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THE EFFECT OF VARIATION IN THE RATIO
OF SPECIFIC HEATS WITH TEMPERATURE AND PRESSURE
ON HORSEPOWER REQUIREMENTS OF RECIPROCATING COMPRESSORS
BY
SELIM PISKIN

A THESIS
PRESENTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE IN CHEMICAL ENGINEERING
AT
NEWARK COLLEGE OF ENGINEERING

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Newark, New Jersey
1973

APPROVAL OF THESIS
THE EFFECT OF VARIATION IN THE RATIO
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SELIM PISKIN

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

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FACULTY COMMITTEE

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ABSTRACT

The expansion and compression of fluids is discussed in relation to the design of reciprocating compressors. As part of this thesis, the design equations for reciprocating compressors are developed for both ideal and real gases.

The resulting design equations contain, as one of the parameters, the ratio of the specific heats. Using published componential specific heat data, a correlation was developed relating the dependence of the ratio of specific heat on temperature and pressure for the more common gases. These correlations were developed so as to be compatible with the compressor design equation and to provide rapid evaluation of the various design equations.

As part of the analysis of the applicability of the design equations, it was demonstrated that inter-stage cooling is always desirable, and that real gases with compressibility factors less than unity have lower power requirements for the same pressure change than the corresponding ideal gas.

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THEORETICAL BACKGROUND

Expansion and Compression of Fluids

A most common problem is the conversion of the mechanical work of a rotating shaft or a moving piston into other forms of energy. "Mechanical work" is defined as the energy that is transferred by the effect of a force acting through a distance and is equal to the product of that force times the distance of action. Thus, when a fluid that is confined under pressure undergoes a change in volume, work is done as the result of the force of pressure moving through the distance corresponding to the volume change.

Work is a form of energy that is incapable of storage as such but is in transition from one form of stored energy to another. Mechanical energy in this transitory form is termed "shaft work", as distinguished from the electrical and other forms of work which may be included in the work terms of a complete energy balance.

An infinitesimal change in the energy of a single system of constant mass m and constant composition is expressed by the following differential form of the energy equation.

$$d(PV) + d\left(\frac{m v^2}{2g_c}\right) + d\left(m z \frac{g}{g_c}\right) + d(m E_f) + dU = d'q - d'w \quad (1)$$

where the energy terms represent, respectively, flow work, external kinetic energy, potential energy, surface energy, internal energy, heat added from the surroundings, and work done upon the surroundings. The work term $d'w$, in general, includes all possible forms of work except flow work, such as shaft, electrical, magnetic and radiant.

In the absence of electrical, magnetic, and radiant forms of work, $d'w$ represents mechanical or shaft work only. If changes in potential and external kinetic energies are also negligible, the shaft work results only from changes in flow work and from work of expansion. The evaluation of shaft work in such systems requires separate consideration of the special cases of nonflow and flow processes, in both isothermal and isentropic systems for reversible and irreversible processes.

Shaft Work in a Flow Process

Applying equation (1) to a reversible flow process and neglecting changes in kinetic, potential, and surface energies, and forms of work other than shaft work, equation (1) becomes

$$d(pv) + dU = d'q - d'w_s \quad (2)$$

where:

$$d'q = T ds \quad (3)$$

$$dU = T ds - p dv \quad (4)$$

$$d(pv) = p dv + v dp \quad (5)$$

Substitution of equation (3), (4) and (5) into equation (1) gives

$$Pdv + v dP + Tds - Pdv = Tds - d'w_s$$

Then equation (1) reduces to

$$-d'w_s = v dP \quad (6)$$

or

$$w_{s, \text{ flow}} = - \int_1^2 v dP \quad (7)$$

Equation (7) represents the shaft work performed by any reversible flow process with negligible kinetic-, potential-, and surface- energy changes and with no electrical, radiant, or magnetic work.

Equation (7) may be used for calculating the work performed by the volume or pressure changes of a fluid from its state properties, only provided these changes take place reversibly.

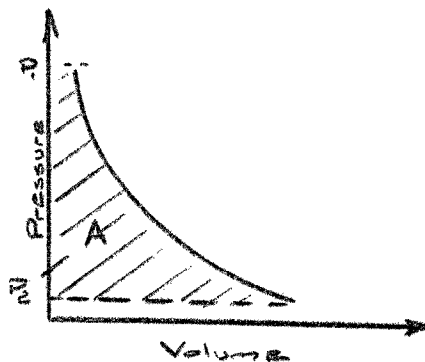


Figure 1.

$w_{s, \text{ flow}} = A$, area as indicated in Figure 1.

Shaft Work from the Energy Properties

For reversible processes under the conditions defined

for equation (7), the shaft work performed may be expressed as changes of the energy functions.

The energy functions, the enthalpy H and the free energy G , are defined by the following relations:

$$H = U + PV \quad (8)$$

$$G = H - TS \quad (9)$$

Differentiation of the relations gives

$$dH = dU + PdV + VdP \quad (10)$$

$$dG = dH - Tds - SdT \quad (11)$$

Substitution of equation (3) into equation (10) gives

$$dH = Tds - PdV + PdV + VdP$$

$$dH = Tds + VdP \quad (12)$$

Substitution of equation (12) into equation (11) gives

$$dG = VdP - SdT \quad (13)$$

In an isentropic or adiabatic process where the entropy is constant, equation (12) reduces to

$$(dH)_s = (VdP)_s \quad (14)$$

Integration of equation (14) gives

$$(\Delta H)_s = \int^2 (VdP)_s = -(W_s)_{s, \text{flow}} \quad (15)$$

In an isothermal process, equation (13) reduces to

$$(dG)_T = (VdP)_T \quad (16)$$

Integration of equation (16) gives

$$(\Delta G)_T = \int^2 (VdP)_T = -(W_s)_T, \text{flow} \quad (17)$$

From equations (15) and (17), the work of reversible flow expansion of a fluid under isentropic or isothermal conditions may be determined either by a pressure-volume integration or as the change of the appropriate energy function. The PV integration must follow the actual reversible path of the change, whereas the thermodynamic energy functions are state properties which are independent of path and are determined directly from the properties of the initial and final states.

Isothermal Flow Expansion

For the reversible isothermal expansion of any fluid under flow conditions, from equation (17) and the definitions of the thermodynamic energy functions,

$$(W_s)_{T, \text{flow}} = - \int_1^2 v dp = -\Delta G = -\Delta H + T\Delta S \quad (18)$$

Equation (18) is restricted to reversible isothermal flow conditions involving only shaft work and neglects changes in kinetic, potential, and surface energies.

For an ideal gas, per mole,

$$(W_s)_{T, \text{flow}} = - \int_1^2 \frac{RT}{p} dp = -RT \ln \frac{p_2}{p_1} \quad (19)$$

Isentropic Flow Expansion

For the reversible isentropic expansion of any fluid under flow conditions, from equation (15)

$$(W_s)_{s, \text{flow}} = - \int_1^2 v dp = -(\Delta H)_s$$

The two most useful thermal capacities are those at constant pressure and at constant volume, defined as follows:

$$C_p = \left(\frac{\partial'q}{\partial T} \right)_p \quad (20)$$

$$C_v = \left(\frac{\partial'q}{\partial T} \right)_v \quad (21)$$

Since, in a reversible process, $dS = d'Q/T$,

$$C_p = T \left(\frac{\partial S}{\partial T} \right)_p \quad \text{or} \quad \left(\frac{\partial S}{\partial T} \right)_p = \frac{C_p}{T} \quad (22)$$

$$C_v = T \left(\frac{\partial S}{\partial T} \right)_v \quad \text{or} \quad \left(\frac{\partial S}{\partial T} \right)_v = \frac{C_v}{T} \quad (23)$$

If entropy is considered to be a function of pressure and temperature, then

$$dS = \left(\frac{\partial S}{\partial P} \right)_T dP + \left(\frac{\partial S}{\partial T} \right)_P dT \quad (24)$$

From equation (13), the following relationship may be derived:

$$\left(\frac{\partial S}{\partial P} \right)_T = - \left(\frac{\partial V}{\partial T} \right)_P \quad (25)$$

Substitution of equations (22) and (25) into equation (24)

gives

$$dS = - \left(\frac{\partial V}{\partial T} \right)_P dP + \frac{C_p}{T} dT \quad (26)$$

Substitution of equation (26) into equation (12) gives

$$dH = \left[v - T \left(\frac{\partial V}{\partial T} \right)_P \right] dP + C_p dT \quad (27)$$

For an ideal gas, per mole,

$$\left(\frac{\partial V}{\partial T} \right)_P = \frac{R}{P} = \frac{V}{T} \quad (28)$$

Substitution of equation (28) into equation (27) gives

$$dH = c_p dT \tag{29}$$

Combining equations (15) and (29) gives

$$(W_s)_{s, flow} = -\Delta H = -\int_1^2 v dP = -\int_1^2 c_p dT \tag{30}$$

Equation (30) applies to the work in reversible isentropic expansion under flow conditions for an ideal gas and neglects changes in external kinetic, potential, and surface energies. Combining equation (30) with the ideal-gas law, for one mole, gives

$$-\int_1^2 \frac{RT}{P} dP = -\int_1^2 c_p dT$$

or

$$\int_1^2 R d \ln P = \int_1^2 c_p d \ln T \tag{31}$$

If the heat capacity, c_p , is assumed to be constant, equation (31) is integrated to give

$$c_p \ln \left(\frac{T_2}{T_1} \right) = R \ln \left(\frac{P_2}{P_1} \right) \tag{32}$$

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{R/c_p} \tag{33}$$

The corresponding volume changes are obtained by combining the ideal gas law with equation (33). Thus;

$$V_2 = V_1 \left(\frac{P_2}{P_1} \right)^{\frac{R}{c_p} - 1} \quad \text{or} \quad \left(\frac{V_2}{V_1} \right)^{\frac{c_p - R}{c_p}} = \frac{P_1}{P_2} \tag{34}$$

Combination of equations (15) and (33) gives

$$(W_s)_{s, flow} = -c_p (T_2 - T_1) = c_p T_1 \left[\left(\frac{P_2}{P_1} \right)^{R/c_p} - 1 \right] \tag{35}$$

Equations (33), (34), and (35) are frequently written in terms of k , the ratio of the heat capacities at constant pressure and constant volume.

From equation (23),

$$C_v = T \left(\frac{\partial S}{\partial T} \right)_v \quad (36)$$

Equation (26) is utilized to set up an expression for $\left(\frac{\partial S}{\partial T} \right)_v$

$$\left(\frac{\partial S}{\partial T} \right)_v = - \left(\frac{\partial V}{\partial T} \right)_P \left(\frac{\partial P}{\partial T} \right)_v + \frac{C_p}{T} \quad (37)$$

Combining equations (36) and (37) gives

$$C_p - C_v = T \left(\frac{\partial V}{\partial T} \right)_P \left(\frac{\partial P}{\partial T} \right)_v \quad (38)$$

For an ideal gas,

$$\left(\frac{\partial V}{\partial T} \right)_P = \frac{R}{P} \quad (39) \quad \left(\frac{\partial P}{\partial T} \right)_v = \frac{R}{V} \quad (40)$$

Substitution of equations (39) and (40) into equation (37) gives

$$C_p - C_v = R \quad (41)$$

$$k = \frac{C_p}{C_v} = \frac{C_p}{C_p - R} = \frac{C_v + R}{C_v} \quad (42)$$

Combination of equation (42) with equations (33), (34), and (35) gives

$$\left(\frac{T_2}{T_1} \right) = \left(\frac{P_2}{P_1} \right)^{k-1/k} = \left(\frac{V_1}{V_2} \right)^{(k-1)} \quad (43)$$

$$\left(\frac{V_2}{V_1} \right)^k = \left(\frac{P_1}{P_2} \right) \quad (44)$$

$$(W_s)_{s, flow} = \frac{RT_1 k}{k-1} \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \quad (45)$$

The above equations are restricted to expansions of ideal gases with constant heat capacity or of those involving small changes in heat capacity.

DESIGN EQUATIONS FOR RECIPROCATING COMPRESSORS

Reciprocating Compressors

The reciprocating compressor is a positive displacement unit with the pressure on the fluid developed within a cylindrical chamber by the action of a moving piston. Figures 2, 3, and 4 illustrate the assembly and arrangements of typical cylinders.

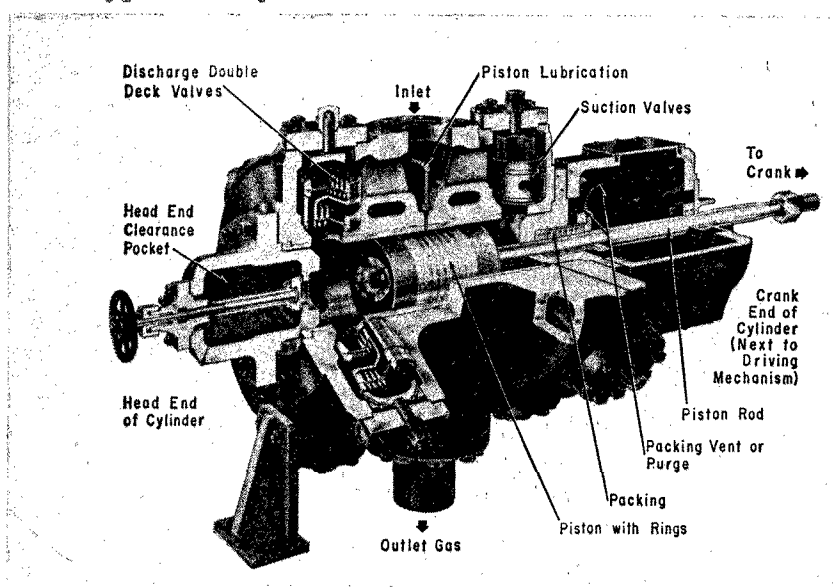


Figure 2. Cut-a-way view of typical high pressure gas cylinder. (Worthington Corporation)

Compressor types, components and arrangements are designated as:

A. Cylinders

1. Single acting: compression of gas takes place only in one end of the cylinder, see Figure 1.

2. Double acting: compression of gas takes place in both ends of the cylinder.

B. Frame

The cylinders are arranged on the main frame of

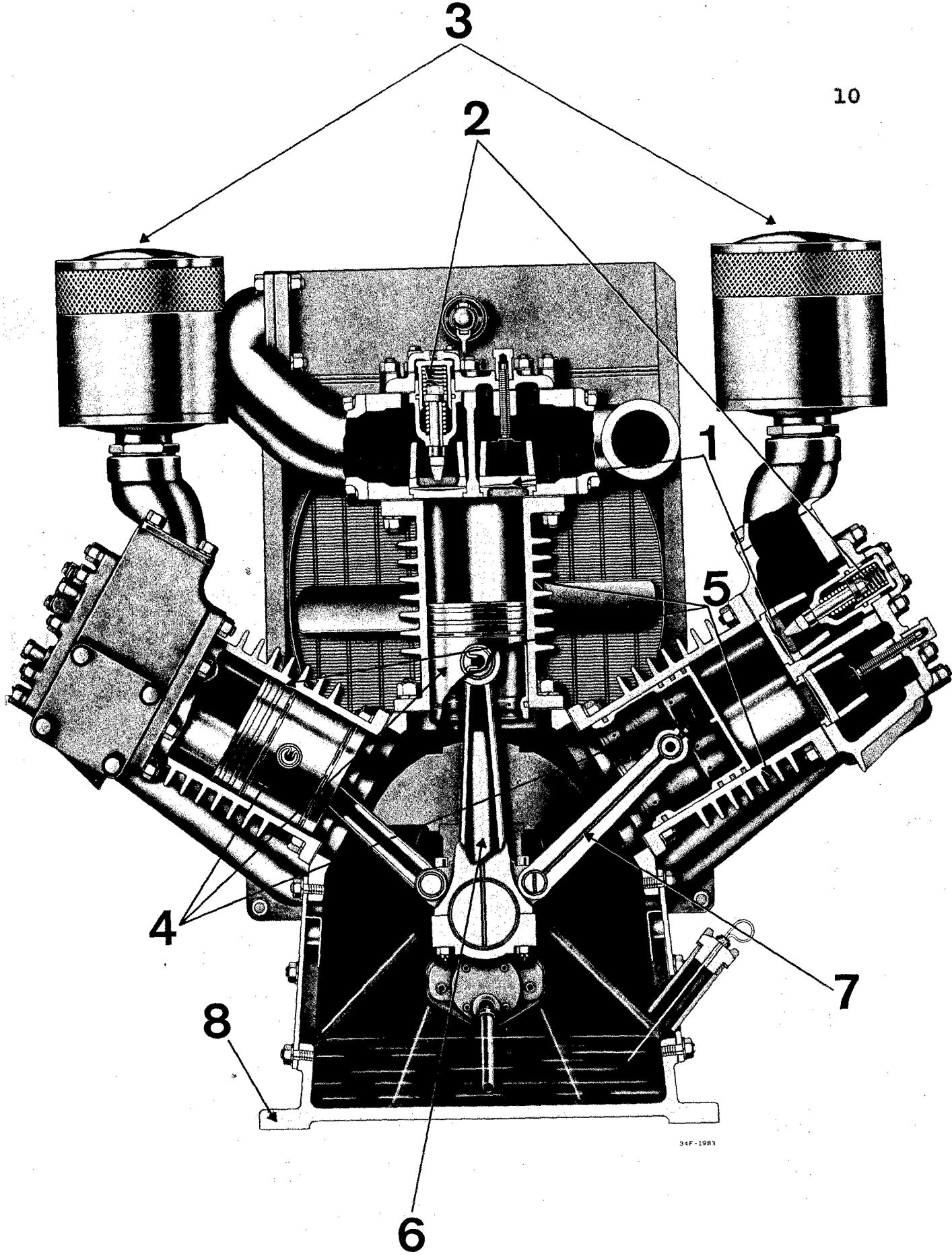


Figure 3. Cut-a-way view of radial design compressor cylinder.

(Worthington Corp., Bulletin no: 3430-B1A)

Figure 3. Cut-a-way view of radial design compressor cylinders.

1. Valves
2. Unloaders
3. Suction muffler-filler
4. Pistons
5. Radial design cylinders
6. Piston rod
7. Rod rifle
8. Crankcase

Figure 4. Cut-a-way view of duplex compressor cylinders.

