to evaluate the dependence of the index of refraction on the pressure and the temperature in the range of interest.

The present study was undertaken in an effort to meet present needs in this area. With this aim in view, it was decided to compute thermodynamic data and values of the index of refraction over a temperature range from 273°K to 2,500°K and a pressure range of 1 atmosphere to 1,000 atmospheres.

For these computations it was necessary to select the appropriate theories. A multitude of different equations of state have been used for the description of gas imperfections (2-13, 29, 31). For the ranges of  $p$  and  $T$  investigated here, the virial equation of state <sup>(14)</sup> furnishes results which seem to agree best with experimental results. Also, a great number of expressions for the intermolecular potential are found in the literatures. However, the most commonly used potential for monatomic, diatomic gases and mixtures of such gases, is the Lennard-Jones "(6-12)" potential <sup>(26)</sup>. By using the reduced virial coefficients in the virial equation of state, thermodynamic properties can be easily computed from the thermodynamic relations.

At high temperatures, the index of refraction at a fixed frequency of gases such as nitrogen, oxygen, air and argon shows a very

complicated dependence on the type of gas and density. However, a simplified theory is presented in Born and Wolf <sup>(22)</sup>. It is based on the further development of the well known Lorentz-Lorenz equation <sup>(28)</sup>. Results computed with this theory show excellent agreement with experimental values. From references 12, 13 and 22, we can see that for a given type of gas and a given density, the index of refraction is almost independent of the wavelengths of the incident light in the visible wavelength region of interest here. An example is given in Table 1-1 <sup>(12)</sup>.

Table 1-1. The Index of Refraction of Argon at 25°C

P (atm)	n					
	$\lambda_0 = 6678\text{Å}$	5876 Å	5016 Å	4922 Å	4713 Å	4471 Å
1	1.0002567	1.0002580	1.0002596	1.0002597	1.0002604	1.0002611
21.4	1.00555	1.00576	1.00575	1.00576	1.00581	1.00581
100.8	1.02753	1.02761	1.02777	1.02782	1.02788	1.02791
690.8	1.13458	1.13505	1.13582	1.13602	1.13633	1.13669
1040.4	1.16024	1.16078	1.16160	1.16191	1.16222	1.16264

Therefore, values of the index of refraction computed for one wavelength in the visible range may be used for the whole visible range.

From computations carried out here, it was found out that the percentage of dissociation at 2,500°K (the highest temperature considered in this paper) is 9 percent for oxygen and only 0.02 percent for nitrogen. Therefore, the simple gas model is employed in the

calculations of this paper; that is each species present is considered to be undissociated insofar as its equation of state is concerned. Considering this small degree of dissociation, this approach appears to be justified.

The equations used can be readily included in a computer program for a gas-dynamic problem requiring the thermodynamic properties of the gases investigated here.

## CHAPTER II

## PREVIOUS WORK

Although numerous publications of thermodynamic properties of nitrogen, oxygen, air and argon have appeared, few of these are extended sufficiently in the ranges of pressures and temperatures for the present purposes. In addition, the calculations and experiments have usually been carried out only for a limited number of properties.

Figures 2-1, 2-2, 2-3 and 2-4 summarize the ranges of the previous work (2-13, 29, 31, 33) on nitrogen, oxygen, air and argon, respectively. The areas denoted by numbers indicate the ranges of pressure and temperature for a certain property (or properties) that have been covered in previous work of other authors. The letters "T" and "E" indicate that the work was based on a theoretical approach or an experimental approach, respectively.

In some of these papers, equations of state other than the virial equation of state were used. However, with the exception of Michels, Wouter and de Boer's paper (33), the intermolecular potential used in all of the reviewed previous publications is the Lennard-Jones potential. In this paper, the equation of state used is Van der Waals equation of state, and the intermolecular potential used is the corrected rigid-sphere potential.

From Figures 2-1 to 2-4, it can be seen that some of the thermodynamic properties (internal energy, enthalpy, entropy, specific heats)

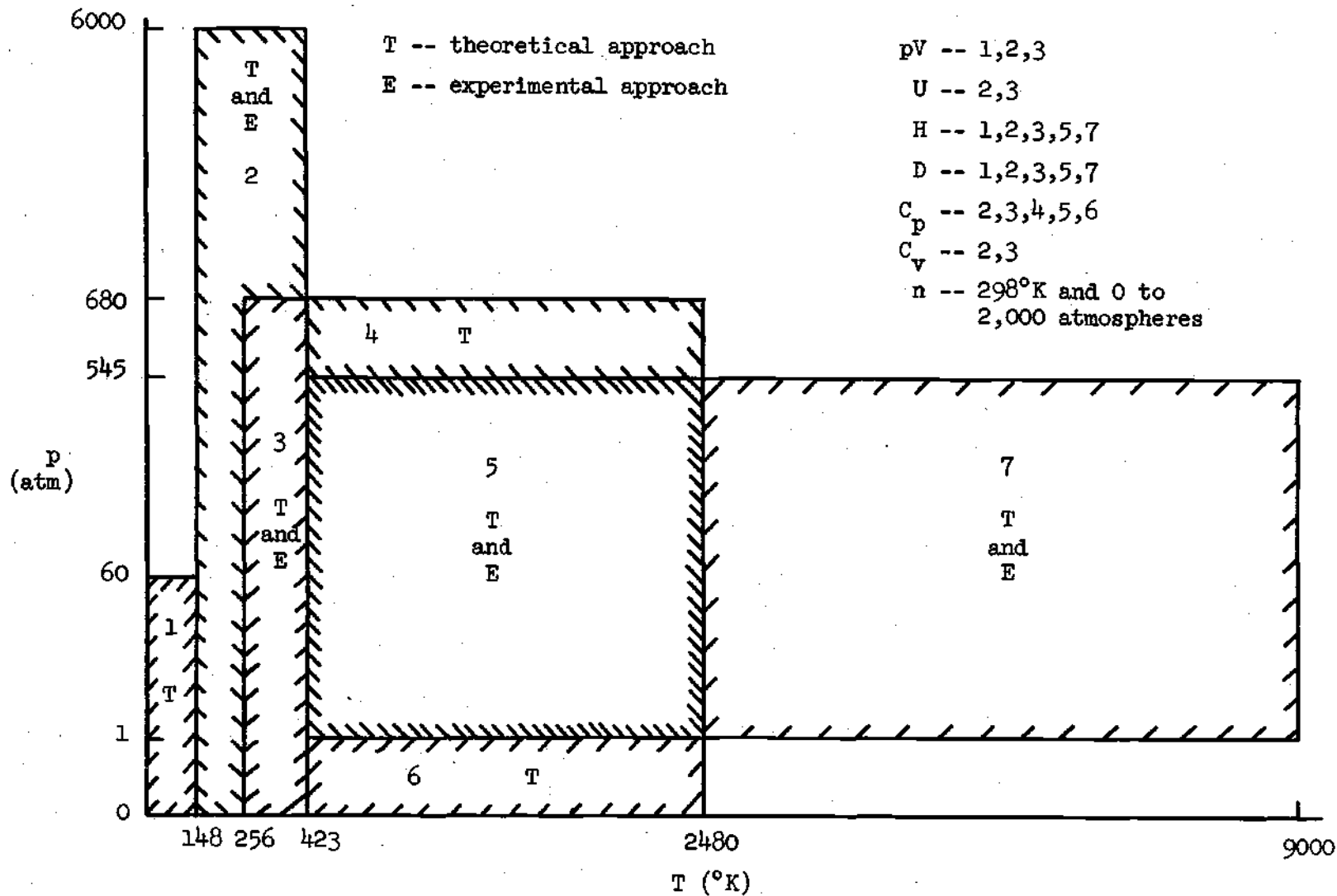


Figure 2-1. Ranges of Previous Work on  $N_2$

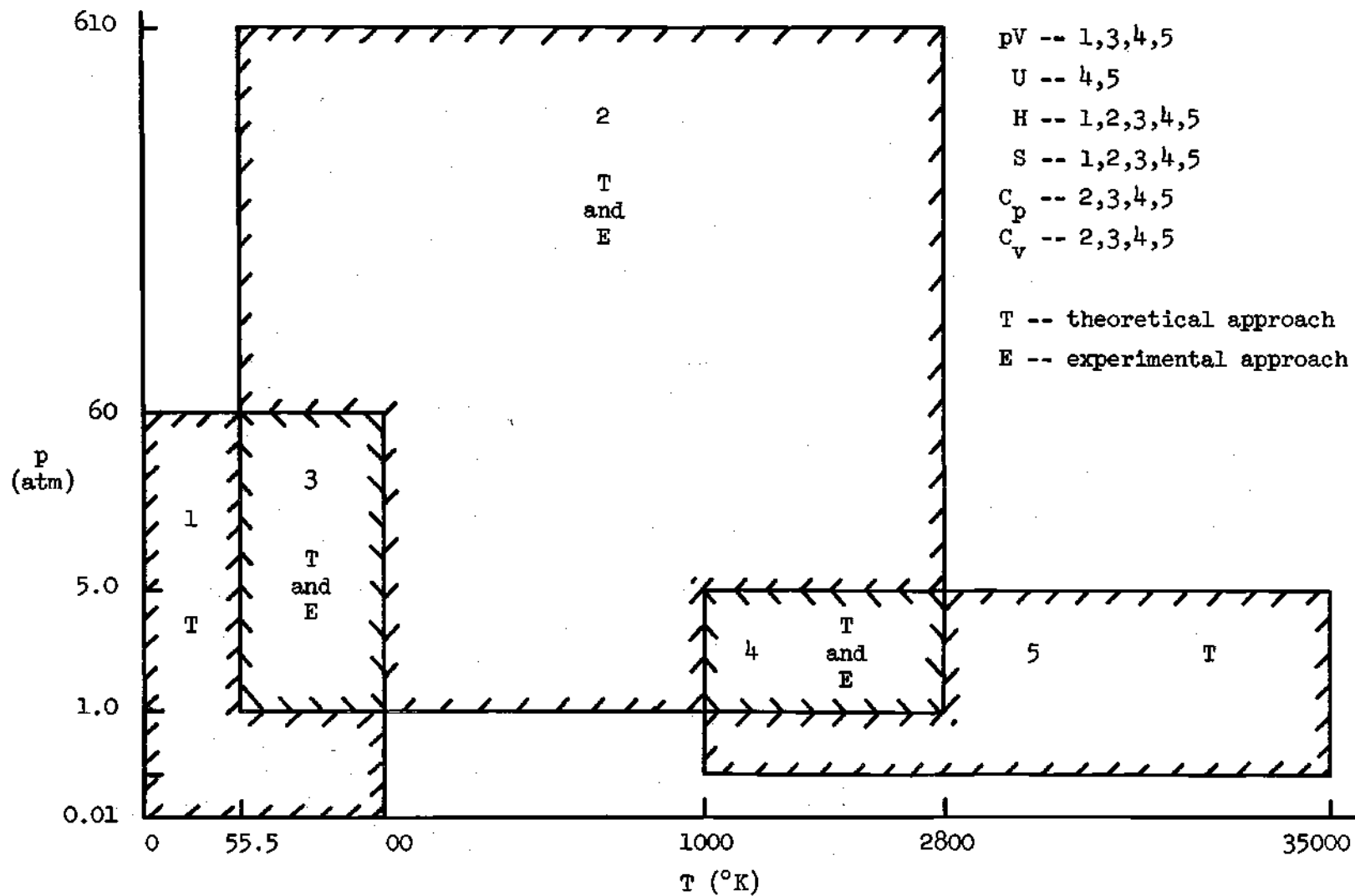


Figure 2-2. Ranges of Previous Work on  $O_2$

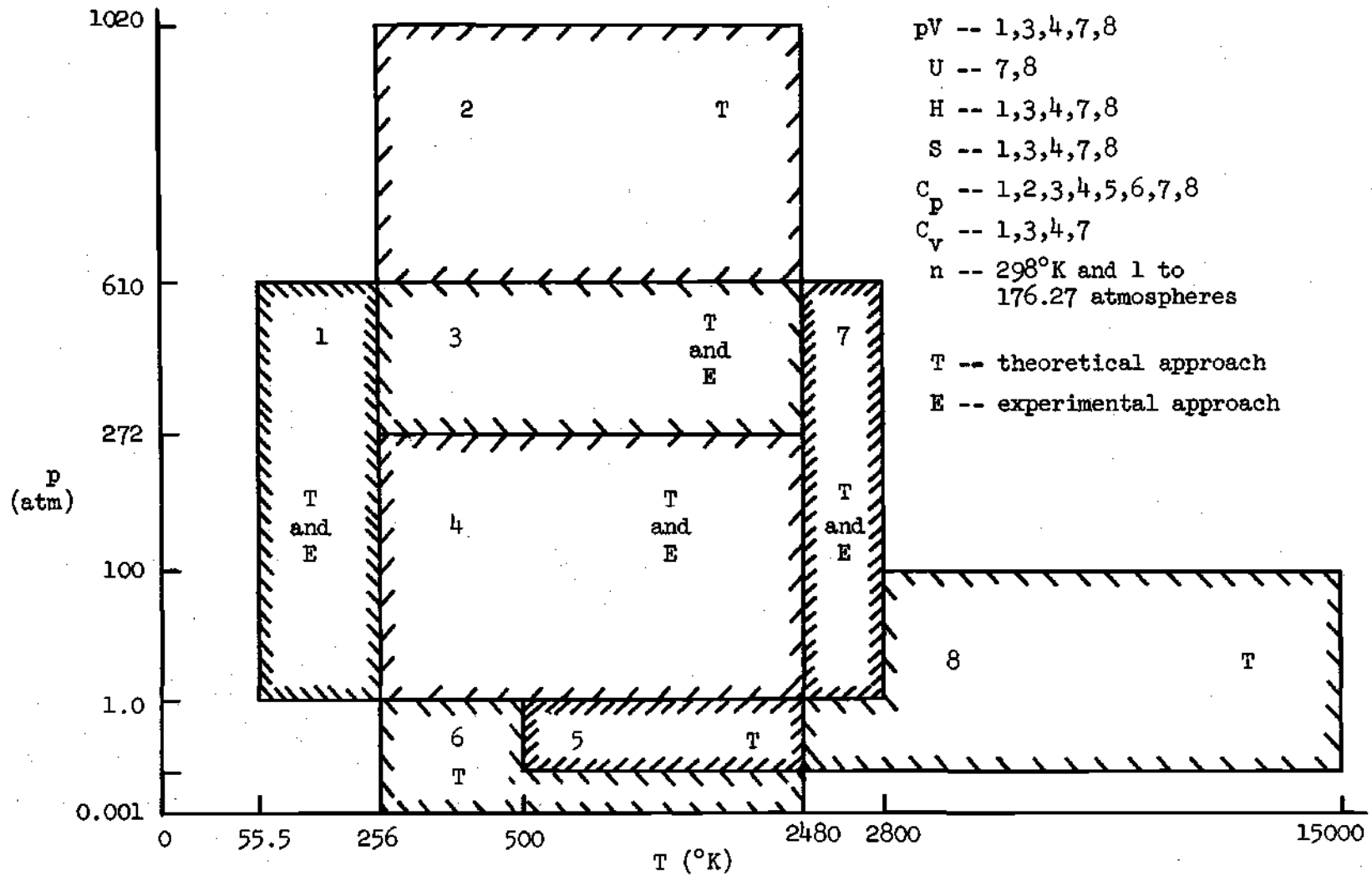


Figure 2-3. Ranges of Previous Work on Air

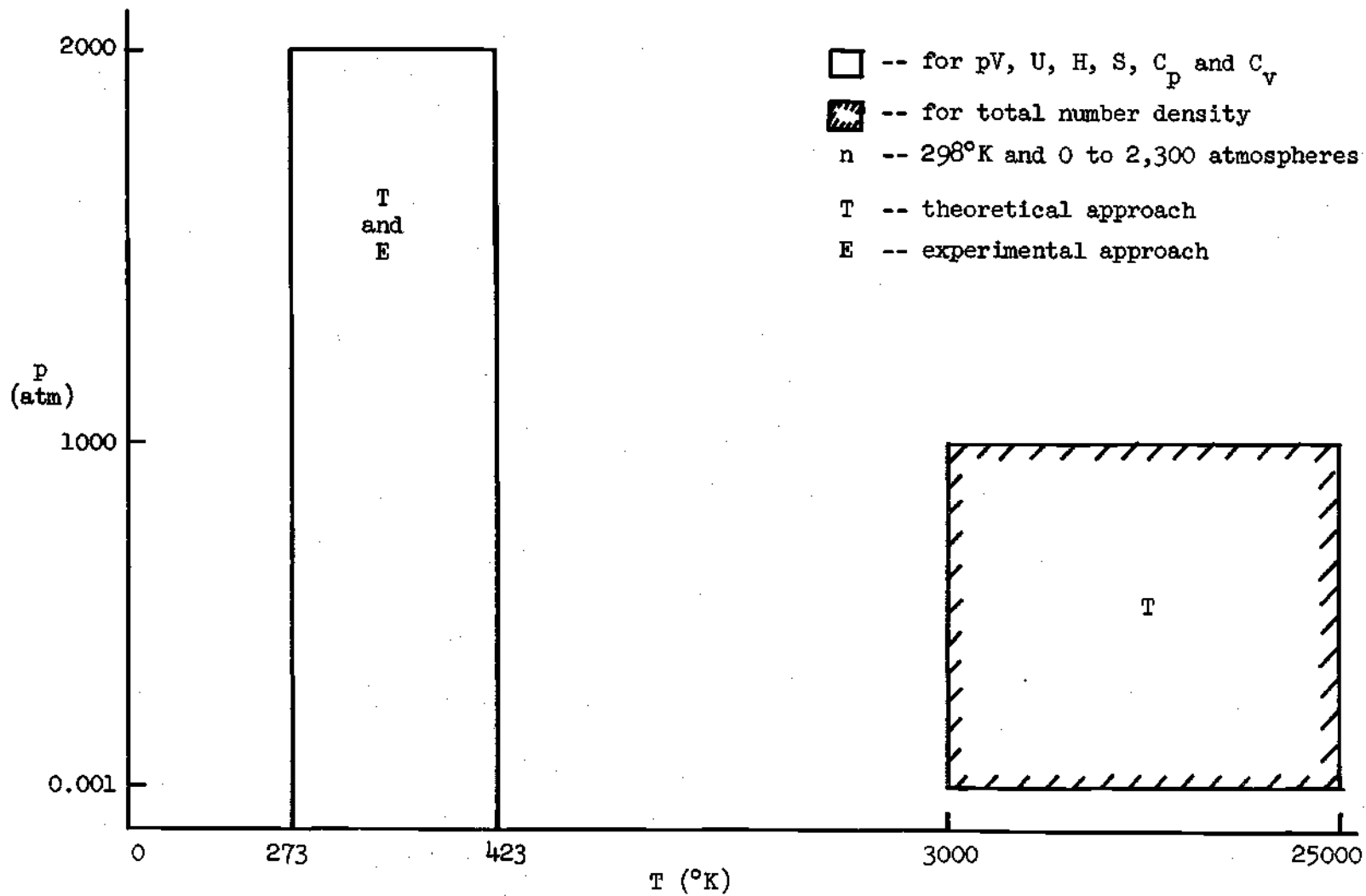


Figure 2-4. Ranges of Previous Work on  $A_r$

and the index of refraction for nitrogen, oxygen, air and argon, especially for argon, are missing in the pressure range of 500-1,000 atmospheres, and the temperature range of 400-2,500°K. For this reason and in order to allow comparison with some of the known data, a pressure range of 1 to 1,000 atmospheres and a temperature range of 273 to 2,500°K is chosen for present work.

The previous work is summarized and reviewed in two texts, both are heavily used in the present work:

J. O. Hirschfelder and C. F. Curtiss <sup>(14)</sup> present the equations for calculating the thermodynamic properties by using reduced virial coefficients and the virial equation of state.

M. Born and E. Wolf <sup>(22)</sup> present a method, as discussed in Chapter III, for calculating the index of refraction, by using Lorentz-Lorenz equation and molar (or atomic) refractivity.

## CHAPTER III

## THEORY

A. Properties of Real Gases

For the computation of the thermodynamic properties of real gases, it is necessary to include the effects of the intermolecular force in the properties of the system. In the following considerations, use is made of the general theoretical approach as described by Hirschfelder, Curtiss and Bird <sup>(14)</sup> with a modification due to van Kampen <sup>(32)</sup>.

A-1. Partition Function

For the pressure and temperature ranges under consideration, it may be assumed that the particles are indistinguishable and the molecular gas can be treated according to the modified Maxwell-Boltzmann statistical model. Further assumptions that will be made for the present computations are:

a) The classical partition function may be used rather than expressions based on quantum mechanical considerations, because the difference between successive energy levels is much smaller than the basic energy measure -  $kT$ .

b) The pair potential  $\epsilon_2$  describe the intermolecular interactions with sufficient accuracy.

With these assumptions, the partition function may be written as

$$Z' = \frac{1}{h^{3n'} n'!} \int_{\text{p-space}} e^{-\beta H'(r,p)} dr dp \quad (3-1)$$

where

$$H'(r,p) = \sum_{i=1}^{3n'} \frac{p_i^2}{2m} + \phi(r) \quad (3-2)$$

with

$$\phi(r) = \sum_{i=1}^{n'} \sum_{j>i}^{n'} \epsilon_2(|r_i - r_j|) \quad (3-3)$$

Here,  $H'$  is the Hamiltonian composed of kinetic and potential energy,  $n'$  is the total number of particles in the system,  $h$  is Planck's constant,  $r$  and  $p$  are the coordinates and the momenta,  $\epsilon_2$  is the pair-potential acting between particles  $i$  and  $j$  in the gas; consistent with its definition its value depends only on the distance,  $|r_i - r_j|$ , between the two particles.

