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BOILING HEAT TRANSFER FOR OXYGEN, NITROGEN, HYDROGEN, AND HELIUM

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FOREWORD

This Technical Note represents a collection of several essentially separate works some of which have been reported in less detail elsewhere (see Advances in Cryogenic Engineering, Volumes 10 and 11). It may be well to specifically identify the contributions of the various authors. The first author did a major portion of the work on pool boiling, section 2. The second author was the major contributor to forced convection, section 3, and the properties, section 6. The third author made some contributions to all sections and wrote section 4 on boiling variables. Also special credit is due to Mrs. Dorothy Johnson who assisted in the final editing and the typing of several drafts of the manuscript.

The work in section 3 was partially supported by NASA Contract R-45, and that assistance is gratefully acknowledged.

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Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium

E. G. Brentari, P. J. Giarratano, and R. V. Smith

12441

This study has been conducted to provide an orderly examination of the information relative to boiling heat transfer for four cryogenic fluids. The general approach has been to examine experimental data with respect to the predictive correlations which would appear to have probable success and which would be likely to be used by design engineers. These correlations were graphically and statistically compared. The results are discussed, and when it appears a best or acceptable recommendation can be made, computation aids for designers are included. These aids are in the form of graphical presentations for preliminary studies and equations for computer studies. The authors have also indicated the apparent limits for the use of these correlations, when possible. The effect of many variables which would often be significant are not included in the predictive correlations. The influence of these variables is discussed in a separate section on boiling variables.

Keywords: boiling, cryogenic, film, forced-convection, free-convection, helium, hydrogen, nitrogen, nucleate, oxygen

author

1. Introduction

Although the boiling phenomenon has been studied for at least a hundred years and has been the subject of many papers, it is not well understood. All this work has not been a failure, however, even though complete understanding has not been achieved. From a designer's point of view, the predictive expressions have become increasingly more reliable but also more abundant. The purpose of this study is to test these predictive expressions with the available experimental data in order that a better choice of expression can be made.

2. Nucleate and Film Pool Boiling Design Correlations for O_2, N_2, H_2, and He

The purposes of this section are to present the available cryogenic pool boiling heat transfer data from the literature and selectively to evaluate and present the best available predictive correlations as functions of significant system parameters for use by the cryogenic design engineer. The basic approach was to search the literature to gather experimental cryogenic boiling data which were then compared with existing correlations evaluated for the cryogenic fluids. In presenting the data, effects of heating surface geometry, finish, and material were not discriminated from each other. From these correlations, the ones which best appeared to describe the data were selected for presentation in the cryogenic range. Generally, the selected correlations fell within the spread of the experimental data and thus should provide engineering utility for many design studies.

2.1. Presentation of Experimental Data

The experimental data for oxygen, nitrogen, hydrogen, and helium are respectively presented by figures 2.1, 2.2, 2.3, and 2.4, for one atmosphere, with the exception of the nucleate regime for helium, which is shown at 1/2 atmosphere because more data were available at that pressure. The correlations appear to describe the data adequately, but the general correlations show a tendency to be slightly lower than the visual average of the data. The circles represent the maximum experimental nucleate pool boiling heat fluxes. No minimum film boiling data were found for the cryogenic range.

In general, the widths of the bands of data indicate the spread of each respective investigator under constant experimental conditions. However, this is not true for the oxygen and nitrogen nucleate boiling data of Lyon [1964] and Lyon, et al. [1964]. These deceptively wide bands are due to his careful investigations of extensive ranges of heater geometries, orientations, and surfaces. As previously stated, there is no discriminiation between these effects in this paper. Tables 2.1 - 2.4 summarize by fluid the experimental systems shown in the figures.