1. Intercooler
2. Cooling fan
3. Wristpin
4. Crankshaft
5. Main bearings
6. Pulley
7. Oil pump

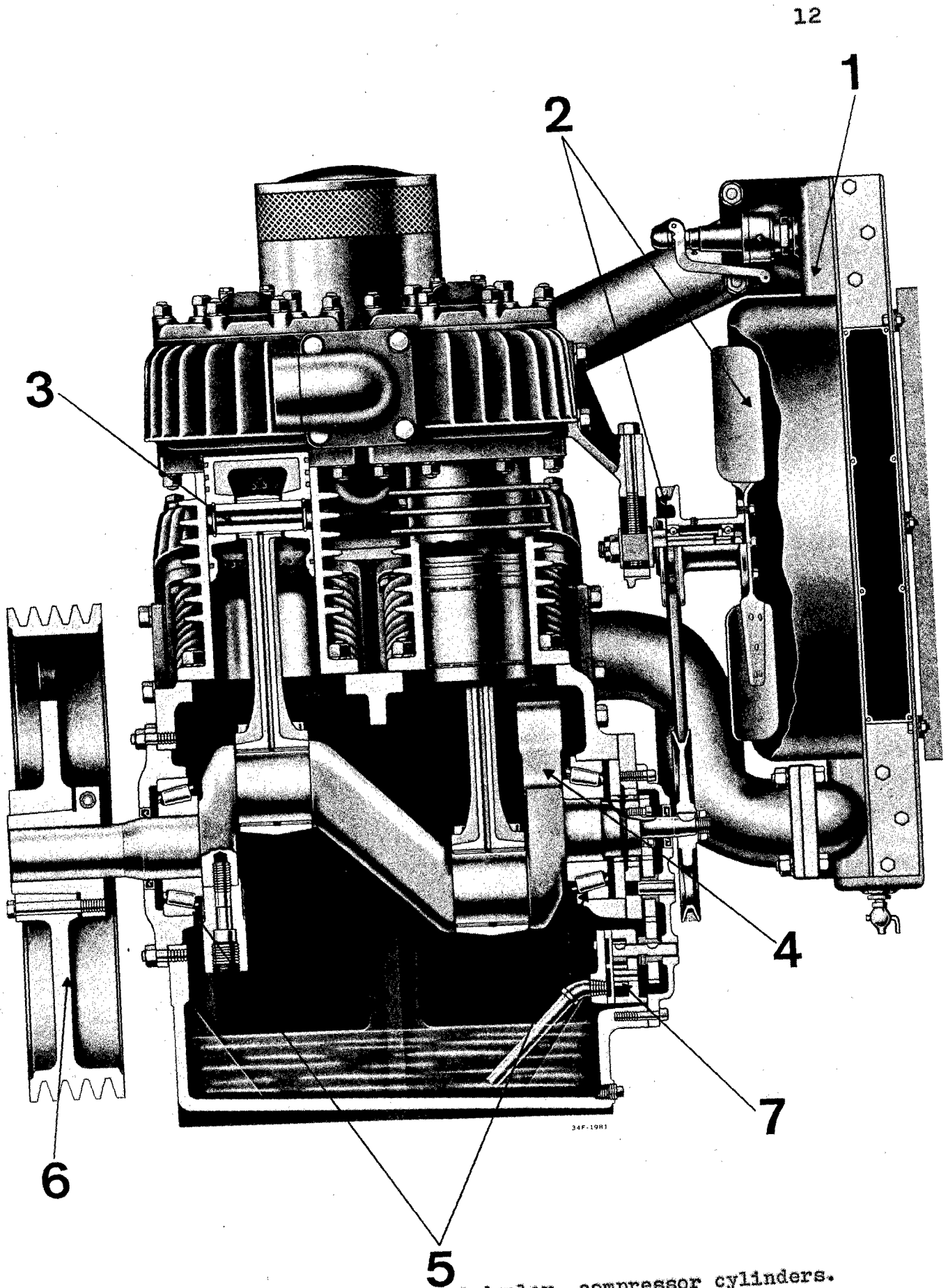


Figure 4. Cut-a-way view of duplex compressor cylinders.
 (Worthington Corp., Bulletin no: 3430-B1a)

the compressor to provide balanced crankshaft power loading, access for maintenance, piping convenience, and floor space to suit plant layout. Common designations by position of the cylinder are horizontal, vertical, radial (Figure 3), duplex (Figure 4), etc.

- C. Suction and Discharge Valves
- D. Piston
- E. Piston Rings
- F. Cylinders
- G. Piston Rod
- H. Piston Rod packing

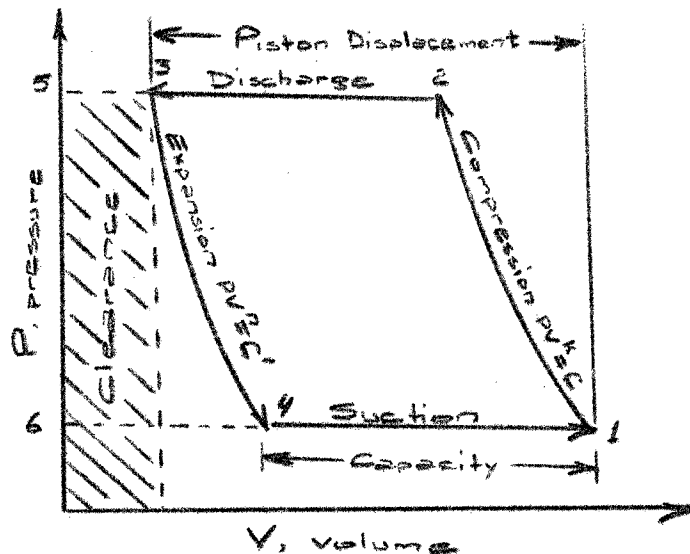
Most of the compressors have water-cooled cylinder jackets; however, some have air cooling, while a few have no cooling.

Ideal Reciprocating Compression Diagram

For an ideal gas of constant heat capacity, pressure-volume relationship in a reversible adiabatic compression is given by equation 44.

$$P_1 V_1^k = P_2 V_2^k \quad \text{or} \quad P V^k = C, \text{ a constant} \quad (46)$$

This relationship and the cycle of compression are represented in Figure 5.

FIGURE 5 - IDEAL COMPRESSION DIAGRAM

The compression operation stepwise is:

Step 1: start of the compression stroke the cylinder is full of gas at suction pressure and suction temperature (neglecting valve loss). The piston moves during compression toward step (2) with suction and discharge valves closed.

Step 2: start of gas discharge from the cylinder. Gas has slightly exceeded the system pressure and discharge valve opens releasing gas to the system. The piston begins to sweep the gas from the cylinder as it moves toward condition (3).

Step 3: completion of gas discharge from the cylinder. All the gas to be removed from the cylinder by the piston stroke has passed through the discharge valve. This also is the point of start of the return stroke of the piston, but not the beginning of the cylinder suction. As

the piston starts its return stroke and the pressure in the cylinder is lowered slightly below discharge pressure, the discharge valve closes. The volume of gas left in the cylinder between the end of the piston and the end of the cylinder (clearance volume) expands from step (3) to step (4) as the piston returns.

Step 4: start of gas suction into the cylinder.

The cylinder pressure has dropped below the system suction pressure and the suction valve opens to admit new gas into the cylinder as it returns to step (1).

The compression and expansion steps are nonflow in character. Since the gas flows into and out of the cylinder under the restraint of pressure, the net effect of the over-all operation is a flow process, even through an intermediate nonflow step is involved. The over-all work requirements and changes in thermodynamic properties follow the equations developed for expansion or compression under flow conditions. So, for ideal gases of constant heat capacity, the work of reversible adiabatic compression is given by equation (45).

The network is equivalent to the area of 1-2-3-4 in Figure 5, and the equation can also be derived by evaluating the area of 1-2-3-4 from equation (15),

$$\begin{aligned}
 -(w_s)_s &= \int v dp = A_{1-2-3-4} \\
 A_{1-2-3-4} &= \int_{P_3}^{P_2} v dp - \int_{P_3}^{P_1} v dp
 \end{aligned}$$

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From equation (46),

$$PV^k = P_1 V_1^k \quad V = V_1 \left(\frac{P_1}{P} \right)^{1/k}$$

$$PV^n = P_4 V_4^n \quad V = V_4 \left(\frac{P_4}{P} \right)^{1/n}$$

Thus

$$A_{1-2-3-4} = \int_{P_1}^{P_2} V_1 \left(\frac{P_1}{P} \right)^{1/k} dP - \int_{P_3}^{P_4} V_4 \left(\frac{P_4}{P} \right)^{1/n} dP \quad (47)$$

The integration of equation (47) gives

$$-W = \frac{k}{k-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] - \frac{n}{n-1} P_4 V_4 \left[\left(\frac{P_4}{P_3} \right)^{\frac{n-1}{n}} - 1 \right]$$

If the gas in the clearance space expands reversibly and adiabatically, exponents n and k become identical. Because P_1 and P_4 as well as P_2 and P_3 are the same, the network becomes

$$-W = \frac{k}{k-1} P_1 (V_1 - V_4) \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] \quad (48)$$

The clearance volume gases expand on the intake stroke and occupy some of the cylinder volume, thus reducing the quantity of gas that can be taken in on the suction stroke. This compressor capacity reduction may be expressed in terms of the ratio of the gas intake to the piston displacement, which ratio is called volumetric efficiency. For the development of an equation for the volumetric efficiency, the following terms are defined from Figure 5:

$$V_c = V_3 = \text{clearance volume}$$

$$V_e = V_4 = \text{volume to which clearance gases expand}$$

$$V_d = V_1 - V_3 = \text{displacement volume}$$

$$C = V_c / V_d = V_3 / (V_1 - V_3) = \text{ratio of clearance to displacement volume}$$

$$V_{\text{net}} = V_d + V_c - V_e = V_1 - V_4 = \text{net volume of intake gases, which is also known as the capacity of the compressor.}$$

For reversible adiabatic expansion, from equation (44),

$$V_{net} = V_d \left(1 + \frac{V_c}{V_d} - \frac{V_e}{V_d} \right)$$

$$\frac{V_e}{V_d} = \frac{V_c}{V_d} \left(\frac{P_2}{P_1} \right)^{1/k} = C \left(\frac{P_2}{P_1} \right)^{1/k}$$

$$V_{net} = V_d \left[1 + C - C \left(\frac{P_2}{P_1} \right)^{1/k} \right] \quad (49)$$

$$\text{Volumetric efficiency, } E_v = \frac{V_{net}}{V_d} = \left[1 + C - C \left(\frac{P_2}{P_1} \right)^{1/k} \right] \quad (50)$$

Combining equations (49) and (50) with equation (48)

gives

$$-W = \frac{k}{k-1} P_1 V_d E_v \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \quad (51)$$

Where $\frac{P_2}{P_1}$ is known as the compression ratio, R

In equation (51), all terms are dimensionless except P_1 and V_d . It is customary to express the suction pressure, P_1 , in pounds per square inch absolute (psia.) and the piston displacement V_d in cubic feet per minute (cfm.).

Introducing the unit time and conversion factors, equation (51) becomes one for power.

Theoretical gas horsepower, TGHP, is defined as

$$\text{TGHP} = \frac{144}{33,000} \frac{k}{k-1} P_1 V_d E_v \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \quad (52)$$

or in terms of the compression ratio, R_c , of measuring pressure, P_o , and suction temperature,

$$\text{TGHP} = \frac{144}{33,000} \frac{k}{k-1} P_o \bar{V}_o \left[(R_c)^{(k-1)/k} - 1 \right] \quad (53)$$

or per mole of gas,

$$\text{TGHP} = \frac{144}{33,000} \frac{k}{k-1} RT_1 \left[(R_c)^{(k-1)/k} - 1 \right] \quad (54)$$

where \dot{V}_g , the capacity of gas in cfm. at suction temperature, T_1 , in $^{\circ}\text{R}$, is corrected by the gas laws from suction pressure P_1 to the measuring pressure P_0 and R is the universal constant ($R = 10.71 \text{ psi} \cdot \text{ft}^3/\text{mole } ^{\circ}\text{R}$).

Equations (52), (53), and (54) apply to the gas horsepower in reciprocating compressors with the reversible adiabatic compression-expansion cycle, ideal gases of constant heat capacity, and neglect changes in external kinetic, potential, and surface energies.

Actual Gas Horsepower

The actual compression operation is neither adiabatic nor reversible. If heat is added or removed during the compression or expansion of a gas, the resulting path is called polytropic. For a polytropic reversible process, from equation (12)

$$\Delta H = Q + \int v dp = Q - W_L \quad (55)$$

then the shaft work for a polytropic reversible becomes

$$-W_L = \int v dp = \Delta H - Q \quad (56)$$

where the shaft work for an adiabatic reversible process is

$$-W_L = \int v dp = \Delta H$$

The adiabatic efficiency is a measure of the nearness of a reversible path to adiabatic conditions, and defined as follows:

$$\eta = \frac{\Delta H}{\int v dp} = \frac{\Delta H}{\int v dp + Q} = 1 - \frac{Q}{\int v dp} \quad (57)$$

For an irreversible path

$$\eta < \frac{\Delta H}{\int v dp}$$

then equation (12) may be written:

$$\Delta H = Q + \int v dP + T_{av} \Delta S_{production}$$

The term, ΔS production, is the entropy generated by the irreversibility, i.e., friction and turbulence, in the gas during compression. The irreversibility is mostly caused by pressure drop through suction and discharge valves.

Irreversibility is most frequently expressed as an efficiency. Such a reversible efficiency is defined for an adiabatic process, as

$$E_r = \frac{(-W_s)_{rev.}}{(-W_s)_{irrev.}} = \frac{\int v dP}{\int v dP + T_{av} \Delta S_{prod.}} \quad (59)$$

The product of the adiabatic and reversible efficiencies is defined as the compression efficiency, E_c .

$$E_c = E_a E_r \quad (60)$$

Introducing the compression efficiency to equations (52), (53), and (54), they become an equation to compute actual gas horsepower for an ideal gas of constant heat capacity. However, in equation (52), the volumetric efficiency (E_v) should be modified in order to make allowances for actual conditions. If the actual P-V path of re-expansion is expressed by $PV^k = \text{a constant}$, the following empirical expression for the volumetric efficiency is obtained:

$$E_v = 1 - 0.01 R_c - C [(R_c)^{1/k} - 1] \quad (61)$$

Bearing friction and other mechanical losses are covered by a mechanical efficiency, which is defined

$$E_m = \left(\int v dP + T_{av} \Delta S_{p-rod} \right) / \text{shaft Input Work} \quad (62)$$

The over-all efficiency (E_o) of a compressor is defined as the product of the adiabatic, the reversible, and the mechanical efficiencies.

$$E_o = E_a E_r E_m = \frac{\Delta H}{\text{shaft input work}} \quad (63)$$

Introducing the over-all efficiency to equations (52), (53), and (54), they become an equation to compute the shaft or brake horsepower for ideal gases of constant heat capacity in reciprocating compressors. The values of E_a , E_r , and E_m are established by known characteristics of the compression. Brake horsepower, BHP

$$\text{Real Gas Horsepower} \quad \text{BHP} = \frac{\text{TGHP}}{E_o} = \frac{144}{33,000} \frac{k}{k-1} \frac{RT_1}{E_o} \left[(R_c)^{(k-1)/k} - 1 \right] \quad (64)$$

The preceding equations have been limited to ideal gases. Many gases deviate from the ideal state when pressures and/or temperatures are above 100 to 500 psia and 100° F. Consequently, the equations can be used only for gases at relatively low pressures or a gas which is difficult to liquefy.

One method to correct deviations from ideal state is the compressibility factor Z defined by the following equation

$$PV = Z NRT \quad (65)$$

Generalized compressibility factors for gases are given in Figure 6 on page 62.

Reduced quantities are ratios of the value to that at the critical state; thus $P_r = P/P_c$ and $T_r = T/T_c$

Substituting equation (65) into equation (64), it becomes one to compute brake horsepower for real gases of constant heat capacity

$$\text{BHP per mole} = \frac{144}{33,000} \frac{k}{k-1} \frac{z_1 R T_1}{E_o} \left[(P_c)^{(k-1)/k} - 1 \right] \quad (66)$$

Mollier Diagrams

The pressure enthalpy charts or Mollier diagrams present the actual relationship of the gas properties under all conditions of the diagram and recognize the deviation from the ideal gas laws.

From equation (15),

$$-(W_s)_{s, \text{flow}} = (\Delta H)_s = H_2 - H_1 \quad (67)$$

where 1 and 2 are suction and discharge conditions. Equation (67) applies to the work in isentropic expansion under flow conditions for a real gas. Introducing the unit time, conversion factor and the over-all efficiency, equation (67) becomes one for brake horsepower

$$\text{BHP} = \frac{778}{33,000} (M) (H_2 - H_1) / E_o \quad (68)$$

where

M = Gas flow rate, lbs./min.

H = Enthalpy of gas, Btu/lb.

E_o = Over-all efficiency of the compressor

(Combination of mechanical and adiabatic efficiency only in this case)

$$\text{or BHP per mole} = \frac{778}{33,000} (MW) (H_2 - H_1) / (E_o) \quad (69)$$

where MW is the molecular weight of the gas.

In the range where compressibility of the gas becomes significant, the use of Mollier diagrams is most helpful and convenient. Since this information is not available for many gases, it is limited to those rather common gases.

Multistage Compression

Two or more stages, with intercooling between stages, are often used in gas compression because of the lower volumetric efficiency at high compression ratios. A single stage reciprocating compressor is generally not designed for a compression ratio greater than 5.

The total work in a multi-stage compression is the sum of the work in the individual stages. Thus, from equation (54), if a constant value of k is assumed, the total work per mole for two-stage compression of an ideal gas becomes

$$W_{GHP} = \frac{144}{33,000} \frac{Rk}{k-1} \left\{ T_1 \left[\left(\frac{P^1}{P_1} \right)^{(k-1)/k} - 1 \right] + T_2 \left[\left(\frac{P_2}{P^1} \right)^{(k-1)/k} - 1 \right] \right\} \quad (70)$$

where P^1 is the intermediate pressure, T_1 is the suction temperature at first stage, T_2 is the suction temperature at second stage.

Variation in the Ratio of Specific Heats

The preceding discussion has been limited to gases with constant heat capacity. Actually, the heat capacities of most gases vary widely with temperature and pressure. Therefore, the ratio of isobaric to isometric specific heats, $C_p/C_v = k$, does not remain constant, but varies with temperature and pressure. The use of a constant specific heat ratio in computing horsepower will cause appreciable errors in many cases.

In this thesis, the data for isobaric and isometric specific heats was obtained from "Thermodynamic Functions of Gases" by F. Din for eight gases: air, ammonia, nitrogen, carbon dioxide, methane, ethane, propane, and ethylene. The ratio of specific heats were computed at various temperatures and pressures as shown in Tables 1, 2, 3, 4, 5, 6, 7 and 8 and it was plotted versus pressure at various temperatures as shown in Graphs 1, 2, 3, 4, 5, 6 and 8.

A specific heat ratio at an average of the values at the inlet and outlet conditions can be obtained from those plots and can be applied in equation (66) instead of using a specific heat ratio at atmospheric pressure and room temperature as usually done. Although a rigorous solution of equation (66) would require integration with k as a variable, sufficient accuracy for engineering purposes is obtained when k is considered constant at an average of the values at the inlet and outlet conditions.

Computing Horsepower by Using Equation 66 and K-Charts
and Mollier Diagrams

The procedure for using the power equation and k-charts is as follows:

Power equation is

$$\text{BHP} = \frac{1444}{33,000} \frac{k}{k-1} \frac{Z_1 N R T_1}{E_0} \left[(R_c)^{(k-1)/k} - 1 \right]$$

E_0 is established by known characteristics of the compression and is taken as 1. So the above equation becomes one for theoretical horsepower. The capacity of compressor is taken as 1 lb-mole/min. Then $N = 1$. T_1 is absolute suction temperature in $^{\circ}\text{R}$, (Rankine) = $^{\circ}\text{F} + 460$. $R = 10.71$ psia cu. ft./lb-mole $^{\circ}\text{R}$. Then the above equation reduces to

$$\text{HP} = \frac{1444}{33,000} \frac{k}{k-1} \frac{Z_1 (1) (10.71) T_1}{1} \left[(R_c)^{(k-1)/k} - 1 \right]$$

or

$$\text{HP} = (0.0467) \frac{k}{k-1} Z_1 T_1 \left[(R_c)^{(k-1)/k} - 1 \right] \quad (71)$$

Z_1 is obtained from compressibility chart at suction conditions.

k is taken as an average of the values at the suction and discharge conditions. Since the discharge temperature

is not known, the average k is found by trial and error method. The procedure is as follows:

A gas is compressed from pressure P_1 at temperature T_1 to pressure P_2 . Average k is taken as k_1 at the suction pressure, P_1 , and temperature, T_1 . Then

$$k_{\text{avg.}} = k_1$$

Substituting $k_{\text{avg.}}$ into equation (43) gives

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}}$$

where $k = k_{\text{avg.}} = k_1$, and the equation is solved for T_2 . Then k_2 is read from the k -charts. k is updated:

$$k'_{\text{avg.}} = \frac{k_1 + k_2}{2}$$

Then T_2 is ~~T_1~~ recalculated.

$$T_2' = T_1 \left(\frac{P_2}{P_1} \right)^{(k-1)/k}$$

where $k = k'_{\text{avg.}} = (k_1 + k_2)/2$. k_2' is found at P_2

T_2' . $k_{\text{avg.}}$ is recalculated:

$$k''_{\text{avg.}} = \frac{k_1 + k_2'}{2}$$

This procedure is continued until two successive $k_{\text{avg.}}$'s are equal. The final $k_{\text{avg.}}$ is substituted in equation (71) yielding the adiabatic horsepower per mole for real gases.