#### A-2. The Configurational Partition Function

In the classical approximation, the Hamiltonian separates into the sum of a kinetic and a potential energy term, the momentum integrations in Eq. (3-1) can be performed immediately, yielding a partition function

$$Z' = \frac{1}{n'!} \left( \frac{2\pi m k T}{h^2} \right)^{3n'/2} Q_n(V, \beta) \quad (3-4)$$

where

$$Q_{n'}(V, \beta) = \int_V dr_1 \dots \int_V dr_{n'} \exp(-\beta\phi) \quad (3-5)$$

is the configurational partition function. With the notation of Eq. (3-3), the configurational partition function may be written as

$$Q_{n'} = \int_V dr_1 \dots \int_V dr_{n'} \exp \left[ -\beta \sum_{i=1}^{n'} \sum_{j=i+1}^{n'} \epsilon_2(|r_i - r_j|) \right] \quad (3-6)$$

introducing the abbreviation

$$\bar{\phi}_{ij} = \exp[-\beta\epsilon_2(|r_i - r_j|)] \quad (3-7)$$

the configurational partition function may be expressed as

$$Q_{n'} = \int_V dr_1 \dots \int_V dr_{n'} \bar{\phi}_{12} \bar{\phi}_{13} \bar{\phi}_{14} \dots \bar{\phi}_{23} \bar{\phi}_{24} \dots \bar{\phi}_{n'-1, n'} \quad (3-8)$$

Following the approach proposed by van Kampen, the configurational partition function may be approximated by restricting the considerations to interactions between particles of groups of 2 particles for the first approximation, of groups of 3 particles for the second approximation, etc. The configurational partition function is then equal to the product of these approximations.

### A-3. First Approximation to Configurational Partition Function

The first approximation to  $Q_{n'}$  may be constructed by considering each of the

$$\binom{n'}{2} = \frac{1}{2} n'(n'-1)$$

interacting pairs in Eq. (3-8) separately, as if any pair were unaffected by the other molecules. Consequently,

$$Q_{n'}^{(1)} = V^{n'} \left[ \frac{1}{V^2} \int dr_1 \int dr_2 \phi_{12} \right] \left[ \frac{1}{V^2} \int dr_1 \int dr_3 \phi_{13} \right] \dots \\ \times \left[ \frac{1}{V^2} \int dr_2 \int dr_3 \phi_{23} \right] \dots \left[ \frac{1}{V^2} \int dr_{n'-1} \int dr_{n'} \phi_{n'-1,n'} \right] \quad (3-9)$$

The first approximation,  $Q_{n'}^{(1)}$ , can be evaluated explicitly by introducing an average distance  $|\vec{\rho}|$  between two particles, which yields

$$Q_{n'}^{(1)} = V^{n'} \left\{ \frac{1}{V} \int_V d\vec{\rho} \exp[-\beta\epsilon_2(|\vec{\rho}|)] \right\}^{n'(n'-1)/2} \quad (3-10)$$

#### A-4. The Second Virial Coefficient

When considering a very large number,  $n'$ , of molecules, Eq. (3-10) may be approximated by

$$Q_{n'}^{(1)} = V^{n'} \exp \left( \frac{1}{2} n' N \int_V d\vec{\rho} \left\{ \exp[-\beta\epsilon_2(|\vec{\rho}|)] - 1 \right\} \right) \quad (3-11)$$

Introducing the Mayer function:

$$f(|\vec{\rho}|) = \exp[-\beta\epsilon_2(|\vec{\rho}|)] - 1 \quad (3-12)$$

and using Eq. (3-4), the following first approximation for the partition function is obtained:

$$Z' = \frac{V^{n'}}{n'!} \left( \frac{2\pi mkT}{h^2} \right)^{3n'/2} e^{-n'Nb(T)} \quad (3-13)$$

where

$$b(T) = - \frac{1}{2} \int_V d\vec{\rho} f(|\vec{\rho}|) \quad (3-14)$$

From the basic relation

$$p(V,T) = kT \left( \frac{\partial \ln Z'}{\partial V} \right)_T \quad (3-15)$$

results

$$p = NkT + N^2 kTb(T) \quad (3-16)$$

or in molar form

$$\frac{pV}{RT} = 1 + \frac{\bar{N}b(T)}{V} \quad (3-17)$$

where  $\bar{N}$  is Avogadro's number,  $V$  is the molar volume, and  $R$  is the universal gas constant. By comparing this expansion with the virial equation of state

$$\frac{pV}{RT} = 1 + \frac{B(T)}{V} + \frac{C(T)}{V^2} + \dots,$$

the first approximation to the real gas equation of state can be equated to the second virial coefficient:

$$B(T) = \bar{N}b(T) \quad (3-18)$$

#### A-5. Third Virial Coefficient

By repeating the above steps in the evaluation of a second approximation to the configurational partition function on groups of 3 interacting particles at a time, the third virial coefficient may be obtained. Assuming that each of the

$$\binom{n'}{3} = \frac{1}{6} n'(n'-1)(n'-2)$$

groups of molecules taken three at a time interact in isolation, it results:

$$\bar{Q}_{n'}^{(2)} = \left[ \frac{1}{v^3} \int_v dr_1 \int_v dr_2 \int_v dr_3 \phi_{12} \phi_{23} \phi_{31} \right] \dots$$

Assume this expression contains  $1/6 n'(n'-1)(n'-2)$  identical multiplicative terms, and is equivalent to

$$Q_{n'}^{(2)} = \left[ \frac{1}{v^3} \int_v dr_1 \int_v dr_2 \int_v dr_3 \phi_{12} \phi_{23} \phi_{31} \right]^{n'(n'-1)(n'-2)/6} \quad (3-19)$$

Eq. (3-19) overcounts the interactions between each two particles, therefore each multiplicative term in Eq. (3-19) has to be divided by

$$\bar{Q}_3^{(1)} = \left[ \frac{1}{v^2} \int_v dr_1 \int_v dr_2 \phi_{12} \right]^3 \quad (3-20)$$

to yield the second approximation to the configurational partition function

$$Q_{n'}^{(2)} = \left[ \frac{v^3 \int_v dr_1 \int_v dr_2 \int_v dr_3 \phi_{12} \phi_{23} \phi_{31}}{\left( \int_v dr_1 \int_v dr_2 \phi_{12} \right)^3} \right]^{n'(n'-1)(n'-2)/6} \quad (3-21)$$

when considering a very large number of molecules and introducing Mayer function as before, it results

$$Q_{n'}^{(2)} = \exp\left[-\frac{1}{2}n'N^2c(T)\right]$$

with

$$c(T) = -\frac{1}{3} \int_v d\vec{\rho}_{12} \int_v d\vec{\rho}_{13} f(|\vec{\rho}_{12}|)f(|\vec{\rho}_{13}|)f(|\vec{\rho}_{23}|) \quad (3-22)$$

so that

$$Q_{n'} \approx Q_{n'}^{(1)} Q_{n'}^{(2)} = v^{n'} \exp n' [-n' b(T) - \frac{1}{2} n'^2 c(T)]$$

from which, it follows that

$$p = NkT[1 + Nb(T) + N^2 c(T)]$$

or in molar form

$$\frac{pV}{RT} = 1 + \frac{\bar{N}b(T)}{V} + \frac{\bar{N}^2 c(T)}{V^2} \quad (3-23)$$

Again, by comparing this expansion with the virial equation of state, the second approximation to the real gas equation of state can be equated to the third virial coefficient:

$$c(T) = \bar{N}^2 c(T) \quad (3-24)$$

#### A-6. Thermodynamic Properties

In order to evaluate thermodynamic properties, it is now possible to write the following general expression for the partition function. In this equation, we denote the second virial coefficient (per molecule) by  $b_1$ , the third by  $b_2$ , and so on. Thus

$$Z' = \exp n' \left( \frac{3}{2} \ln \frac{2\pi mkT e^{2/3}}{h^2 N^{2/3}} - \sum_{k=1}^{\infty} \frac{N^k}{K} b_K \right) \quad (3-25)$$

By using this partition function and thermodynamic relations, we can get following equations

$$U - U_{tr}^{\circ} = -RT^2 \sum_{K=1}^{\infty} \frac{1}{K} \left( \frac{\bar{N}}{V} \right)^K \frac{db_K}{dT} \quad (3-26)$$

$$S - S_{tr}^{\circ} = -R \sum_{K=1}^{\infty} \frac{1}{K} \left( \frac{\bar{N}}{V} \right)^K \left( T \frac{db_K}{dT} + b_K \right) \quad (3-27)$$

$$C_r - C_{V,tr}^{\circ} = -2RT \sum_{K=1}^{\infty} \frac{1}{K} \left( \frac{\bar{N}}{V} \right)^K \frac{db_K}{dT} - RT^2 \sum_{K=1}^{\infty} \frac{1}{K} \left( \frac{\bar{N}}{V} \right)^K \frac{d^2 b_K}{dT^2} \quad (3-28)$$

$$pV - RT = RT \sum_{K=1}^{\infty} \left( \frac{\bar{N}}{V} \right)^K b_K \quad (3-29)$$

### B. Equation of State

In the literature, a multitude of different equations of state have been discussed for the determination of gas imperfections. Some examples are the "Goodman equation of state" (24), "Beattie and Bridgeman equation of state" (25), and "virial equation of state" (14). However, the virial expansion of the equation of state leads to thermodynamic properties which compare favorably with experimental results in the ranges of pressure and temperature under consideration here. Depending on the ranges of pressure and temperature, other approaches may have to be used for the determination of properties. For the temperature range of 273°K to 2,500°K and the pressure range of 1 atmosphere to 1,000 atmospheres of interest here, the virial equation of state is generally the preferred approach in the literature.

#### B-1. The Virial Equation of State

The virial equation of state

$$\frac{pV}{RT} = 1 + \frac{B(T)}{V} + \frac{C(T)}{V^2} + \frac{D(T)}{V^3} + \dots = Z \quad (3-30)$$

where the power series in reciprocal power of  $V$  is called the compressibility factor,  $Z$ .  $B(T)$ ,  $C(T)$ ,  $D(T)$ , etc., the second, third, fourth virial coefficients, represent physically the departures from ideality dependent upon interactions involving two, three, four molecules, and are functions of temperature only.  $V$  is the molar volume,  $p$  is the absolute pressure and  $T$  is the absolute temperature.

Some authors prefer to express their data by defining

$$B' = \frac{B}{RT} \quad (3-31)$$

$$C' = \frac{(C - B^2)}{(RT)^2} \quad (3-32)$$

and expanding the compressibility factor in a power series of pressure (14)

$$\frac{pV}{RT} = 1 + B'(T) p + C'(T) p^2 + \dots \quad (3-33)$$

and there is no difference in physical meaning between Eq. (3-30) and Eq. (3-33).

### C. Intermolecular Potential

Again, a great number of expressions for the potential of the intermolecular force have been proposed in the literature for the gases under investigation. The more frequently used ones are, hard-sphere (rigid-sphere) potential (26), Morse potential (30), square-well potential, Sutherland potential, and Lennard-Jones (6-12) potential (26). However, the most commonly used potential for monatomic gases, diatomic gases and mixtures is Lennard-Jones potential.

### C-1. Lennard-Jones (6-12) Potential

Because of its good coverage of very wide ranges of pressure and temperature, the Lennard-Jones potential is the most commonly used potential. Because of the justifications given in the literature (2, 3, 5, 6) which are based on the good agreement between experimental thermodynamic properties and properties determined in computations using the Lennard-Jones potential, so Lennard-Jones potential is used in present work. Tables of reduced virial coefficients for this potential are available (15), therefore the calculations of thermodynamic properties are greatly simplified.

The Lennard-Jones potential is shown in Eq. (3-34) and Figure (3-1).

$$\phi(r) = 4\epsilon \left[ \left( \frac{\sigma}{r} \right)^{12} - \left( \frac{\sigma}{r} \right)^6 \right] \quad (3-34)$$

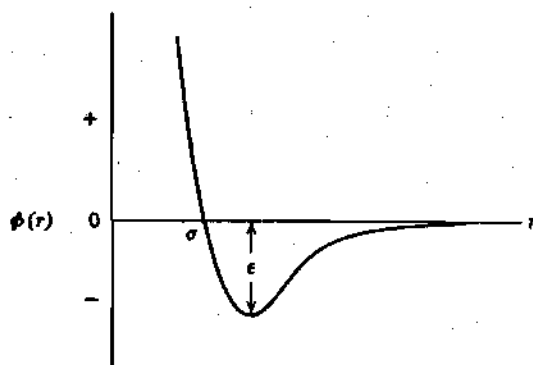


Figure 3-1. The Lennard-Jones Potential

In Eq. (3-34), the parameters  $\sigma$  and  $\epsilon$  (which have dimensions of length and energy, respectively) are characteristic constants of the

chemical species of the interacting molecules.  $\sigma$  is the effective diameter of the molecule. At  $r = \sigma$ , the potential energy is zero, and therefore  $\sigma$  is the distance of closest approach of two molecules when there is no initial kinetic energy. The parameter  $\epsilon$  represents the depth of the potential well at a separation where the intermolecular force is equal to zero, this occurs at a separation of  $r = 2^{1/6}\sigma$ .

At large separations ( $r \gg \sigma$ ), the second term of Eq. (3-34) becomes important and provides the rapid decrease of the attraction force with increasing intermolecular distance. At small separations ( $r \ll \sigma$ ), the first term of Eq. (3-34) is important and provides the rapid increase of the repell force with decreasing intermolecular distance. Thus the shape of this function (Eq. (3-34)) duplicates the shape of the intermolecular potential.

For a mixture composed of  $n$  species of different gases, the parameters  $\sigma$  and  $\epsilon$  are approximated:

$$\sigma = \frac{1}{n} (\sigma_1 + \sigma_2 + \dots + \sigma_n) \quad (3-35)$$

and

$$\epsilon = (\epsilon_1 \epsilon_2 \dots \epsilon_n)^{1/n} \quad (3-36)$$

where  $\sigma_1, \sigma_2, \dots, \sigma_n$  are the effective molecular diameters of the different species and  $\epsilon_1, \epsilon_2, \dots, \epsilon_n$  are the potential wells of the different species. Air, the only mixture under investigation in the present work, is considered to be composed of nitrogen and oxygen only, and we can calculate the values of  $\sigma$  and  $\epsilon$  for air from Eq. (3-35) and (3-36) by using  $n = 2$ . With these expressions, the Lennard-Jones

potential is applicable to mixtures as well as to pure gas components.

#### D. Applications

##### D-1. The Virial Coefficients for the Lennard-Jones (6-12) Potential

In the discussion which follows many of the formulae assume simpler forms if the law of corresponding state is applied and the following reduced quantities, as discussed in Hirschfelder <sup>(14)</sup>, are used:

$$\begin{aligned} r^* &= \frac{r}{\sigma} & T^* &= \frac{kT}{\epsilon} \\ B^* &= \frac{B}{b_0} & C^* &= \frac{C}{b_0^2} \\ B_K^* &= T^{*K} \left( \frac{d^K B^*}{dT^{*K}} \right) & C_K^* &= T^{*K} \left( \frac{d^K C^*}{dT^{*K}} \right) \end{aligned} \quad (3-37)$$

where  $b_0 = z/3 \pi \bar{N} \sigma^3$ , and  $\bar{N}$  is Avogadro's number. The quantities  $B_K^*$  and  $C_K^*$  are dimensionless derivatives occurring in the expressions for the thermodynamic properties.

The reduced quantities defined by Eq. (3-37) can be applied to mixtures as well as to pure gases. The virial coefficients for mixture composed of  $n$  species are defined as

$$B = \sum_{\alpha=1}^n \sum_{\beta=1}^n B_{\alpha\beta} x_{\alpha} x_{\beta} \quad (3-38)$$

and

$$C = \sum_{\alpha=1}^n \sum_{\beta=1}^n \sum_{r=1}^n C_{\alpha\beta r} x_{\alpha} x_{\beta} x_r \quad (3-39)$$

where  $x_i$  is the molar fraction of  $i^{\text{th}}$  species. Tables of the reduced

second and third virial coefficients and their temperature derivatives are found in the literature <sup>(15)</sup>. These tables are used for the computations carried out here and are shown in Appendixes A and B.

The empirical data for  $\sigma$  and  $\epsilon/k$  for nitrogen, oxygen, air and argon are shown in Table (3-1) <sup>(28)</sup>.

Table 3-1.  $\sigma$  and  $\epsilon/k$  for Nitrogen, Oxygen, Air and Argon for Lennard-Jones Potential from Second Virial Coefficient Data

	$\sigma$ (A)	$\epsilon/k$ (°K)	Refs. of data
N <sub>2</sub>	3.698	95.05	17
O <sub>2</sub>	3.58	117.5	18
Air	3.522	99.2	19
Ar	3.405	119.8	9

#### D-2. Equations for Thermodynamic Properties

With the second and third virial coefficients and their derivatives known for nitrogen, oxygen, air and argon, the presented properties were calculated by means of the thermodynamic relations (Eq. (3-26) to (3-29)) and Eq. (3-30), for different pressures ( $p$ ) and temperatures ( $T$ ) in the ranges under consideration.

In molar form the relations used are: \*

##### 1. Molar Volume ( $V$ )

$$Z = 1 + B'(T) p + C'(T) p^2 + \dots \quad (3-40)$$

$$V = \frac{ZRT}{p} \quad (3-41)$$

\* The superscript "o" indicates the values for ideal gases.

## 2. Internal Energy (U)

$$U - U^{\circ} = - \int_V^{\infty} \left[ T \left( \frac{\partial p}{\partial T} \right)_V - p \right] dV$$

$$\frac{U - U^{\circ}}{\bar{N}_e} = - T^* \left[ \frac{B_1^*}{V^*} + \frac{1}{2} \frac{C_1^*}{(V^*)^2} + \dots \right] \quad (3-42)$$

## 3. Enthalpy (H)

$$H - H^{\circ} = pV - RT - \int_V^{\infty} \left[ T \left( \frac{\partial p}{\partial T} \right)_V - p \right] dV$$

$$\frac{H - H^{\circ}}{\bar{N}_e} = T^* \left[ \frac{B_1^* - B_1^*}{V^*} + \frac{C_1^* - \frac{1}{2}C_1^*}{(V^*)^2} + \dots \right] \quad (3-43)$$

## 4. Entropy (S)

$$S - S^{\circ} = -R \ln p + r \ln \frac{pV}{RT} - \int_V^{\infty} \left[ \left( \frac{\partial p}{\partial T} \right)_V - \frac{R}{V} \right] dV$$

$$\frac{S - S^{\circ}}{R} = - \ln p - \left[ \frac{B_1^*}{V^*} + \frac{(B^*)^2 - C^* + C_1^*}{2(V^*)^2} + \dots \right] \quad (3-44)$$

5. Heat Capacity at Constant Volume ( $C_V$ )

$$C_V - C_V^{\circ} = - T \int_V^{\infty} \left( \frac{\partial^2 p}{\partial T^2} \right)_V dV$$

$$\frac{C_V - C_V^{\circ}}{R} = - \frac{2B_1^* + B_2^*}{V^*} - \frac{2C_1^* + C_2^*}{2(V^*)^2} + \dots \quad (3-45)$$

6. Heat Capacity at Constant Pressure ( $C_p$ )

$$C_p - C_p^{\circ} = - R - \frac{T \left( \frac{\partial p}{\partial T} \right)_V^2}{\left( \frac{\partial p}{\partial V} \right)_T} - T \int_V^{\infty} \left( \frac{\partial^2 p}{\partial T^2} \right)_V dV$$

$$\frac{C_p - C_p^o}{R} = -\frac{B_2^*}{V^*} + \frac{[B^* - B_1^*]^2 - C^* + C_1^* - \frac{1}{2} C_2^*}{(V^*)^2} + \dots \quad (3-46)$$

The reduced virial coefficients for the absolute temperatures used in the computations for nitrogen, oxygen, air and argon properties are shown in the Appendixes C - F.\*

#### E. Index of Refraction

A classical theory describing light absorption and the index of refraction of light was developed by Drude (27). The molecular model used in Drude's theory is as follows: The molecule is regarded as a set of particles of charge  $e_i$  and mass  $m_i$ , and each of these particles is harmonically and isotropically bound to its individual equilibrium position. The force constant for the  $i^{\text{th}}$  particle is  $k_i$ , its frequency of vibration is

$$\nu_i = \frac{1}{2\pi} \left( \frac{k_i}{m_i} \right)^{\frac{1}{2}} \quad (3-47)$$

and its displacement from the equilibrium position is

$$\delta r_i = r_i - r_i^{(o)}$$

A beam of incident light exposes the molecule to an alternating electromagnetic field. If the frequency  $\nu_o$  of this light is sufficiently low that the wavelength  $\lambda_o = c/\nu_o$  is large compared to the size of the molecule, the external electric field is essentially uniform

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\* By using interpolation from Appendix A and Appendix B.

throughout the molecule, and has the intensity

$$\vec{E} = \vec{E}_0 \cos(2\pi\nu_0 t) \quad (3-48)$$

The force on the  $i^{\text{th}}$  particle in the molecule is then given by

$$\vec{F}_i = -K_i \delta r_i + r_i \vec{E}_0 \cos(2\pi\nu_0 t) \quad (3-49)$$

According to Newton's second law, the equation of motion of  $i^{\text{th}}$  particle is

$$m_i \frac{d^2}{dt^2} (\delta r_i) + K_i \delta r_i = e_i \vec{E}_0 \cos(2\pi\nu_0 t) \quad (3-50)$$

The steady state solution of this equation is

$$\delta r_i = \left( \frac{e_i}{4\pi^2 m_i} \right) \frac{\vec{E}_0 \cos(2\pi\nu_0 t)}{(\nu_i^2 - \nu_0^2)} \quad (3-51)$$

For small external electric field, the induced dipole moment

$$\vec{\mu}^{(\text{ind})} = \sum_i e_i \delta r_i \quad (3-52)$$

may be written as

$$\vec{\mu}^{(\text{ind})} = \alpha \cdot \vec{E} \quad (3-53)$$

where  $\alpha$  is the polarizability of the object. Since the induced dipole moment is in the direction of the field, the polarizability,  $\alpha$ , is a scalar, hence the following expression for the polarizability of the molecule is obtained

$$\alpha(\nu_0) = \frac{1}{4\pi^2} \sum_i \frac{e_i^2}{m_i (\nu_i^2 - \nu_0^2)} \quad (3-54)$$

The expression for the polarizability is often written in terms of oscillator strengths,  $f_i$ , which are defined as

$$f_i = \frac{e_i/m_i}{e/m} \quad (3-55)$$

in which  $e$  and  $m$  are the charge and mass of an electron. In terms of these quantities

$$\alpha(\nu_0) = \frac{e^2}{4\pi^2 m} \sum_i \frac{f_i}{\nu_i^2 - \nu_0^2} \quad (3-56)$$

is the polarizability of a molecule.