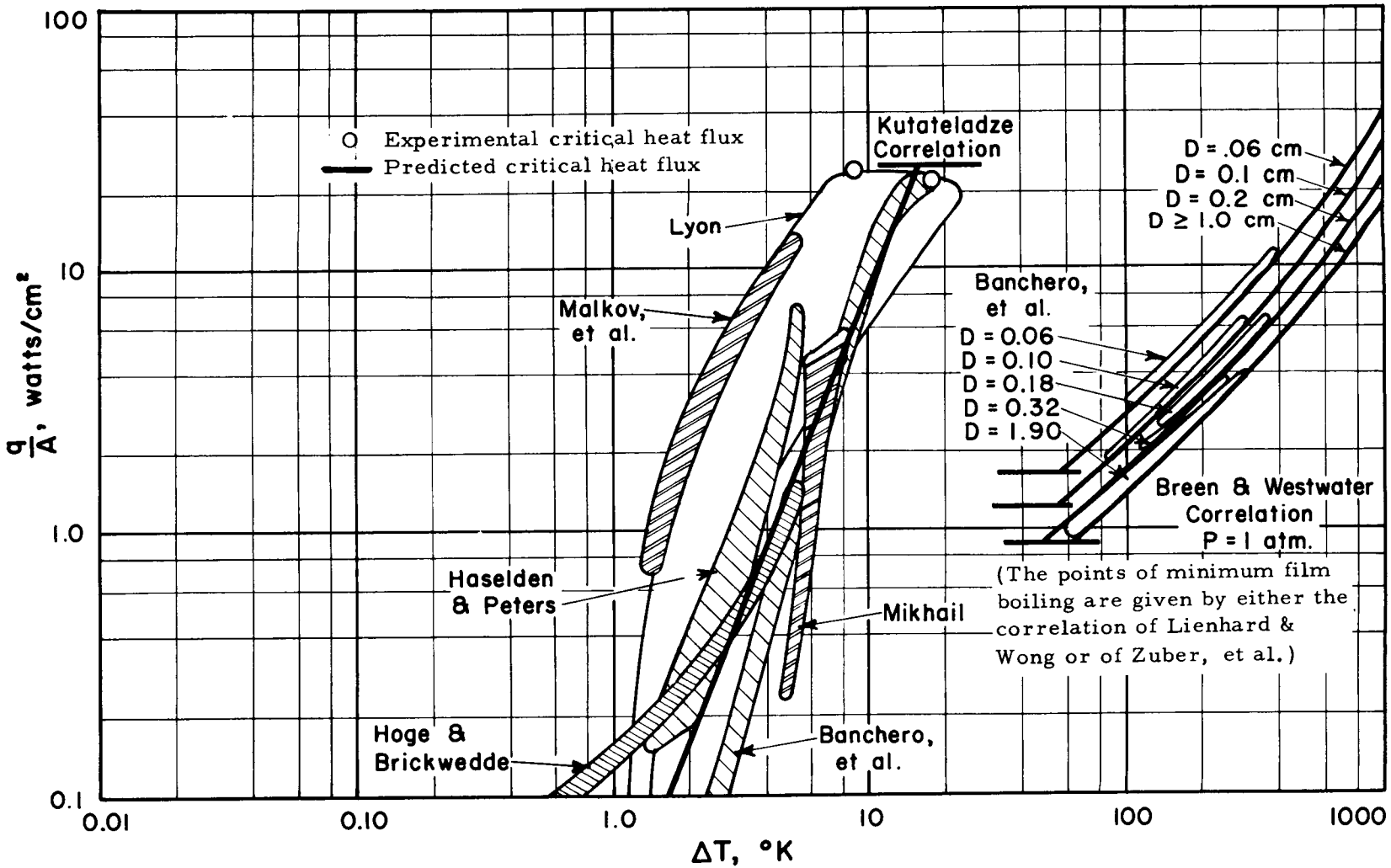

FIGURE 2.1
Experimental Nucleate and Film Pool Boiling of Oxygen at One Atmosphere Compared with the Predictive Correlations of Kutateladze and Breen and Westwater

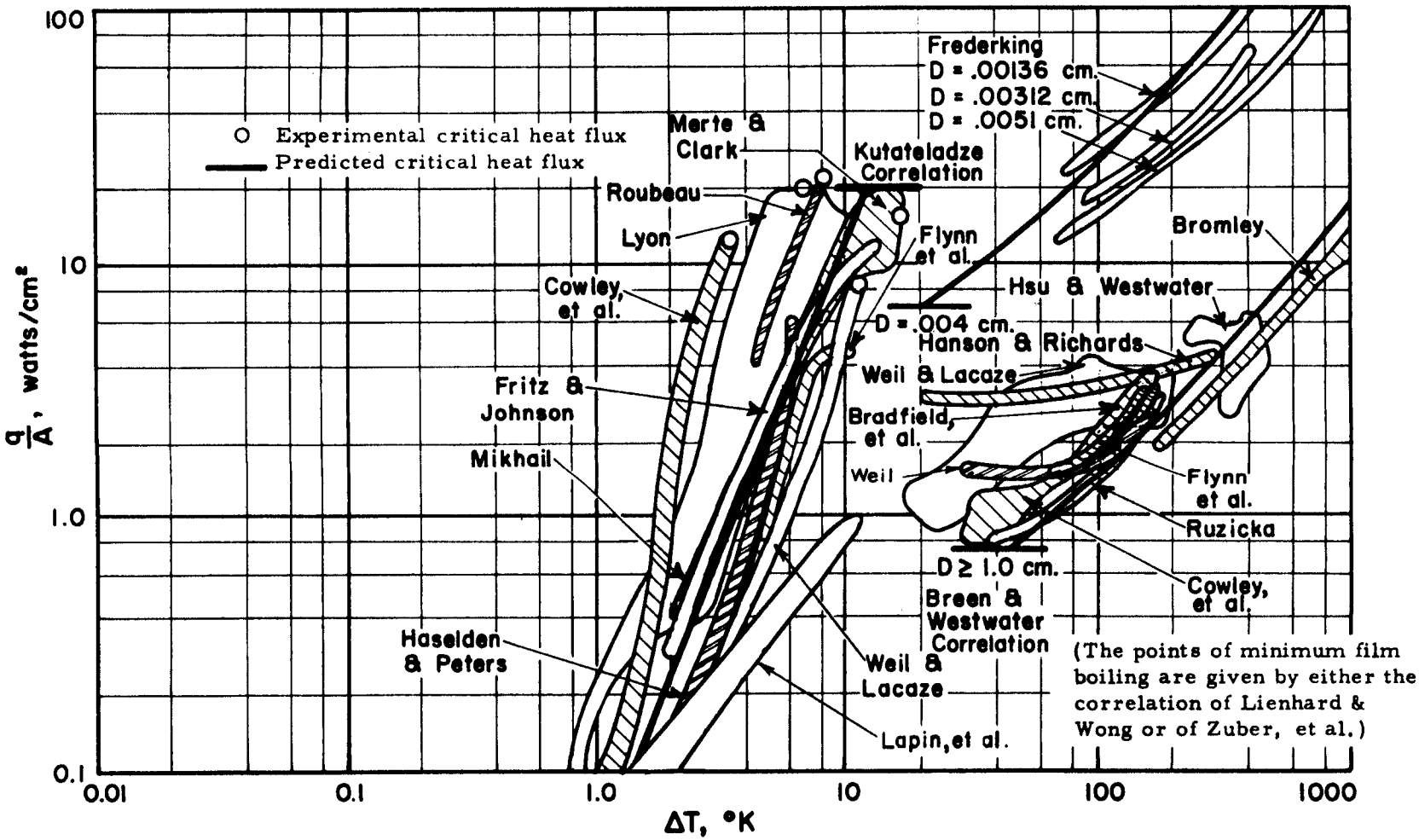

FIGURE 2.2
Experimental Nucleate and Film Pool Boiling of Nitrogen at One Atmosphere Compared with the Predictive Correlations of Kutateladze and Breen and Westwater