The Use of Mollier Diagram

Equation (69) applies to Mollier diagram.

$$\text{BHP per mole} = \left(\frac{778}{33,000} \right) (\text{MW}) (H_2 - H_1) / E_0$$

E_0 is taken as 1. H_1 is the enthalpy of the gas at suction conditions (P_1 and T_1), and is read directly from the diagram. H_2 is the enthalpy at discharge conditions (P_2). Since the process is assumed to be adiabatic, H_2 is read where the constant entropy line intersects the pressure P_2 line. MW is the molecular weight of the gas.

$$HP = (0.02358)(MW)(H_2 - H_1) \quad (72)$$

Equation (72) gives the adiabatic horsepower per mole for real gases.

The Effect of Deviation from Ideal State on Horsepower Requirements

k-charts indicate that k at any pressure and temperature is always greater than k at zero pressure, which is the state of an ideal gas. They also indicate that k becomes greatest as the gas approaches the critical conditions where it deviates the most from the ideal state. Such values of k give greater power requirements than for a perfect gas since the horsepower increases as k-value increases. But the horse power is directly proportional to the compressibility factor Z, which becomes smaller as the gas approaches the critical conditions, which results in reducing power requirements. The net effect depends on the degree of variation in k and Z as the gas deviates from the ideal state. Actually, the compressibility factor Z is more effective on horsepower requirements than k since

the horsepower is directly proportional to it. The author has found out that the deviation from the ideal gas state always results in horsepower reduction, and this is illustrated by a specific example on page 46.

The Effect of Intercooling in Multistage Compression

The theoretical horsepower per mole for ideal gases of constant heat capacity in a two-stage compressor is expressed by Equation (70)

$$HP = \frac{144}{33,000} \frac{Rk}{k-1} \left\{ T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] + T_2 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right] \right\}$$

For real gases with variable heat capacity, this equation becomes

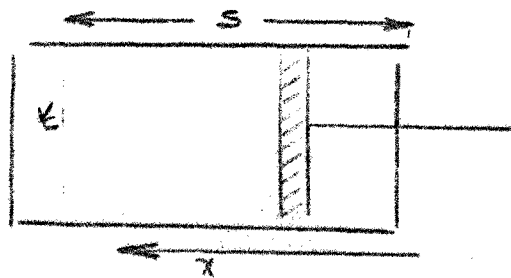
$$HP = \frac{144}{33,000} R \left\{ \frac{k_{a_1}}{k_{a_1}-1} Z_1 T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k_{a_1}-1}{k_{a_1}}} - 1 \right] + \frac{k_{a_2}}{k_{a_2}-1} Z_2 T_2 \left[\left(\frac{P_2}{P_1} \right)^{\frac{k_{a_2}-1}{k_{a_2}}} - 1 \right] \right\} \quad (73)$$

where k_{a_1} and k_{a_2} are average ratios of specific heat; Z_1 and Z_2 are compressibility factors at first and second stages respectively. So the horsepower is direct function of compressibility factor and suction temperature, indirect and exponential function of the average specific heat ratio.

The interstage cooling reduces the suction temperature and compressibility factor and thereby the horsepower, but increases the average specific heat ratio and thereby the

horsepower on the next stage. The increase in horsepower caused by the change in average specific heat ratio is so slight compared to the reduction caused by the change in the compressibility factor and suction temperature that the intercooling always results in reducing horsepower. This statement is illustrated by a specific example on page 55.

Work of Compression as a Function of Piston Movement



The work of compression from Equation (51) is

$$W = \frac{k}{k-1} P_1 V_d E_v \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right]$$

where

V_d : piston displacement volume

E_v : volumetric efficiency from Eq.50

P_1, P_2 : suction and discharge pressure

C : ratio of clearance to displacement volume: V_c/V_d

For single acting cylinder, displacement volume

$$V_d = (A) (s) (\text{RPM})$$

where

A : cross-sectional net area of piston

s : stroke length

RPM: revolutions per minute of crank shaft, or number of compression strokes per minute.

If V_D is defined as displacement volume per compression stroke, then

$$V_D = V_d / \text{RPM} = A s$$

The work per compression stroke

$$W = \frac{k}{k-1} P_1 V_D \left[1 + C - C \left(\frac{P_2}{P_1} \right)^{1/k} \right] \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right] \quad (74)$$

The work, W_x , at a point x along the piston travel is

$$W_x = \frac{k}{k-1} P_1 (V_D)_x \left[1 + C - C \left(\frac{P_2}{P_1} \right)^{1/k} \right] \left[\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right]$$

where $(V_D)_x = A x$

From Equation (43) and (44),

$$\left(\frac{P_2}{P_1} \right)^{(k-1)/k} = \left(\frac{V_1}{V_2} \right)^{k-1}$$

$$\left(\frac{P_2}{P_1} \right)^{1/k} = \left(\frac{V_1}{V_2} \right)$$

where V_1 is the total volume of the cylinder

$$V_1 = V_c + (A) (s)$$

V_x , the volume at a point x , is

$$V_x = V_c + A (s-x)$$

$$\left(\frac{P_2}{P_1} \right)^{(k-1)/k} = \left(\frac{V_c + A s}{V_c + A (s-x)} \right)^{k-1}$$

$$\left(\frac{P_2}{P_1}\right)^{1/k} = \left(\frac{V_c + A s}{V_c + A(s-x)}\right)$$

Then W_x becomes

$$W_x = \left(\frac{k}{k-1}\right) P_1 A x \left[1 + C - C \left(\frac{V_c + A s}{V_c + A(s-x)}\right)\right] \left[\left(\frac{V_c + A s}{V_c + A(s-x)}\right) - 1\right] \quad (75)$$

A , C , V_c , and s are known characteristics of the compressor. k is assumed to remain constant. The above equation gives the work per compression stroke at any point along the piston movement.

In the following pages, the horsepower requirements are computed by using both k -charts and Mollier diagrams for three gases. These gases are Ethane, Carbon-dioxide and Ammonia whose k -values vary most widely with temperature and pressure. The results are then compared. A compression ratio of 4 is generally taken because it is the most common compression ratio. The gas is assumed to be cooled down to an appropriate temperature in order to be within the temperature range of k -charts. The same conclusion is valid for the rest of the gases.

Computing Horsepower Requirements to Compress Ethane

I. First stage: Ethane is compressed from 1 atmosphere at 27° F suction temperature to 4 atmosphere.

A. By k-chart

$$P_1 = 1 \text{ atm.}$$

$$T_1 = 27^\circ \text{ F, } 487^\circ \text{ R}$$

$$P_2 = 4 \text{ atm.}$$

$$R_c = P_2/P_1 = 4$$

$$K_1 = 1.21 \text{ (from Graph 1)}$$

$$T_2 = T_1 (R_c)^{(K-1)/K}$$

$$T_2 = (487) (4)^{(1.21-1)/1.21}$$

$$T_2 = 620^\circ \text{ R, } 160^\circ \text{ F}$$

$$K_2 = 1.17$$

$$K_{av.} = (K_1 + K_2)/2 = (1.21 + 1.17)/2$$

$$K_{av.} = 1.19$$

$$T_2' = (487) (4)^{(1.19-1)/1.19}$$

$$T_2' = 608^\circ \text{ R, } 148^\circ \text{ F}$$

$$K_2' = 1.175$$

$$K_{av.}' = 1.192$$

$$T_2'' = 609^\circ \text{ R, } 149^\circ \text{ F}$$

$$K_2'' = 1.175$$

$$K_{av.}'' = 1.192$$

$$K_{av.}' = K_{av.}'' = 1.192$$

$$T_r = 487/550 = 0.885$$

$$P_r = 1/48.5 = 0.0206$$

$$Z = 1 \text{ (From Figure 6.2.)}$$

$$HP = (0.0467) (K/K-1) (Z_1) (T_1) \left[(R_c)^{(K-1)/K} - 1 \right] \quad (71)$$

$$HP = (0.0467) (1.192/1.192-1) (1) (487)$$

$$\left[(4) (1.192-1)/1.192 - 1 \right]$$

$$HP = (0.0467) (1.192) (487) (1.25-1)/(0.192)$$

$$HP = 35.4$$

B. By Mollier Diagram (From Reference No. 8)

$$P_1 = 1 \text{ atm.}$$

$$T_1 = 27^\circ \text{ F}$$

$$H_1 = 306.5 \text{ Btu/lb}$$

$$P_2 = 4 \text{ atm.}$$

$$H_2 = 35.7 \text{ Btu/lb}$$

$$MW = 30.068$$

From Equation (72)

$$HP = (0.02358) (MW) (H_2 - H_1)$$

$$HP = (0.02358) (30.068) (357 - 306.5)$$

$$HP = 35.7$$

II. Second Stage: Ethane is cooled down to 81° F and compressed from 4 atm. to 16 atm.

A. By k-charts

$$P_1 = 4 \text{ atm.}$$

$$T_1 = 81^\circ \text{ F, } 541^\circ \text{ R}$$

$$K_1 = 1.215$$

$$T_2 = 541 (4) (1.215-1)/1.215$$

$$T_2 = 690^\circ \text{ R, } 230^\circ \text{ F}$$

$$K_2 = 1.19$$

$$K_a = 1.202$$

$$T_2' = 541 (4) (1.202-1)/1.202$$

$$T_2' = 220^\circ \text{ F, } 680^\circ \text{ R}$$

$$K_2' = 1.19$$

$$K_a' = 1.202$$

$$T_r = 0.982$$

$$P_r = 0.0825$$

$$z = 0.97$$

$$HP = (0.0467) (1.202/1.202-1) (0.97) (541)$$

$$\left[(4) (1.202-1) 1.202 \right]^{-1}$$

$$HP = 379$$

B. By Mollier Diagram

$$P_1 = 4 \text{ atm.}$$

$$T_1 = 81^\circ \text{ F}$$

$$H_1 = 326 \text{ Btu/lb}$$

$$H_2 = 378 \text{ Btu/lb.}$$

$$HP = (0.02358) (30.068) (378-326)$$

$$HP = 36.8$$

III. Third stage: Ethane is cooled down to 117° F and compressed to 64 atm.

A. By k-charts

$$P_1 = 16 \text{ atm., } 235 \text{ psia.}$$

$$T_1 = 117^\circ \text{ F, } 577^\circ \text{ R}$$

$$K_1 = 1.29$$

$$T_2 = 577 (4)^{(1.29-1)/1.29}$$

$$T_2 = 788^\circ \text{ R, } 328^\circ \text{ F}$$

$$K_2 = 1.26$$

$$K_{av.} = 1.275$$

$$T_2' = 577 (4)^{(1.275-1)/1.275}$$

$$T_2' = 778^\circ \text{ R, } 318^\circ \text{ F}$$

$$K_2' = 1.27$$

$$K_{av.}' = 1.28$$

$$T_r = 1.05$$

$$P_r = 0.33$$

$$z = 0.90$$

$$HP = (0.0467) (1.28/1.28-1) (0.9) (577)$$

$$\left[(4)^{(1.28-1)/1.28} - 1 \right]$$

$$HP = 39.4$$

B. By Mollier Diagram

$$P_1 = 16 \text{ atm.}$$

$$T_1 = 117^\circ \text{ F}$$

$$H_1 = 331 \text{ Btu/lb}$$

$$P_2 = 64 \text{ atm.}$$

$$H_2 = 384 \text{ Btu/lb}$$

$$H_2 - H_1 = 384 - 331 = 53 \text{ Btu/lb}$$

$$\text{HP} = (0.02358) (30.068) (53)$$

$$\text{HP} = 37.5$$

IV. Fourth stage: Ethane is cooled down to 153° F and compressed up to 128 atm. (1880 psia.)

A. By k-charts

$$P_1 = 64 \text{ atm., } 938 \text{ psia.}$$

$$T_1 = 153^\circ \text{ F, } 613^\circ \text{ R } R_c = 2.0$$

$$K_1 = 2.26$$

$$T_2 = 613 (2) (2.26-1)/2.26$$

$$T_2 = 898^\circ \text{ R, } 438^\circ \text{ F}$$

$$K_2 = 1.26$$

$$K_a = 1.76$$

$$T_2' = 613 (2) (1.76-1)/1.76$$

$$T_2' = 825^\circ \text{ R, } 365^\circ \text{ F}$$

$$K_2' = 1.39$$

$$K_a' = 1.825$$

After successive trial K_a is found to be 1.82

$$T_p = 1.115$$

$$P_p = 1.32$$

$$z = 0.62$$

$$HP = (0.0467) (1.82/1.82-1) (0.62) (613)$$

$$\left[(2) \frac{(1.82-1)}{1.82-1} \right]$$

$$HP = 14.2$$

B. By Mollier Diagram (From Figure 7)

$$P_1 = 64 \text{ atm., } 938 \text{ psia.}$$

$$T_1 = 153^\circ \text{ F}$$

$$H_1 = 144 \text{ Btu/lb}$$

$$P_2 = 128 \text{ atm., } 1880 \text{ psia.}$$

$$H_2 = 164 \text{ Btu/lb}$$

$$HP = (0.02368) (30.068) (164-144)$$

$$HP = 14.1$$

V. Special case: It is assumed that ethane is compressed from 1200 psia at 153° F , where k becomes greatest, to 2400 psia. in order to prove the validity of the equation where k varies most widely at the suction and discharge conditions.

A. By k -charts

$$P_1 = 1200 \text{ psia}$$

$$T_1 = 153^\circ \text{ F}$$

$$K_1 = 3.01 \quad (3.01-1)/3.01$$

$$T_2 = 613 \text{ (2)}$$

$$T_2 = 972^\circ \text{ R, } 512^\circ \text{ F}$$

$$K_2 = 1.20$$

$$K_a = 2.105 \quad (2.105-1)/2.105$$

$$T_2' = 613 \text{ (2)}$$

$$T_2' = 894^\circ \text{ R, } 434^\circ \text{ F}$$

$$K_a' = 2.16 \quad (2.16-1)/2.16$$

$$T_2'' = 613 \text{ (2)}$$

$$T_2'' = 887^\circ \text{ R, } 427^\circ \text{ F}$$

$$K_2' = 1.305$$

$$K_a = 2.16$$

$$T_r = 1.115$$

$$P_r = 1.675$$

$$z = 0.48$$

$$HP = (0.0467)(2.16/2.16-1) (0.48) (613)$$

$$HP = 11.5 \quad \left[(2) (2.16-1)/2.16 - 1 \right]$$

B. By Mollier Diagram

$$P_1 = 1200 \text{ psia}$$

$$T_1 = 153^\circ \text{ F}$$

$$HP = 38$$

B. By Mollier Diagram

$$MW = 44.011$$

$$H_1 = 188.5 \text{ kilocal./kilogram (From Figure 8)}$$

$$H_2 = 209 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 20.5 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 20.5 \text{ kilocal./kilogram} \times$$

$$\frac{1 \text{ Btu}}{0.252 \text{ kilocal}} \times \frac{1 \text{ kilogram}}{2.205 \text{ lb.}}$$

$$H_2 - H_1 = 36.9 \text{ Btu/lb.}$$

From Equation (72)

$$HP = (0.02358) (MW) (H_2 - H_1)$$

$$HP = (0.02358) (44.011) (36.9)$$

$$HP = 38.2$$

II. Second Stage: Carbon dioxide is cooled down to 140° F and compressed from 60 psia. to 240 psia.

A. By using k- charts

$$P_1 = 60 \text{ psia}$$

$$T_1 = 140^\circ \text{ F, } 600^\circ \text{ R}$$

$$K_1 = 1.29$$

$$T_2 = 600 (4) \frac{(1.29-1)}{1.29}$$

$$T_2 = 818^\circ \text{ R, } 358^\circ \text{ F}$$

$$K_2 = 1.26$$

$$P_2 = 2400 \text{ psia}$$

$$H_2 = 132 \text{ Btu/lb}$$

$$H_2 - H_1 = 132 - 116 = 16 \text{ Btu/lb}$$

$$HP = (0.02358) (30.068) (16)$$

$$HP = 11.3$$

TABULATION OF RESULTS FOR ETHANE COMPRESSION

<u>Stage</u>	<u>HP PER MOLE</u>			
	<u>P₁ Atm.</u>	<u>R_c</u>	<u>K-Chart</u>	<u>Mollier Diagram</u>
I	1	4	35.4	35.7
II	4	4	37.9	36.8
III	16	4	39.4	37.5
IV	64	2	14.2	14.1
Special Case	1200 psia	2	11.5	11.3
Total			138.4	135.4
% error = $\frac{135.4 - 138.4}{135.4}$			= % 2.2	

Computing Horsepower to Compress Carbon Dioxide

I. First stage: Carbon dioxide is compressed from 15 psia. at 32° F to 60 psia.

A. By k-charts

$$P_1 = 15 \text{ psia}$$

$$T_1 = 32^\circ \text{ F}, 492^\circ \text{ R}$$

$$K_1 = 1.35 \text{ (From Graph 2)}$$

$$T_2 = (492) (4) \frac{(1.35-1)}{1.35}$$

$$T_2 = 703^\circ \text{ R}, 243^\circ \text{ F}$$

$$K_2 = 1.27$$

$$K_a' = 1.31$$

$$T_2' = (492) (4) \frac{(1.31-1)}{1.31}$$

$$K_2' = 1.27$$

$$K_a'' = 1.31$$

$$K_a' = K_a'' = 1.31$$

$$T_R = 0.697$$

$$P_R = 0.014$$

$$K = 1 \text{ (From Figure 6)}$$

From Equation (71)

$$HP = (0.0467) (K/K-1) (P_1)(T_1) \left[(\dot{R}_c)^{K-1/K} - 1 \right]$$

$$HP = (0.0467) (1.31/1.31-1) (1) (492)$$

$$\left[(4) \frac{(1.31-1)}{1.31} - 1 \right]$$

$$K'_a = 1.275$$

After successive trial, K_a is found to be 1.27

$$T_r = 1.1$$

$$P_r = 0.056$$

$$z = 0.99$$

$$HP = (0.0467) (1.27/1.27-1) (0.99) (600)$$

$$\left[(4) \frac{(1.27-1)}{1.27-1} \right]$$

$$HP = 43.8$$

B. By Mollier Diagram

$$P_1 = 60 \text{ psia.}$$

$$P_2 = 240 \text{ psia.}$$

$$T_1 = 140^\circ \text{ F, } 50^\circ \text{ C}$$

$$H_1 = 200 \text{ kilocal./kilogram}$$

$$H_2 = 224.5 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 24.5 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 44.1 \text{ Btu/lb.}$$

$$HP = (0.02358) (44.011) (44.1)$$

$$HP = 43.9$$

III. Third stage: Carbon dioxide is cooled down to 122° F and compressed from 240 psia. to 960 psia.

A. By using k-charts

$$P_1 = 240 \text{ psia}$$

$$T_1 = 122^\circ \text{ F, } 582^\circ \text{ R}$$

$$K_1 = 1.38$$

$$T_2 = 582 \text{ (4)} \quad (1.38-1)/1.38$$

$$T_2 = 852^\circ \text{ R, } 392^\circ \text{ F}$$

$$K_2 = 1.24$$

$$K_a' = 1.31$$

$$T_2' = 582 \text{ (4)} \quad (1.31-1)/1.31$$

$$T_2' = 808^\circ \text{ R, } 348^\circ \text{ F}$$

$$K_2' = 1.30$$

$$K_a'' = 1.34$$

After successive trial, K_a is found to be 1.33

$$T_r = 1.063$$

$$P_r = 0.224$$

$$Z = 0.935$$

$$HP = (0.0467) (1.33/1.33-1) (0.935) (582)$$

$$HP = 42 \quad \left[(4) \frac{(1.33-1)}{1.33} - 1 \right]$$

B. By using Mollier Diagram

$$P_1 = 240 \text{ psia, } 16.35 \text{ atm.}$$

$$T_1 = 122^\circ \text{ F, } 50^\circ \text{ C}$$

$$H_1 = 195.5 \text{ kilocal./kilogram}$$

$$P_2 = 960 \text{ psia., } 65.3 \text{ atm.}$$

$$H_2 = 218 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 22.5 \text{ kilocal./kilogram}$$

$$HP = (0.02358) (44.011) \frac{22.5}{0.252 \times 2.205}$$

$$HP = 42$$

IV. Fourth stage: Carbon dioxide is cooled down to 122° F and compressed from 960 psia to 1920 psia.

A. By using k-charts

$$K_1 = 1.85$$

$$T_2 = 582 (2) \frac{(1.85-1)}{1.85}$$

$$T_2 = 800^\circ \text{ R, } 340^\circ \text{ F}$$

$$K_2 = 1.60$$

$$K_a = 1.725$$

After successive trials, K_a is found to be 1.75.