The defining equation for the electric susceptibility is the Clausius-Mosotti relation

$$\chi^{(e)} = \frac{3}{4\pi N} \frac{\epsilon - 1}{\epsilon + 2} \quad (3-57)$$

where  $N$  is the number density of molecules;  $\epsilon$  is the dielectric constant;  $\chi^{(e)}$  is the electric susceptibility.

If the molecules have no permanent dipole moment, the polarizability,  $\alpha$ , is identical with the electric susceptibility,  $\chi^{(e)}$ , and it results for the Clausius-Mosotti relation

$$\frac{\epsilon - 1}{\epsilon + 2} = \frac{4\pi}{3} N\alpha(\nu_0) \quad (3-58)$$

Since the index of refraction,  $n$ , is defined as the ratio of the velocity of light in vacuum to the velocity of light in a medium, it follows directly from Maxwell's equation

$$\text{curl } \vec{E} = \frac{\mu\epsilon}{c^2} \cdot \frac{\partial^2 \vec{E}}{\partial t^2} \quad (3-59)$$

for the index of refraction

$$n = (\mu\epsilon)^{\frac{1}{2}}$$

For the ranges of pressure and temperature considered in the present report, the permeability,  $\mu$ , is very nearly unity, so that  $n$  is approximately equal to  $\sqrt{\epsilon}$ . In connection with Eq. (3-58), this leads to the well-known Lorentz-Lorenz formula (20, 21)

$$\alpha = \frac{3}{4\pi N} \frac{n^2 - 1}{n^2 + 2} \quad (3-60)$$

where  $\alpha$  = mean polarizability,  $N$  = the number of molecules per unit volume, and  $n$  = index of refraction.

Instead of the mean polarizability,  $\alpha$ , one often uses another quantity  $A$ , called molar refractivity. (In the case of monatomic substances, it is called atomic refractivity). This essentially the total polarizability of a mole of the substance, being defined as

$$A = \frac{4\pi}{3} \bar{N}\alpha \quad (3-61)$$

If  $M$  is the molecular weight,  $\rho$  is the density, then the molar volume,  $V$ , is

$$V = \frac{\bar{N}}{N} = \frac{M}{\rho} \quad (3-62)$$

Hence the molar refractivity may be written in the form

$$A = \frac{M}{\rho} \frac{n^2 - 1}{n^2 + 2} \quad (3-63)$$

Eq. (3-63) shows that  $A$  has the dimensions and the order of magnitude of a molar volume.

For a gas,  $n^2$  is nearly unity, so that

$$A \sim \frac{M}{\rho} \frac{n^2 - 1}{3} \quad (3-64)$$

Eq. (3-63) gives the explicit dependence of the index of refraction, for light of any one particular visible color, on the density, and it should hold when the density is changed provided that isotropy is preserved (22). In the case of gases, it is found that  $n^2 - 1$  and  $\rho$  are very nearly proportional to each other as demanded by the Eq. (3-64). But even at high pressure, when  $n$  will differ appreciably from unity, the molar refractivity remains substantially constant (22), as illustrated in Table 3-2.

Table 3-2. The Molar Refractivity  $A$  of Air at Different Pressures and at about  $14.5^\circ\text{C}$  and Sodium Light with Wavelength  $5890 \text{ \AA}$  (Reference 22)

Pressure in atm	$n$	$A$ ( $\text{ft}^3/\text{lb-mole}$ )
1.00	1.0002929	2.170
42.13	1.01241	2.177
96.16	1.02842	2.178
136.21	1.04027	2.174
176.27	1.05213	2.170

With the molar (or atomic) refractivity and density known for nitrogen, oxygen, air and argon, we can calculate the index of refraction from Eq. (3-63).

The molar (or atomic) refractivity for nitrogen, oxygen, air and argon are shown in Table 3-3.

Table 3-3. The Molar (Atomic) Refractivity for Nitrogen, Oxygen, Air and Argon for Sodium Light with Wavelength 5890 Å

	N <sub>2</sub>	O <sub>2</sub>	Air	Ar
A (cm <sup>3</sup> /g-mole)	125.9694	125.4781	135.4664	170.3220
Refs. of data	13	15	15	12

## CHAPTER IV

## RESULTS AND DISCUSSIONS

The numerical results are obtained using the theoretical approach outlined in Chapter III. They are presented in tabular form for  $N_2$ ,  $O_2$ , air and  $A_r$ , and in graphical form for air and argon only.

A. Tabulated Results

For each gas, the tabulated results are presented in the following order: isotherm ( $pV$ ), density ( $\rho$ ), internal energy ( $U$ ), enthalpy ( $H$ ), entropy ( $S$ ), specific heat at constant pressure ( $C_p$ ), specific heat at constant volume ( $C_v$ ) and index of refraction ( $n$ ).

Table 4-1 to Table 4-8	Properties of Nitrogen
Table 4-9 to Table 4-16	Properties of Oxygen
Table 4-17 to Table 4-24	Properties of Air
Table 4-25 to Table 4-32	Properties of Argon

Table 4-1 Isotherms(pv) of N<sub>2</sub>  
 p (atm), T (°K), pv (atm-cm<sup>3</sup>/g)

T \ p	1	2	5	10	20	50	100	200	500	1000
273	799.28	798.94	797.94	796.36	793.52	787.62	786.47	816.72	1167.90	2621.34
300	878.56	878.41	877.99	877.36	876.41	875.98	883.32	928.27	1305.13	2739.95
500	1465.12	1465.73	1467.55	1470.62	1476.89	1496.70	1533.13	1618.70	1977.18	2913.88
700	2051.22	2052.10	2054.77	2059.24	2068.23	2095.63	2142.81	2242.76	2587.46	3311.38
900	2637.16	2638.19	2641.27	2646.40	2656.70	2687.81	2740.32	2847.90	3190.95	3830.47
1100	3223.02	3224.09	3227.31	3232.68	3243.43	3275.81	3330.13	3440.19	3781.56	4387.84
1300	3808.86	3809.96	3813.27	3818.79	3829.84	3863.05	3918.60	4030.44	4371.97	4961.17
1500	4394.70	4395.83	4399.23	4404.91	4416.26	4450.32	4507.17	4621.14	4965.17	5545.63
1700	4980.53	4981.70	4985.19	4991.02	5002.67	5037.61	5092.82	5212.13	5560.17	6137.29
1900	5566.37	5567.57	5571.16	5577.14	5589.09	5624.92	5684.52	5803.31	6156.40	6733.89
2100	6152.18	6153.38	6156.97	6162.95	6174.91	6210.76	6270.39	6389.20	6742.02	7318.08
2300	6737.99	6739.19	6742.78	6748.77	6760.74	6796.60	6856.25	6975.08	7327.70	7902.61
2500	7323.80	7325.00	7328.95	7334.58	7346.56	7382.44	7442.12	7560.97	7913.46	8487.48

Table 4-2 Density( $\rho$ ) of  $N_2$

p (atm), T ( $^{\circ}$ K),  $\rho$  ( $kg/m^3$ )

T \ P	1	2	5	10	20	50	100	200	500	1000
273	1.25112	2.50332	6.26614	12.5572	25.2040	63.4822	127.151	244.883	428.119	381.484
300	1.13823	2.27684	5.69486	11.3979	22.8204	57.0792	113.209	215.454	383.103	364.971
500	0.68254	1.36451	3.40704	6.7999	13.5420	33.4067	65.226	123.556	252.885	343.185
700	0.48752	0.94761	2.43336	4.8562	9.6701	23.8591	46.667	89.176	193.239	301.980
900	0.37920	0.75810	1.89303	3.7788	7.5281	18.6025	36.492	70.227	156.693	261.065
1100	0.31027	0.62033	1.54928	3.0934	6.1663	15.2634	30.029	58.136	132.221	227.902
1300	0.26255	0.52494	1.31121	2.6186	5.2222	12.9431	25.519	49.622	114.365	201.565
1500	0.22755	0.45498	1.13656	2.2702	4.5287	11.2351	22.187	43.279	100.701	180.322
1700	0.20078	0.40147	1.00297	2.0036	3.9979	9.9253	19.624	38.372	89.925	162.938
1900	0.17965	0.35922	0.89748	1.7930	3.5784	8.8890	17.592	34.463	81.216	148.503
2100	0.16254	0.32503	0.81209	1.6226	3.2389	8.0505	15.948	31.303	74.162	136.648
2300	0.14841	0.29677	0.74153	1.4818	2.9583	7.3566	14.585	28.674	68.234	126.540
2500	0.13654	0.27304	0.68226	1.3634	2.7224	6.7728	13.437	26.452	63.184	117.821

Table 4-3 Internal Energy(U) of N<sub>2</sub>

p (atm), T (°K), U (Kcal/Kg-mole)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-1.57	-3.14	-7.86	-15.73	-31.51	-78.88	-156.41	-295.58	-501.38	-450.25
300	132.90	131.51	127.35	120.40	106.53	65.18	-1.70	-120.79	-308.36	-288.53
500	1128.31	1127.60	1125.45	1121.89	1114.82	1094.06	1060.97	1000.90	870.35	781.37
700	2123.33	2122.88	2121.55	2119.34	2114.96	2102.09	2081.53	2043.61	1953.03	1861.77
900	3118.21	3117.91	3117.02	3115.53	3112.58	3103.90	3089.99	3064.14	3000.13	2927.17
1100	4113.01	4112.78	4112.07	4110.90	4108.57	4101.71	4090.68	4070.03	4017.78	3954.96
1300	5107.80	5107.61	5107.05	5106.12	5104.26	5098.78	5089.95	5073.35	5030.83	4978.38
1500	6102.59	6102.45	6102.03	6101.33	6099.95	6095.86	6089.28	6076.90	6045.20	6006.10
1700	7097.38	7097.29	7097.01	7096.55	7095.64	7092.96	7088.66	7080.62	7060.45	7036.75
1900	8092.17	8092.12	8091.99	8091.77	8091.33	8090.06	8088.05	8084.42	8076.24	8069.31
2100	9086.92	9086.89	9086.80	9086.66	9086.37	9085.54	9084.25	9081.99	9077.43	9075.42
2300	10081.7	10081.7	10081.6	10081.5	10081.4	10081.0	10080.4	10079.6	10078.7	10081.9
2500	11076.4	11076.4	11076.4	11076.4	11076.4	11076.5	11076.6	11077.2	11080.1	11088.9

Table 4-4 Enthalpy (H) of N<sub>2</sub>

p (atm), T (°K), H (Kcal/Kg-mole)

$\begin{matrix} P \\ T \end{matrix}$	1	2	5	10	20	50	100	200	500	1000
273	-1.80	-3.61	-9.00	-17.94	-35.63	-86.83	-164.17	-281.48	-397.71	-375.79
300	186.81	185.32	180.87	173.50	159.98	117.39	55.54	-37.04	-132.70	-125.71
500	1582.83	1582.52	1581.61	1580.14	1577.32	1569.90	1560.83	1553.15	1577.44	1628.16
700	2978.13	2978.29	2978.77	2979.59	2981.31	2986.98	2998.05	3025.08	3126.47	3285.84
900	4373.21	4373.60	4374.80	4376.80	4380.83	4393.23	4414.75	4460.37	4607.39	4842.50
1100	5768.14	5768.63	5770.11	5772.58	5777.55	5792.64	5818.34	5871.45	6037.62	6308.43
1300	7163.04	7163.60	7165.29	7168.10	7173.74	7190.78	7219.56	7278.25	7458.91	7755.23
1500	8557.95	8558.58	8460.47	8563.62	8569.93	8588.96	8620.89	8685.45	8881.54	9202.68
1700	9952.85	9953.55	9955.65	9959.14	9966.13	9987.16	10022.3	10092.9	10305.2	10651.4
1900	11347.8	11348.5	11350.8	11354.7	11362.3	11385.4	11423.8	11500.6	11729.7	12101.2
2100	12742.6	12743.4	12745.7	12749.7	12757.5	12781.0	12820.1	12898.3	13131.4	13510.2
2300	14137.5	14138.3	14140.7	14144.6	14152.6	14176.6	14216.5	14296.1	14533.2	14918.9
2500	15532.3	15533.1	15535.6	15539.6	15547.8	15572.2	15612.8	15693.9	15935.0	16327.5

Table 4-5 Entropy (S) of N<sub>2</sub>

p (atm), T (°K), S (Kcal/Kg-mole-°K)

T \ p	1	2	5	10	20	50	100	200	500	1000
273	-0.0029	-1.3834	-3.2133	-4.6053	-6.0115	-7.9166	-9.4258	-11.0207	-13.1125	-14.4297
300	0.3266	-1.0535	-2.8816	-4.2708	-5.6713	-7.5590	-9.0398	-10.5864	-12.6320	-13.9886
500	2.1095	0.7310	-1.0923	-2.4736	-3.8583	-5.6997	-7.1085	-8.5395	-10.4613	-11.8948
700	3.2832	1.9051	0.0830	-1.2963	-2.6271	-4.5073	-5.8991	-7.3017	-9.1765	-10.5989
900	4.1597	2.7818	0.9601	-0.4184	-1.7978	-3.6238	-5.0090	-6.4002	-8.2527	-9.6112
1100	4.8595	3.4868	1.6601	0.2819	-1.0969	-2.9212	-4.3038	-5.6905	-7.5334	-8.9345
1300	5.4421	4.0643	2.2428	0.8648	-0.5136	-2.3369	-3.7180	-5.1019	-6.9385	-8.3338
1500	5.9411	4.5633	2.7420	1.3640	0.0142	-1.8367	-3.2166	-4.5984	-6.4298	-7.8197
1700	6.3776	5.0000	3.1785	1.8007	0.4227	-1.3993	-2.7783	-4.1583	-5.9856	-7.3706
1900	6.7654	5.3877	3.5665	2.1887	0.8109	-1.0107	-2.3889	-3.7676	-5.5915	-6.9721
2100	7.1145	5.7367	3.9155	2.5377	1.1600	-0.6664	-2.0395	-3.4178	-5.2405	-6.6199
2300	7.4317	6.0540	4.2327	2.8550	1.4773	-0.3440	-1.7719	-3.0998	-4.9216	-6.2999
2500	7.7224	6.3447	4.5235	3.1458	1.7681	-0.0531	-1.4308	-2.8085	-4.6295	-6.0067

Table 4-6 Specific Heat at Constant Pressure ( $C_p$ ) of  $N_2$

$p$  (atm),  $T$  ( $^{\circ}K$ ),  $C_p$  (Kcal/Kg-mole- $^{\circ}K$ )

$T \backslash P$	1	2	5	10	20	50	100	200	500	1000
273	6.9874	7.0005	7.0395	7.1034	7.2273	7.5639	7.9961	8.3752	7.8805	8.1317
300	6.9848	6.9954	7.0268	7.0783	7.1783	7.4522	7.8166	8.1207	8.1039	8.1606
500	6.9776	6.9809	6.9910	7.0076	7.0401	7.1326	7.2708	7.4920	7.8345	7.9525
700	6.9758	6.9774	6.9821	6.9899	7.0053	7.0499	7.1196	7.2422	7.5031	7.7160
900	6.9751	6.9760	6.9786	6.9830	6.9918	7.0174	7.0583	7.1339	7.3181	7.5222
1100	6.9748	6.9754	6.9772	6.9802	6.9862	7.0039	7.0325	7.0866	7.2272	7.4048
1300	6.9746	6.9751	6.9764	6.9785	6.9828	6.9956	7.0166	7.0568	7.1663	7.3166
1500	6.9745	6.9748	6.9758	6.9773	6.9804	6.9896	7.0047	7.0344	7.1183	7.2422
1700	6.9744	6.9746	6.9753	6.9763	6.9785	6.9849	6.9956	7.0169	7.0796	7.1792
1900	6.9743	6.9745	6.9749	6.9756	6.9770	6.9812	6.9883	7.0028	7.0479	7.1254
2100	6.9743	6.9744	6.9748	6.9745	6.9764	6.9798	6.9855	6.9972	7.0344	7.1004
2300	6.9743	6.9744	6.9746	6.9751	6.9760	6.9786	6.9831	6.9925	7.0231	7.0791
2500	6.9743	6.9743	6.9745	6.9649	6.9756	6.9776	6.9812	6.9886	7.0135	7.0608

Table 4-7 Specific Heat at Constant Volume ( $C_v$ ) of  $N_2$

$p$  (atm),  $T$  ( $^{\circ}K$ ),  $C_v$  (Kcal/Kg-mole- $^{\circ}K$ )

$T \backslash P$	1	2	5	10	20	50	100	200	500	1000
273	4.9754	4.9771	4.9821	4.9904	5.0069	5.0546	5.1272	5.2387	5.3538	5.3313
300	4.9751	4.9764	4.9804	4.9871	5.0004	5.0387	5.0973	5.1905	5.3053	5.2951
500	4.9742	4.9747	4.9762	4.9788	4.9838	4.9985	5.0222	5.0658	5.1628	5.2309
700	4.9740	4.9743	4.9752	4.9768	4.9798	4.9889	5.0037	5.0322	5.1065	5.1911
900	4.9739	4.9741	4.9848	4.9759	4.9781	4.9847	4.9955	5.0165	5.0745	5.1520
1100	4.9739	4.9741	4.9746	4.9755	4.9772	4.9824	4.9910	5.0079	5.0553	5.1231
1300	4.9738	4.9740	4.9744	4.9752	4.9766	4.9809	4.9880	5.0021	5.0420	5.1011
1500	4.9738	4.9740	4.9743	4.9749	4.9762	4.9798	4.9858	4.9978	5.0320	5.0838
1700	4.9738	4.9739	4.9742	4.9748	4.9758	4.9790	4.9842	4.9945	5.0242	5.0700
1900	4.9738	4.9739	4.9742	4.9746	4.9755	4.9783	4.9828	4.9918	5.0179	5.0586
2100	4.9738	4.9739	4.9741	4.9745	4.9753	4.9778	4.9819	4.9899	5.0134	5.0502
2300	4.9738	4.9739	4.9741	4.9744	4.9752	4.9774	4.9811	4.9884	5.0096	5.0432
2500	4.9738	4.9738	4.9740	4.9744	4.9751	4.9771	4.9804	4.9870	5.0064	5.0372

Table 4-8. Index of Refraction (n) of N<sub>2</sub>

p (atm), T (°K), n Dimensionless

T \ p	1	2	5	10	20	50	100	200	500	1000
273	1.00030	1.00060	1.00151	1.00302	1.00607	1.01532	1.03077	1.05959	1.10514	1.09346
300	1.00027	1.00055	1.00137	1.00275	1.00550	1.01377	1.02738	1.05236	1.09386	1.08934
500	1.00016	1.00033	1.00082	1.00164	1.00326	1.00805	1.01574	1.02990	1.06156	1.08391
700	1.00012	1.00023	1.00059	1.00117	1.00233	1.00575	1.01126	1.02155	1.04691	1.07369
900	1.00009	1.00018	1.00046	1.00091	1.00181	1.00448	1.00880	1.01696	1.03797	1.06358
1100	1.00007	1.00015	1.00037	1.00074	1.00148	1.00368	1.00724	1.01403	1.03201	1.05541
1300	1.00006	1.00013	1.00032	1.00063	1.00126	1.00312	1.00615	1.01197	1.02766	1.04895
1500	1.00005	1.00011	1.00027	1.00055	1.00109	1.00271	1.00535	1.01044	1.02434	1.04375
1700	1.00005	1.00010	1.00024	1.00048	1.00096	1.00239	1.00473	1.00925	1.02173	1.03950
1900	1.00004	1.00009	1.00022	1.00043	1.00086	1.00214	1.00424	1.00831	1.01962	1.03598
2100	1.00004	1.00008	1.00020	1.00039	1.00078	1.00194	1.00384	1.00755	1.01791	1.03309
2300	1.00004	1.00007	1.00018	1.00036	1.00071	1.00177	1.00351	1.00691	1.01647	1.03063
2500	1.00003	1.00007	1.00016	1.00033	1.00066	1.00163	1.00324	1.00637	1.01525	1.02850

Table 4-9 Isotherms(pv) of O<sub>2</sub>

p (atm), T (°K), pv (atm-cm<sup>3</sup>/g)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	699.34	698.61	696.43	692.83	685.80	666.01	637.36	596.27	602.84	1046.50
300	768.80	768.28	766.74	764.23	759.40	746.41	729.76	715.23	821.86	1500.23
500	1282.47	1282.75	1283.61	1285.06	1288.09	1298.08	1317.79	1368.65	1612.81	2324.97
700	1795.64	1796.22	1797.96	1800.88	1806.77	1824.90	1856.61	1925.66	2177.87	2748.33
900	2308.66	2309.39	2311.57	2315.20	2322.51	2344.65	2382.31	2460.47	2717.65	3221.96
1100	2821.62	2822.43	2824.87	2828.92	2837.06	2861.58	2902.86	2986.97	3251.61	3733.79
1300	3334.53	3335.38	3337.92	3342.15	3350.63	3376.14	3418.91	3505.37	3772.19	4241.65
1500	3847.43	3848.29	3850.89	3855.23	3863.90	3889.95	3933.54	4021.30	4289.28	4751.54
1700	4360.32	4361.21	4363.87	4368.30	4377.16	4403.78	4448.23	4537.44	4807.67	5266.63
1900	4873.22	4874.12	4876.84	4881.37	4890.43	4917.61	4962.95	5053.73	5326.95	5785.27
2100	5386.11	5387.04	5389.81	5394.44	5403.70	5431.45	5477.69	5570.11	5846.87	6306.45
2300	5899.01	5899.95	5902.79	5907.51	5916.16	5945.29	5992.46	6086.57	6367.25	6829.50
2500	6411.89	6412.84	6415.69	6420.44	6429.94	6458.53	6505.83	6600.39	6882.02	7344.62