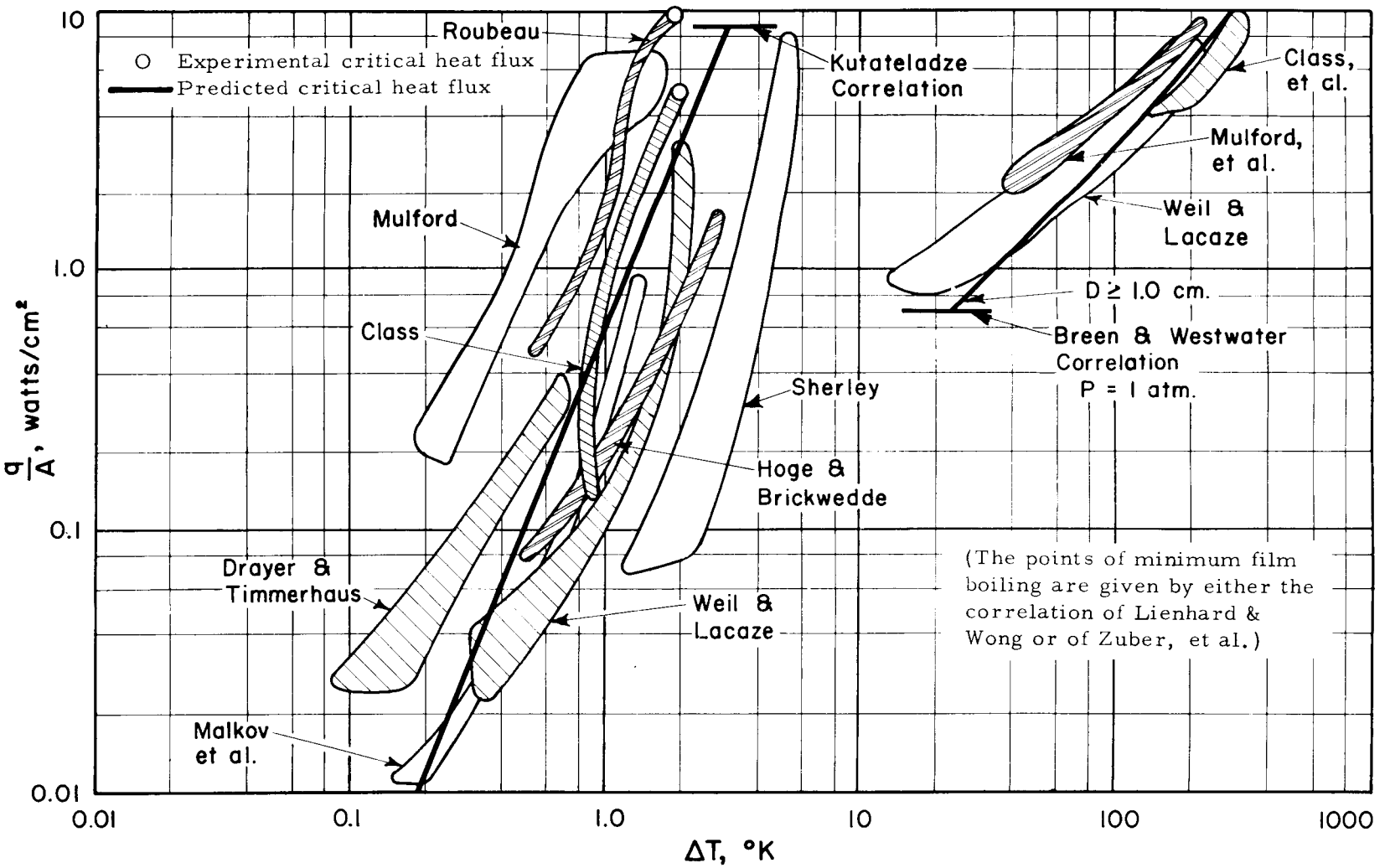

FIGURE 2.3
Experimental Nucleate and Film Pool Boiling of Hydrogen at One Atmosphere Compared with the Predictive Correlations of Kutateladze and Breen and Westwater