$$T_F = 1.063$$

$$P_F = 0.836$$

$$z = 0.69$$

$$HP = (0.0467) (1.75/1.75-1) (0.69) (582)$$

$$\left[(2) \frac{(1.75-1)}{1.75} - 1 \right]$$

$$HP = 15.1$$

B. By Mollier Diagram

$$P_1 = 960 \text{ psia, } 65.3 \text{ atm.}$$

$$T_1 = 122^\circ \text{ F, } 50^\circ \text{ C}$$

$$H_1 = 182 \text{ kilocal./kilogram}$$

$$P_2 = 1920 \text{ psia.}, 130.8 \text{ atm.}$$

$$H_2 = 189.5 \text{ kilocal./kilogram}$$

$$H_2 - H_1 = 189.5 - 181.5 = 8 \text{ kilocal./kilogram}$$

$$HP = (0.02358) (44.011) \frac{8}{(0.252) (2.205)}$$

$$HP = 14.35$$

TABULATION OF RESULTS FOR CARBON DIOXIDE COMPRESSION

Stage	P_1 (psia)	R_c	HP Per Mole	
			K-Chart	Mollier Diagram
I	15	4	38.0	38.2
II	60	4	43.8	43.9
III	240	4	42.0	42.0
IV	960	2	<u>15.1</u>	<u>14.35</u>
Total			138.9	139.05
$\% \text{ error} = \frac{139.05 - 138.9}{139.05} \times 100 = \% 0.7$				

The Effect of Deviation From Ideal State on Horsepower Requirements

It is assumed that carbon dioxide is compressed from 1 atm. at 122° F suction temperature to 4 atm., where the compressibility factor, Z, is equal to 1, which is the state of perfect gas. The same gas is compressed from 100 atm. at the same suction pressure to 400 atm., where the compressibility factor, Z, equals 0.43, which is the state of imperfect gas. The horsepower requirements are computed for both cases as follows:

Case I:

$$P_1 = 1 \text{ atm.}$$

$$T_1 = 122^\circ \text{ F, } 582^\circ \text{ R}$$

$$Z_1 = 1$$

$$K_1 = 1.30$$

$$T_2 = 582 (4) (1.30-1)/1.30$$

$$T_2 = 800^\circ \text{ R, } 340^\circ \text{ F}$$

$$K_2 = 1.25$$

$$K_{av.} = \frac{(1.30 + 1.25)}{2} = 1.275$$

$$T_2 = 582 (4) (1.275-1)/1.275$$

$$T_2 = 785^\circ \text{ R, } 325^\circ \text{ F}$$

$$K_2 = 1.25$$

$$K_{av.} = 1.275$$

$$HP = (0.0467) (1.275 / (1.275 - 1)) (582) \left[(4) \frac{(1.275 - 1)}{1.275} - 1 \right]$$

$$HP = 44.2 \text{ per mole}$$

Case II

$$P_1 = 100 \text{ atm.} \quad P_2 = 200 \text{ atm.}$$

$$T_1 = 582^\circ \text{ R}$$

$$K_1 = 3.02$$

$$T_2 = 582 (4) \frac{(3.02 - 1)}{3.02}$$

$$T_2 = 1468^\circ \text{ R, } 1008^\circ \text{ F}$$

K data is not available at 1008° F . But $K_{av.}$ cannot be greater than $K_1 (= 3.02)$. $K_{av.}$ is assumed to be equal to K_1 .

$$K_{av.} = 3.02$$

$$P_r = \frac{1469}{1070.9} = 1.36$$

$$Z = 0.43$$

$$HP = (0.0467) \left(\frac{3.02}{3.02 - 1} \right) (0.43) (582) \left[(4) \frac{3.02 - 1}{3.02} - 1 \right]$$

$$HP = 26.8 \text{ per mole}$$

Horsepower is 26.8 per mole in Case II while it is 44.2 in Case I. So, horsepower requirements per mole decreases as the gas deviates from the ideal state.

Computing Horsepower Requirements to Compress Ammonia

I. First stage: Ammonia is compressed from 1 atm. at 117°F to 4 atm.

A. By using K-charts

$$P_1 = 1 \text{ atm.}$$

$$T_1 = 117^{\circ} \text{F}$$

$$K_1 = 1.305$$

$$T_2 = 577 \text{ (4)} \quad (1.305-1)/1.305$$

$$T_2 = 797^{\circ} \text{R, } 337^{\circ} \text{F}$$

$$K_2 = 1.27$$

$$K_a = 1.287$$

$$T_2' = 577 \text{ (4)} \quad (1.287-1)/1.287$$

$$T_2' = 785^{\circ} \text{R, } 325^{\circ} \text{F}$$

$$K_2' = 1.275$$

$$K_a' = 1.29$$

$$T_r = 0.79$$

$$P_r = 0.00897$$

$$Z = 1$$

$$HP = (0.0467) (1.29/(1.29-1)) (1) (577)$$

$$HP = 43.8 \quad \left[(4) (1.29-1)/1.29 - 1 \right]$$

B. By using Mollier diagram (From Figure 9)

$$P_1 = 1 \text{ atm.}$$

$$T_1 = 153^\circ \text{ F, } 320^\circ \text{ K}$$

$$H_1 = 9600 \text{ cal./g-mole}$$

$$P_2 = 4 \text{ atm.}$$

$$H_2 = 10,600 \text{ cal./g-mole}$$

$$\text{MW} = 17.032$$

$$H_2 - H_1 = 10,600 - 9600 = 1000 \text{ cal./g-mole}$$

From Equation (72),

$$\text{HP} = (0.02358) (\text{MW}) (H_2 - H_1)$$

where enthalpy is in Btu/lb.

Introducing conversion factors, Equation (72) becomes

$$\text{HP} = (0.0025) (\text{MW}) (H_2 - H_1)$$

where enthalpy is in cal/g-mole.

$$\text{HP} = (0.0025) (17.032) (1000)$$

$$\text{HP} = 42.5$$

II. Second stage: Ammonia is cooled down to 189° F and compressed from 4 atm. to 16 atm.

A. By using K-charts

$$P_1 = 4 \text{ atm.}$$

$$T_1 = 189^\circ \text{ F, } 649^\circ \text{ R}$$

$$T_2 = 649 (4) (1.305-1)/305$$

$$T_2 = 896^\circ \text{ R, } 436^\circ \text{ F}$$

$$K_2 = 1.27$$

$$K_a = 1.287$$

$$T_2' = 649 (4) (1.287-1)/1.287$$

$$T_2' = 883^\circ \text{R}, 423^\circ \text{F}$$

$$K_2' = 1.275$$

$$K_R' = 1.29$$

$$T_F = 0.093$$

$$P_F = 0.0355$$

$$Z = 0.985$$

$$HP = (0.0467) (1.29/1.29-1) (0.985) (649)$$

$$\left[(4) (1.29-1)/1.29 - 1 \right]$$

$$HP = 49.3$$

B. By using Mollier diagram

$$P_1 = 4 \text{ atm.}$$

$$T_1 = 189^\circ \text{F}, 360^\circ \text{K}$$

$$H_1 = 9875 \text{ cal./g-mole}$$

$$P_2 = 16 \text{ atm.}$$

$$H_2 = 11,000 \text{ cal/g-mole}$$

$$H_2 - H_1 = 1,125 \text{ cal/g-mole}$$

$$HP = (0.0025) (17.032) (1125)$$

$$HP = 47.8$$

III. Third stage: Ammonia is cooled down to 189°F and compressed from 16 atm. to 64 atm.

A. By using K-charts

$$P_1 = 16 \text{ atm., } 235 \text{ psia.}$$

$$T_1 = 189^\circ \text{ F, } 649^\circ \text{ R}$$

$$K_1 = 1.39$$

$$T_2 = 649 \text{ (4) } (1.39-1)/1.39$$

$$T_2 = 957^\circ \text{ F, } 497^\circ \text{ R}$$

$$K_2 = 1.35$$

$$K_2 = 1.37$$

$$T_2 = 649 \text{ (4) } (1.37-1)/1.37$$

$$T_2 = 943^\circ \text{ F, } 483^\circ \text{ R}$$

$$K_2 = 1.36$$

$$K_2 = 1.375$$

$$T_2 = 649 \text{ (4) } (1.375-1)/1.375$$

$$T_2 = 947^\circ \text{ F, } 487^\circ \text{ R}$$

$$K_2 = 1.36$$

$$K_2 = 1.375$$

$$T_2 = 0.903$$

$$P_2 = 0.1435$$

$$Z = 0.92$$

$$HP = (0.0467) (1.375/1.375-1) (0.92) (649)$$

$$\left[(4) (1.375-1)/1.375 - 1 \right]$$

$$HP = 47$$

B. By using Mollier diagram

$$P_1 = 16 \text{ atm.}$$

$$T_1 = 189^\circ \text{F, } 361^\circ \text{K}$$

$$H_1 = 10,800 \text{ cal./g-mole}$$

$$P_2 = 64 \text{ atm.}$$

$$H_2 = 9700 \text{ cal./g-mole}$$

$$H_2 - H_1 = (10,800 - 9700) = 9700 \text{ cal./g-mole}$$

$$HP = (0.0025) (17.032) (900)$$

$$HP = 46.7$$

IV. Fourth stage: Ammonia is cooled down to 225°F and compressed from 64 atm. to 128 atm. (1880 psia.)

A. By using K-charts

$$P_1 = 64 \text{ atm., } 940 \text{ psia}$$

$$T_1 = 225^\circ \text{F, } 685^\circ \text{R}$$

$$K_1 = 2.30$$

$$T_2 = 685 (2) (2.30-1)/2.30$$

$$T_2 = 1011^\circ \text{R, } 551^\circ \text{F}$$

$$K_2 = 1.42$$

$$K_a = 1.86$$

$$T_2' = 685 (2) (1.86-1)/1.86$$

$$T_2' = 942^\circ \text{R, } 482^\circ \text{F}$$

$$K_2' = 1.53$$

$$K_a' = 1.915$$

$$T_2'' = 685 (2) (1.915-1)/1.915$$

$$T_2'' = 952^\circ \text{R}, 492^\circ \text{F}$$

$$K_2'' = 1.52$$

$$K_a'' = 1.91$$

$$T_r = 0.038$$

$$P_r = 0.574$$

$$Z = 0.635$$

$$\text{HP} = (0.0467) (1.91/1.91-1) (0.635) (685) \\ \left[(2) (1.91-1)/1.91 - 1 \right]$$

$$\text{HP} = 16.7$$

B. By using Mollier diagram

$$P_1 = 64 \text{ atm.}$$

$$T_1 = 685^\circ \text{R}, 380^\circ \text{K}$$

$$H_1 = 9050 \text{ cal./g-mole}$$

$$P_2 = 128 \text{ atm.}$$

$$H_2 = 9450 \text{ ca./g-mole}$$

$$H_2 - H_1 = (9450 - 9050) = 400 \text{ cal./g-mole}$$

$$\text{HP} = (0.0025) (17.032) (400)$$

$$\text{HP} = 17$$

V. Fifth stage: Ammonia is cooled down to 297°F and compressed to 256 atm.

A. By using K- charts

$$P_1 = 128 \text{ atm.}, 1880 \text{ psia.}$$

$$T_1 = 297^\circ \text{ F}, 757^\circ \text{ R}$$

$$K_1 = 3.5$$

$$T_2 = 757 (2) (3.5-1)/3.5$$

$$T_2 = 1240^\circ \text{ R}, 780^\circ \text{ F}$$

780° F - curve is not available, but K_2 is estimated.

$$K_2 = 1.20$$

$$K_a = 2.35$$

$$T_2' = 757 (2) (2.35-1)/2.35$$

$$T_2' = 1126^\circ \text{ R}, 666^\circ \text{ F}$$

$$K_2' = 1.30$$

$$K_a' = 2.40$$

$$T_2'' = 757 (2) (2.40-1)/2.40$$

$$T_2'' = 1132^\circ \text{ R}, 472^\circ \text{ F}$$

$$K_2'' = 1.30$$

$$K_a'' = 2.40$$

$$T_F = 1.038$$

$$P_F = 1.148$$

$$Z = 0.47$$

$$HP = (0.0467) (2.40/2.40-1) (0.47) (757)$$

$$\left[(2) (2.40-1)/2.40 - 1 \right]$$

$$HP = 14.1$$

B. By using Mollier diagram

$$P_1 = 128 \text{ atm.}$$

$$T_1 = 757^\circ \text{R, } 420^\circ \text{K}$$

$$H_1 = 8550$$

$$P_2 = 256 \text{ atm.}$$

$$H_2 = 8850$$

$$H_2 - H_1 = (8850 - 8550) = 300 \text{ cal./g-mole}$$

$$HP = (0.0025) (17.032) (300)$$

$$HP = 12.75$$

TABLEULATION OF RESULTS FOR AMMONIA COMPRESSION

Stage	P_1 (atm.)	R_c	HP Per Mole	
			K-Charts	Mollier Dia.
I	1	4	43.8	42.5
II	4	4	49.3	47.8
III	16	4	47.0	46.7
IV	64	2	16.7	17.0
V	128	2	<u>14.1</u>	<u>12.75</u>
TOTAL			170.9	163.75

$$\% \text{ error} = \frac{163.75 - 170.9}{163.75} \times 100 = \% 4.36$$

The Effect of Inter-stage Cooling on Horsepower Requirements

The inter-cooling always results in power reduction.

The amount of reduction depends on the amount of cooling,

how close the gas is to the critical conditions and how K varies with temperature.

The effect of inter-cooling on horsepower requirements is illustrated by the following example.

It is assumed that there is ammonia gas at 1000 psia and 297° F at the discharge of some stage, and it is to be compressed to 4000 psia on the next stage. It is intended to see how much horsepower per mole of gas can be saved by cooling the gas from 297° F to 225° F.

A. With Inter-cooling

$$P_1 = 1000 \text{ psia.}$$

$$T_1 = 225^{\circ} \text{ F, } 685^{\circ} \text{ R}$$

$$K_1 = 3.00$$

$$T_2 = 685 (4) (3.00-1)/3.00$$

$$T_2 = 1728^{\circ} \text{ F, } 1268^{\circ} \text{ F}$$

K is not known at 1268° F. But $K \geq 1$
under any condition

$$K_2 \leq 1.2 \text{ at } 1268^{\circ} \text{ F}$$

K_2 is taken 1.2

$$K_a = (3.00 + 1.2)/2$$

$$K_a = 2.10$$

$$T_r = 0.938$$

$$P_r = 0.613$$

$$Z = 0.60$$

$$HP = (0.0467) (2.1/(2.1-1)) (0.60) (685)$$

$$\left[(4) \frac{(2.1-1)}{2.1} - 1 \right]$$

$$HP = 38.9$$

B. Without Inter-cooling

$$P_1 = 1000 \text{ psia}$$

$$T_1 = 297^\circ \text{ F}, 757^\circ \text{ R}$$

$$K_1 = 1.70$$

$$T_2 = 757 (4) \frac{(1.70-1)}{1.70}$$

$$T_2 = 1340^\circ \text{ R}, 880^\circ \text{ F}$$

K_2 is not known, but can be taken at 1.2.

$$K_a = (1.70 + 1.20)/2$$

$$K_a = 1.45$$

$$T_F = 1.038$$

$$P_F = 0.613$$

$$Z = 0.80$$

$$HP = (0.0467) (1.45/(1.45-1)) (0.80) (757)$$

$$\left[(4) \frac{(1.45-1)}{1.45} - 1 \right]$$

$$HP = 49.2$$

The volumetric capacity is computed as follows:

A. With Inter-cooling

$$P_v \sqrt{N} = ZNRT$$

$$N = 1 \text{ #-mole/min.}$$

$$R = 10.71$$

$$T = 685^{\circ} \text{ R}$$

$$Z = 0.60$$

$$P = 1000 \text{ psia}$$

$$V = \frac{ZNRT}{P}$$

$$V = \frac{(0.60) (10.71) (685)}{1000}$$

$$V = 4.3 \text{ cfm}$$

B. Without Inter-cooling

$$T = 757^{\circ} \text{ R}$$

$$Z = 0.80$$

$$V = \frac{(0.80) (10.71) (757)}{1000}$$

$$V = 6.48 \text{ cfm}$$

TABULATION OF RESULTS

	<u>With Inter-Cooling</u>	<u>Without Inter-Cooling</u>
P_1	1000 psia	1000 psia
R_c	4	4
T_1	685° R	757° R
Z	0.60	0.80
N	1 #-mole	1 #-mole
V_1	4.3 cfm	6.48 cfm
K_a	2.10	1.45
HP/#-mole	38.9	49.2

Horsepower savings per mole = $49.2 - 38.9 = 10.3$

Ammonia is the gas whose K varies most widely with temperature. Therefore, the conclusion is valid for the other gases that are studied.

CONCLUSIONS

The validity of the method of computing horsepower by using equation (66) and the k-charts is proved. Interstage cooling results in power reduction. Deviation from ideal state reduces horsepower requirements.

RECOMMENDATIONS

1. A specific heat ratio at an average of the values at suction and discharge conditions is recommended to be used in computing horsepower requirements instead of using the specific heat ratio at atmospheric pressure and room temperature.

2. A k-chart can be made out and used with Eq. (66) in computing horsepower requirements when a Mollier diagram for the gas is not available. It is easier to generate a k-chart than a Mollier diagram.

3. The compressibility factor must be taken into account - particularly at high pressures.

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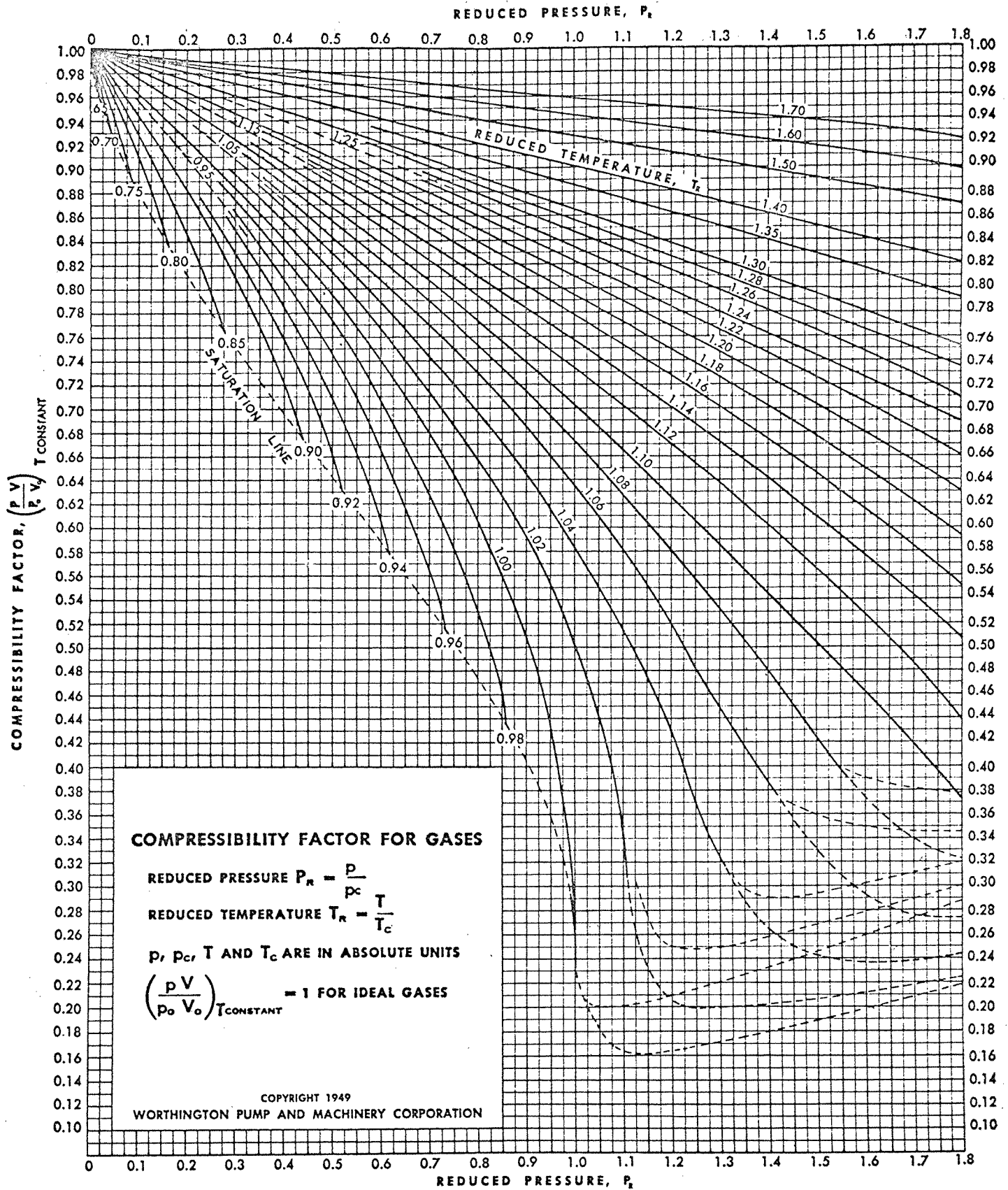


Figure 6. Compressibility factor for gases. (Courtesy Worthington Corp., Research Bulletin P-7637, 1949.)