Table 4-10 Density( $\rho$ ) of  $O_2$

p (atm), T ( $^{\circ}K$ ),  $\rho$  ( $Kg/m^3$ )

T \ p	1	2	5	10	20	50	100	200	500	1000
273	1.42992	2.86284	7.17953	14.4336	29.1630	75.0738	156.898	335.416	829.406	955.568
300	1.30074	2.60323	6.52111	13.0851	26.3366	66.9897	137.032	279.629	608.376	666.562
500	0.77975	1.55915	3.89528	7.7817	15.5269	38.5184	75.885	146.129	310.018	430.113
700	0.55690	1.11345	2.78093	5.5528	11.0695	27.3988	53.862	103.860	229.583	363.857
900	0.43315	0.86603	2.16304	4.3193	8.6114	21.3251	41.976	81.285	183.983	310.370
1100	0.35441	0.70861	1.77000	3.5349	7.0496	17.4729	34.449	66.958	153.770	267.824
1300	0.29989	0.59963	1.49794	2.9921	5.9690	14.8098	29.249	57.055	132.549	235.757
1500	0.25991	0.51971	1.29840	2.5939	5.1761	12.8536	25.422	49.735	116.570	210.458
1700	0.22934	0.45859	1.14577	2.2892	4.5692	11.3539	22.481	44.078	104.000	189.875
1900	0.20520	0.41033	1.02525	2.0486	4.0896	10.1675	20.149	39.575	93.862	172.853
2100	0.18566	0.37126	0.92768	1.8538	3.7012	9.2056	18.256	35.906	85.516	158.568
2300	0.16952	0.33899	0.84706	1.6928	3.3801	8.4100	16.688	32.859	78.527	146.424
2500	0.15596	0.31187	0.77934	1.5575	3.1105	7.7418	15.371	30.301	72.653	136.145

Table 4-11 Internal Energy(U) of O<sub>2</sub>

p (atm), T (°K), U (Kcal/Kg-mole)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-1.88	-3.76	-9.42	-18.91	-38.12	-97.42	-200.97	-417.39	-948.28	-1067.86
300	133.41	131.75	126.75	118.40	101.59	50.40	-36.40	-207.60	-574.22	-635.03
500	1134.71	1133.86	1131.30	1127.04	1118.56	1093.46	1052.87	977.26	804.31	680.66
700	2135.52	2134.98	2133.35	2130.64	2125.26	2109.35	2083.66	2035.48	1916.29	1792.10
900	3136.19	3135.81	3134.67	3132.78	3129.01	3117.90	3099.92	3065.99	2979.10	2875.70
1100	4136.79	4136.51	4135.69	4134.31	4131.57	4123.48	4110.37	4085.53	4020.93	3939.86
1300	5137.34	5137.12	5136.45	5135.33	5133.11	5126.53	5115.85	5095.54	5042.05	4972.81
1500	6137.88	6137.69	6137.12	6136.18	6134.30	6128.74	6119.71	6102.47	6056.64	5996.15
1700	7138.41	7138.26	7137.80	7137.03	7135.50	7130.97	7123.60	7109.51	7071.92	7021.88
1900	8138.95	8138.83	8138.47	8137.88	8136.70	8133.20	8127.51	8116.65	8087.72	8049.42
2100	9139.48	9139.40	9139.15	9138.73	9137.90	9135.43	9131.44	9123.85	9103.89	9078.23
2300	10140.0	10140.0	10139.8	10139.6	10139.1	10137.7	10135.4	10131.1	10120.3	10108.0
2500	11140.5	11140.5	11140.4	11140.2	11139.9	11139.0	11137.5	11134.9	11128.5	11122.5

Table 4-12 Enthalpy (H) of O<sub>2</sub>  
 p (atm), T (°K), H (Kcal/Kg-mole)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-2.45	-4.89	-12.24	-24.52	-49.15	-123.40	-246.23	-471.97	-794.72	-806.05
300	187.14	185.08	178.89	168.60	148.05	87.03	-11.00	-182.75	-436.66	-460.95
500	1590.03	1589.40	1587.50	1584.37	1578.23	1560.83	1535.11	1495.39	1446.47	1449.52
700	2992.05	2991.95	2991.67	2991.22	2990.40	2988.50	2987.11	2990.17	3030.82	3126.28
900	4393.80	4393.98	4394.53	4395.46	4397.35	4403.37	4414.41	4439.77	4532.89	4700.82
1100	5795.44	5795.79	5796.85	5798.62	5802.18	5813.07	5831.85	5871.41	6000.20	6220.59
1300	7196.99	7197.42	7198.72	7200.88	7205.23	7218.41	7240.81	7286.99	7432.60	7679.50
1500	8598.51	8598.99	8600.44	8602.86	8607.70	8622.33	8647.02	8697.43	8853.93	9118.16
1700	10000.0	10000.6	10002.1	10004.8	10010.2	10026.3	10053.3	10108.1	10276.1	10557.9
1900	11401.6	11402.1	11403.9	11406.8	11412.6	11430.2	11459.6	11518.9	11699.0	11998.9
2100	12803.1	12803.7	12805.6	12808.8	12815.1	12834.2	13866.0	12929.9	13122.5	13441.0
2300	14204.6	14205.3	14207.3	14210.8	14217.6	14238.1	14272.4	14340.9	14546.3	14884.0
2500	15606.1	15606.8	15608.9	15612.4	15619.5	15640.6	15675.9	15746.4	15957.3	16303.5

Table 4-13 Entropy (S) of O<sub>2</sub>

p (atm), T (°K), S (Kcal/Kg-mole-°K)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-0.0034	-1.3846	-3.2162	-4.6112	-6.0238	-7.9519	-9.5122	-11.2532	-13.8304	-15.3425
300	0.3277	-1.0528	-2.8823	-4.2739	-5.6794	-7.5341	-9.0997	-10.7343	-13.0270	-14.4706
500	2.1194	0.7408	-1.0830	-2.4649	-3.8510	-5.6967	-7.1130	-8.5587	-10.5166	-11.9747
700	3.2987	1.9206	0.0982	-1.2814	-2.6129	-4.4953	-5.8906	-7.3001	-9.1930	-10.6322
900	4.1794	2.8015	0.9796	-0.3991	-1.7789	-3.6062	-4.9936	-6.3891	-9.2527	-9.6743
1100	4.8826	3.5048	1.6832	0.3048	-1.0741	-2.8990	-4.7825	-5.6710	-7.5189	-8.9265
1300	5.4679	4.0901	2.2687	0.8905	-0.4880	-2.3118	-3.6935	-5.0788	-6.9191	-8.3195
1500	5.9694	4.5916	2.7702	1.3921	0.0138	-1.8092	-3.1899	-4.5732	-6.4089	-7.8045
1700	6.4079	5.0302	3.2088	1.8309	0.4527	-1.3698	-2.7497	-4.1315	-5.9634	-7.3546
1900	6.7976	5.4199	3.5985	2.2207	0.8427	-0.9795	-2.3587	-3.7392	-5.5679	-6.9553
2100	7.1483	5.7706	3.9493	2.5715	1.1936	0.6282	-2.0069	-3.3864	-5.2125	-6.5965
2300	7.4670	6.0893	4.2680	2.8903	1.5125	-0.3090	-1.6873	-3.0659	-4.8897	-6.2707
2500	7.7592	6.3815	4.5602	3.1825	1.8047	-0.0167	-1.3947	-2.7730	-4.5957	-5.9753

Table 4-14 Specific Heat at Constant Pressure ( $C_p$ ) of  $O_2$

p (atm), T ( $^{\circ}K$ ),  $C_p$  (Kcal/Kg-mole- $^{\circ}K$ )

$\begin{matrix} P \\ T \end{matrix}$	1	2	5	10	20	50	100	200	500	1000
273	7.0232	7.0390	7.0862	7.1639	7.3160	7.7405	8.3108	8.7268	7.3610	6.7940
300	7.0201	7.0327	7.0705	7.1327	7.2543	7.5940	8.0610	8.5488	7.3089	6.7458
500	7.0113	7.0153	7.0270	7.0465	7.0847	7.1940	7.3580	7.6215	8.0080	8.0882
700	7.0092	7.0111	7.0166	7.0258	7.0440	7.0968	7.1790	7.3235	7.6237	7.8445
900	7.0084	7.0095	7.0126	7.0179	7.0283	7.0589	7.1075	7.1968	7.4094	7.6303
1100	7.0080	7.0087	7.0107	7.0140	7.0206	7.0401	7.0715	7.1308	7.2826	7.4679
1300	7.0078	7.0083	7.0098	7.0122	7.0169	7.0311	7.0541	7.0981	7.2158	7.3724
1500	7.0077	7.0081	7.0092	7.0110	7.0147	7.0255	7.0433	7.0777	7.1724	7.3055
1700	7.0076	7.0079	7.0088	7.0102	7.0130	7.0213	7.0351	7.0619	7.1376	7.2493
1900	7.0076	7.0078	7.0084	7.0095	7.0116	7.0180	7.0285	7.0492	7.1091	7.2015
2100	7.0075	7.0077	7.0082	7.0089	7.0105	7.0152	7.0231	7.0388	7.0854	7.1606
2300	7.0075	7.0076	7.0079	7.0085	7.0096	7.0130	7.0186	7.0301	7.0625	7.1251
2500	7.0075	7.0075	7.0078	7.0083	7.0091	7.0118	7.0163	7.0256	7.0544	7.1050

Table 4-15 Specific Heat at Constant Volume ( $C_v$ ) of  $O_2$

$p$  (atm),  $T$  ( $^{\circ}K$ ),  $C_v$  (Kcal/Kg-mole- $^{\circ}K$ )

$T \backslash p$	1	2	5	10	20	50	100	200	500	1000
273	5.0046	5.0067	5.0131	5.0237	5.0450	5.1088	5.2130	5.3988	5.6140	5.5987
300	5.0042	5.0058	5.0108	5.0190	5.0354	5.0839	5.1612	5.2934	5.4707	5.4832
500	5.0030	5.0036	5.0052	5.0078	5.0131	5.0287	5.0536	5.0991	5.1992	5.2669
700	5.0028	5.0031	5.0040	5.0055	5.0086	5.0176	5.0323	5.0604	5.1335	5.2150
900	5.0027	5.0029	5.0036	5.0046	5.0068	5.0131	5.0236	5.0439	5.1000	5.1748
1100	5.0027	5.0028	5.0033	5.0041	5.0058	5.0107	5.0188	5.0347	5.0796	5.1441
1300	5.0026	5.0028	5.0032	5.0039	5.0052	5.0092	5.0159	5.0291	5.0667	5.1228
1500	5.0026	5.0027	5.0031	5.0037	5.0048	5.0082	5.0139	5.0252	5.0576	5.1069
1700	5.0026	5.0027	5.0030	5.0035	5.0045	5.0075	5.0124	5.0221	5.0504	5.0940
1900	5.0026	5.0027	5.0029	5.0034	5.0043	5.0069	5.0112	5.0198	5.0447	5.0837
2100	5.0026	5.0027	5.0029	5.0033	5.0041	5.0064	5.0102	5.0178	5.0401	5.0751
2300	5.0026	5.0026	5.0029	5.0032	5.0039	5.0060	5.0094	5.0162	5.0362	5.0678
2500	5.0026	5.0026	5.0028	5.0031	5.0038	5.0056	5.0088	5.0150	5.0332	5.0621

Table 4-16 Index of Refraction (n) of O<sub>2</sub>

p (atm), T (°K), n Dimensionless

T \ P	1	2	5	10	20	50	100	200	500	1000
273	1.00026	1.00052	1.00131	1.00264	1.00534	1.01376	1.02884	1.06204	1.15651	1.18137
300	1.00024	1.00048	1.00119	1.00239	1.00482	1.01228	1.02517	1.05161	1.11372	1.12489
500	1.00014	1.00029	1.00071	1.00142	1.00284	1.00705	1.01391	1.02685	1.05729	1.07983
700	1.00010	1.00020	1.00051	1.00102	1.00203	1.00502	1.00981	1.01906	1.04230	1.06737
900	1.00008	1.00016	1.00040	1.00079	1.00158	1.00390	1.00769	1.01490	1.03385	1.05735
1100	1.00006	1.00013	1.00032	1.00065	1.00129	1.00320	1.00631	1.01227	1.02826	1.04942
1300	1.00005	1.00011	1.00027	1.00055	1.00109	1.00271	1.00535	1.01045	1.02434	1.04345
1500	1.00005	1.00010	1.00024	1.00047	1.00095	1.00235	1.00465	1.00911	1.02140	1.03875
1700	1.00004	1.00008	1.00021	1.00042	1.00084	1.00208	1.00411	1.00807	1.01908	1.03494
1900	1.00004	1.00008	1.00019	1.00037	1.00075	1.00186	1.00369	1.00725	1.01722	1.03179
2100	1.00003	1.00007	1.00017	1.00034	1.00068	1.00168	1.00334	1.00657	1.01568	1.02915
2300	1.00003	1.00006	1.00015	1.00031	1.00062	1.00154	1.00305	1.00602	1.01440	1.02690
2500	1.00003	1.00006	1.00015	1.00028	1.00057	1.00142	1.00281	1.00555	1.01332	1.02501

Table 4-17 Isotherms(pv) of Air

p (atm), T (°K), pv (atm-cm<sup>3</sup>/g)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	772.91	772.53	771.40	769.58	766.17	757.74	749.75	756.45	958.03	1898.90
300	849.57	849.37	848.79	847.87	846.25	843.14	843.74	866.65	1109.03	2091.85
500	1416.76	1417.23	1418.65	1421.05	1425.93	1441.37	1469.69	1536.06	1813.08	2534.40
700	1983.53	1984.25	1986.41	1990.03	1997.32	2019.51	2057.65	2138.27	2141.80	2991.28
900	2550.19	2551.06	2553.66	2558.00	2566.70	2592.93	2637.13	2727.30	3012.01	3533.87
1100	3116.73	3117.62	3120.30	3124.75	3133.68	3160.53	3205.59	3296.79	3579.16	4078.99
1300	3683.28	3684.19	3686.94	3691.51	3700.68	3728.21	3774.27	3867.01	4150.25	4639.02
1500	4249.82	4250.76	4253.58	4258.28	4267.68	4295.91	4343.03	4437.55	4723.34	5207.10
1700	4816.36	4817.32	4820.22	4825.04	4834.68	4863.61	4911.84	5008.29	5297.73	5780.37
1900	5382.90	5383.89	5386.86	5391.80	5401.69	5431.33	5480.68	5579.18	5873.01	6357.21
2100	5949.43	5950.43	5953.43	5958.43	5968.42	5998.37	6048.21	6147.59	6443.34	6928.23
2300	6515.95	6516.95	6519.95	6524.95	6534.95	6564.91	6614.77	6714.17	7009.79	7493.88
2500	7082.46	7083.47	7086.47	7091.47	7101.47	7131.46	7181.34	7280.76	7576.30	8059.78

Table 4-18 Density( $\rho$ ) of Air

p (atm), T ( $^{\circ}$ K),  $\rho$  (Kg/m<sup>3</sup>)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	1.29381	2.58890	6.48172	12.9941	26.1040	65.9855	133.378	264.393	521.907	526.622
300	1.17706	2.35468	5.89076	11.7943	23.6336	59.3020	118.519	230.773	450.843	478.046
500	0.70584	1.41120	3.52447	7.0371	14.0259	34.6893	68.042	130.203	275.774	394.571
700	0.50415	1.00794	2.51710	5.0250	10.0134	24.7585	48.599	93.534	207.057	334.306
900	0.39213	0.78399	1.95797	3.9093	7.7921	19.2832	37.920	73.333	166.002	282.976
1100	0.32085	0.64151	1.60241	3.2003	6.3823	15.8201	31.196	60.665	139.697	245.159
1300	0.27150	0.54286	1.35614	2.7089	5.4044	13.4113	26.495	51.720	120.475	215.563
1500	0.23530	0.47050	1.17548	2.3484	4.6864	11.6390	23.025	45.070	105.857	192.046
1700	0.20763	0.41517	1.03730	2.0725	4.1368	10.2804	20.359	39.934	94.380	172.999
1900	0.18577	0.37148	0.92819	1.8547	3.7026	9.2058	18.246	35.848	85.135	157.302
2100	0.16808	0.33611	0.83985	1.6783	3.3510	8.3356	16.534	32.533	77.600	144.337
2300	0.15347	0.30689	0.76688	1.5326	3.0605	7.6163	15.118	29.788	71.329	133.442
2500	0.14119	0.28235	0.70557	1.4101	2.8163	7.0112	13.925	27.470	65.995	124.073

Table 4-19 Internal Energy(U) of Air

p (atm), T (°K), U (Kcal/Kg-mole)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-1.43	-2.87	-7.18	-14.57	-28.82	-72.46	-145.10	-282.37	-536.95	-541.42
300	132.25	130.98	127.18	120.83	108.12	70.06	7.63	-108.20	-325.61	-351.60
500	1121.91	1121.26	1119.31	1116.07	1109.63	1090.64	1060.13	1003.73	874.00	770.58
700	2111.19	2110.79	2109.57	2107.54	2103.52	2091.67	2072.59	2036.95	1948.71	1852.89
900	3100.36	3100.09	3099.26	3097.89	3095.15	3087.10	3074.11	3049.72	2987.64	2912.90
1100	4089.47	4089.25	4088.62	4087.56	4085.45	4079.21	4069.14	4050.08	4000.68	3938.61
1300	5078.55	5078.37	5077.85	5076.99	5075.27	5070.19	5061.95	5046.30	5005.27	4952.39
1500	6067.63	6067.49	6067.09	6066.42	6065.10	6061.17	6054.80	6042.70	6010.86	5969.57
1700	7056.71	7056.61	7056.33	7055.86	7054.92	7052.16	7047.69	7039.21	7017.11	6989.01
1900	8045.79	8045.73	8045.57	8045.29	8044.75	8043.16	8040.59	8035.80	8023.81	8010.02
2100	9034.85	9034.82	9034.73	9034.57	9034.27	9033.37	9031.96	9029.39	9023.49	9018.41
2300	10023.9	10023.9	10023.8	10023.7	10023.6	10023.0	10022.2	10020.8	10018.0	10017.4
2500	11013.0	11012.9	11012.9	11012.9	11012.8	11012.7	11012.5	11012.2	11012.6	11016.6

Table 4-20 Enthalpy (H) of Air

p (atm), T (°K), H (Kcal/Kg-mole)

T \ p	1	2	5	10	20	50	100	200	500	1000
273	-1.70	-3.41	-8.51	-16.98	-33.81	-83.19	-160.35	-287.81	-451.53	-453.46
300	186.31	184.91	180.69	173.70	159.86	119.69	58.00	-41.82	-172.41	-182.56
500	1577.96	1577.64	1576.69	1575.13	1572.16	1563.90	1552.81	1539.32	1544.33	1586.43
700	2968.94	2969.04	2969.34	2969.86	2970.94	2974.62	2982.06	3001.08	3078.23	3214.28
900	4359.74	4360.07	4361.07	4362.74	4366.11	4376.44	4394.33	4432.21	4555.42	4760.70
1100	5750.38	5750.79	5752.02	5754.09	5758.24	5770.84	5792.29	5836.61	5976.29	6209.90
1300	7140.99	7141.46	7142.87	7145.22	7149.92	7164.15	7188.17	7237.19	7388.96	7642.62
1500	8531.61	8532.14	8533.71	8536.34	8541.61	8557.48	8584.14	8638.08	8802.80	9076.53
1700	9922.23	9922.81	9924.56	9927.47	9933.30	9950.83	9980.16	10039.2	10217.5	10511.8
1900	11312.8	11313.5	11315.4	11318.6	11325.0	11344.2	11376.2	11440.4	11632.9	11948.3
2100	12703.4	12704.1	12706.1	12709.5	12716.2	12736.3	12769.8	12836.9	13037.3	13365.1
2300	14094.0	14094.7	14096.7	14100.2	14107.0	14127.5	14161.6	14229.9	14433.6	14767.0
2500	15484.6	15485.3	15487.4	15490.8	15497.8	15518.7	15553.4	15622.9	15830.0	16168.9

Table 4-21 Entropy (S) of Air

p (atm), T ( $^{\circ}$ K), S (Kcal/Kg-mole- $^{\circ}$ K)

T \ p	1	2	5	10	20	50	100	200	500	1000
273	-0.0026	-1.2820	-3.2120	-4.6029	-6.0067	-7.9058	-9.4087	-11.0076	-13.1775	-14.4605
300	0.3257	-1.0541	-2.8816	-4.2698	-5.6685	-7.5513	-9.0267	-10.5735	-12.6655	-14.0711
500	2.1030	0.7247	-1.0985	-2.4794	-3.8635	-5.7032	-7.1099	-8.5384	-10.4624	-11.9071
700	3.2731	1.8951	0.0730	-1.3061	-2.6867	-4.5162	-5.9070	-7.3084	-9.1829	-10.6095
900	4.1469	2.7691	0.9474	-0.4311	-1.8103	-3.6360	-5.0207	-6.4114	-8.2638	-9.6751
1100	4.8446	3.4480	1.6453	0.2671	-1.1116	-2.9356	-4.3178	-5.7039	-7.5457	-8.9471
1300	5.4254	4.0476	2.2262	0.8482	-0.5302	-2.3534	-3.7342	-5.1178	-6.9539	-8.3495
1500	5.9229	4.5451	2.7238	1.3459	-0.0323	-1.8548	-3.2346	-4.6163	-6.4478	-7.8383
1700	6.3580	4.9803	3.1590	1.7811	0.4032	-1.4189	-2.7979	-4.1781	-6.0058	-7.3917
1900	6.7447	5.3670	3.5457	2.1679	0.7901	-1.0316	-2.4099	-3.7889	-5.6136	-6.9955
2100	7.0926	5.7149	3.8937	2.5159	1.1382	-0.6833	-2.0613	-3.4397	-5.2626	-6.6424
2300	7.4089	6.0312	4.2099	2.8322	1.4545	-0.3669	-1.7447	-3.1228	-4.9449	-6.3237
2500	7.6988	6.3211	4.4998	3.1221	1.7444	-0.0769	-1.4546	-2.8324	-4.6538	-6.0316