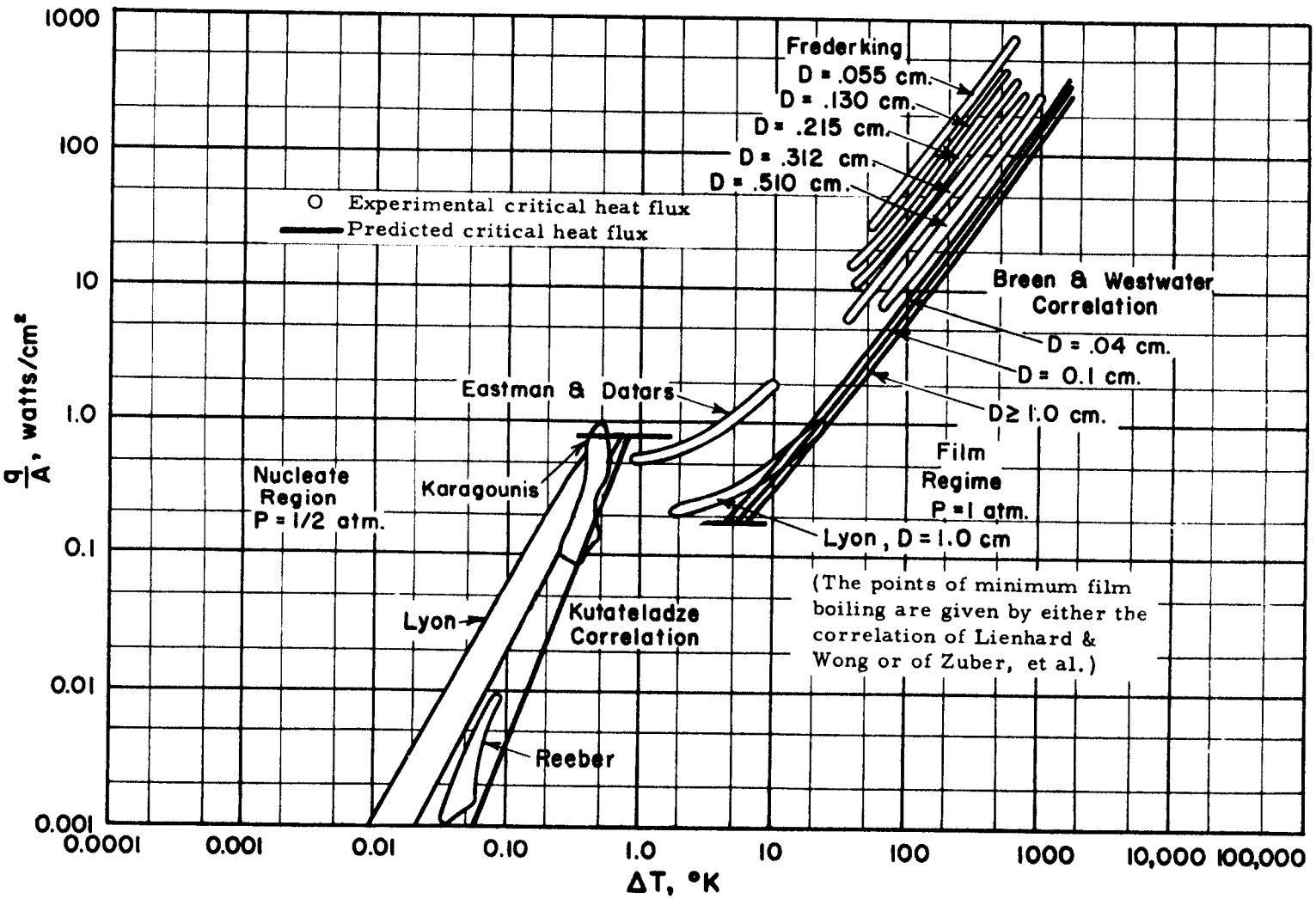

FIGURE 2.4
Experimental Nucleate and Film Pool Boiling of Helium Compared with the Predictive Correlation of Kutatela ze and Breen and Westwater

TABLE 2.1
EXPERIMENTAL OXYGEN POOL BOILING SYSTEMS

Author	Heating Mechanism	Geometry of Heater	Dimensions of Heater	Orientation of Heater	Material of Heater Surface	Surface Condition
NUCLEATE BOILING						
Banchero, et al. [1951]	Electrical	Cylinders	D = 1.905 (cm), L = 5.080 (cm), 0.064 - 0.323 cm Diam. Wires	Horizontal	Copper, 304 St. Steel, K-Monel, 24 ST Aluminum, Platinum	Smooth and Clean
Haselden and Peters [1949]	Electrical	Cylinders	D = 1.588 (cm) L = 7.62 (cm) D = 0.952 (cm) L = 30.48 (cm)	Horizontal and Vertical	Copper	Clean
Hoge and Brickwedde [1942]		Cylinder	D = 1.041 (cm) L = 8.572 (cm)	Horizontal		
Malkov, et al. [1958]	Electrical	Coil tube	D = 4.5 (cm)		Monel	
Mikhail [1952]		Cylinder		Horizontal		Smooth and Rough
Lyon [1964]	Electrical	Cylinders	D = 0.952 - 6.985 (cm) L = 4.445 - 10.414 (cm)	Horizontal and Vertical	Copper, Gold, Nickel, Cu_2O, Cu_2S, Triocytl-phosphate Film, Phenylacetonitrile Film	Clean, Smooth and Rough
Lyon, et al. [1964]	Electrical	Ring	6.858 (cm) O.D. x 6.452 (cm) I.D.	Horizontal	Platinum	Smooth and Clean
FILM BOILING						
Banchero, et al. [1951]	Electrical	Cylinders	D = 1.905 (cm), L = 5.080 (cm), 0.064 - 0.323 cm Diam. Wires	Horizontal	Copper, 304 St. Steel, K-Monel, 24 ST Aluminum, Platinum	Smooth and Clean

TABLE 2.2
EXPERIMENTAL NITROGEN POOL BOILING SYSTEMS

Author	Heating Mechanism	Geometry of Heater	Dimensions of Heater	Orientation of Heater	Material of Heater Surface	Surface Condition
NUCLEATE BOILING						
Cowley, et al. [1962]		Cylinder	D = 4.13 (cm) L = 25.40 (cm)		Copper	
Flynn, et al. [1962]	Electrical	Cylinder	D = 1.588 (cm) L = 5.080 (cm)	Horizontal	Copper	Clean
Haselden and Peters [1949]	Electrical	Cylinders	D = 1.588 (cm) L = 7.62 (cm) D = 0.952 (cm) L = 30.48 (cm)	Horizontal and Vertical	Copper	Clean
Lapin, et al. [1965]	Electrical	Cylinder	D = 1.27 (cm) L = 5.40 (cm)	Vertical	Watlow Fire Rod Heater	
Lyon [1964]	Electrical	Cylinders	D = 0.952 - 6.985 (cm) L = 4.445 - 10.414 (cm)	Horizontal and Vertical	Copper, Gold, Nickel, Cu_2O, Cu_2S, Triocytl-phosphate Film, Phenylacetonitrile Film	Clean, Smooth and Rough
Lyon, et al. [1964]	Electrical	Ring	6.858 (cm) O.D. x 6.452 (cm) I.D.	Horizontal	Platinum	Smooth and Clean
Merte and Clerk [1962]	Cooldown	Sphere	D = 2.540 (cm)		Electrolytic Tough Pitch Copper	Smooth and Clean
Mikhail [1952]		Cylinder		Horizontal		Smooth and Rough
Roubeau * [1960]	Electrical	Flat Plate	A = 5 $(cm)^2$	Horizontal	Copper	
Weil and Lacaze [1950]		Circular plate made from winding tubing in a spiral	A = 49.5 $(cm)^2$	Horizontal	Copper	

* Roubeau used Helium to pressurize his experimental system, thus the reported pressures may not be the same as for a single component system.