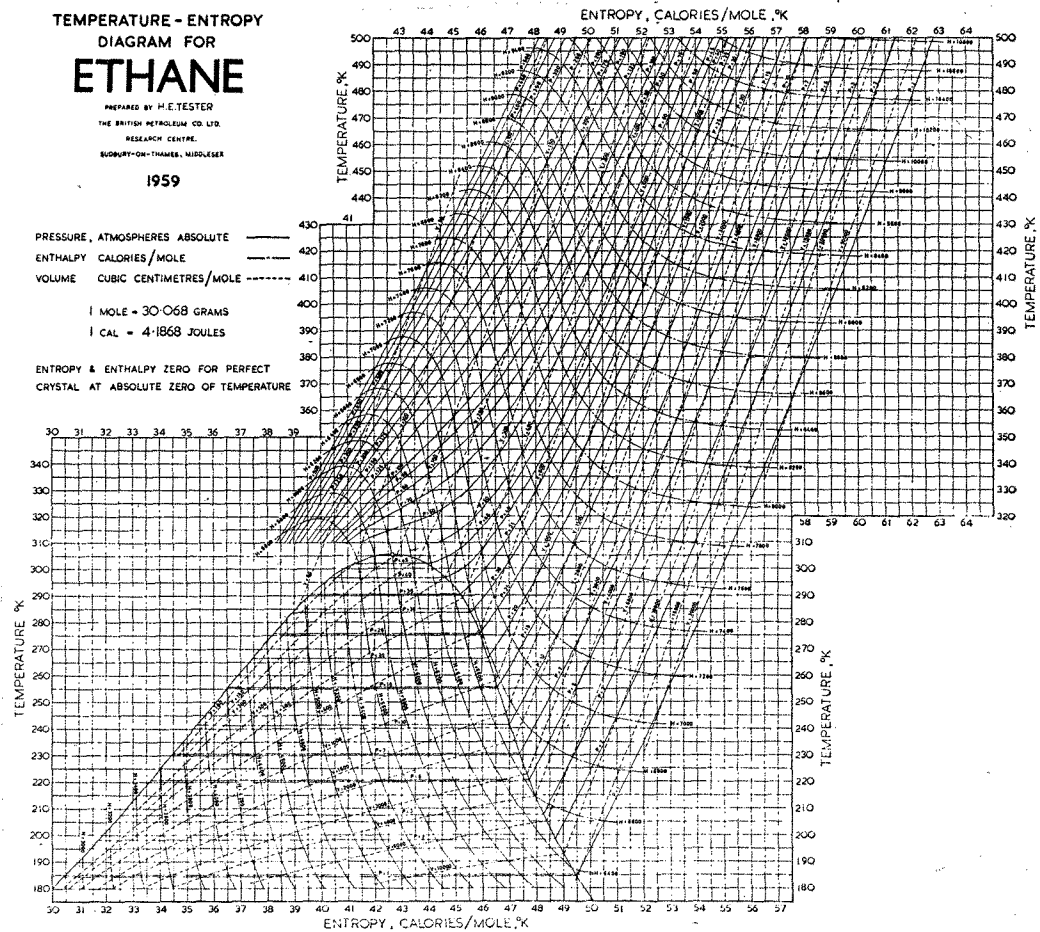
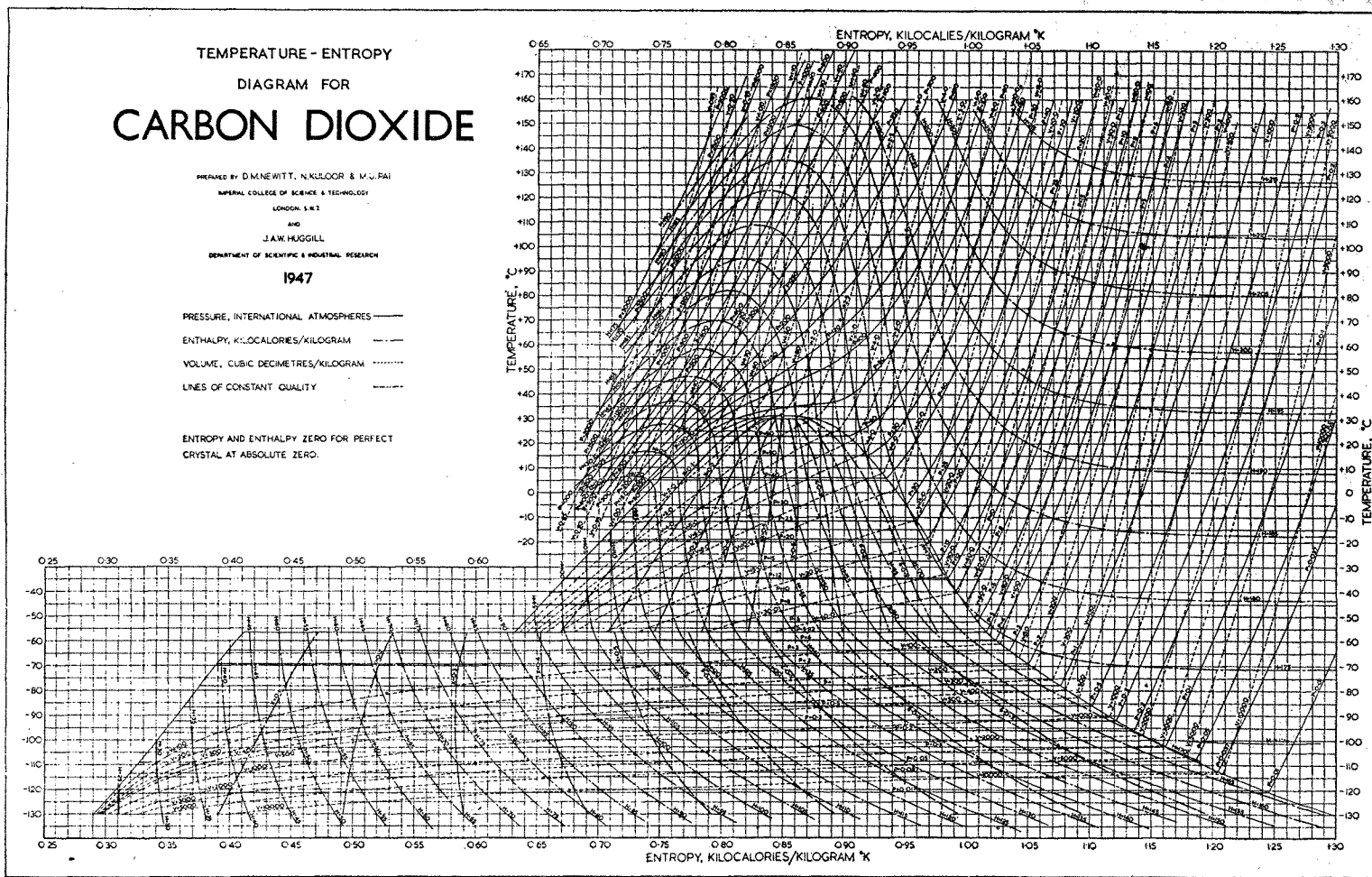


Figure 7. Mollier Diagram for Ethane.

Figure 8. Mollier diagram for Carbon Dioxide.



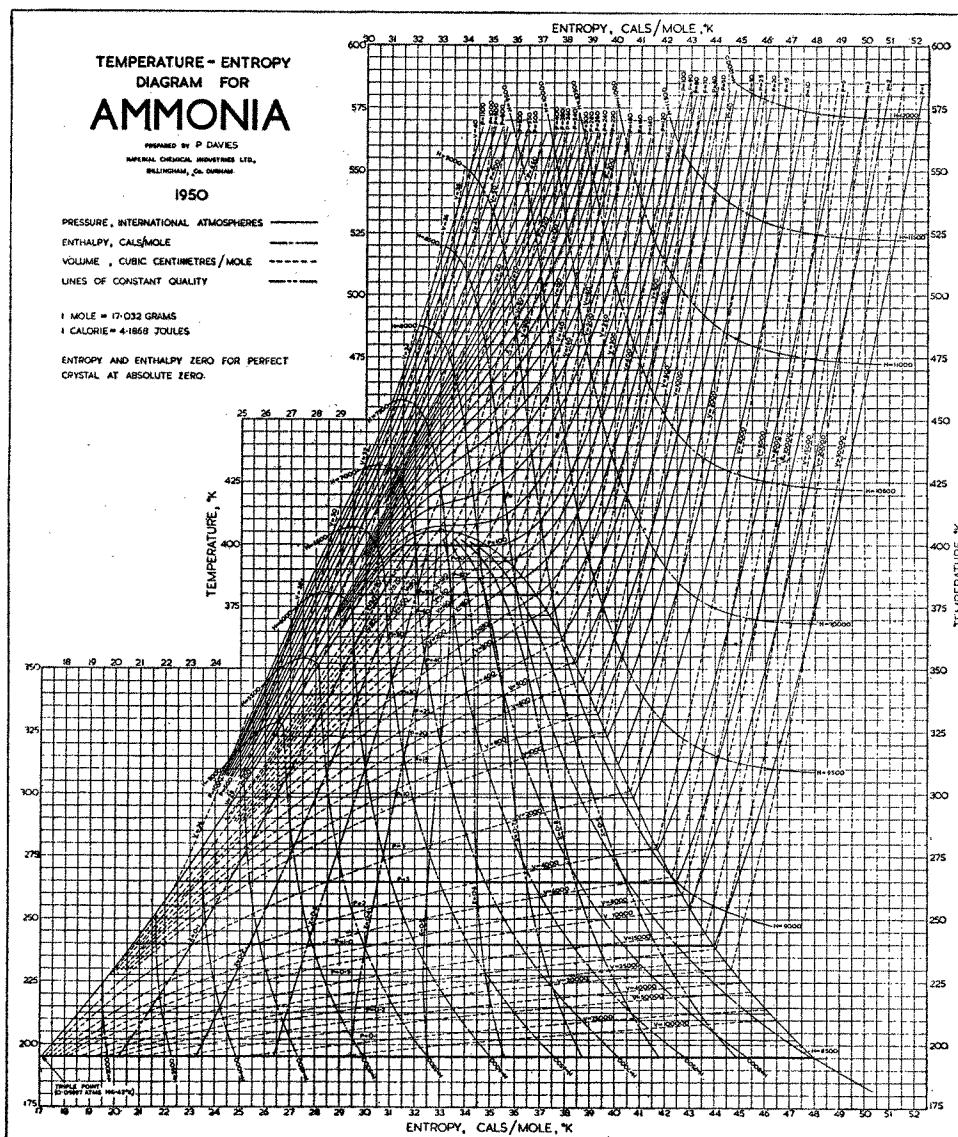
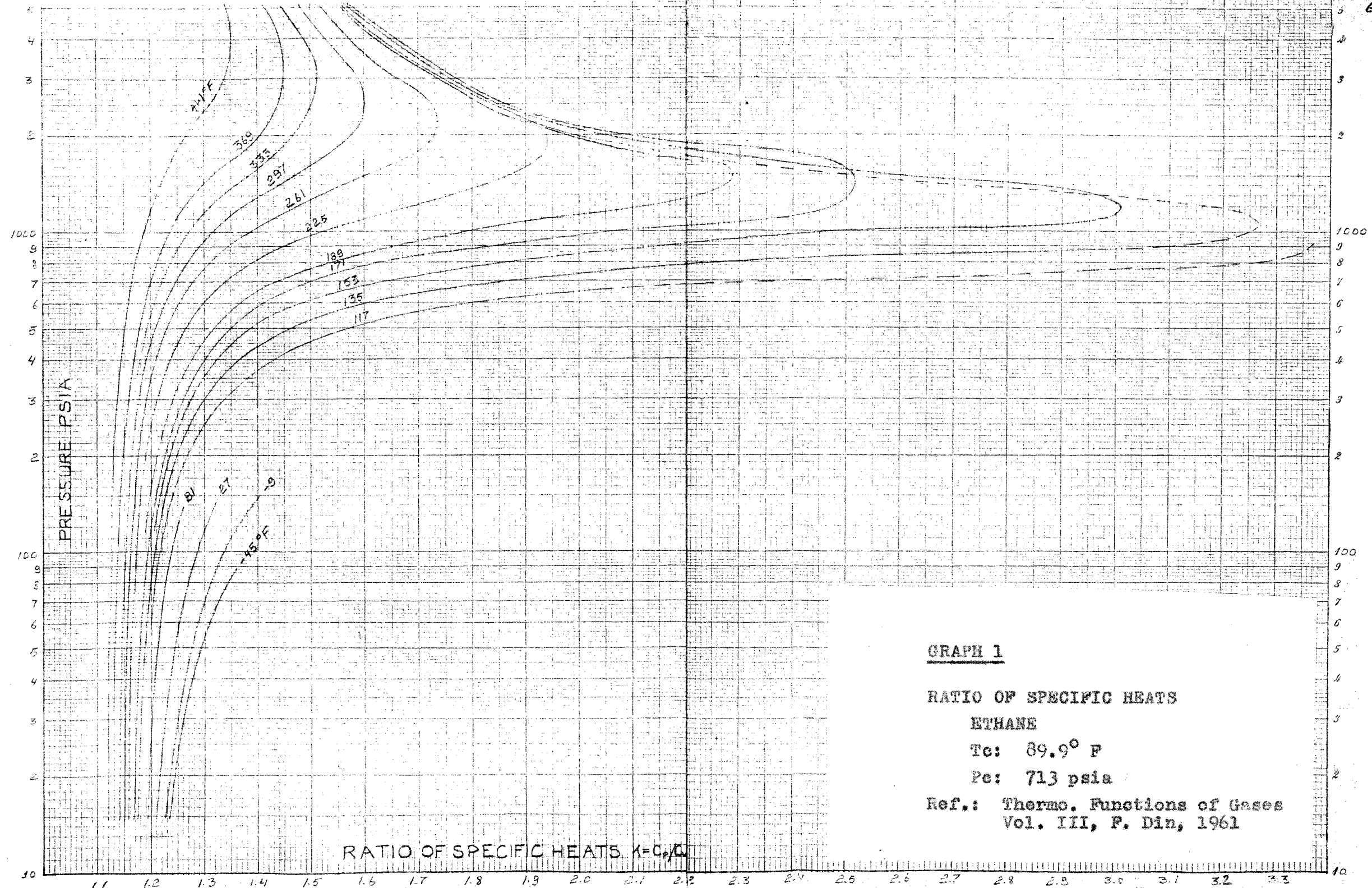


Figure 9. Mollier diagram for Ammonia.