Table 4-22 Specific Heat at Constant Pressure ( $C_p$ ) of Air

$p$  (atm),  $T$  ( $^{\circ}\text{K}$ ),  $C_p$  (Kcal/Kg-mole- $^{\circ}\text{K}$ )

$T \backslash P$	1	2	5	10	20	50	100	200	500	1000
273	6.9648	6.9768	7.0125	7.0713	7.1858	7.5027	7.9308	8.3773	7.7696	7.7401
300	6.9625	6.9721	7.0009	7.0481	7.1403	7.3968	7.7520	8.1834	8.1104	8.0168
500	6.9559	6.9589	6.9680	6.9830	7.0126	7.0973	7.2257	7.4374	7.7928	7.9370
700	6.9542	6.9557	6.9599	6.9670	6.9810	7.0219	7.0861	7.2008	7.4543	7.6765
900	6.9536	6.9544	6.9568	6.9608	6.9688	6.9923	7.0299	7.1001	7.2754	7.4795
1100	6.9533	6.9539	6.9555	6.9582	6.9635	6.9794	7.0051	7.0540	7.1830	7.3502
1300	6.9532	6.9536	6.9548	6.9567	6.9606	6.9722	6.9912	7.0279	7.1283	7.2680
1500	6.9531	6.9534	6.9542	6.9557	6.9585	6.9670	6.9809	7.0083	7.0855	7.2000
1700	6.9530	6.9532	6.9538	6.9548	6.9569	6.9629	6.9730	6.9930	7.0514	7.1431
1900	6.9529	6.9531	6.9535	6.9542	6.9556	6.9597	6.9667	6.9808	7.0235	7.0950
2100	6.9529	6.9530	6.9533	6.9538	6.9548	6.9579	6.9631	6.9736	7.0067	7.0647
2300	6.9529	6.9530	6.9532	6.9536	6.9544	6.9569	6.9611	6.9696	6.9969	7.0462
2500	6.9529	6.9529	6.9531	6.9534	6.9541	6.9560	6.9594	6.9662	6.9886	7.0302

Table 4-23 Specific Heat at Constant Volume ( $C_v$ ) of Air

$p$  (atm),  $T$  ( $^{\circ}\text{K}$ ),  $C_v$  (Kcal/Kg-mole- $^{\circ}\text{K}$ )

$T \backslash P$	1	2	5	10	20	50	100	200	500	1000
273	4.9467	4.9483	4.9529	4.9606	4.9758	5.0204	5.0899	5.2039	5.3472	5.3488
300	4.9464	4.9477	4.9513	4.9574	4.9695	5.0048	5.0597	5.1509	5.2811	5.2927
500	4.9457	4.9461	4.9474	4.9497	4.9541	4.9672	4.9883	5.0275	5.1189	5.1929
700	4.9455	4.9457	4.9465	4.9479	4.9506	4.9585	4.9716	4.9968	5.0640	5.1453
900	4.9454	4.9455	4.9462	4.9471	4.9491	4.9548	4.9642	4.9827	5.0341	5.1054
1100	4.9454	4.9455	4.9460	4.9467	4.9482	4.9528	4.9603	4.9750	5.0169	5.0782
1300	4.9453	4.9455	4.9458	4.9465	4.9477	4.9515	4.9577	4.9699	5.0051	5.0581
1500	4.9453	4.9454	4.9457	4.9463	4.9473	4.9505	4.9558	4.9662	4.9963	5.0426
1700	4.9453	4.9454	4.9457	4.9461	4.9470	4.9498	4.9543	4.9633	4.9895	5.0302
1900	4.9453	4.9454	4.9456	4.9460	4.9468	4.9492	4.9532	4.9611	4.9840	5.0201
2100	4.9453	4.9453	4.9456	4.9459	4.9466	4.9488	4.9523	4.9593	4.9799	5.0123
2300	4.9453	4.9453	4.9455	4.9458	4.9465	4.9484	4.9516	4.9580	4.9766	5.0061
2500	4.9453	4.9453	4.9455	4.9458	4.9464	4.9481	4.9510	4.9568	4.9738	5.0009

Table 4-24 Index of Refraction (n) of Air

p (atm), T (°K), n Dimensionless

$\begin{matrix} P \\ T \end{matrix}$	1	2	5	10	20	50	100	200	500	1000
273	1.00031	1.00063	1.00157	1.00315	1.00633	1.01602	1.03284	1.06477	1.12959	1.13080
300	1.00028	1.00057	1.00143	1.00286	1.00573	1.01439	1.02884	1.05644	1.11151	1.11841
500	1.00017	1.00034	1.00085	1.00170	1.00340	1.00841	1.01652	1.03170	1.06760	1.09730
700	1.00012	1.00024	1.00061	1.00122	1.00243	1.00600	1.01179	1.02273	1.05059	1.08218
900	1.00009	1.00019	1.00047	1.00095	1.00189	1.00467	1.00920	1.01781	1.04048	1.06939
1100	1.00008	1.00016	1.00039	1.00077	1.00155	1.00383	1.00756	1.01472	1.03402	1.06000
1300	1.00007	1.00013	1.00033	1.00066	1.00131	1.00325	1.00642	1.01255	1.02932	1.05268
1500	1.00006	1.00011	1.00028	1.00057	1.00113	1.00282	1.00558	1.01093	1.02574	1.04689
1700	1.00005	1.00010	1.00025	1.00050	1.00100	1.00249	1.00493	1.00968	1.02294	1.04220
1900	1.00004	1.00009	1.00022	1.00045	1.00090	1.00223	1.00442	1.00869	1.02069	1.03834
2100	1.00004	1.00008	1.00020	1.00041	1.00081	1.00202	1.00401	1.00789	1.01885	1.03516
2300	1.00004	1.00007	1.00019	1.00037	1.00074	1.00184	1.00366	1.00722	1.01732	1.03249
2500	1.00003	1.00007	1.00017	1.00034	1.00068	1.00170	1.00337	1.00666	1.01602	1.03020

Table 4-25 Isotherms(pv) of Ar

p (atm), T (°K), pv (atm-cm<sup>3</sup>/g)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	560.31	559.77	558.16	555.51	550.29	535.35	512.81	476.64	432.30	614.30
300	615.93	615.54	614.39	612.51	608.85	598.74	584.75	567.52	601.88	945.92
500	1027.37	1027.55	1028.09	1029.01	1030.93	1037.23	1049.57	1081.15	1231.03	1664.67
700	1438.45	1438.84	1440.00	1441.96	1445.90	1457.99	1479.06	1524.66	1689.00	2054.79
900	1849.43	1849.92	1851.41	1853.88	1858.84	1873.88	1899.41	1952.29	2125.30	2461.62
1100	2260.37	2260.92	2262.58	2265.36	2270.92	2287.67	2315.84	2375.15	2552.73	2877.53
1300	2671.27	2671.85	2673.60	2676.51	2682.33	2699.86	2729.21	2788.50	2970.91	3290.10
1500	3082.16	3082.75	3084.54	3087.52	3093.47	3111.37	3141.30	3201.52	3385.11	3700.88
1700	3493.05	3493.66	3495.49	3498.55	3504.66	3523.01	3553.65	3615.12	3801.12	4116.35
1900	3903.94	3904.56	3906.42	3909.53	3915.75	3934.41	3965.54	4027.89	4215.59	4530.69
2100	4314.83	4315.46	4317.37	4320.54	4326.89	4345.94	4377.69	4441.17	4631.47	4948.16
2300	4725.71	4726.36	4728.31	4731.55	4738.03	4757.48	4789.85	4854.50	5047.63	5366.73
2500	5136.60	5137.25	5139.22	5142.49	5149.04	5168.68	5201.36	5266.59	5461.11	5781.43

Table 4-26 Density ( $\rho$ ) of Ar

p (atm), T ( $^{\circ}$ K),  $\rho$  (Kg/m<sup>3</sup>)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	1.78474	3.57291	8.95798	18.0016	36.3445	93.3976	195.003	419.604	1138.18	1627.88
300	1.62357	3.24917	8.13810	16.3262	32.8478	83.5089	171.014	352.409	830.73	1057.18
500	0.97336	1.94639	4.86339	9.7181	19.4000	48.2053	95.267	184.988	406.16	600.72
700	0.69513	1.39001	3.47221	6.9350	13.8323	34.2938	67.610	131.177	296.03	486.67
900	0.54071	1.08113	2.70065	5.3941	10.7594	26.6827	52.648	102.444	235.26	406.24
1100	0.44241	0.88460	2.20986	4.4143	8.8070	21.8563	43.181	84.276	195.87	347.52
1300	0.37435	0.73854	1.87014	3.7362	7.4562	18.5195	36.641	71.723	168.30	303.94
1500	0.32445	0.64877	1.62099	3.2389	6.4652	16.0701	31.834	62.470	147.71	270.21
1700	0.28628	0.57247	1.43041	2.8583	5.7067	14.1924	28.140	55.323	131.54	242.93
1900	0.25615	0.51222	1.27994	2.5579	5.1076	12.7084	25.217	49.654	118.61	220.72
2100	0.23176	0.46345	1.15811	2.3145	4.6222	11.5050	22.843	45.033	107.96	202.10
2300	0.21161	0.42316	1.05746	2.1135	4.2212	10.5098	20.878	41.199	99.06	186.33
2500	0.19468	0.38931	0.97291	1.1445	3.8842	9.6737	19.226	37.975	91.56	172.97

Table 4-27 Internal Energy (U) of Ar

p (atm), T (°K), U (Kcal/Kg-mole)

T \ P	1	2	5	10	20	50	100	200	500	1000
273	-1.64	-3.29	-8.25	-16.56	-33.36	-85.20	-175.87	-368.88	-917.67	-1231.67
300	79.00	77.53	73.13	65.76	50.94	57.87	-71.11	-226.13	-606.49	-772.19
500	675.71	674.95	672.69	668.93	661.43	639.19	602.99	534.55	368.89	226.79
700	1271.98	1271.49	1270.05	1267.64	1262.85	1248.66	1225.63	1181.95	1070.31	944.10
900	1868.12	1867.79	1866.78	1865.10	1861.76	1851.86	1835.78	1805.17	1724.89	1624.53
1100	2464.21	2463.97	2463.23	2462.01	2459.58	2452.37	2440.65	2418.26	2358.78	2281.06
1300	3060.26	3060.07	3059.48	3058.50	3056.54	3050.75	3041.32	3023.24	2974.73	2909.75
1500	3656.29	3656.13	3655.62	3654.79	3653.13	3648.20	3640.16	3624.71	3582.93	3525.95
1700	4252.32	4252.18	4251.77	4251.09	4249.72	4245.66	4239.04	4226.29	4191.69	4144.14
1900	4848.35	4848.24	4847.92	4847.38	4846.31	4843.13	4837.93	4827.93	4800.80	4763.59
2100	5444.38	5444.30	5444.07	5443.68	5442.90	5440.59	5436.83	5429.62	5410.21	5384.07
2300	6040.41	6040.36	6040.22	6039.97	6039.49	6038.06	6035.74	6031.34	6019.82	6005.27
2500	6636.43	6636.40	6636.31	6636.16	6635.87	6635.01	6633.62	6631.02	6624.57	6617.51

Table 4-28 Enthalpy (H) of Ar

p (atm), T (°K), H (Kcal/Kg-mole)

T \ p	1	2	5	10	20	50	100	200	500	1000
273	-2.17	-4.33	-10.84	-21.72	-43.56	-109.59	-220.10	-432.14	-812.44	-811.33
300	132.62	130.78	125.27	116.09	97.73	42.96	-46.29	-209.69	-500.80	-569.92
500	1129.88	1129.30	1127.56	1124.69	1119.05	1102.87	1078.37	1038.38	977.27	967.61
700	2126.35	2126.24	2125.92	2125.40	2124.42	2121.91	2119.08	2118.08	2142.23	2118.34
900	3122.60	3122.74	3123.16	3123.88	3125.34	3129.97	3138.49	3158.18	3232.24	3373.71
1100	4118.75	4119.04	4119.92	4121.38	4124.32	4133.31	4148.78	4181.32	4287.80	4474.98
1300	5114.83	5115.19	5116.29	5118.12	5121.81	5132.96	5151.88	5190.83	5313.73	5525.25
1500	6110.87	6111.28	6112.50	6114.55	6118.65	6131.03	6151.92	6194.49	6326.78	6552.56
1700	7106.91	7107.37	7108.73	7111.00	7115.54	7129.24	7152.23	7198.79	7341.63	7582.99
1900	8102.95	8103.45	8104.93	8107.40	8112.34	8127.21	8152.11	8202.31	8354.97	8610.94
2100	9099.00	9099.53	9101.14	9103.82	9109.19	9125.31	9152.25	9206.37	9369.76	9641.69
2300	10095.0	10095.6	10097.4	10100.2	10106.0	10123.4	10152.4	10210.5	10384.9	10673.3
2500	11091.1	11091.7	11093.5	11096.5	11102.5	11120.7	11150.9	11211.4	11392.4	11691.0

Table 4-29 Entropy (S) of Ar

p (atm), T ( $^{\circ}$ K), S (Kcal/Kg-mole- $^{\circ}$ K)

$\begin{matrix} p \\ T \end{matrix}$	1	2	5	10	20	50	100	200	500	1000
273	-0.0030	-1.3837	-3.2140	-4.6069	-6.0152	-7.9302	-9.4691	-11.1715	-13.8698	-15.5479
300	0.2324	-1.1477	-2.9763	-4.3662	-5.7685	-7.6637	-9.1646	-10.7799	-13.1108	-14.6709
500	1.5060	0.1276	-1.6959	-3.0773	-4.4625	-6.3055	-7.7178	-9.1581	-11.1143	-12.5881
700	2.3443	0.9662	-0.8560	-2.2355	-3.6166	-5.4478	-6.8314	-8.2482	-10.1376	-11.5810
900	2.9702	1.5923	-0.2295	-1.6081	-2.9877	-4.8143	-6.2007	-7.5946	-9.4555	-10.8768
1100	3.4699	2.0921	0.2706	-1.1077	-2.4865	-4.3110	-5.6939	-7.0814	-8.9274	-10.3345
1300	3.8860	2.5082	0.6867	-0.6914	-2.0698	-3.8932	-5.2745	-6.6590	-8.4977	-9.8922
1500	4.2423	2.8645	1.0431	-0.3348	-1.7131	-3.5359	-4.9163	-6.2991	-8.1335	-9.5283
1700	4.5540	3.1762	1.3549	0.0230	-1.4011	-3.2235	-4.6032	-5.9846	-7.8157	-9.2064
1900	4.8309	3.4532	1.6319	0.2540	-1.1235	-2.9460	-4.3251	-5.7054	-7.5336	-8.9207
2100	5.0802	3.7024	1.8811	0.5033	-0.8745	-2.6963	-4.0749	-5.4544	-7.2802	-8.6142
2300	5.1267	3.9290	2.1077	0.7299	-0.6479	-2.4694	-3.8476	-5.2263	-7.0502	-8.4314
2500	5.5143	4.1366	2.3153	0.9376	-0.4401	-2.2615	-3.6395	-5.0178	-6.8405	-8.2201

Table 4-30 Specific Heat at Constant Pressure ( $C_p$ ) of Ar  
 $p$  (atm),  $T$  ( $^{\circ}\text{K}$ ),  $C_p$  (Kcal/Kg-mole- $^{\circ}\text{K}$ )

$T \backslash P$	1	2	5	10	20	50	100	200	500	1000
273	4.9940	5.0080	5.0498	5.1188	5.2544	5.6388	6.1832	6.7489	5.7817	4.0807
300	4.9912	5.0024	5.0358	5.0909	5.1991	5.5052	5.9435	6.4869	5.5572	3.9223
500	4.9835	4.9870	4.9974	5.0145	5.0484	5.1459	5.2946	5.5421	5.5900	6.0711
700	4.9817	4.9833	4.9882	4.9964	5.0125	5.0596	5.1336	5.2661	5.5554	5.7926
900	4.9809	4.9819	4.9847	4.9893	4.9985	5.0256	5.0690	5.1494	5.3463	5.5620
1100	4.9806	4.9812	4.9829	4.9859	4.9917	5.0089	5.0369	5.0898	5.2280	5.4034
1300	4.9804	4.9808	4.9821	4.9842	4.9884	5.0007	5.0209	5.0598	5.1652	5.3093
1500	4.9803	4.9806	4.9816	4.9832	4.9864	4.9960	5.0116	5.0420	5.1265	5.2477
1700	4.9803	4.9805	4.9812	4.9825	4.9850	4.9923	5.0045	5.0283	5.0958	5.1968
1900	4.9802	4.9804	4.9810	4.9819	4.9838	4.9894	4.9988	5.0172	5.0706	5.1535
2100	4.9801	4.9803	4.9807	4.9814	4.9828	4.9871	4.9941	5.0082	5.0498	5.1169
2300	4.9801	4.9802	4.9805	4.9810	4.9821	4.9851	4.9903	5.0007	5.0322	5.0854
2500	4.9801	4.9802	4.9804	4.9808	4.9816	4.9839	4.9879	4.9960	5.0210	5.0648

Table 4-31 Specific Heat at Constant Volume ( $C_v$ ) of Ar

$p$  (atm),  $T$  ( $^{\circ}\text{K}$ ),  $C_v$  (Kcal/Kg-mole- $^{\circ}\text{K}$ )

$T \backslash p$	1	2	5	10	20	50	100	200	500	1000
273	2.9820	2.9840	2.9899	2.9999	3.0199	3.0803	3.1809	3.3719	3.6923	3.6568
300	2.9815	2.9829	2.9873	2.9946	3.0092	3.0526	3.1226	3.2481	3.4521	3.4845
500	2.9805	2.9809	2.9823	2.9847	2.9893	3.0030	3.0250	3.0658	3.1606	3.2368
700	2.9803	2.9805	2.9813	2.9827	2.9853	2.9932	3.0060	3.0308	3.0967	3.1757
900	2.9802	2.9819	2.9847	2.9819	2.9837	2.9892	2.9983	3.0160	3.0656	3.1343
1100	2.9801	2.9803	2.9807	2.9814	2.9828	2.9871	2.9941	3.0080	3.0473	3.1054
1300	2.9801	2.9802	2.9806	2.9812	2.9823	2.9858	2.9916	3.0030	3.0359	3.0858
1500	2.9801	2.9802	2.9805	2.9810	2.9820	2.9850	2.9900	2.9996	3.0278	3.0714
1700	2.9801	2.9802	2.9804	2.9809	2.9817	2.9843	2.9886	2.9970	3.0216	3.0600
1900	2.9801	2.9802	2.9804	2.9808	2.9815	2.9838	2.9875	2.9949	3.0166	3.0509
2100	2.9801	2.9801	2.9803	2.9807	2.9813	2.9833	2.9867	2.9933	3.0126	3.0433
2300	2.9801	2.9801	2.9803	2.9806	2.9812	2.9830	2.9860	2.9919	3.0092	3.0369
2500	2.9801	2.9801	2.9803	2.9805	2.9811	2.9827	2.9854	2.9908	3.0065	3.0318

Table 4-32 Index of Refraction (n) of Ar

p (atm), T (°K), n Dimensionless

T \ P	1	2	5	10	20	50	100	200	500	1000
273	1.00029	1.00057	1.00143	1.00288	1.00583	1.01499	1.03140	1.06803	1.18950	1.27710
300	1.00026	1.00052	1.00130	1.00262	1.00526	1.01340	1.02751	1.05701	1.13663	1.17543
500	1.00016	1.00031	1.00078	1.00156	1.00311	1.00773	1.01530	1.02977	1.06582	1.09798
700	1.00011	1.00022	1.00056	1.00111	1.00222	1.00550	1.01085	1.02108	1.04781	1.07907
900	1.00009	1.00017	1.00043	1.00086	1.00172	1.00428	1.00844	1.01645	1.03792	1.06583
1100	1.00007	1.00014	1.00035	1.00071	1.00141	1.00350	1.00692	1.01353	1.03154	1.05621
1300	1.00006	1.00012	1.00030	1.00060	1.00119	1.00297	1.00587	1.01151	1.02708	1.04910
1500	1.00005	1.00010	1.00026	1.00052	1.00104	1.00257	1.00510	1.01002	1.02375	1.04360
1700	1.00005	1.00009	1.00023	1.00046	1.00091	1.00227	1.00451	1.00887	1.02114	1.03917
1900	1.00004	1.00008	1.00020	1.00041	1.00082	1.00204	1.00404	1.00796	1.01905	1.03556
2100	1.00004	1.00007	1.00019	1.00037	1.00074	1.00184	1.00366	1.00722	1.01734	1.03254
2300	1.00003	1.00007	1.00017	1.00034	1.00068	1.00168	1.00334	1.00660	1.01590	1.02999
2500	1.00003	1.00006	1.00016	1.00031	1.00062	1.00155	1.00308	1.00609	1.01470	1.02783

### B. Graphical Results

The graphical results for air and argon presented are: compressibility factor vs. pressure with temperature as parameter, enthalph vs. pressure with temperature as parameter, entropy vs. temperature with pressure as parameter, specific heat at constant pressure vs. temperature with pressure as parameter, index of refraction vs. temperature with pressure as parameter, and index of refraction vs. pressure with temperature as parameter.