TABLE 2.2 (continued)
EXPERIMENTAL NITROGEN POOL BOILING SYSTEMS

Author	Heating Mechanism	Geometry of Heater	Dimensions of Heater	Orientation of Heater	Material of Heater Surface	Surface Condition
FILM BOILING						
Bradfield, et al. [1960]	Stored (sensible) heat	Cylinder	D = 3.76 (cm), L = 14.0 (cm)	Vertical	Copper, Graphite, Chrome, St. Stl.	
Bromley [1950]	Electrical	Cylinder	D = 0.889 (cm)	Horizontal	Carbon	Polished
Cowley, et al. [1962]		Cylinder	D = 4.13 (cm) L = 25.40 (cm)		Copper	
Flynn, et al. [1962]	Electrical	Cylinder	D = 1.588 (cm) L = 5.080 (cm)	Horizontal	Copper	Clean
Hanson and Richards [1956]	Electrical	Cylinder	D = 1.90 (cm), L = 12.35 (cm)	Horizontal	Stainless Steel	
Hsu and Westwater [1958]	Steam	Cylindrical	D = 0.952 → 1.90 (cm), L = 6.60 → 16.5 (cm)	Vertical	Copper, Stainless Steel	Polished
Ruzicka [1958]	Electrical	Cylinders	D = 1.0 (cm), L = 14.3 (cm); D = 1.5 (cm), L = 14.5 (cm); D = 2.0 (cm), L = 14.51 (cm)		Copper	Rough
Weil [1951]		Circular plate made from winding tubing in a spiral	A = 49.5 $(cm)^2$	Horizontal	Copper	
Weil and Lacaze [1950]		Circular plate made from winding tubing in a spiral	A = 49.5 $(cm)^2$	Horizontal	Copper	

TABLE 2.3
EXPERIMENTAL HYDROGEN POOL BOILING SYSTEMS

Author	Heating Mechanism	Geometry of Heater	Dimensions of Heater	Orientation of Heater	Material of Heater Surface	Surface Condition
NUCLEATE BOILING						
Class, et al. [1960]	Electrical	Flat Plate	2.54 (cm) Wide L = 55.88 (cm)	Vertical, 45°, Horizontal	Karma Alloy, Silicone Grease	Smooth and Rough
Drayer and Timmerhaus [1962]	Gas Heat Exchanger	Cylinder	D = 1.595 (cm) L = 11.278 (cm)	Vertical	Brass	Smooth
Hoge and Brickwedde [1942]		Cylinder	D = 1.041 (cm) L = 8.572 (cm)	Horizontal		
Malkov, et al. [1958]	Electrical	Coil tube	D = 4.5 (cm)		Monel	
Mulford and Nigon [1952]	Electrical	Cylinder	D = 1.2 (cm), L = 5.0 (cm)	Horizontal	Copper	
Weil and Lacaze [1951]		Circular plate made from winding tubing in a spiral	A = 49.5 $(cm)^2$	Horizontal	Copper	
FILM BOILING						
Class, et al. [1960]	Electrical	Flat Plate	2.54 (cm) Wide L = 55.88 (cm)	Vertical, 45°, Horizontal	Karma Alloy, Silicone Grease	Smooth and Rough
Mulford and Nigon [1952]	Electrical	Cylinder	D = 1.2 (cm), L = 5.0 (cm)	Horizontal	Copper	
Weil and Lacaze [1951]		Circular plate made from winding tubing in a spiral	A = 49.5 $(cm)^2$	Horizontal	Copper	

TABLE 2.4
EXPERIMENTAL HELIUM POOL BOILING SYSTEMS

Author	Heating Mechanism	Geometry of Heater	Dimensions of Heater	Orientation of Heater	Material of Heater Surface	Surface Condition
NUCLEATE BOILING						
Karagounis [1956]	Electrical	Flat Plate, Cylinders	0.25 (cm) Wide L = 6.4 (cm); D = 0.20 - 0.32 (cm) L = 4.0 cm		Aluminum	
Lyon [1965]	Electrical	Ring	6.858 (cm) O.D. x 6.452 (cm) I.D.	Horizontal	Platinum	Smooth and Clean
Reeber [1963]	Electrical	Circular Flat Plate	$A = 11.4\ (cm)^2$	Vertical	Silver	Polished
TRANSITION BOILING						
Eastman and Dators [1963]	Electrical	Rectangular prisms	W, T = .02 → 0.2 (cm), L = 1.0 → 2.0 (cm)	Vertical	Antimony	Cleaned, Blasted, Electro-polished
FILM BOILING						
Frederking [1959]	Electrical	Cylinders	D = 0.51 → 0.00136 (cm), L = 4.12 → 0.593 (cm)	Horizontal	Platinum	
Lyon [1965]	Electrical	Ring	6.858 (cm) O.D. x 6.452 (cm) I.D.	Horizontal	Platinum	Smooth and Clean