GRAPH 1

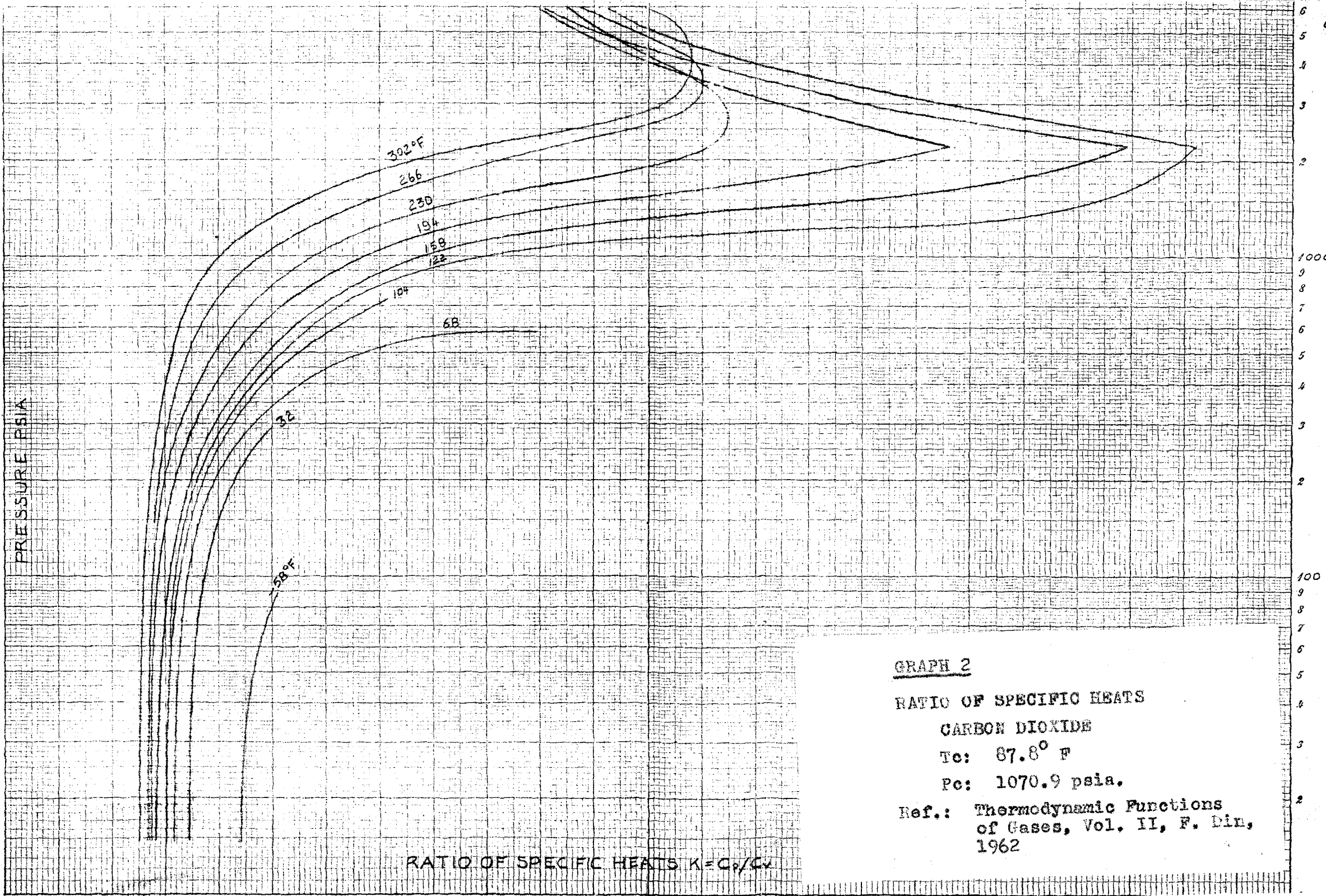
RATIO OF SPECIFIC HEATS
ETHANE

Tc: 89.9° F

Pc: 713 psia

Ref.: Thermo. Functions of Gases
Vol. III, F. Din, 1961

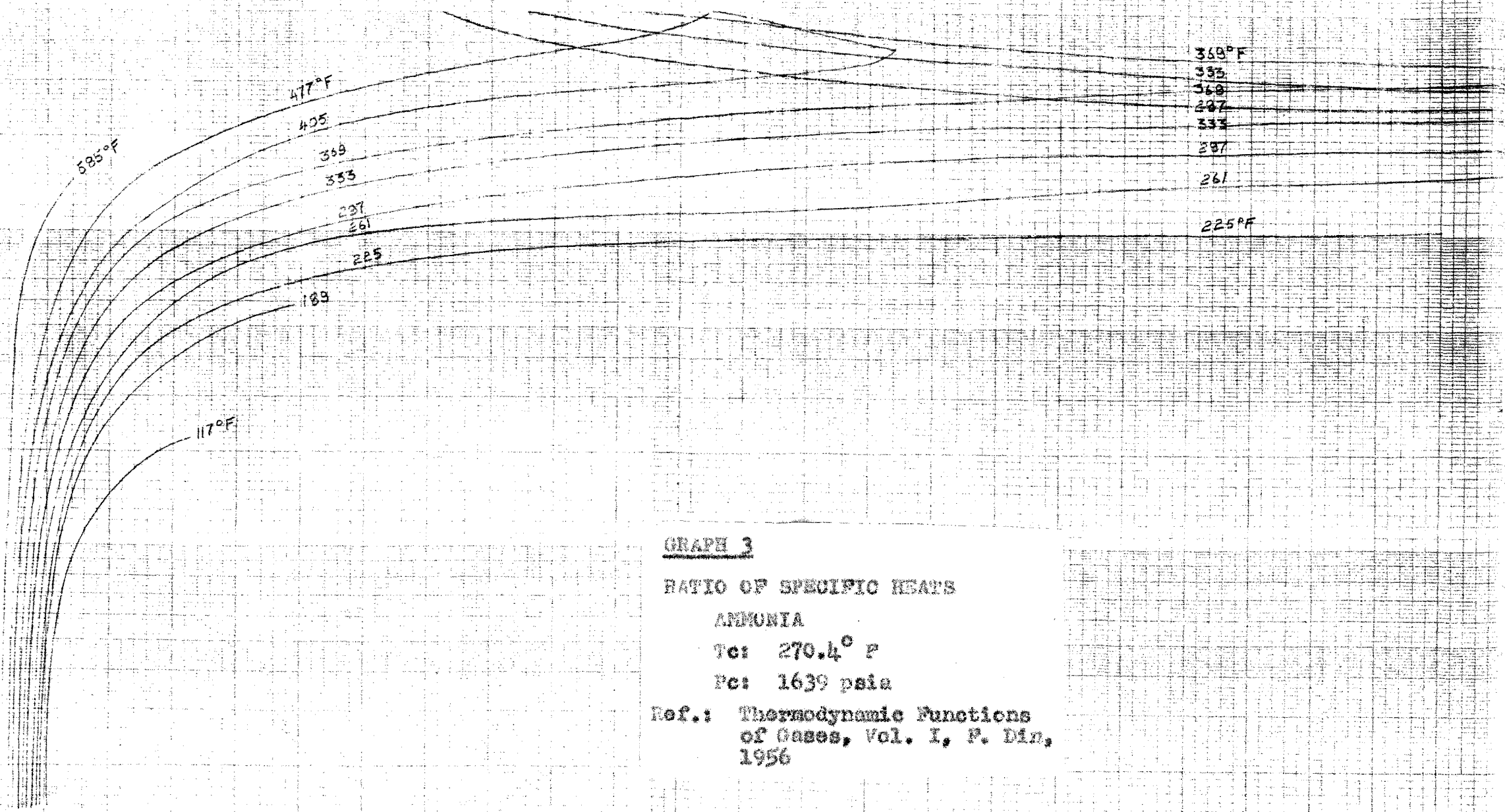
RATIO OF SPECIFIC HEATS $k=C_p/C_v$



GRAPH 2
 RATIO OF SPECIFIC HEATS
 CARBON DIOXIDE
 Tc: 87.8° F
 Pc: 1070.9 psia.
 Ref.: Thermodynamic Functions
 of Gases, Vol. II, F. Din,
 1962

RATIO OF SPECIFIC HEATS $k = C_p/C_v$

PRESSURE PSIA



GRAPH 3

RATIO OF SPECIFIC HEATS

AMMONIA

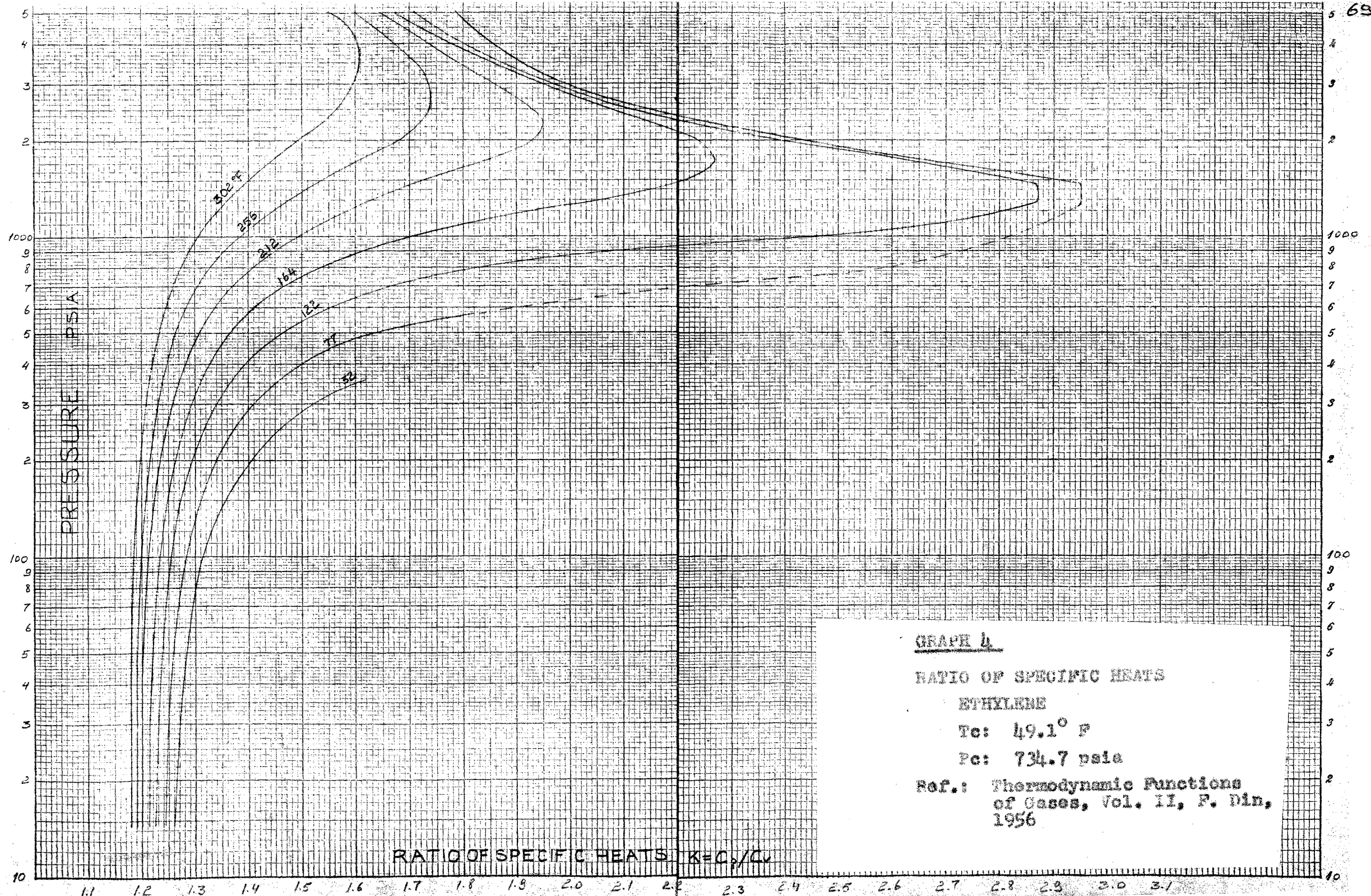
Tc: 270.4° F

Pc: 1639 psia

Ref.: Thermodynamic Functions
of Gases, Vol. I, F. Din,
1956

RATIO OF SPECIFIC HEATS $K = C_p/C_v$

1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5



GRAPH 4

RATIO OF SPECIFIC HEATS

ETHYLENE

T_c : 49.1° F

P_c : 734.7 psia

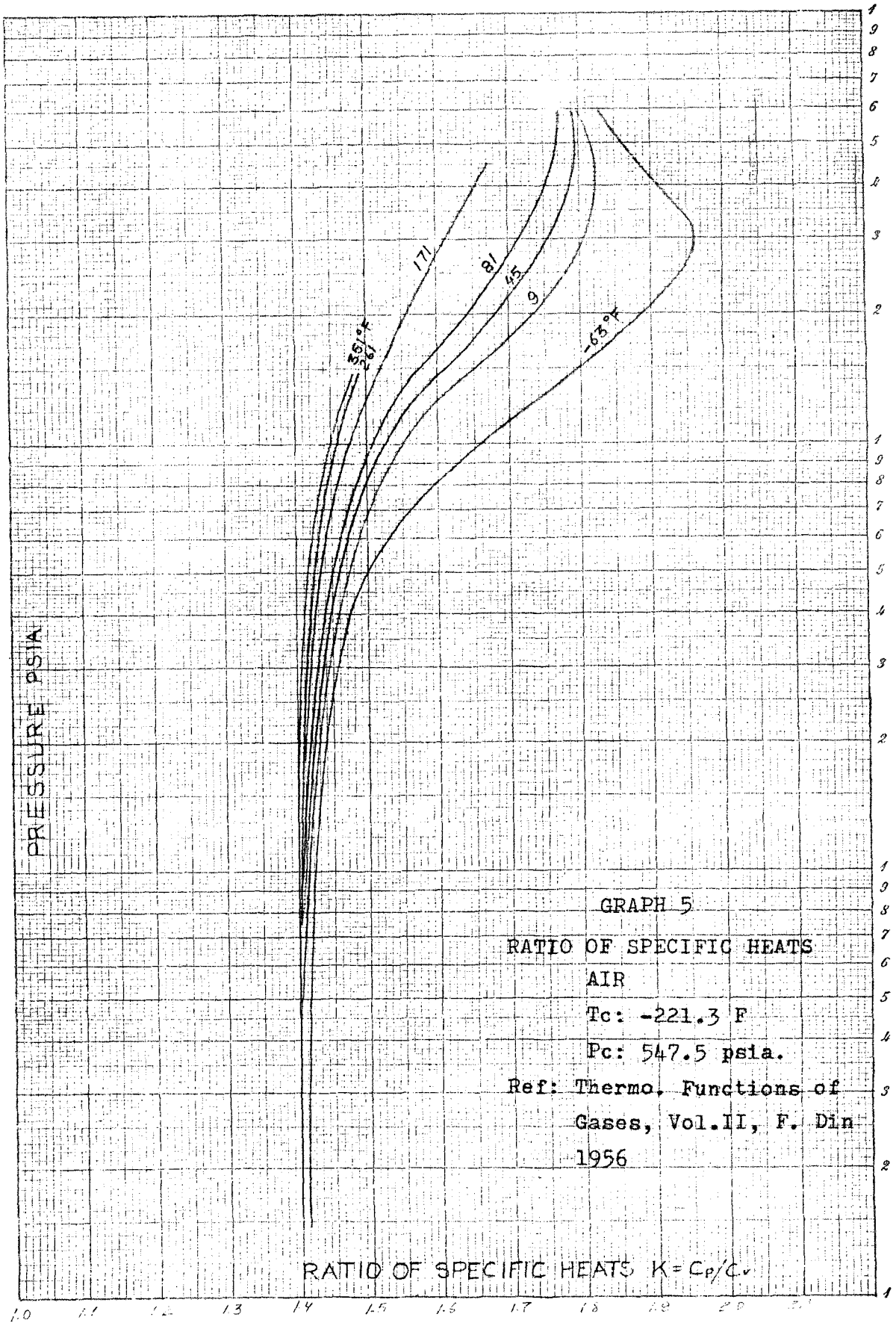
Ref.: Thermodynamic Functions
of Gases, Vol. II, P. Din,
1956

5 69
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3
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1000
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4
3
2
100
9
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7
6
5
4
3
2
10

RATIO OF SPECIFIC HEATS $K=C_p/C_v$

1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1



GRAPH 5

RATIO OF SPECIFIC HEATS

AIR

Tc: -221.3 F

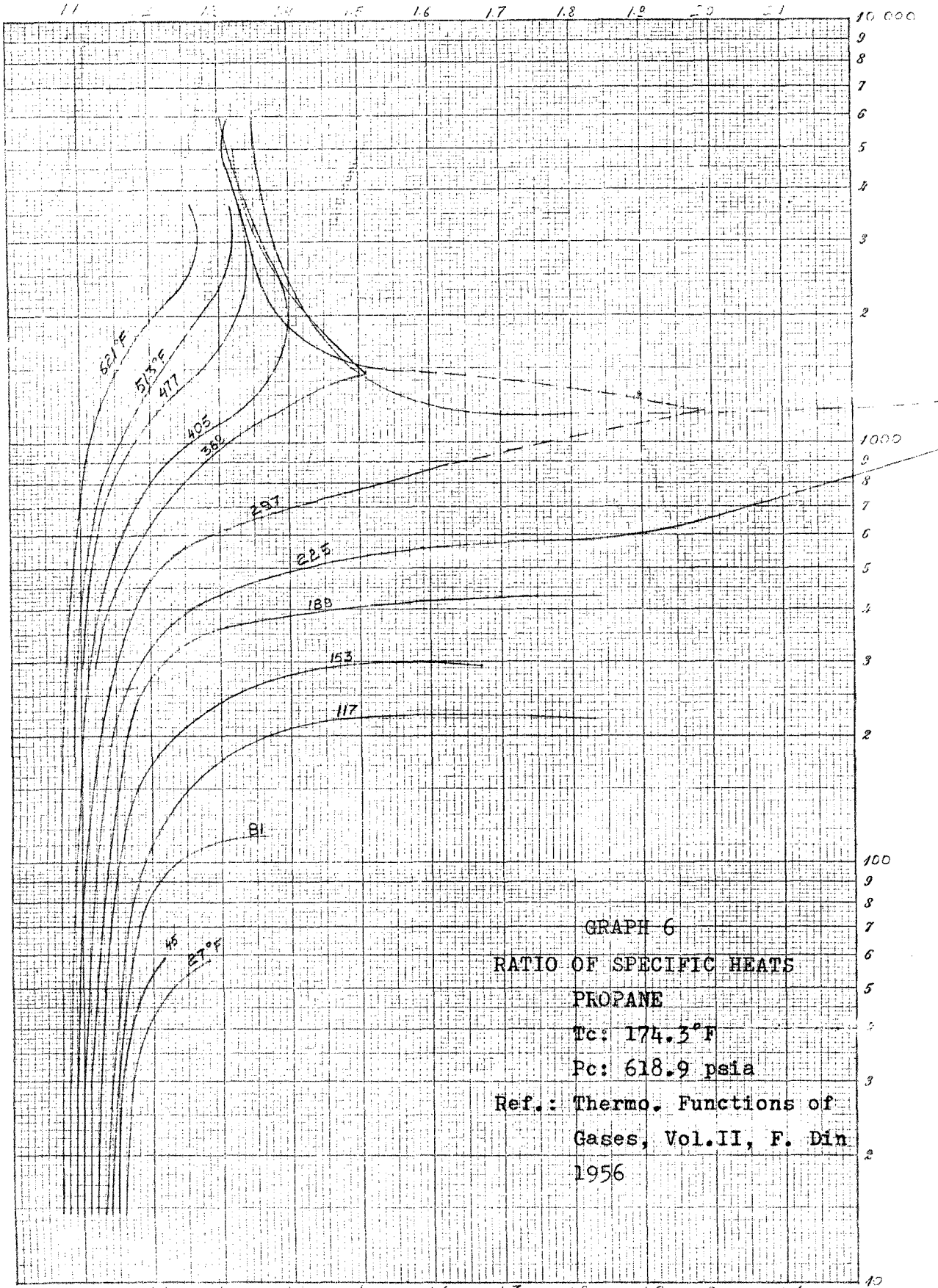
Pc: 547.5 psia.

Ref: Thermo. Functions of
Gases, Vol. II, F. Din
1956

RATIO OF SPECIFIC HEATS $K = C_p/C_v$

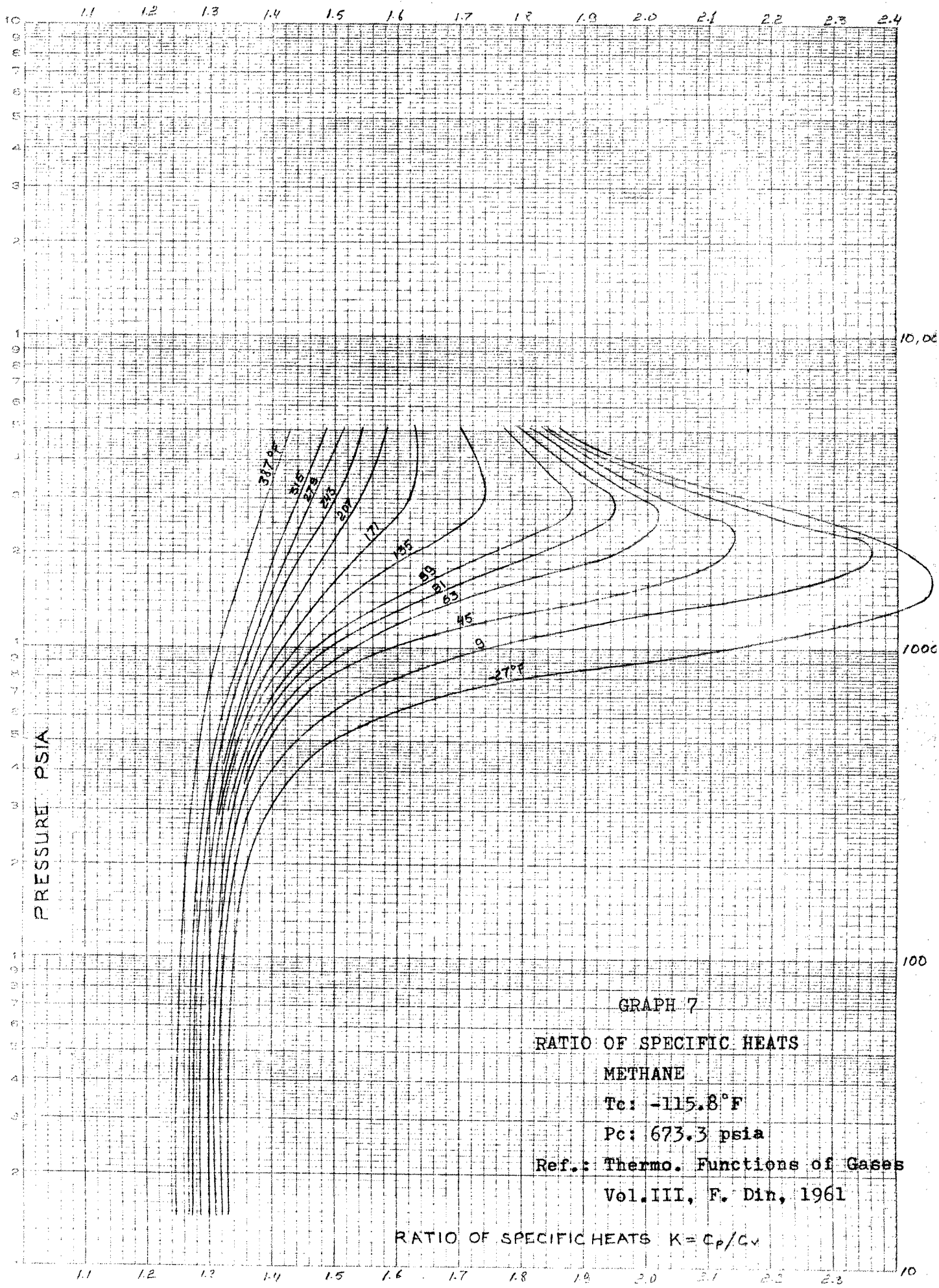
1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1