Figure 4-1 to Figure 4-6     Diagrams for Air

Figure 4-7 to Figure 4-12     Diagrams for Argon

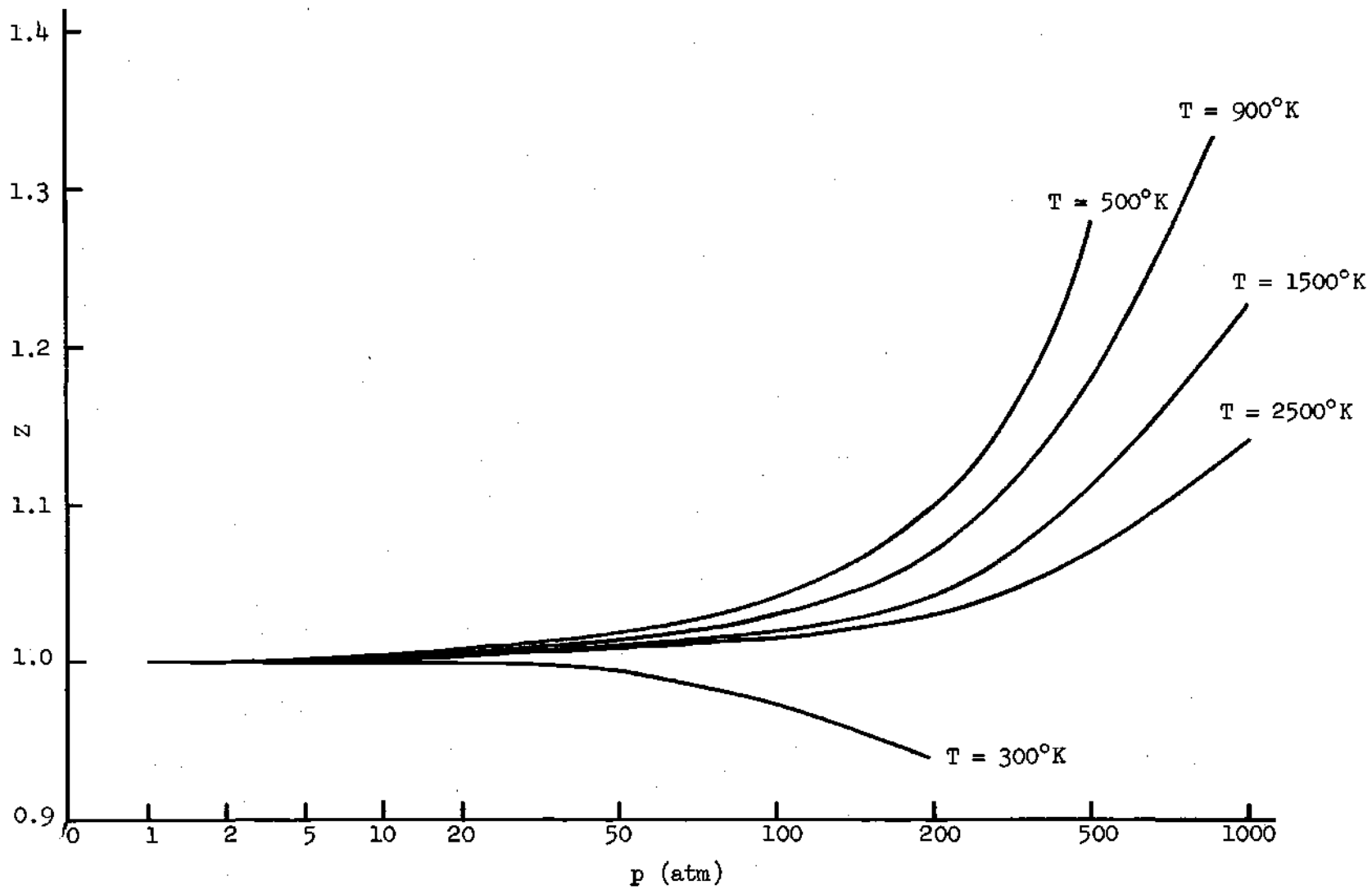


Figure 4-1. Compressibility Factor-Pressure Diagram of Air

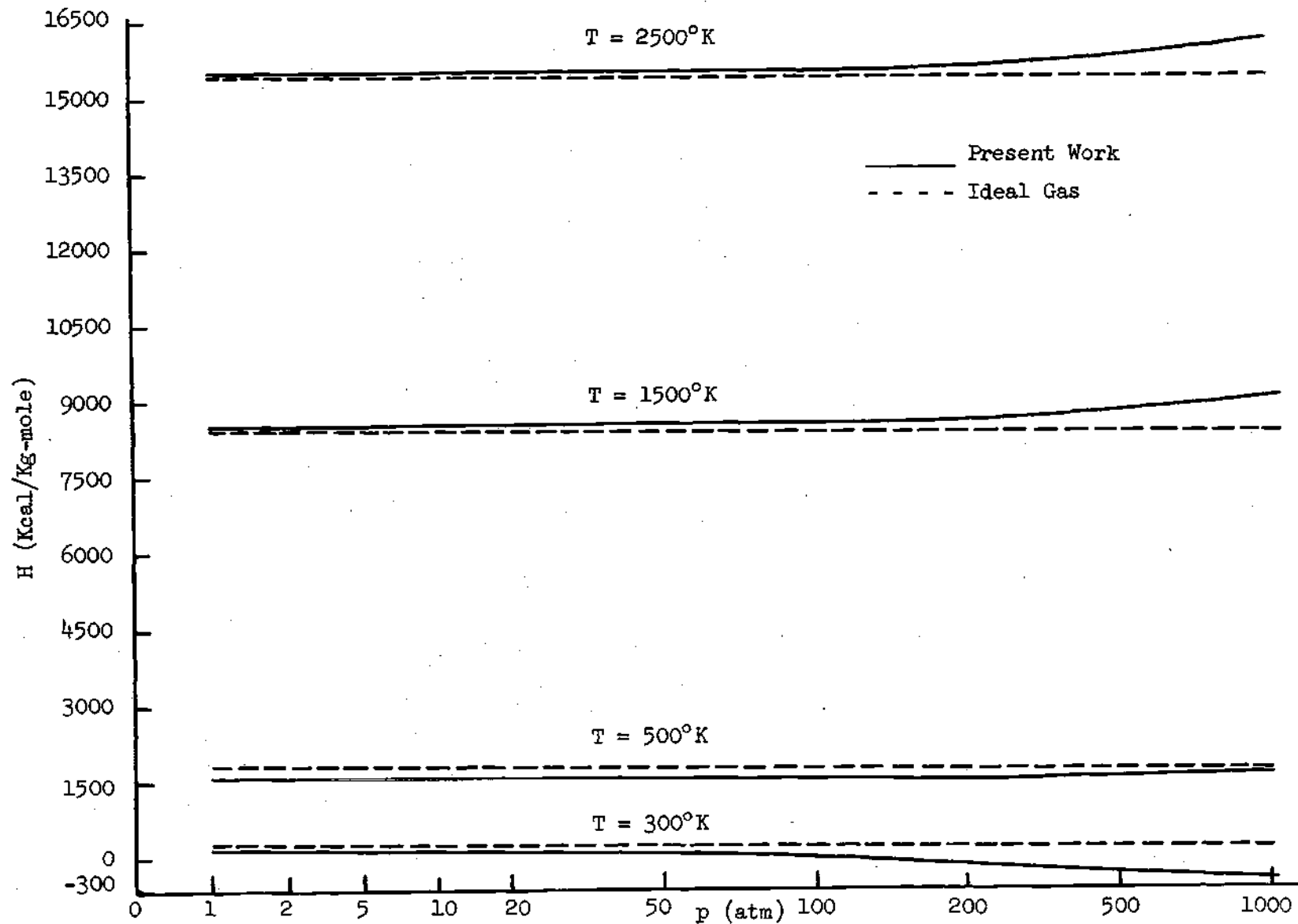


Figure 4-2. Enthalpy-Pressure Diagram of Air

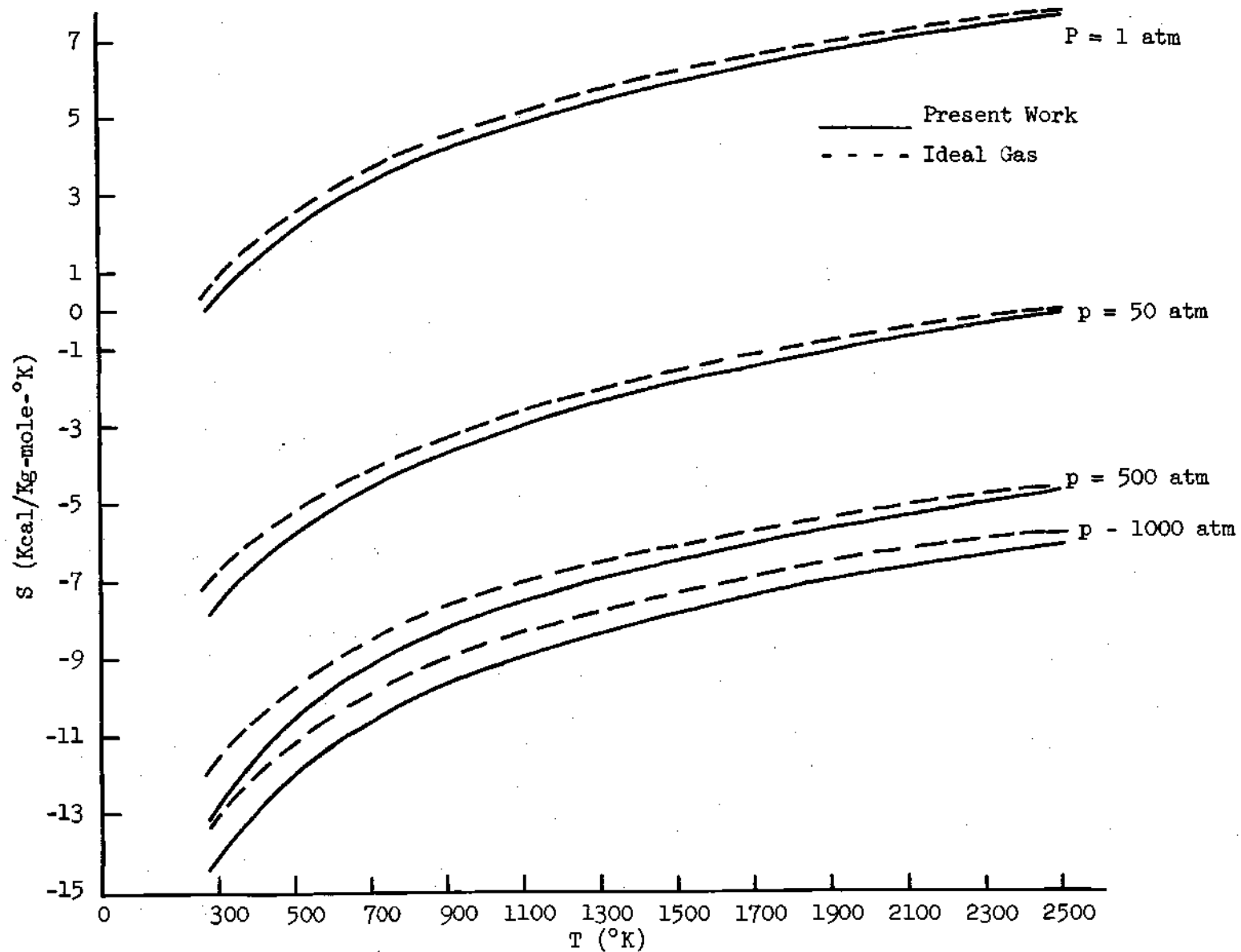


Figure 4-3. Entropy-Temperature Diagram of Air

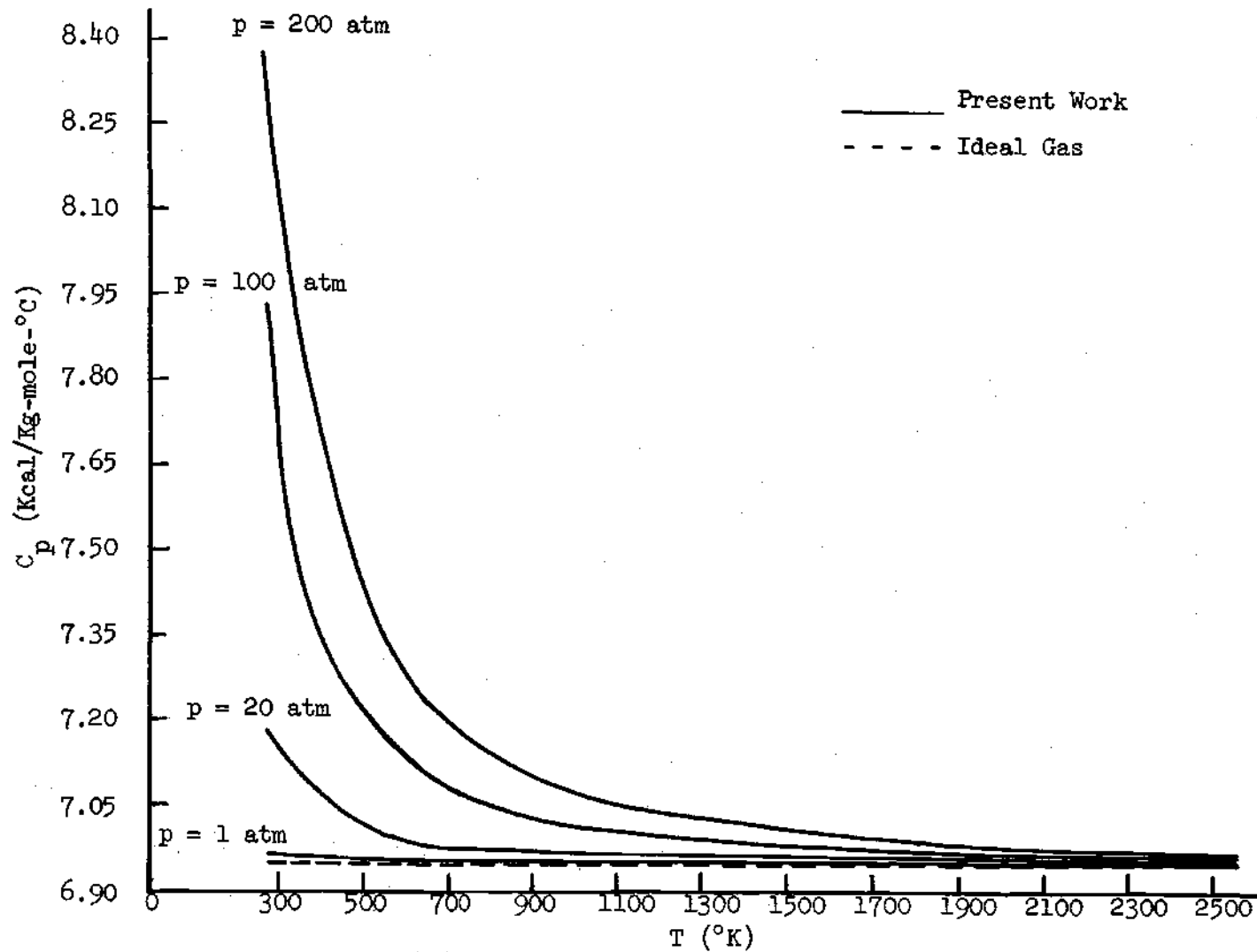


Figure 4-4. Specific Heat-Temperature Diagram of Air

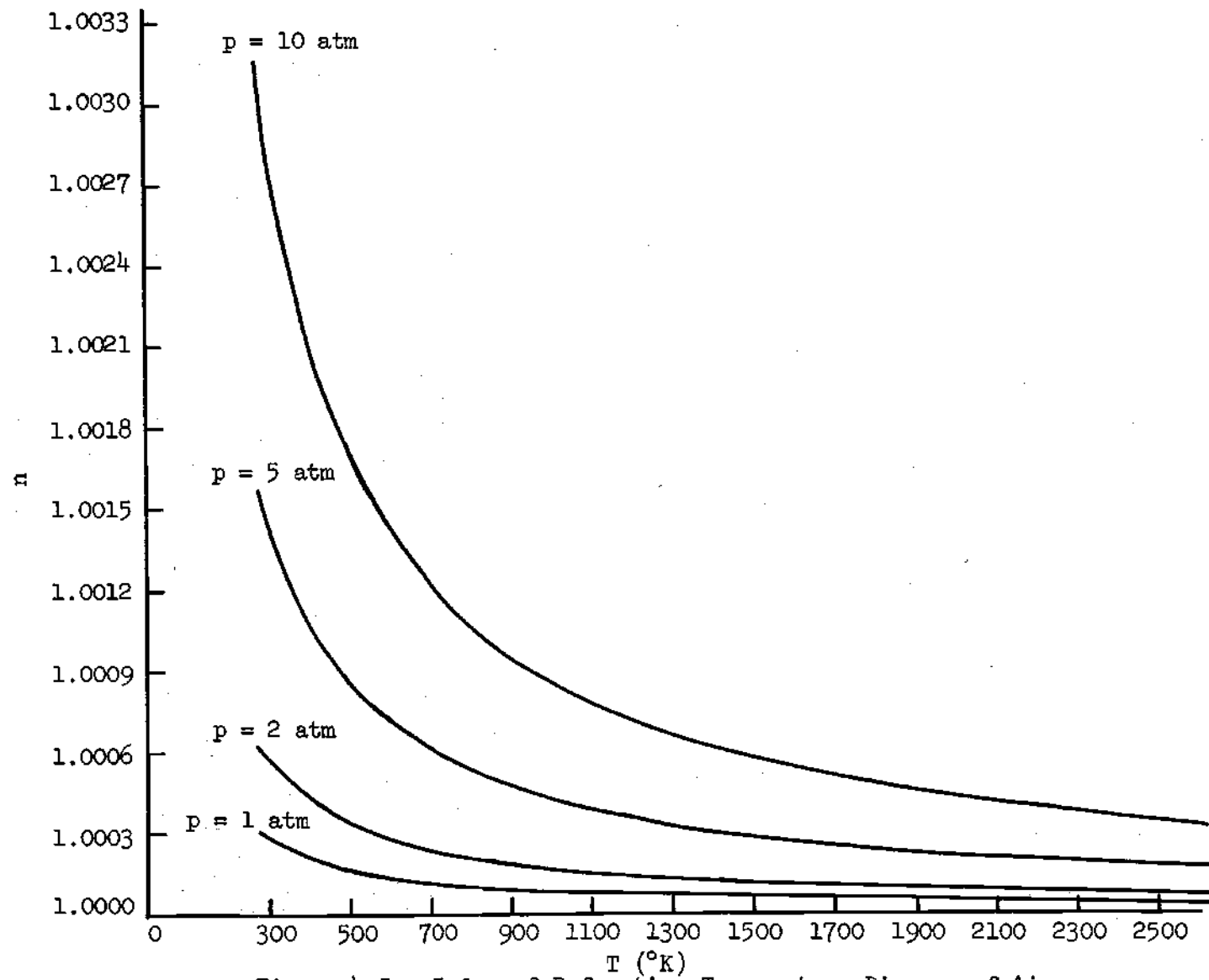


Figure 4-5. Index of Refraction-Temperature Diagram of Air

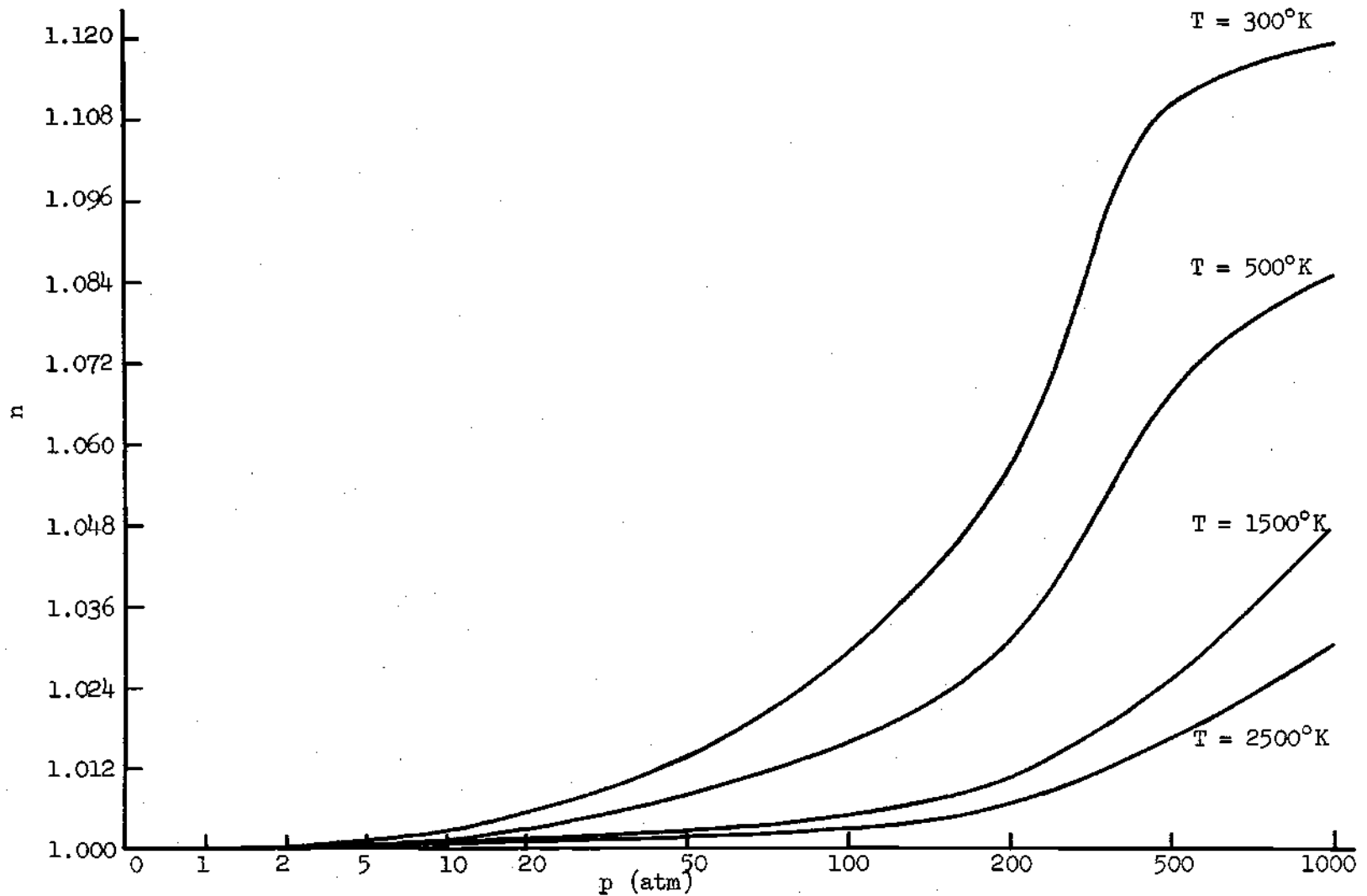


Figure 4-6. Index of Refraction-Pressure Diagram of Air

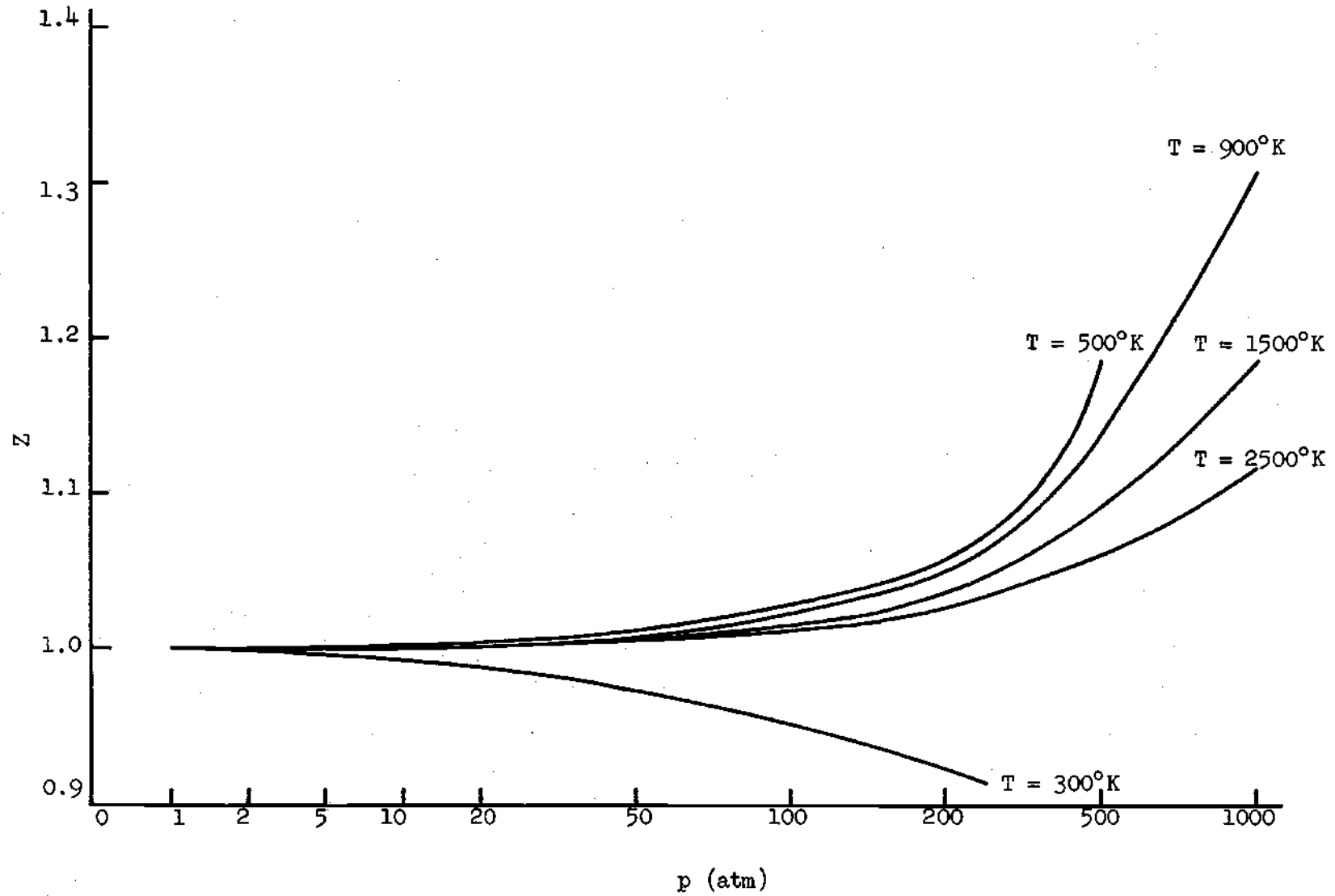


Figure 4-7. Compressibility Factor-Pressure Diagram of Ar