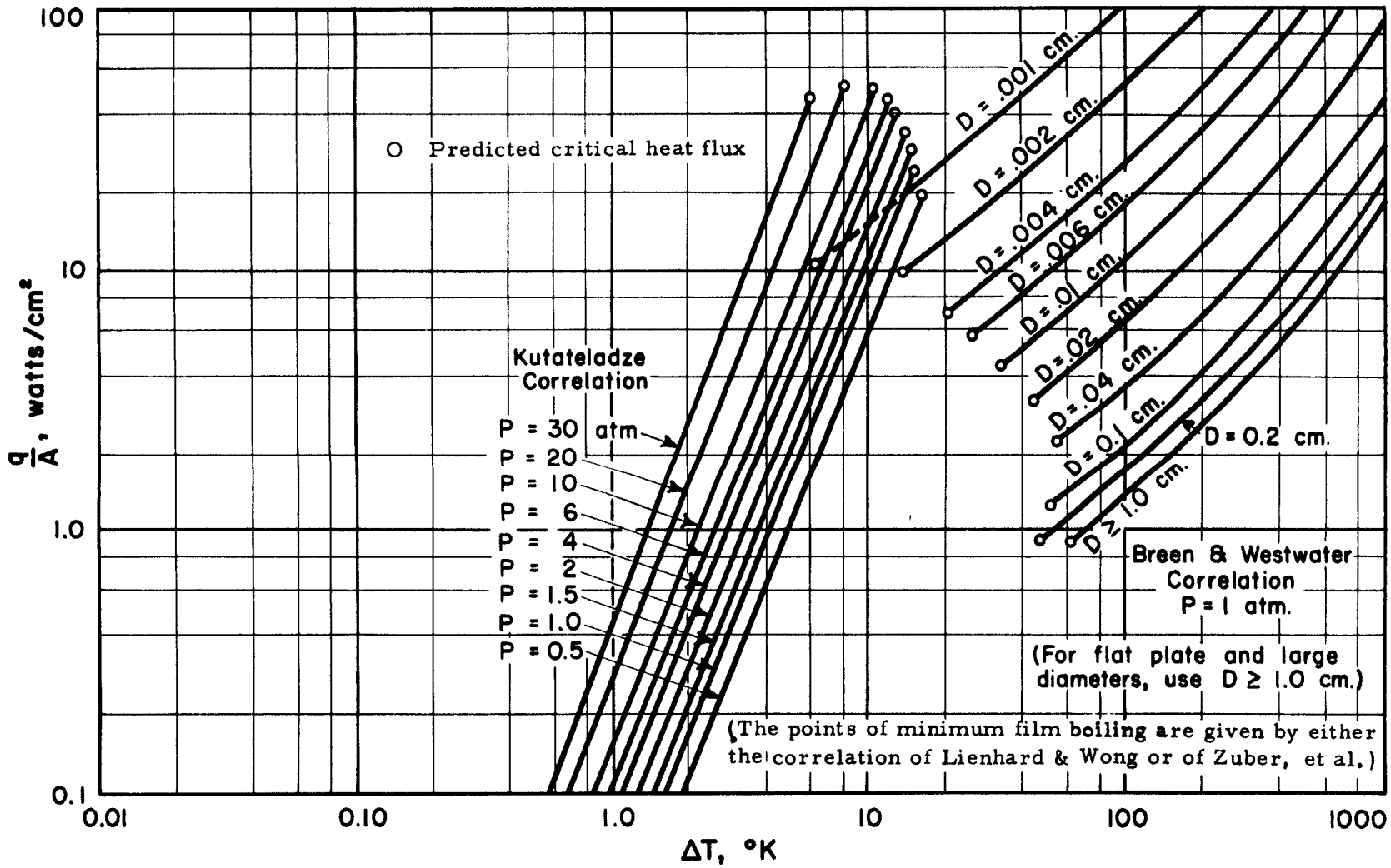

FIGURE 2.5
Predictive Nucleate and Film Pool Boiling Correlations for Oxygen

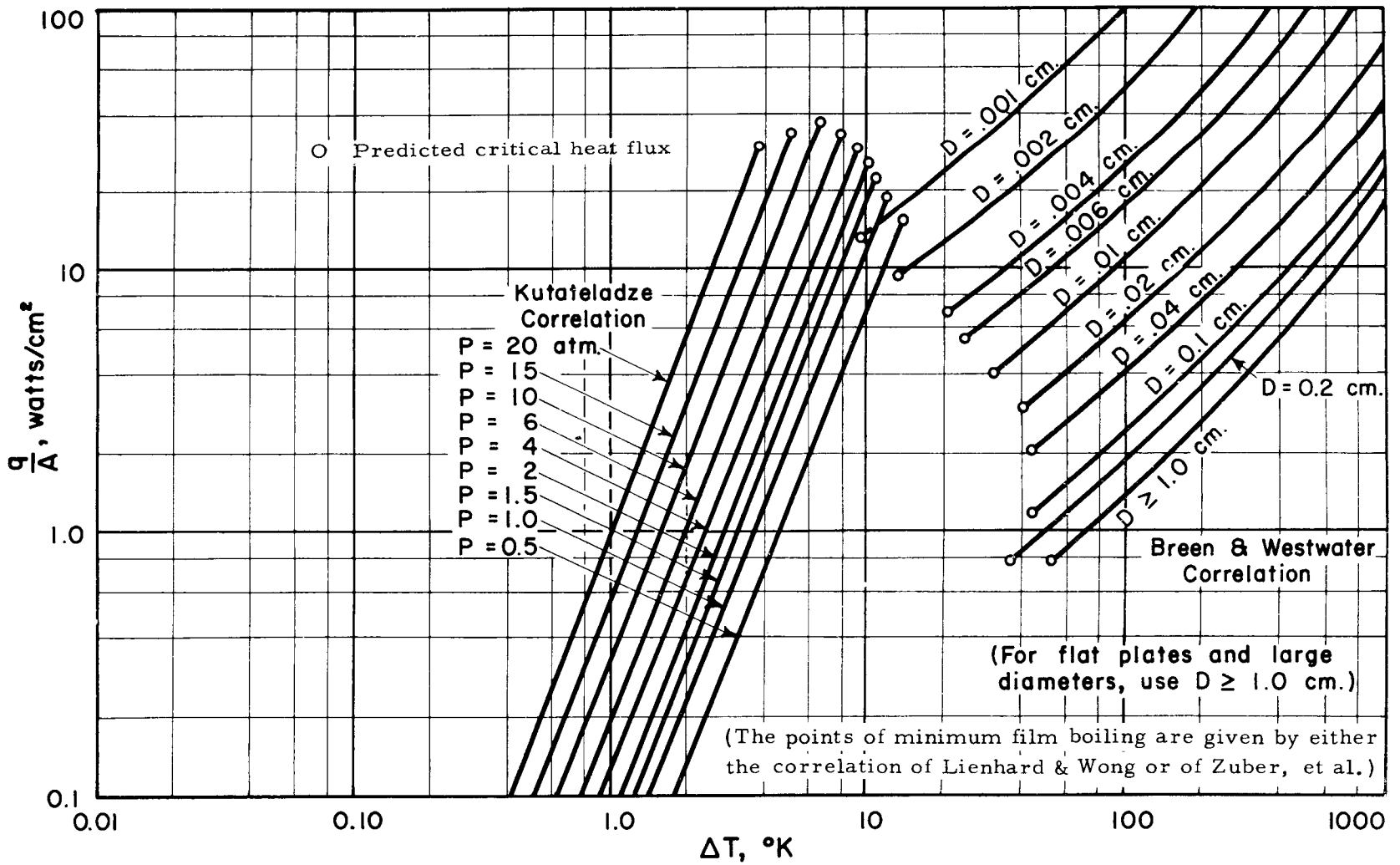

FIGURE 2.6
Predictive Nucleate and Film Pool Boiling Correlations for Nitrogen

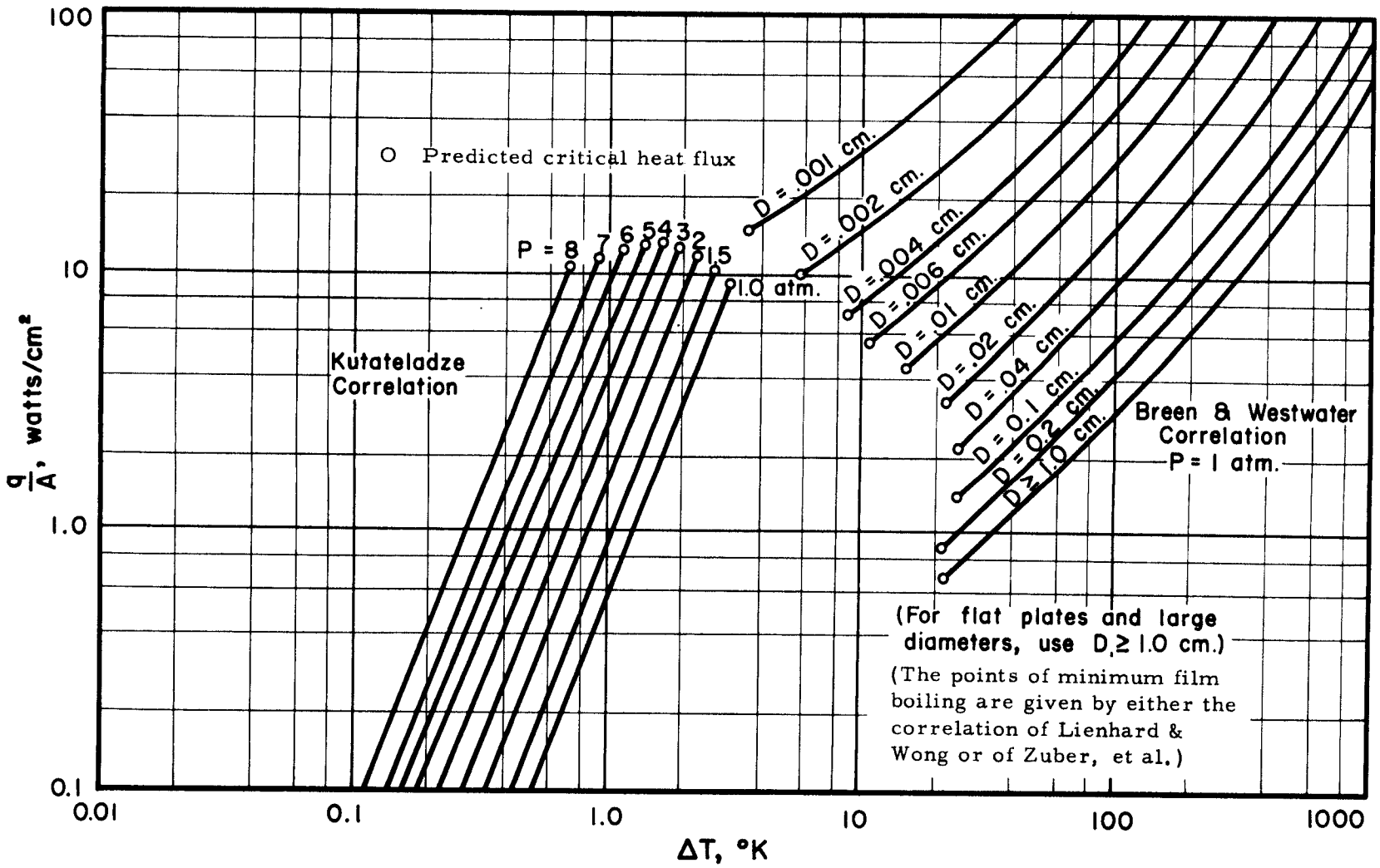

FIGURE 2.7