PRESSURE PSIA



GRAPH 6
RATIO OF SPECIFIC HEATS
PROPANE
Tc: 174.3°F
Pc: 618.9 psia
Ref.: Thermo. Functions of
Gases, Vol. II, F. Din
1956

RATIO OF SPECIFIC HEATS $K = C_p/C_v$



GRAPH 7

RATIO OF SPECIFIC HEATS

METHANE

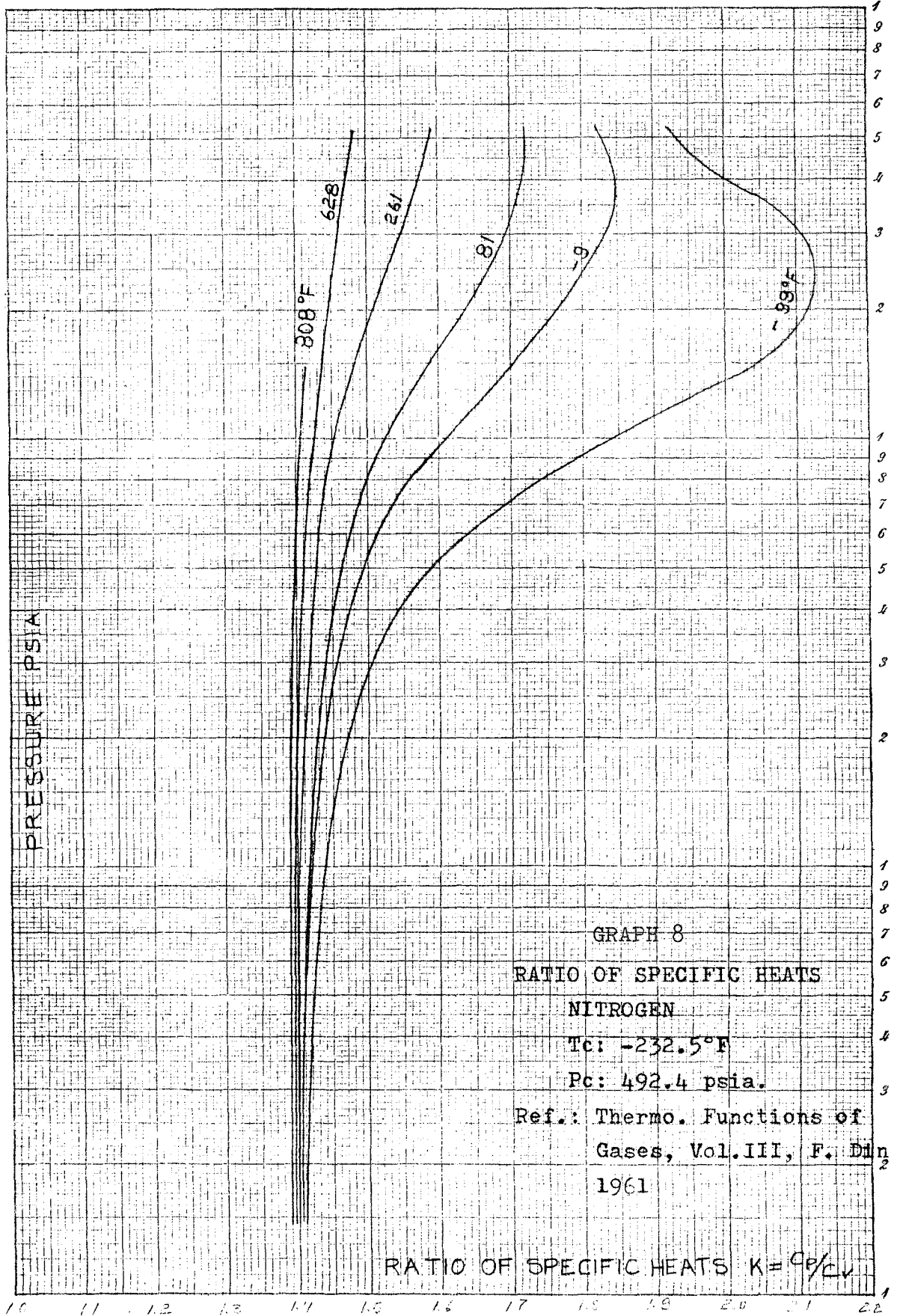
$T_c: -115.8^\circ\text{F}$

$P_c: 673.3 \text{ psia}$

Ref.: Thermo. Functions of Gases

Vol. III, F. Din, 1961

RATIO OF SPECIFIC HEATS $K = C_p/C_v$



GRAPH 8

RATIO OF SPECIFIC HEATS

NITROGEN

Tc: -232.5°F

Pc: 492.4 psia.

Ref.: Thermo. Functions of
Gases, Vol. III, F. Din
1961

RATIO OF SPECIFIC HEATS $K = \frac{C_p}{C_v}$

APPENDIX

ETHANE - TABLE 1

Pressure (Atm.)	Pressure (Psia.)	TEMPERATURE ° F								
		27			81			117		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	11.92	9.84	1.21	12.75	10.70	1.192	13.33	11.29	1.18
4	58.8	12.58	10.04	1.25	13.12	10.81	1.215	13.62	11.36	1.20
10	147	13.84	10.46	1.325	13.92	11.03	1.26	14.21	11.49	1.24
20	294				15.87			15.56	11.71	1.33
30	441				19.68			17.61	11.94	1.475
40	588							21.48	12.19	1.77
50	735							34.27		
60	882									
80	1176							39.32		
100	1470							29.50		
150	2205							23.30	12.57	1.855
200	2940							21.38	12.24	1.745
250	3675							20.41	12.08	1.69
300	4410							19.79	12.23	1.62
350	5145							19.37	12.46	1.56

Cp: Specific heat at constant pressure, Cal./Mole, °K.
 Cv: Specific heat at constant volume, Cal./Mole, °K.
 K: Cp/Cv, ratio of specific heats.

TABLE 1: The ratio of isobaric to isometric specific heats of Ethane.
 Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. III, p. 207.

ETHANE - TABLE 1

Pressure (Psia.)	TEMPERATURE ° F								
	135			153			171		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	13.62	11.58	1.175	13.91	11.88	1.17	14.21	12.18	1.168
58.8	13.89	11.64	1.19	14.14	11.93	1.185	14.42	12.22	1.22
147	14.40	11.75	1.225	14.61	12.03	1.215	14.83	12.32	1.205
294	15.57	12.01	1.295	15.61	12.28	1.27	15.70	12.54	1.25
441	17.17	12.24	1.40	16.92	12.51	1.35	16.79	12.76	1.32
588	19.73	12.45	1.585	18.8	12.70	1.48	18.26	12.94	1.41
735	24.92	12.63	1.965	21.96	12.86	1.705	20.5	13.10	1.53
882	38.40	12.77	3.01	27.54	13.0	2.12	23.74	13.24	1.79
1176	43.64			39.76	13.19	3.01	32.95	13.42	2.455
1470	32.92			34.76	13.26	2.62	33.89	13.48	2.515
2205	24.40	12.83	1.90	25.58	13.10	1.95	26.50	13.38	1.98
2940	21.95	12.50	1.755	22.56	12.78	1.765	23.17	13.08	1.775
3675	20.76	12.34	1.68	21.17	12.51	1.69	21.62	12.79	1.69
4410	20.06	12.44	1.61	20.37	12.61	1.615	20.71	12.77	1.62
5145	19.57	12.63	1.55	19.82	12.75	1.555	20.11	12.82	1.57

ETHANE - TABLE 1

TEMPERATURE ° F

Pressure (Psia.)	189			225			261		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	14.5	12.49	1.16	15.11	13.10	1.15	15.72	13.7	1.15
58.8	14.69	12.53	1.17	15.26	13.13	1.16	15.85	13.73	1.155
147	15.06	12.61	1.195	15.57	13.2	1.18	16.10	13.79	1.167
294	15.84	12.79	1.24	16.16	13.36	1.21	16.56	13.94	1.19
441	16.75	13.0	1.29	16.86	13.53	1.245	17.11	14.09	1.215
588	17.97	13.19	1.36	17.73	13.69	1.295	17.77	14.22	1.25
735	19.65	13.35	1.47	18.79	13.84	1.36	18.54	14.33	1.295
882	21.92	13.48	1.625	20.07	13.95	1.44	19.40	14.43	1.345
1176	27.99	13.65	2.05	23.34	14.13	1.65	21.40	14.61	1.465
1470	31.40	13.72	2.29	26.44	14.22	1.86	23.48	14.73	1.595
2205	27.05	13.68	1.98	26.84	14.28	1.88	25.69	14.83	1.735
2940	23.75	13.41	1.77	24.62	14.14	1.74	24.75	14.83	1.67
3675	22.08	13.1	1.69	22.96	13.89	1.65	23.53	14.73	1.595
4410	21.08	12.97	1.63	21.87	13.70	1.60	22.56	14.56	1.55
5145	20.44	12.98	1.575	21.15	13.63	1.55	21.86	14.44	1.515

ETHANE - TABLE 1

Pressure (Psia.)	TEMPERATURE ° F								
	297			333			441		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	16.32	14.31	1.14	16.91	14.9	1.135	18.66	16.67	1.12
58.8	16.43	14.34	1.145	17.0	14.92	1.14	18.73	16.69	1.12
147	16.63	14.39	1.55	17.18	14.97	1.15	18.85	16.73	1.125
294	17.03	14.51	1.175	17.51	15.07	1.16	19.06	16.8	1.135
441	17.47	14.63	1.19	17.88	15.17	1.18	19.27	16.87	1.145
488	17.97	14.74	1.22	18.28	15.27	1.195	19.52	16.94	1.15
735	18.55	14.84	1.25	18.74	15.35	1.22	19.79	17.01	1.165
882	19.18	14.92	1.285	19.22	15.42	1.25	20.06	17.07	1.175
1176	20.59	15.09	1.365	20.28	15.56	1.305	20.60	17.17	1.20
1470	22.09	15.20	1.455	21.40	15.65	1.37	21.18	17.22	1.23
2205	24.44	15.34	1.595	23.47	15.81	1.49	22.45	17.31	1.30
2940	24.50	15.40	1.59	24.05	15.57	1.515	23.22	17.38	1.335
3675	23.71	15.35	1.545	23.75	15.87	1.50	23.51	17.43	1.35
4410	23.02	15.26	1.51	23.29	15.83	1.47	23.57	17.47	1.35
5145	22.44	15.16	1.48	22.85	15.79	1.45	23.52	17.51	1.34

CARBON DIOXIDE - TABLE 2

Pressure (Atm.)	Pressure (Psia.)	TEMPERATURE ° F								
		-58			68			104		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	.194	.134	1.45	.204	.155	1.315	.208	.160	1.30
3	44.1	.211	.144	1.465	.209	.157	1.33	.211	.162	1.305
5	73.5	.230	.154	1.49	.215	.160	1.345	.216	.164	1.32
10	147				.230	.168	1.37	.228	.169	1.35
20	294				.266	.182	1.46	.254	.177	1.435
30	441				.314	.197	1.595	.284	.188	1.51
40	588				.428	.215	1.99	.316	.199	1.59
60	882							.437		
80	1176									
100	1470									
150	2205							.772	.247	3.12
200	2940							.670	.243	2.76
300	4410							.560	.242	2.32
400	5880							.514	.241	2.14

Cp: Specific heat at constant pressure, Kilocalories/Kilogramms, °C.
 Cv: Specific heat at constant volume, Kilocalories/Kilogramms, °C.
 K: Cp/Cv, ratio of specific heats.

TABLE 2: The ratio of isobaric to isometric specific heats of Carbon Dioxide.
 Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. I, p. 124.

CARBON DIOXIDE - TABLE 2

Pressure (Psia.)	TEMPERATURE ° F								
	122			158			194		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	.210	.162	1.30	.214	.167	1.28	.218	.171	1.275
44.1	.213	.164	1.30	.216	.168	1.29	.220	.172	1.28
73.5	.217	.166	1.31	.220	.169	1.30	.222	.173	1.28
147	.227	.169	1.345	.227	.171	1.33	.228	.175	1.30
294	.249	.176	1.415	.244	.176	1.39	.241	.178	1.355
441	.275	.184	1.84	.264	.181	1.46	.256	.182	1.41
588	.301	.193	1.56	.283	.186	1.52	.271	.185	1.465
882	.370	.210	1.76	.328	.195	1.68	.304	.192	1.585
1176	.527	.230	2.30	.405	.207	1.96	.351	.198	1.77
1470		.255		.550	.219	2.51	.423	.204	2.07
2205	.768	.239	3.22	.692	.224	3.09	.592	.215	2.76
2940	.656	.236	2.78	.587	.225	2.61	.527	.217	2.43
4410	.542	.234	2.32	.486	.220	2.21	.462	.214	2.14
5880	.496	.233	2.13	.444	.221	2.01	.428	.213	2.00

CARBON DIOXIDE - TABLE 2

Pressure (Psia.)	TEMPERATURE °F								
	230			266			302		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	.221	.175	1.265	.225	.179	1.255	.229	.183	1.25
44.1	.223	.176	1.27	.227	.180	1.26	.230	.183	1.253
73.5	.225	.176	1.28	.228	.180	1.27	.231	.184	1.256
147	.229	.177	1.29	.231	.181	1.28	.234	.185	1.267
294	.239	.180	1.33	.240	.183	1.31	.242	.186	1.30
441	.250	.182	1.375	.246	.185	1.33	.246	.188	1.31
588	.261	.181	1.41	.253	.187	1.35	.250	.189	1.32
882	.286	.190	1.505	.272	.191	1.425	.261	.192	1.36
1176	.320	.194	1.65	.298	.193	1.545	.278	.193	1.44
1470	.363	.199	1.825	.328	.196	1.675	.306	.194	1.58
2205	.483	.209	2.31	.401	.203	1.975	.367	.200	1.835
2940	.493	.211	2.34	.471	.207	2.28	.457	.204	2.24
4410	.457	.210	2.18	.459	.207	2.22	.467	.205	2.28
5880	.428	.209	2.05	.435	.206	2.11	.450	.205	2.20

AMMONIA - TABLE 3

Pressure (Atm.)	Pressure (Psia.)	<u>TEMPERATURE °F</u>								
		117			189			225		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	8.832	6.76	1.305	9.037	7.0	1.29	9.169	7.14	1.285
5	73.5	9.7	7.31	1.325	9.5	7.27	1.305	9.5	7.32	1.30
10	147	11.3	8.01	1.41	10.2	7.6	1.34	10.1	7.56	1.335
20	294				11.3	8.32	1.43	11.2	8.07	1.395
40	588				17.9	10.6	1.69	14.8	9.22	1.605
60	882							22.8	11.2	2.015

Cp: Specific heat at constant pressure, Calories/Mole, °K.

Cv: Specific heat at constant volume, Calories/Mole, °K.

K: Cp/Cv, ratio of specific heats

TABLE 3: Theratio of isobaric to isometric specific heats of Ammonia.
Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. I, p. 96

AMMONIA - TABLE 3

Pressure (Psia.)	TEMPERATURE ° F								
	261			297			333		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	9.3	7.28	1.28	9.45	7.43	1.27	9.6	7.58	1.265
73.5	9.6	7.42	1.295	9.7	7.54	1.285	9.8	7.67	1.28
147	10.0	7.60	1.315	10	7.68	1.30	10	7.78	1.285
294	10.8	7.96	1.355	10.7	7.96	1.345	10.6	8	1.325
588	13.2	8.81	1.50	12.4	8.55	1.45	11.8	8.44	1.40
882	17.3	10.0	1.73	14.9	9.2	1.62	13.4	8.9	1.505
1176	27.4	11.8	2.33	18.8	10	1.88	15.6	9.4	1.66
1323	45.	13.6	3.31	21.5	10.5	2.05	17.1	9.7	1.765
1470	133	19.9	6.68	25.1	11.2	2.24	18.8	9.9	1.90
1764				35	12.8	2.74	23	11.1	2.07
2352				51.5	14.4	3.58	43.3	13.7	3.16
2940				32.9	12.4	2.65	44.2	12.8	3.45
3528				27.3	12.1	2.26	33.8	12.5	2.70
4410				23.7	11.9	1.99	27.2	12.3	2.21
4998				22.7	11.8	1.925	25.1	12.2	2.06

AMMONIA - TABLE 3

Pressure (Psia.)	<u>TEMPERATURE ° F</u>											
	369			405			477			585		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	9.74	7.73	1.26	9.88	7.88	1.25	10.2	8.19	1.245	10.63	8.64	1.23
73.5	9.9	7.81	1.27	10	7.95	1.255	10.3	8.26	1.247	10.8	8.70	1.24
147	10.1	7.9	1.28	10.2	8.03	1.27	10.5	8.34	1.26	10.9	8.77	1.24
294	10.6	8.09	1.31	10.6	8.19	1.295	10.8	8.48	1.275	11.1	8.90	1.24
588	11.5	8.43	1.365	11.4	8.49	1.345	11.4	8.72	1.31	11.4	9.08	1.25
882	12.6	8.8	1.435	12.3	8.8	1.40	12.0	8.9	1.35	11.7	9.2	1.27
1176	14.1	9.2	1.535	13.4	9.1	1.47	12.7	9.1	1.395	12.0	9.2	1.30
1323	15.0	9.4	1.595	14	9.3	1.505	13	9.2	1.415	12.2	9.2	1.32
1470	16.1	9.6	1.68	14.7	9.5	1.55	13.4	9.3	1.44	12.3	9.2	1.34
1764	18.8	10.4	1.805	16.3	10	1.63	14.1	9.4	1.50			
2352	28.2	11.9	2.37	21.2	10.8	1.965	15.6	9.6	1.63			
2940	40.3	12.5	3.22	26	11.4	2.28	17.3	9.6	1.80			
3528	39.1	12.4	3.15	30.2	11.7	2.58	19.3	9.7	2.01			
4410	30.7	12.3	2.49	29.7	11.9	2.50	22.4	9.8	2.28			
4998	27.2	12.2	2.245	27.5	11.8	2.35	22.7	9.7	2.34			

ETHYLENE - TABLE 4

TEMPERATURE °F

Pressure (Bars)	Pressure (Psia.)	32			77			122		
		Cp	Cv	k	Cp	Cv	k	Cp	Cv	k
0	0	1.461	1.167	1.252	1.539	1.244	1.235	1.621	1.327	1.221
1	14.5	1.472	1.168	1.26	1.549	1.245	1.243	1.629	1.328	1.225
5	72.5	1.521	1.174	1.296	1.588	1.251	1.265	1.662	1.334	1.246
10	145.0	1.594	1.185	1.345	1.644	1.261	1.303	1.707	1.344	1.27
20	290.0	1.82	1.216	1.50	1.800	1.286	1.40	1.819	1.367	1.332
30	435.0				2.034	1.320	1.54	1.964	1.394	1.41
40	580.0				2.48	1.367	1.815	2.169	1.423	1.53
50	725.0					1.438		2.461	1.458	1.69
60	870.0					1.530		2.95	1.500	1.965
70	1015					1.559		3.8	1.543	2.46
80	1160				5.4			4.3	1.582	2.72
90	1305				4.7			4.6	1.6011	2.87
100	1450				4.1	1.39	2.95	4.6	1.603	2.87
120	1740				3.43	1.36	2.52	4.1	1.582	2.59
140	2030				3.13	1.35	2.32	3.71	1.565	2.37
160	2320				2.92	1.344	2.17	3.43	1.554	2.21
200	2990				2.70	1.341	2.01	3.071	1.545	1.99
250	3625				2.54	1.339	1.895	2.853	1.543	1.85
300	4350				2.45	1.339	1.83	2.726	1.544	1.77
350	5075				2.39	1.340	1.78	2.644	1.548	1.71

Cp: Specific heat at constant pressure, Joules/Gramme, °C

Cv: Specific heat at constant volume, Joules/Gramme, °C

K: Cp/Cv, ratio of specific heats

TABLE 4: The ratio of isobaric to isometric specific heats of Ethylene.

Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. II, p. 113.

ETHYLENE - TABLE 4

TEMPERATURE ° F

Pressure (Psia.)	164			212			256		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
0	1.706	1.412	1.21	1.793	1.499	1.20	1.881	1.587	1.19
14.5	1.713	1.413	1.21	1.798	1.500	1.20	1.886	1.588	1.19
72.5	1.740	1.419	1.226	1.821	1.505	1.21	1.906	1.594	1.195
145.0	1.776	1.427	1.245	1.851	1.512	1.225	1.933	1.603	1.205
290.0	1.859	1.446	1.285	1.914	1.527	1.253	1.988	1.618	1.23
435.0	1.960	1.468	1.336	1.985	1.542	1.29	2.045	1.634	1.25
580.0	2.079	1.489	1.395	2.066	1.557	1.318	2.106	1.648	1.28
725.0	2.228	1.511	1.474	2.156	1.571	1.378	2.175	1.661	1.31
870.0	2.417	1.534	1.572	2.260	1.585	1.425	2.247	1.672	1.345
1015	2.640	1.557	1.70	2.378	1.598	1.49	2.324	1.681	1.38
1160	2.921	1.579	1.852	2.508	1.610	1.56	2.406	1.689	1.425
1305	3.23	1.600	2.02	2.648	1.621	1.635	2.494	1.696	1.47
1450	3.52	1.615	2.18	2.798	1.632	1.715	2.590	1.702	1.52
1740	3.704	1.630	2.27	3.047	1.650	1.85	2.760	1.713	1.61
2030	3.630	1.628	2.23	3.212	1.660	1.945	2.889	1.721	1.68
2320	3.469	1.622	2.14	3.240	1.662	1.95	2.976	1.726	1.723
2990	3.172	1.615	1.965	3.129	1.663	1.88	3.010	1.731	1.74
3625	2.937	1.614	1.82	2.956	1.662	1.78	2.942	1.732	1.70
4350	2.796	1.615	1.73	2.829	1.663	1.70	2.854	1.733	1.65
5075	2.703	1.619	1.674	2.738	1.666	1.643	2.775	1.735	1.60

ETHYLENE - TABLE 4TEMPERATURE ° F

<u>Pressure</u> <u>(Psia.)</u>	<u>302</u>		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>
0	1.969	1.675	1.175
14.5	1.974	1.676	1.18
72.5	1.995	1.684	1.185
145.0	2.021	1.695	1.19
290.0	2.074	1.716	1.205
435.0	2.130	1.739	1.225
580.0	2.190	1.761	1.24
725.0	2.24	1.779	1.26
870.0	2.29	1.792	1.28
1014	2.35	1.803	1.30
1160	2.41	1.812	1.33
1305	2.46	1.818	1.355
1450	2.52	1.822	1.385
1740	2.63	1.827	1.44
2030	2.73	1.828	1.495
2320	2.82	1.829	1.54
2990	2.92	1.83	1.60
3625	2.94	1.83	1.61
4350	2.89	1.83	1.58
5075	2.83	1.83	1.545

AIR - TABLE 5

		<u>TEMPERATURE ° F</u>								
<u>Pressure (Atm.)</u>	<u>Pressure (Psia.)</u>	<u>-63</u>			<u>9</u>			<u>45</u>		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	29.26	20.7	1.41	29.12	20.8	1.40	29.11	20.8	1.40
10	147	30.14	21.1	1.43	29.72	20.9	1.42	29.61	20.9	1.42
20	294	31.23	21.5	1.455	30.41	21.1	1.44	30.19	21.1	1.43
30	441	32.38	21.8	1.48	31.12	21.3	1.46	30.76	21.2	1.45
40	588	33.61	22.0	1.53	31.83	21.5	1.48	31.34	21.4	1.465
50	735	34.93	22.2	1.57	32.55	21.7	1.50	31.91	21.5	1.48
60	882	36.32	22.4	1.62	33.3	21.8	1.53	32.5	21.6	1.50
80	1176	39.09	22.8	1.71	34.85	22.0	1.58	33.72	21.8	1.55
100	1470	41.63	23.1	1.80	36.37	22.2	1.64	34.98	21.9	1.60
150	2205		23.5			22.6			22.2	
200	2940	46.8	23.9	1.96	41.05	22.8	1.80	39.18	22.4	1.75
250	3675	46.8	24.1	1.94	41.93	23.0	1.82	40.18	22.6	1.78
300	4410	46.2	24.3	1.90	42.19	23.2	1.82	40.69	22.8	1.79
400	5880	44.63	24.5	1.83	42.00	23.4	1.80	40.94	23.0	1.79

Cp: Specific heat at constant pressure, Joules/mole, °K
 Cv: Specific heat at constant volume, Joules/mole, °K
 K: Cp/Cv, ratio of specific heats

TABLE 5: The ratio of isobaric to isometric specific heats of Air.
 Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. II, p. 43.

AIR - TABLE 5

TEMPERATURE ° F

Pressure (Psia.)	81			261			351		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	29.13	20.8	1.40	29.28	20.9	1.40	29.36	21.0	1.40
147	29.54	20.9	1.41	29.50	20.9	1.41	29.54	21.0	1.40
294	30.02	21.0	1.43	29.75	21.0	1.42	29.76	21.1	1.41
441	30.51	21.1	1.45	30.00	21.0	1.43	29.97	21.1	1.42
588	30.99	21.2	1.46	30.25	21.1	1.43	30.18	21.2	1.42
735	31.47	21.3	1.48	30.49	21.2	1.44	30.38	21.2	1.43
882	31.95	21.4	1.49	30.72	21.2	1.45	30.58	21.2	1.44
1176	32.94	21.5	1.53	31.18	21.3	1.464	30.97	21.2	1.46
1470	33.94	21.6	1.57	31.64	21.3	1.49	31.32	21.2	1.48
2205		21.8							
2940	37.61	22.0	1.71						
3675	38.66	22.2	1.74						
4410	39.37	22.4	1.76						
5880	39.98	22.6	1.77						

PROPANE - TABLE 6

<u>Pressure</u> <u>(Atm.)</u>	<u>Pressure</u> <u>(Psia.)</u>	<u>TEMPERATURE ° F</u>								
		<u>27</u>			<u>81</u>			<u>117</u>		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	16.4	14.1	1.16	17.7	15.5	1.14	18.7	16.5	1.13
6	88.2				19.6	16.4	1.195	19.9	17.0	1.17
10								22.0	17.7	1.24

Cp: Specific heat at constant pressure, Calories/Mole, °K.

Cv: Specific heat at constant volume, Calories/Mole, °K.

K: Cp/Cv, ratio of specific heats

TABLE 6: The ratio of isobaric to isometric specific heats of Propane.

Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. II, p. 132.

PROPANE - TABLE 6

TEMPERATURE ° F

Pressure (Atm.)	Pressure (Psia.)	153			189			225		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	19.6	17.5	1.12	20.5	18.5	1.11	21.5	19.5	1.10
6	88.2	20.4	17.7	1.15	21.2	18.7	1.35	22.0	19.6	1.12
10	147.0	21.3	18.2	1.17	21.7	18.9	1.15	22.4	19.8	1.13
20	294.0	32.6	19.5	1.67	23.9	19.7	1.21	23.9	20.2	1.18
30	441				38.0	20.7	1.84	27.1	20.7	1.31
40	588							40.0	21.3	1.88
50	735									
60	882									
80	1176							40.6	24.1	1.68
100	1470							36.7	24.6	1.49
150	2205							32.3	23.9	1.41
200	2940							30.7	22.3	1.38
250	3675							29.7	21.7	1.37
300	4410							28.9	21.3	1.36
400	5880							28.1	20.8	1.35

PROPANE - TABLE 6

Pressure (Psia.)	TEMPERATURE ° F								
	297			369			405		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	23.5	21.5	1.09	25.5	23.5	1.085	26.4	24.4	1.08
88.2	23.9	21.5	1.11	25.7	23.5	1.093	26.6	24.4	1.09
147.0	24.1	21.6	1.115	25.9	23.5	1.10	26.8	24.4	1.10
204.0	24.9	21.8	1.14	26.4	23.6	1.12	27.2	24.5	1.11
441	26.1	21.9	1.19	27.2	23.7	1.15	27.8	24.5	1.135
588	28.3	22.2	1.275	28.2	23.8	1.185	28.5	24.7	1.155
735	32.5	22.5	1.445	29.4	24.0	1.225	29.3	24.8	1.18
882	37.2	22.9	1.625	30.8	24.2	1.27	30.4	25.0	1.215
1176				34.3	24.8	1.38	33.5	25.4	1.32
1470	41.3	26.2	1.58	38.6	25.5	1.51	36.8	25.9	1.38
2205	35.4	25.9	1.365	37.2	26.6	1.40	37.4	26.7	1.40
2940	33.0	24.4	1.35	35.0	25.8	1.36	35.7	26.2	1.36
3675	31.7	23.7	1.34	33.5	25.0	1.34	34.3	25.6	1.34
4410	30.8	23.3	1.32	32.6	24.6	1.325	33.5	25.3	1.325
5880	30.0	22.8	1.315	31.8	24.3	1.31	32.6	25.0	1.30

PROPANE - TABLE 6

Pressure (Psia.)	TEMPERATURE ° F								
	477			513			621		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	28.1	26.1	1.075	28.8	26.9	1.075	30.7	28.7	1.07
88.2	28.3	26.1	1.085	29.0	26.9	1.08	30.8	28.7	1.07
147.0	28.5	26.1	1.092	29.1	26.9	1.08	30.9	28.8	1.07
204.0	28.8	26.2	1.10	29.4	27.0	1.09	31.1	28.8	1.08
441	29.1	26.2	1.11	29.7	27.0	1.10	31.3	28.9	1.085
588	29.5	26.3	1.12	30.1	27.0	1.115	31.5	28.9	1.09
735	30.0	26.4	1.135	30.5	27.1	1.125	31.7	28.9	1.10
882	30.6	26.5	1.155	30.9	27.2	1.135	31.9	28.9	1.105
1176	32.6	26.7	1.22	32.4	27.3	1.19	32.4	28.9	1.12
1470	34.3	27.0	1.27	33.7	27.5	1.225	33.1	28.8	1.15
2205	36.2	27.1	1.335	35.6	27.4	1.30	34.8	28.3	1.23
2940	36.0	26.9	1.34	35.9	27.2	1.32	35.2	27.7	1.27
3675	35.2	26.3	1.34	35.1	26.6	1.32	34.5	27.3	1.26
4410									
5880									

METHANE - TABLE 7

TEMPERATURE ° F

Pressure (Atm.)	Pressure (Psia)	9			45			63		
		Cp	Cv	k	Cp	Cv	k	Cp	Cv	k
1	14.7	8.3	6.3	1.32	8.43	6.43	1.31	8.51	6.5	1.31
5	73.5	8.36	6.34	1.32	8.50	6.47	1.315	8.58	6.54	1.31
10	147	8.47	6.38	1.33	8.61	6.50	1.325	8.68	6.57	1.32
20	294	8.77	6.46	1.36	8.85	6.57	1.35	8.9	6.63	1.325
40	588	9.67	6.56	1.475	9.41	6.66	1.415	9.37	6.71	1.40
50	735	10.30	6.61	1.56	9.80	6.70	1.46	9.69	6.75	1.44
60	882	11.03	6.64	1.66	10.27	6.73	1.525	10.06	6.78	1.48
80	1176	12.62	6.68	1.89	11.30	6.77	1.70	10.87	6.82	1.59
100	1470	14.13	6.72	2.11	12.34	6.81	1.815	11.74	6.86	1.71
140	2058	16.05	6.78	2.36	14.65	6.88	2.13	13.60	6.93	1.965
180	2646	14.93	6.83	2.19	14.53	6.94	2.095	14.14	6.99	2.02
200	2940	14.44	6.86	2.10	14.19	6.97	2.035	13.99	7.02	1.99
250	3675	13.73	6.91	1.99	13.64	7.02	1.945	13.55	7.07	1.915
300	4410	13.24	6.95	1.905	13.24	7.08	1.875	13.21	7.12	1.855
350	5145	12.88	6.98	1.84	12.94	7.10	1.825	12.95	7.16	1.81

Cp: Specific heat at constant pressure, Cal./Mole, °K.

Cv: Specific heat at constant volume, Cal./Mole, °K.

K: Cp/Cv, ratio of specific heats.

TABLE 7: The ratio of isobaric to isometric specific heats of Methane.

Ref.: "Thermodynamic Functions of Gases," F. Din. Vol. III, p. 52

METHANE - TABLE 7

TEMPERATURE °F

Pressure (Psia)	81			99			135		
	<u>CV</u>	<u>CV</u>	<u>K</u>	<u>CV</u>	<u>CV</u>	<u>K</u>	<u>CV</u>	<u>CV</u>	<u>K</u>
14.7	8.59	6.58	1.305	8.68	6.66	1.305	8.87	6.83	1.30
73.5	8.66	6.61	1.31	8.75	6.69	1.305	8.94	6.85	1.305
147	8.75	6.64	1.32	8.84	6.72	1.315	9.03	6.87	1.315
294	8.95	6.7	1.335	9.03	6.77	1.33	9.22	6.92	1.335
588	9.40	6.78	1.385	9.46	6.85	1.38	9.6	7.0	1.37
735	9.66	6.81	1.42	9.68	6.88	1.41	9.8	7.03	1.39
882	9.95	6.84	1.455	9.93	6.90	1.44	9.99	7.05	1.42
1176	10.59	6.88	1.54	10.48	6.94	1.51	10.39	7.09	1.465
1470	11.32	6.91	1.64	11.04	6.97	1.585	10.81	7.12	1.52
2058	12.81	6.98	1.835	12.38	7.04	1.76	11.71	7.19	1.63
2646	13.65	7.04	1.94	13.24	7.10	1.87	12.41	7.25	1.71
2940	13.73	7.07	1.945	13.42	7.13	1.88	12.65	7.28	1.74
3675	13.43	7.13	1.89	13.23	7.20	1.84	12.7	7.35	1.73
4410	13.16	7.18	1.84	13.06	7.25	1.80	12.7	7.41	1.715
5145	12.96	7.23	1.79	12.91	7.30	1.77	12.68	7.46	1.70

METHANE - TABLE 7

TEMPERATURE ° F

Pressure (Psia)	315			387		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	10.14	8.02	1.265	10.73	8.61	1.25
73.5	10.21	8.04	1.27	10.78	8.62	1.25
147	10.28	8.05	1.275	10.84	8.63	1.26
294	10.43	8.07	1.295	10.95	8.65	1.27
588	10.70	8.11	1.32	11.16	8.68	1.285
735	10.81	8.12	1.33	11.27	8.69	1.30
882	10.92	8.13	1.345	11.37	8.70	1.305
1176	11.11	8.16	1.36	11.55	8.72	1.325
1470	11.27	8.18	1.38	11.70	8.74	1.34
2058	11.55	8.22	1.405	11.96	8.78	1.36
2646	11.94	8.29	1.44	12.29	8.84	1.39
2940	12.22	8.34	1.47	12.51	8.88	1.41
3675	12.40	8.39	1.48	12.69	8.93	1.42
4410	12.53	8.44	1.485	12.82	8.97	1.43
5145						

METHANE - TABLE 7

Pressure (PSia)	TEMPERATURE ° F								
	171			207			243		
	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
14.7	9.1	7.03	1.295	9.34	7.26	1.29	9.6	7.5	1.28
73.5	9.17	7.05	1.30	9.41	7.28	1.295	9.67	7.52	1.285
147	9.25	7.07	1.31	9.49	7.29	1.30	9.75	7.53	1.295
294	9.43	7.11	1.325	9.66	7.32	1.32	9.91	7.55	1.31
588	9.75	7.17	1.36	9.97	7.38	1.35	10.22	7.61	1.34
735	9.95	7.20	1.38	10.12	7.41	1.37	10.35	7.63	1.355
882	10.11	7.22	1.40	10.26	7.43	1.38	10.47	7.65	1.37
1176	10.43	7.26	1.44	10.53	7.45	1.415	10.7	7.67	1.395
1470	10.75	7.29	1.475	10.78	7.48	1.44	10.9	7.7	1.415
2058	11.35	7.36	1.54	11.20	7.55	1.485	11.24	7.76	1.45
2940	11.85	7.42	1.60	11.78	7.64	1.54	11.73	7.83	1.50
3675	12.05	7.45	1.62	12.0	6.69	1.56	11.97	7.88	1.52
4410	12.24	7.52	1.63	12.21	7.75	1.575	12.18	7.94	1.53
5145	12.37	7.58	1.63	12.37	7.81	1.585	12.35	7.99	1.545

NITROGENTEMPERATURE OF

<u>Pressure</u> <u>(Atm.)</u>	<u>Pressure</u> <u>(Psia.)</u>	<u>261</u>			<u>628</u>			<u>808</u>		
		<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>	<u>Cp</u>	<u>Cv</u>	<u>k</u>
1	14.7	29.09	20.8	1.40	29.33	21.0	1.395	29.45	21.2	1.39
5	73.5	29.17	"	1.402	29.36	"	"	29.47	"	"
10	147	29.29	"	1.41	29.4	"	1.40	29.5	"	"
20	294	29.49	"	1.418	29.46	"	1.403	29.54	"	1.393
40	588	29.88	20.5	1.43	29.6	"	1.41	29.64	"	1.40
60	882	30.27	"	1.45	29.75	"	1.418	29.73	"	1.402
80	1176	30.66	21.0	1.46	29.88	"	1.425	29.82	"	1.407
100	1470	31.05	"	1.478	30.01	"	1.43	29.93	"	1.412
140	2058	31.79	21.1	1.507	30.27	"	1.443			
200	2940	32.68	21.2	1.542	30.63	21.1	1.454			
250	3675	33.29	21.3	1.565	30.88	"	1.464			
300	4410	33.81	21.4	1.58	31.11	"	1.474			
350	5145	34.20	21.5	1.59	31.31	"	1.483			

NITROGEN

TEMPERATURE °F

<u>Pressure (Atm.)</u>	<u>Pressure (Psia.)</u>	<u>-99</u>			<u>-9</u>			<u>81</u>		
		<u>Cp</u>	<u>Cv</u>	<u>K</u>	<u>Cp</u>	<u>Cv</u>	<u>K</u>	<u>Cp</u>	<u>Cv</u>	<u>K</u>
1	14.7	28.97	20.6	1.405	28.95	20.6	1.405	28.93	20.6	1.408
5	73.5	29.43	20.6	1.43	29.13	20.6	1.415	29.14	"	1.415
10	147	30.04	20.7	1.45	29.48	20.7	1.425	29.35	20.7	1.42
20	294	31.33	20.8	1.505	30.13	20.7	1.454	29.77	"	1.437
40	588	34.30	21.0	1.63	31.59	20.9	1.51	30.66	20.8	1.475
60	882	37.94	21.4	1.775	33.21	21.0	1.58	31.60	20.9	1.51
80	1176	41.70	21.6	1.93	34.83	21.2	1.643	32.55	21.0	1.55
100	1470	44.72	21.9	2.04	36.35	21.4	1.70	33.45	21.1	1.585
140	2058	47.34	22.3	2.12	38.52	21.6	1.785	34.98	21.3	1.64
200	2940	47.80	22.7	2.105	40.21	22.0	1.83	36.20	21.5	1.69
250	3675	47.25	23.1	2.045	41.01	22.2	1.85	37.10	21.7	1.71
300	4410	46.93	23.4	1.96	41.31	22.4	1.84	37.61	21.8	1.725
350	5145	46.54	23.8	1.92	41.30	22.7	1.82	37.84	22.0	1.72

C_p : Specific heat at constant pressure, Joules/Mole, °K

C_v : specific heat at constant volume, Joules/Mole, °K

K: C_p/C_v , ratio of specific heats

Table 6: The ratio of isobaric to isometric specific heats of Nitrogen.

Ref.: "Thermodynamic Functions of Gases," F. Din, Vol. III, p. 151.