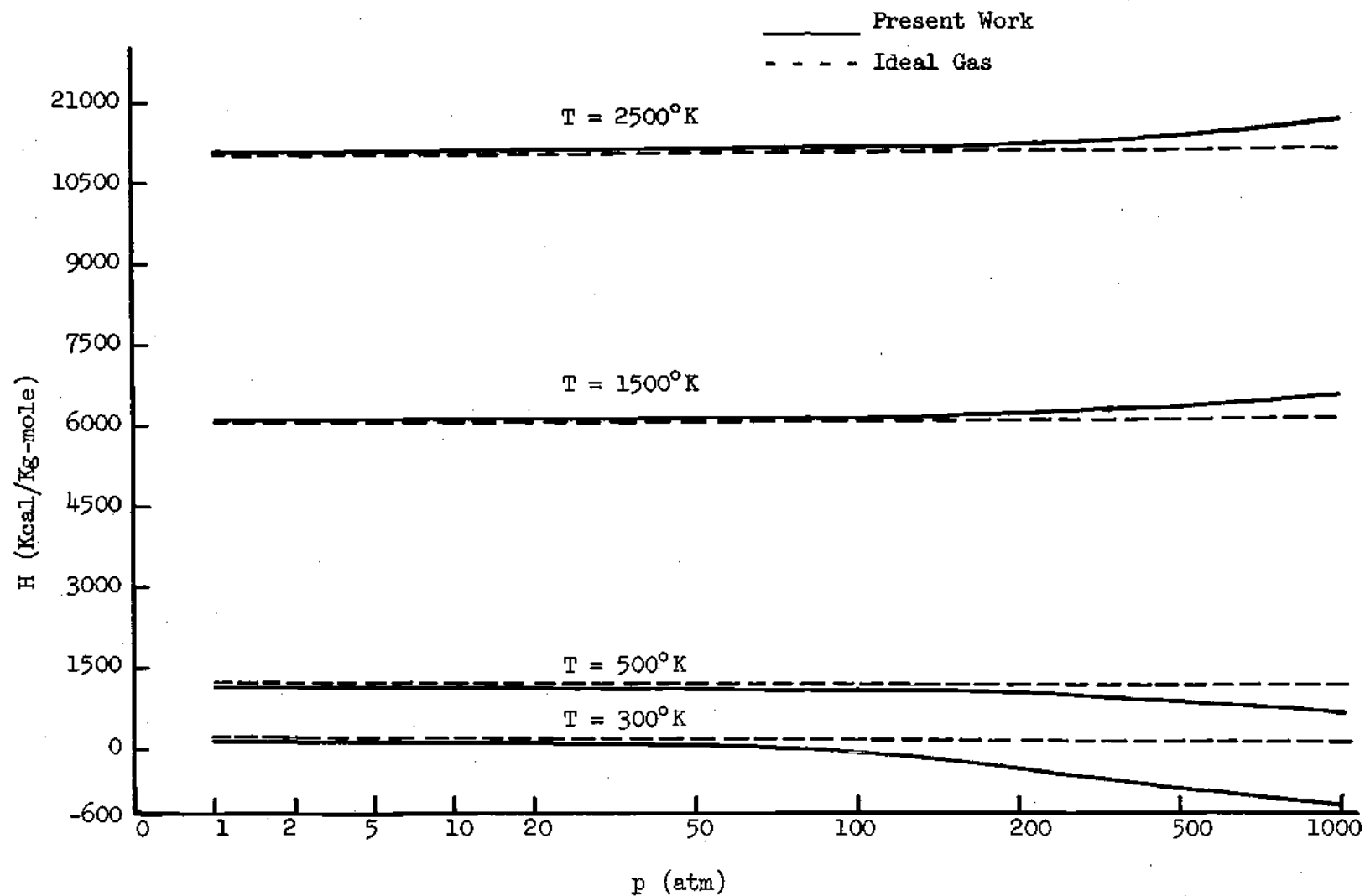


Figure 4-8. Enthalpy-Pressure Diagram of Ar

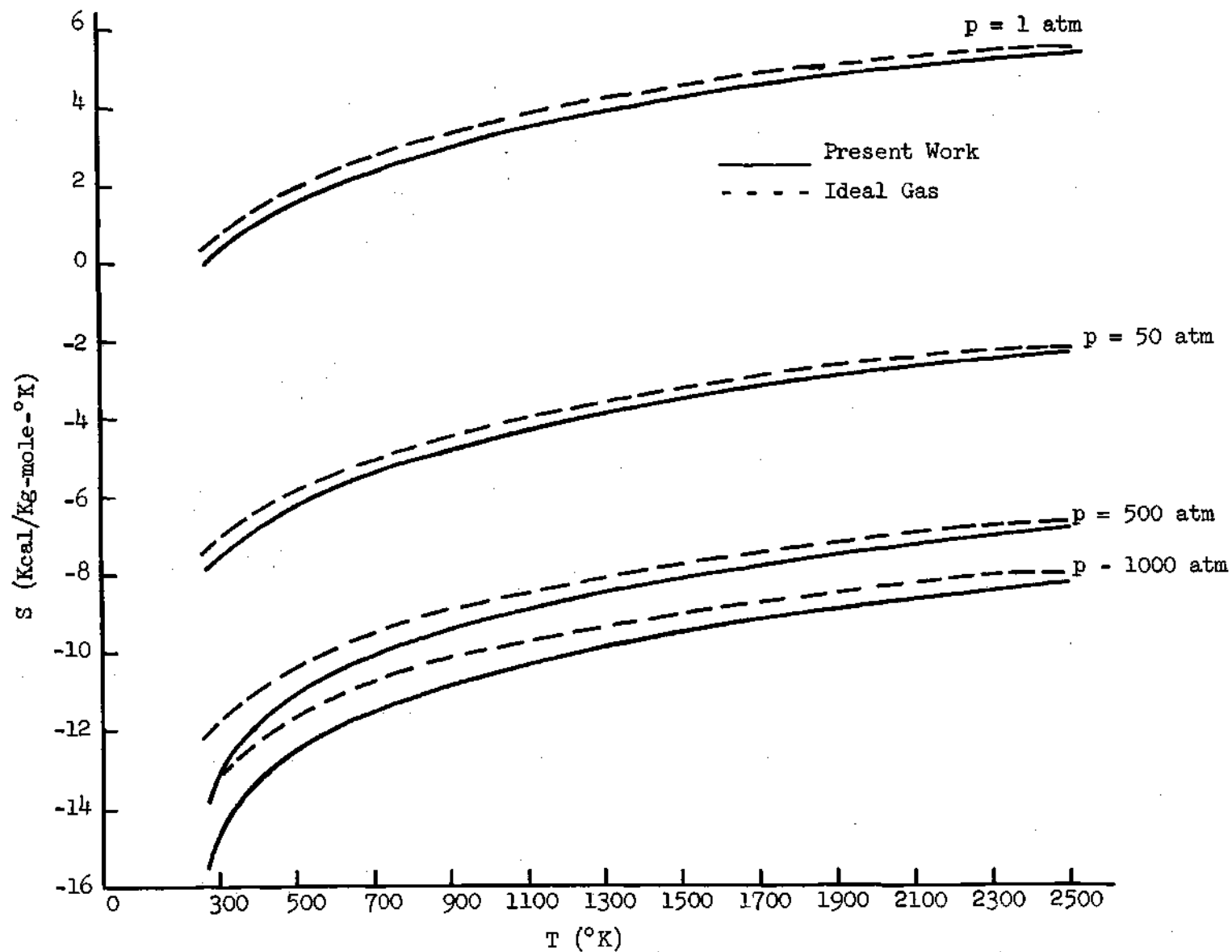


Figure 4-9. Entropy-Temperature Diagram of Ar

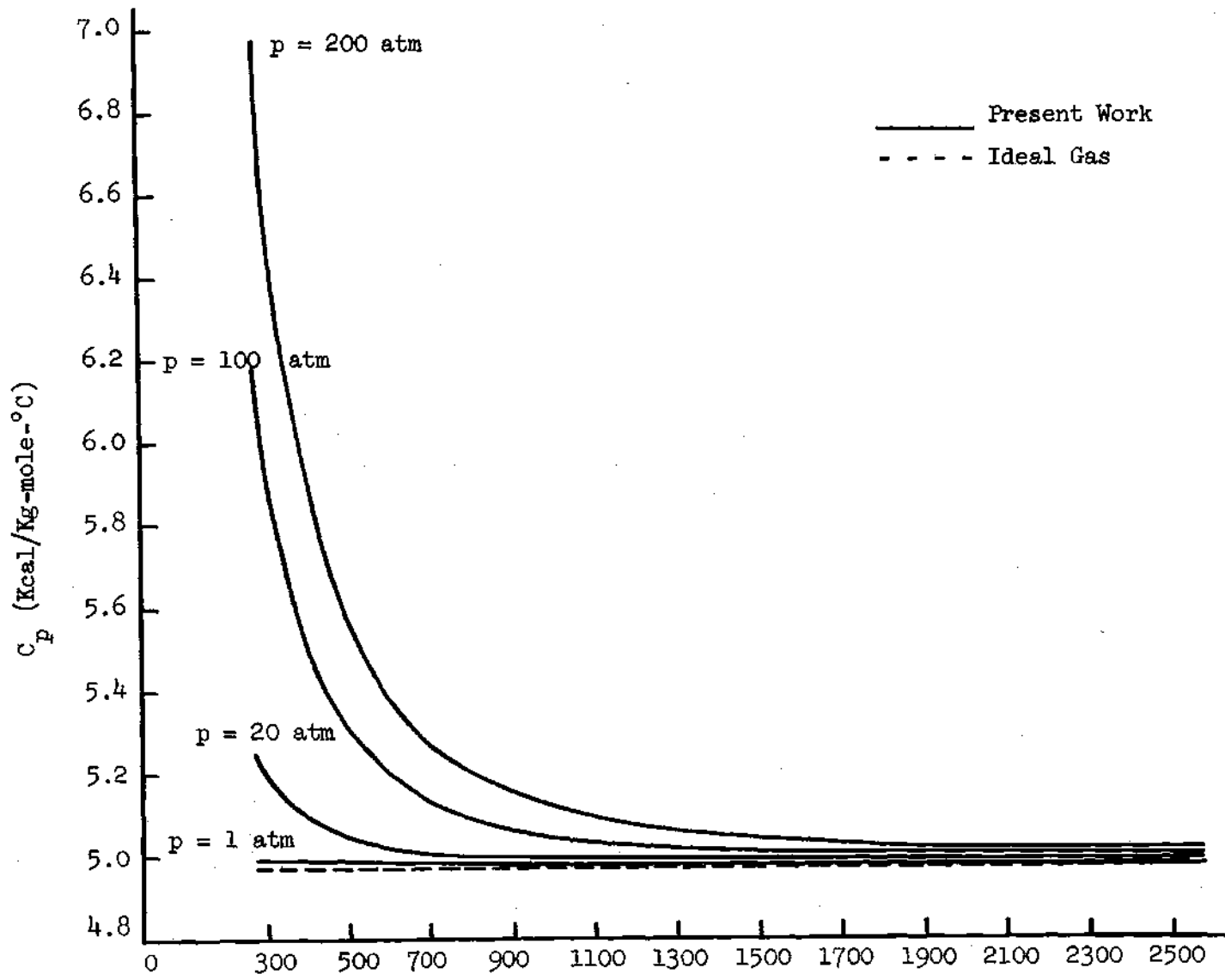


Figure 4-10. Specific Heat-Temperature Diagram of Ar

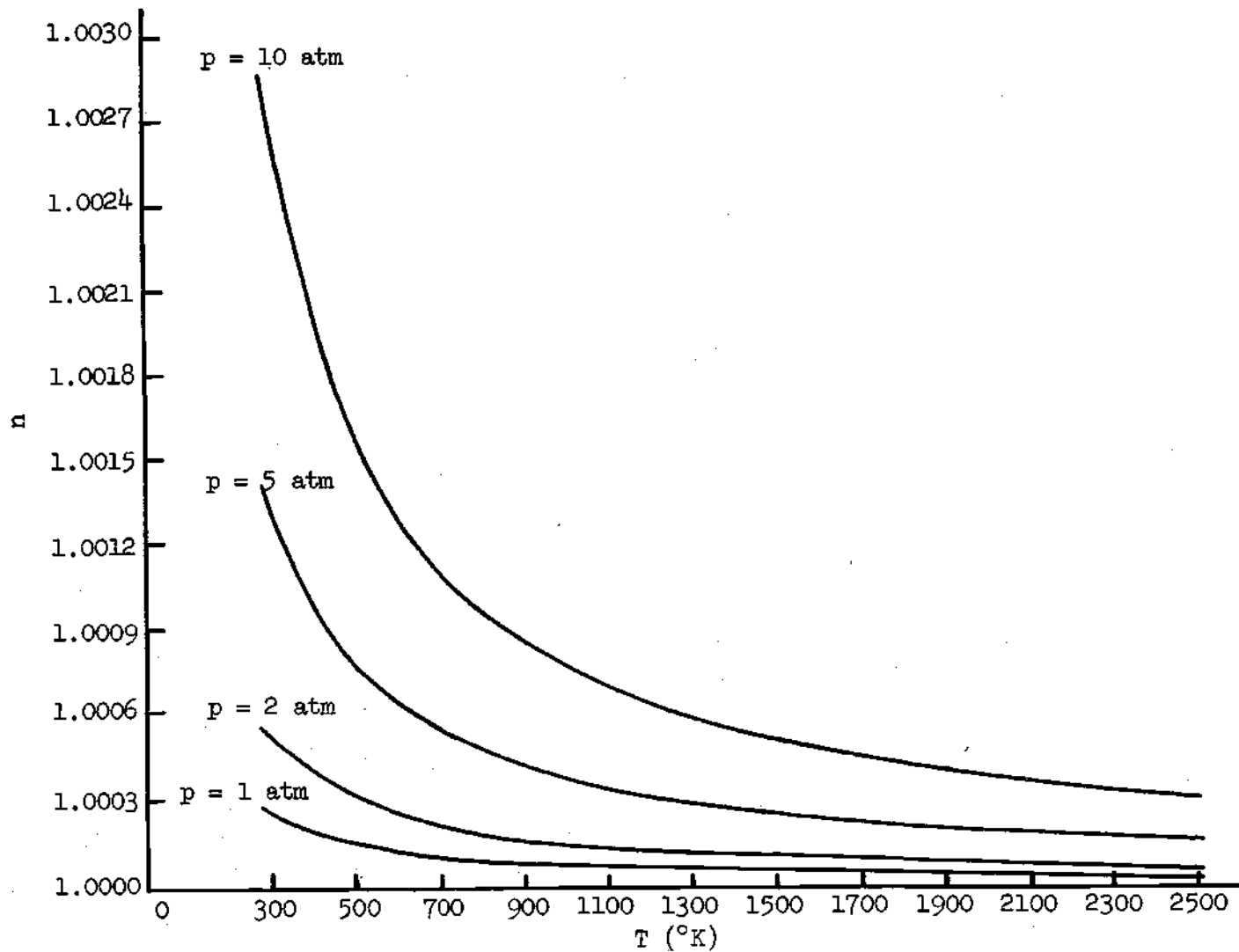


Figure 4-11. Index of Refraction-Temperature Diagram of Ar

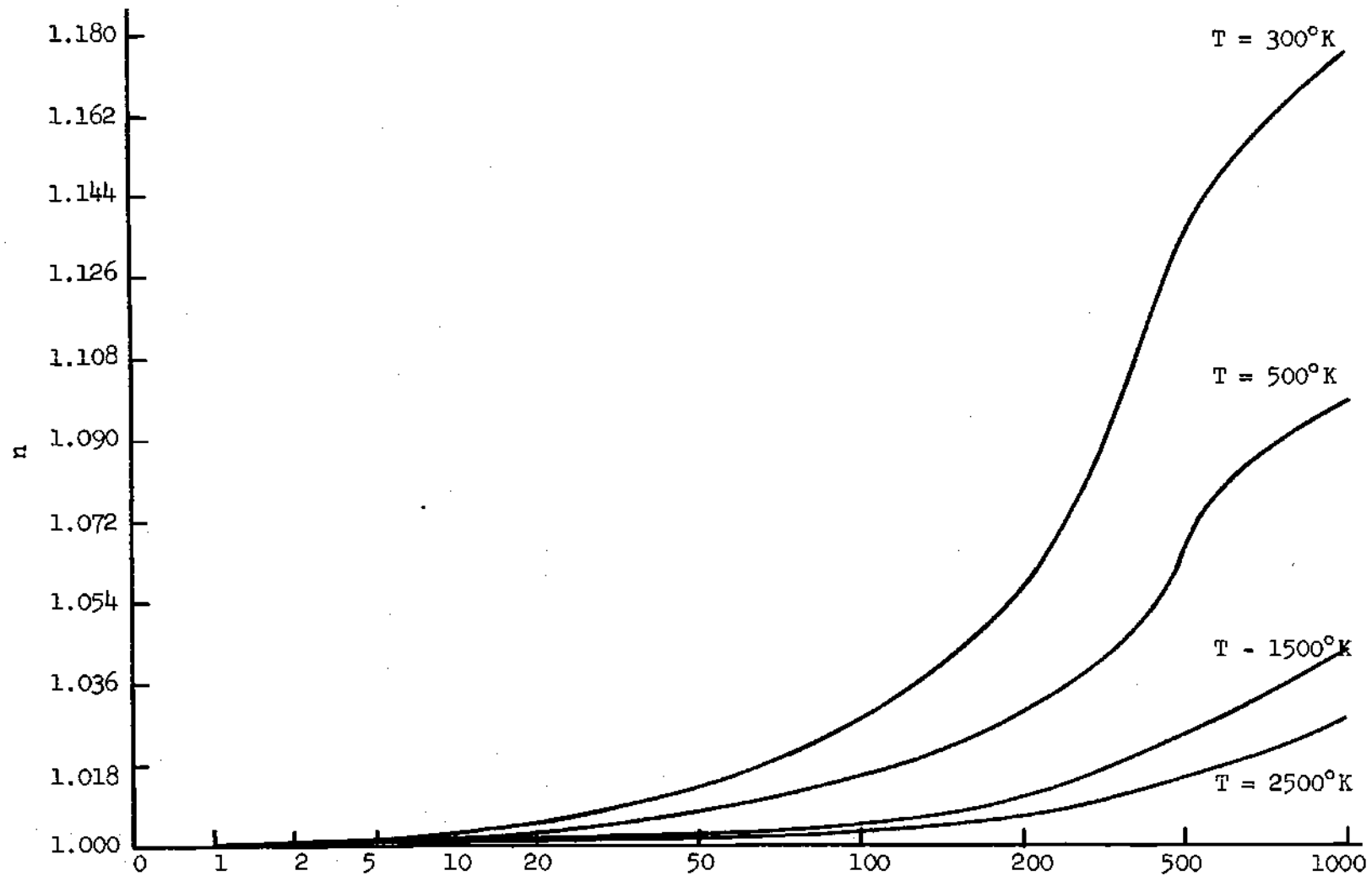


Figure 4-12. Index of Refraction-Pressure Diagram of Ar

### C. Discussions of Results

The results of the present calculations were compared to previous work, Ref. (2, 3, 5, 6, 7, 9, 12, 13, 29, 33), and shown in Table (4-33). At low pressure ranges, the deviations are almost negligible, but at high pressure and low temperature ranges, the deviations, as might be expected, are much greater.

Compared with Ref. (2, 3, 5, 6), all the properties presented almost have the same deviation under specified pressure and temperature.

In Ref. 33, the equation of state used is the Van der Waals equation of state:

$$\left( p + \frac{a}{V^2} \right) (V - b) = RT$$

with constant coefficients "a" and "b". The intermolecular potential used is the corrected rigid-sphere potential. The deviation is much greater than the others, and the maximum deviation occurs at highest pressure and lowest temperature region.

From Eq. (3-43):

$$\frac{H-H^0}{\bar{N}_e} = T^* \left[ \frac{B^* - B_1^*}{V^*} + \frac{C^* - \frac{1}{2}C_1^*}{(V^*)^2} + \dots \right] \quad (3-43)$$

and Appendix E, we can see that at low temperatures (around and below 400°K), the terms in parenthesis of Eq. (3-43) are negative and decreasing with an increase in pressure, while they are positive and increasing with an increase in pressure in high temperature regions (above 400°K). Therefore, the slopes of the curves in Fig. (4-2) are negative when the temperatures are around or below 400°K, and are

Table 4-33. Comparison of Results with Previous Work

References Compared With	Gases	Properties	Pressure Range (atm)	Temperature Range ( $^{\circ}$ K)	Deviation (%)
3	Nz	pV,U,H,S, $C_p$ , $C_v$	1-1,000	273-423	0.21-3.07
5	N <sub>2</sub>	pV,U,H,S, $C_p$ , $C_v$	1-1,000	273-423	0.20-3.01
7	N <sub>2</sub>	pV	200-1,000	273-423	0.50-4.40
13	N <sub>2</sub>	n	60-1,000	298	0.00-4.30
33	N <sub>2</sub>	pV	200-1,000	273-423	0.10-30.1
2	Ar	U,H,S, $C_p$ , $C_v$	1-1,000	273-423	2.36-4.75
6	Ar	pV,U,H,S, $C_p$ , $C_v$	200-1,000	273-423	0.36-4.75
9	Ar	pV	1-1,000	273-423	0.43-3.62
12	Ar	n	60-1,000	298	0.00-1.60
29	N <sub>2</sub> ,O <sub>2</sub> ,Air	$\rho$ ,H,S, $C_p$ , $C_v$	1-500	273-2500	1.03-2.14

positive when the temperatures are above 400°K. For the same reason, the slopes of the curves in Figure (4-8) are negative when the temperatures are around or below 600°K, and are positive when the temperatures are above 600°K.

From Eq. (3-63):

$$A = \frac{M}{\rho} \frac{n^2 - 1}{n^2 + 2} \quad (3-63)$$

the index of refraction,  $n$ , is:

$$n = \left( \frac{M + 2A\rho}{M - A\rho} \right) \quad (4-1)$$

where  $M$  and  $A$  are constants.

Tables (4-18) and (4-26) (densities of air and argon), show that in a low pressure range, the density for a fixed temperature increases rapidly with the increase in pressure. However, in a higher pressure range, this increase in density at  $T = \text{constant}$  is much slower. This effect shifts to higher pressure if higher temperatures are considered. For this reason it can be expected that, from Eq. (4-1), the index of refraction at a given temperature increases rapidly with an increase in pressure in the low pressure region, and increases slowly with an increase in pressure in a higher pressure region. The resulting inflection points on the curves can be seen in Figure (4-6) and (4-12), and the inflection points moved to high pressure region when the temperature is increasing.

## APPENDIX A

THE SECOND VIRIAL COEFFICIENT AND THE ZERO-PRESSURE JOULE-THOMSON COEFFICIENT FOR THE LENNARD-JONES (6-12) POTENTIAL<sup>a</sup>

$$B(T) = b_0 B^*(T^*)$$

$$T^* = kT/\epsilon$$

$$b_0 = 2/3\pi\bar{N}\sigma^3$$

$$\mu^{\circ}C_p^{\circ} = b_0(B_1^* - B^*)$$

$$B_1^* = T^*(dB^*/dT^*)$$

$$B_2^* = T^{*2}(d^2B^*/dT^{*2})$$

$T^*$	$B^*$	$B_1^*$	$B_2^*$	$B_1^* - B^*$
0.30	-27.880581	76.607256	-356.87679	104.488
0.35	-18.754895	45.247713	-189.46536	64.003
0.40	-13.798835	30.267080	-116.36604	44.066
0.45	-10.754975	21.989482	-78.87795	32.744
0.50	-8.720205	16.923690	-57.33952	25.644
0.55	-7.2740858	13.582156	-43.88245	20.8563
0.60	-6.1979708	11.248849	-34.91869	17.4468
0.65	-5.3681918	9.5455096	-28.64050	14.9137
0.70	-4.7100370	8.2571145	-24.06266	12.9672
0.75	-4.1759283	7.2540135	-20.61311	11.4299
0.80	-3.7342254	6.4541400	-17.94190	10.1884
0.85	-3.3631193	5.8034061	-15.82546	9.1665
0.90	-3.0471143	5.2649184	-14.11557	8.3120
0.95	-2.7749102	4.8127607	-12.71081	7.5877
1.00	-2.5380814	4.4282616	-11.53985	6.9663
1.05	-2.3302208	4.0976659	-10.55133	6.4279
1.10	-2.1463742	3.8106421	-9.70744	5.9570
1.15	-1.9826492	3.5592925	-8.97985	5.5419
1.20	-1.8359492	3.3374893	-8.34700	5.1734
1.25	-1.7037784	3.1404074	-7.79217	4.8442
1.30	-1.5841047	2.9642040	-7.30227	4.5483
1.35	-1.4752571	2.8057826	-6.86692	4.2810
1.40	-1.3758479	2.6626207	-6.47777	4.0385
1.45	-1.2847160	2.5326459	-6.12805	3.8174
1.50	-1.2008832	2.4141403	-5.81225	3.6150
1.55	-1.1235183	2.3056683	-5.52578	3.4292
1.60	-1.0519115	2.2060215	-5.26485	3.2579

<sup>a</sup> R. B. Bird and E. L. Spatz, University of Wisconsin, CM-599 (1950).

## Appendix A (Continued)

$T^*$	$B^*$	$B_1^*$	$B_2^*$	$B_1^* - B^*$
0.65	- 0.98545337	2.1141772	- 5.02628	3.0996
1.70	- 0.92361639	2.0292621	- 4.80738	2.9529
1.75	- 0.86594279	1.9505276	- 4.60587	3.8165
1.80	- 0.81203328	1.8773287	- 4.41980	2.6894
1.85	- 0.76153734	1.8091057	- 4.24750	2.5706
1.90	- 0.71414733	1.7453722	- 4.08753	2.4595
1.95	- 0.66959030	1.6857016	- 3.93863	2.3553
2.00	- 0.62762535	1.6297207	- 3.79972	2.2573
2.10	- 0.55063308	1.5275444	- 3.54814	2.0782
2.20	- 0.48170997	1.4366294	- 3.32647	1.9183
2.30	- 0.41967761	1.3552188	- 3.12974	1.7749
2.40	- 0.36357566	1.2819016	- 2.95401	1.6455
2.50	- 0.31261340	1.2155320	- 2.79614	1.5281
2.60	- 0.26613345	1.1551691	- 2.65355	1.4213
2.70	- 0.22358626	1.1000353	- 2.52416	1.3236
2.80	- 0.18450728	1.0494802	- 2.40623	1.2340
2.90	- 0.14850215	1.0029572	- 2.29831	1.1515
3.00	- 0.11523390	0.9600031	- 2.19920	1.0752
3.10	- 0.08441245	0.9202229	- 2.10785	1.0046
3.20	- 0.05578696	0.8832774	- 2.02340	0.93906
3.30	- 0.02913997	0.8488746	- 1.94511	0.87802
3.40	- 0.00428086	0.8167606	- 1.87231	0.82104
3.50	0.01895684	0.7867145	- 1.80447	0.76776
3.60	0.04072012	0.7585430	- 1.74108	0.71782
3.70	0.06113882	0.7320758	- 1.68174	0.67094
3.80	0.08032793	0.7071630	- 1.62605	0.62684
3.90	0.09839014	0.6836715	- 1.57371	0.58528
4.00	0.11541691	0.6614830	- 1.52441	0.54607
4.10	0.13149021	0.6404922	- 1.47789	0.50900
4.20	0.14668372	0.6206045	- 1.43394	0.47392
4.30	0.16106381	0.6017352	- 1.39234	0.44067
4.40	0.17469039	0.5838082	- 1.35291	0.40912
4.50	0.18761774	0.5667545	- 1.31548	0.37914
4.60	0.19989511	0.5505118	- 1.27991	0.35062
4.70	0.21156728	0.5350237	- 1.24606	0.32346
4.80	0.22267507	0.5202387	- 1.21381	0.29756
4.90	0.23325577	0.5061101	- 1.18305	0.27285
5.0	0.24334351	0.4925951	- 1.15367	0.24925
6.0	0.32290437	0.3839722	- 0.919393	0.06107
7.0	0.37608846	0.3982566	- 0.757930	-0.96783
8.0	0.41343396	0.2524801	- 0.639879	-0.16095
9.0	0.44059784	0.2097011	- 0.549792	-0.23090

## Appendix A (Continued)

$\pi^*$	$B^*$	$B_1^*$	$B_2^*$	$B_1^* - B^*$
10.0	0.46087529	0.1758670	0.478779	-0.28501
20.0	0.52537420	0.0286638	0.170403	-0.49671
30.0	0.52692546	-0.0174929	0.072012	-0.54442
40.0	0.51857502	-0.0393115	0.024109	-0.55789
50.0	0.50836143	-0.0516478	0.003927	-0.56001
60.0	0.49821261	-0.0593621	0.022147	-0.55758
70.0	0.48865069	-0.0645039	0.034817	-0.55316
80.0	0.47979009	-0.0670719	0.044056	-0.54787
90.0	0.47161504	-0.0706470	0.051031	-0.54226
100.0	0.46406948	-0.0725244	0.056441	-0.53659
200.0	0.41143168	-0.0775400	0.077296	-0.48897
300.0	0.38012787	-0.0765245	0.077296	-0.45665
400.0	0.35835117	-0.0747534	0.082055	-0.43310

## APPENDIX B

THE THIRD VIRIAL COEFFICIENT AND ITS DERIVATIVES FOR THE  
LENNARD-JONES (6-12) POTENTIAL<sup>a</sup>

$$T^* = kT/\epsilon$$

$$c^* = c/b_0^2$$

$$b_0 = 2/3 \pi N_0 \sigma^3$$

$$c_1^* = T^* (dc^*/dT^*)$$

$T^*$	$c^*$	$c_1^*$	$c_2^*$
0.70	-3.37664	28.68	-220.
0.75	-1.79197	18.05	-140.
0.80	-0.84953	11.60	-92.1
0.85	-0.27657	7.561	-62.1
0.90	+0.07650	4.953	-42.7
0.95	0.29509	3.234	-29.8
1.00	0.42966	2.078	-21.0
1.05	0.51080	1.292	-14.9
1.10	0.55762	0.7507	-10.6
1.15	0.58223	0.3760	-7.52
1.20	0.59240	+0.1159	-5.29
1.25	0.59326	-0.0646	-3.66
1.30	0.58815	-0.1889	-2.46
1.35	0.57933	-0.2731	-1.57
1.40	0.56831	-0.3288	-0.910
1.45	0.55611	-0.3641	-0.420
1.50	0.54339	-0.3845	-0.050
1.55	0.53059	-0.3943	+0.224
1.60	0.51803	-0.3963	0.427
1.65	0.50587	-0.3929	0.572
1.70	0.49425	-0.3858	0.680
1.75	0.48320	-0.3759	0.755
1.80	0.47277	-0.3643	0.806
1.85	0.46296	-0.3516	0.837
1.90	0.45376	-0.3382	0.854
1.95	0.44515	-0.3245	0.859
2.00	0.43710	-0.3109	0.856

<sup>a</sup> R. B. Bird, E. L. Spatz, and J. O. Hirschfelder, J. Chem. Phys., 18, 1395 (1950).

## Appendix B (Continued)

$T^*$	$C^*$	$C_1^*$	$C_2^*$
2.10	0.42260	-0.2840	0.830
2.20	0.40999	-0.2588	0.794
2.30	0.39900	-0.2355	0.749
2.40	0.38943	-0.2142	0.700
2.50	0.38108	-0.1950	0.651
2.60	0.37378	-0.1777	0.602
2.70	0.36737	-0.1621	0.557
2.80	0.36173	-0.1482	0.514
2.90	0.35675	-0.1358	0.473
3.00	0.35234	-0.1247	0.439
3.10	0.34842	-0.1148	0.400
3.20	0.34491	-0.1060	0.369
3.30	0.34177	-0.09826	0.340
3.40	0.33894	-0.09133	0.313
3.50	0.33638	-0.08510	0.288
3.60	0.33407	-0.07963	0.266
3.70	0.33196	-0.07462	0.246
3.80	0.33002	-0.07024	0.227
3.90	0.32825	-0.06634	0.210
4.00	0.32662	-0.06286	0.194
4.10	0.32510	-0.05989	0.183
4.20	0.32369	-0.05709	0.169
4.30	0.32238	-0.05458	0.156
4.40	0.32115	-0.05237	0.145
4.50	0.32000	-0.05040	0.134
4.60	0.31891	-0.04865	0.125
4.70	0.31788	-0.04712	0.116
4.80	0.31690	-0.04579	0.108
4.90	0.31596	-0.04461	0.100
5.0	0.31508	-0.04359	0.0934
6.0	0.30771	-0.03893	0.0449
7.0	0.30166	-0.03989	0.0258
8.0	0.29618	-0.04231	0.0192
9.0	0.29103	-0.04529	0.0183
10.0	0.28610	-0.04825	0.0199
20.0	0.24643	-0.06437	0.0502
30.0	0.21954	-0.06853	0.0654
40.0	0.20012	-0.06714	0.0717
50.0	0.18529	-0.06566	0.0742
60.0	0.17347	-0.06388	0.0750
70.0	0.16376	-0.06203	0.0748
80.0	0.15560	-0.06025	0.0741

## Appendix B (Continued)

$T^*$	$C^*$	$C_1^*$	$C_2^*$
90.0	0.14860	-0.05857	0.0732
100.0	0.14251	-0.05700	0.0722
200.0	0.10679	-0.04599	0.0619
300.0	0.08943	-0.03970	0.0547
400.0	0.07862	-0.03551	0.0496

## Appendix C

## Reduced virial coefficients for nitrogen

T(°K)	T*	B*	B <sub>1</sub> *	B <sub>2</sub> *	C*	C <sub>1</sub> *	C <sub>2</sub> *
273	2.872173	-0.153099	1.015903	-2.328341	0.358136	-0.139251	0.484409
300	3.156234	-0.068315	0.899054	-2.060360	0.346446	-0.109851	0.382567
500	5.260390	0.264060	0.464311	-1.092667	0.309261	-0.042377	0.080771
700	7.364545	0.389703	0.287923	-0.714895	0.299662	-0.040772	0.023394
900	9.468701	0.450102	0.193843	-0.516508	0.288719	-0.046677	0.019050
1100	11.572856	0.471020	0.152714	-0.430276	0.279860	-0.050785	0.024666
1300	13.677012	0.484592	0.121740	-0.365389	0.271513	-0.054177	0.031041
1500	15.781168	0.498164	0.090766	-0.300502	0.263166	-0.057569	0.037417
1700	17.885324	0.511735	0.059752	-0.235615	0.254819	-0.060961	0.043793
1900	19.989480	0.525306	0.028819	-0.170727	0.246472	-0.064353	0.050168
2100	22.093635	0.525699	0.018994	-0.149804	0.240800	-0.065032	0.053382
2300	24.197791	0.526025	0.009288	-0.129101	0.235142	-0.065697	0.056581
2500	26.301946	0.526352	-0.000424	-0.108398	0.229484	-0.066361	0.059779

## Appendix D

## Reduced virial coefficients for oxygen

T(°K)	T*	B*	B <sub>1</sub> *	B <sub>2</sub> *	C*	C <sub>1</sub> *	C <sub>2</sub> *
273	2.323404	-0.406548	1.338060	-3.088612	0.396760	-0.230515	0.737532
300	2.553191	-0.287890	1.183424	-2.720295	0.377197	-0.185798	0.624936
500	4.255319	0.154639	0.610166	-1.410927	0.322965	-0.055701	0.161809
700	5.957447	0.319519	0.388594	-0.929362	0.308024	-0.039128	0.046964
900	7.659574	0.400721	0.271468	-0.680067	0.294046	-0.041486	0.021447
1100	9.361702	0.447932	0.197463	-0.524106	0.289247	-0.046361	0.018879
1300	11.063830	0.467737	0.160207	-0.445973	0.281880	-0.049965	0.023123
1500	12.765957	0.478715	0.135151	-0.393484	0.275127	-0.052979	0.028281
1700	14.468085	0.489694	0.110095	-0.340994	0.268375	-0.055453	0.033438
1900	16.170213	0.500672	0.085039	-0.288504	0.261623	-0.058196	0.038596
2100	17.872340	0.511651	0.059984	-0.236013	0.254870	-0.060940	0.043175
2300	19.574468	0.522630	0.034928	-0.183525	0.248118	-0.063684	0.048911
2500	21.276596	0.525572	0.022771	-0.157842	0.242997	-0.064773	0.052140

Appendix E

Reduced virial coefficients for air

T(°K)	T*	B*	B <sub>1</sub> *	B <sub>2</sub> *	C*	C <sub>1</sub> *	C <sub>2</sub> *
273	2.752061	-0.203259	1.073739	-2.462818	0.364436	-0.154870	0.534633
300	3.024194	-0.107777	0.950379	-2.177094	0.351392	-0.122305	0.429564
500	5.040323	0.246552	0.488215	-1.144223	0.314783	-0.043402	0.091444
700	7.056452	0.378197	0.305108	-0.751266	0.301351	-0.040027	0.025427
900	9.072581	0.455315	0.207245	-0.544638	0.290672	-0.045505	0.018416
1100	11.088710	0.467897	0.159841	-0.445206	0.281781	-0.050005	0.023198
1300	13.104839	0.480901	0.130163	-0.383032	0.273783	-0.053255	0.029308
1500	15.120968	0.493905	0.100485	-0.320861	0.265785	-0.056505	0.035417
1700	17.137097	0.506909	0.070807	-0.258688	0.257787	-0.059755	0.041525
1900	19.153226	0.519913	0.041129	-0.196515	0.249789	-0.063005	0.047634
2100	21.169355	0.525556	0.023266	-0.158898	0.243286	-0.064740	0.051977
2300	23.185484	0.525868	0.013961	-0.139061	0.237864	-0.065377	0.055042
2500	25.201613	0.526181	0.004655	-0.119224	0.232443	-0.066014	0.058106

## Appendix F

## Reduced virial coefficients for argon

T(°K)	T*	B*	B <sub>1</sub> *	B <sub>2</sub> *	C*	C <sub>1</sub> *	C <sub>2</sub> *
273	2.278798	-0.432830	1.362480	-3.174507	0.401330	-0.240440	0.758541
300	2.504174	-0.310673	1.213012	-2.790188	0.380775	-0.194278	0.648955
500	4.173623	0.142676	0.625850	-1.445531	0.324062	-0.057829	0.172693
700	5.843072	0.310419	0.401019	-0.956158	0.308867	-0.039661	0.052511
900	7.512521	0.395229	0.279670	-0.697426	0.298851	-0.041130	0.022417
1100	9.181970	0.444289	0.203544	-0.536870	0.290133	-0.045829	0.018591
1300	10.851419	0.466367	0.163334	-0.452523	0.282722	-0.049622	0.022480
1500	12.520868	0.477135	0.138760	-0.401041	0.276100	-0.052314	0.027538
1700	14.190317	0.489902	0.114184	-0.349560	0.269477	-0.055005	0.032600
1900	15.859766	0.498670	0.089610	-0.298078	0.262854	-0.057696	0.037655
2100	17.529215	0.509438	0.065035	-0.246596	0.256232	-0.060387	0.042714
2300	19.198664	0.520206	0.040460	-0.195114	0.249609	-0.063078	0.047772
2500	20.868114	0.525509	0.024657	-0.161862	0.244096	-0.064644	0.051620

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