Predictive Nucleate and Film Pool Boiling Correlations for Hydrogen

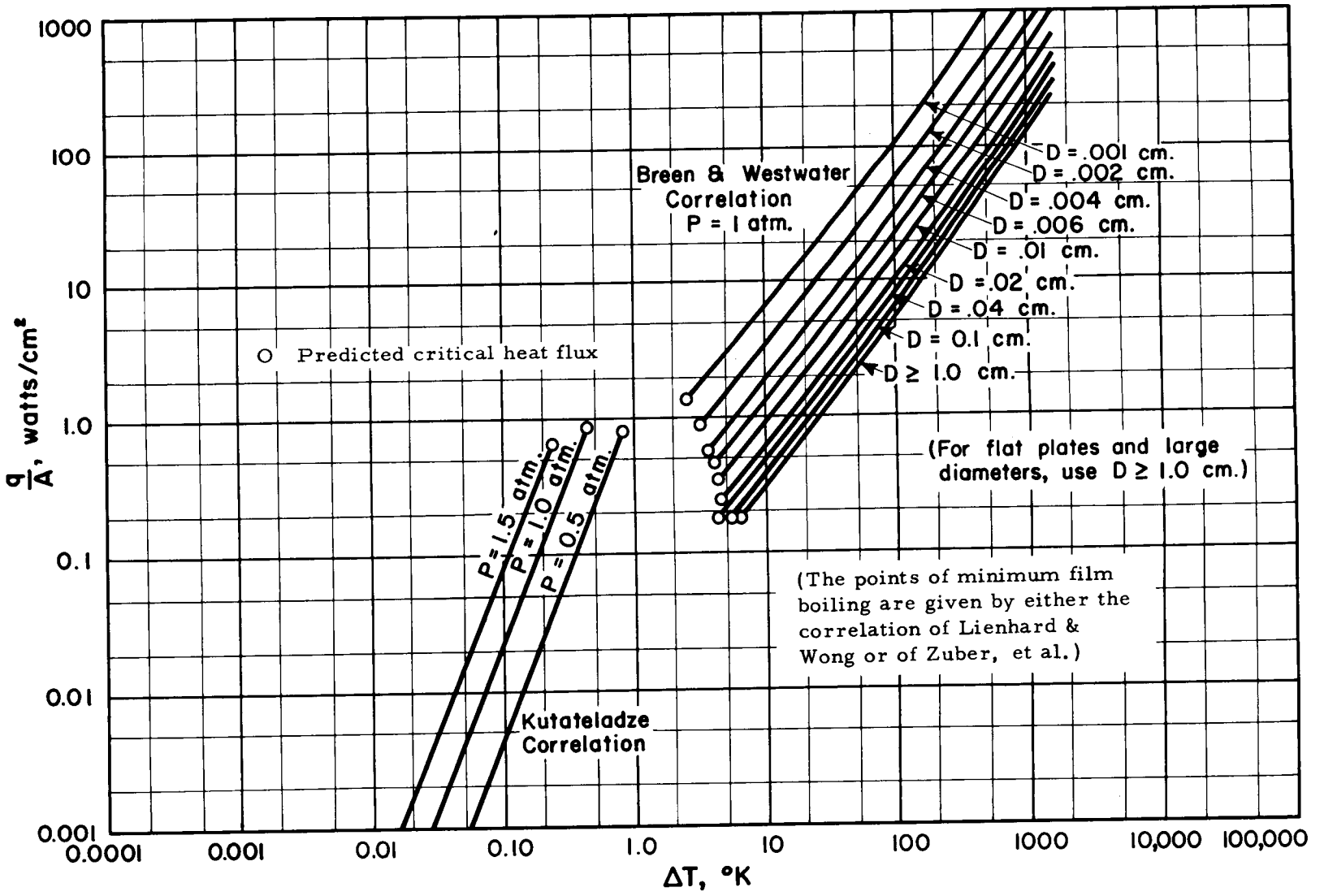

FIGURE 2.8
Predictive Nucleate and Film Pool Boiling Correlations for Helium

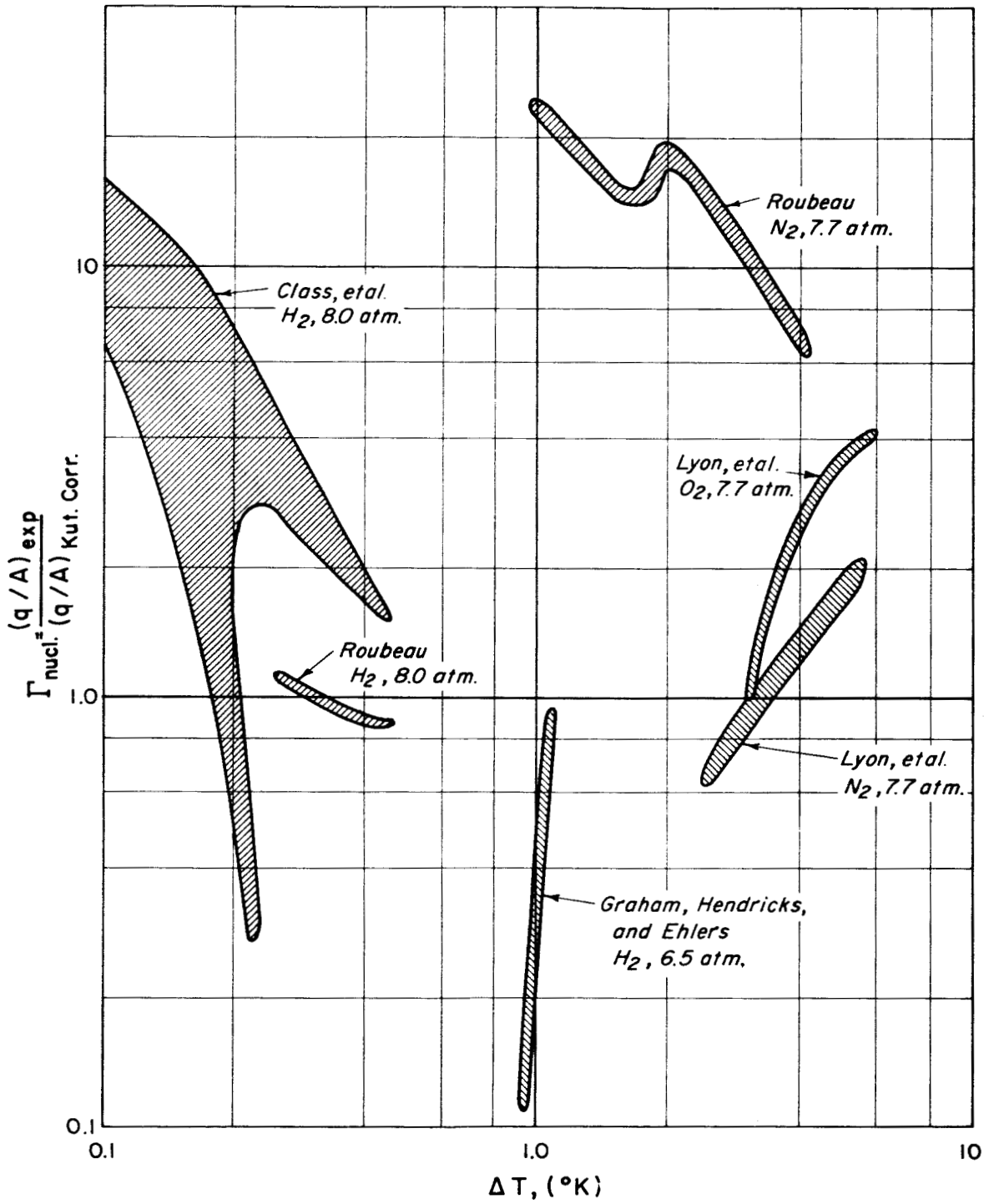

FIGURE 2.9
Comparison of Elevated Pressure Data with the General Kutateladze Correlation

2.2. Presentation of Predictive Nucleate Correlations

One experimental difficulty which could contribute significantly to the experimental scatter is that of accurately measuring ΔT. These inaccuracies would then introduce large fluctuations in $\frac{q}{A}$ for the higher heat fluxes, when compared to the correlations where ΔT is cubed. It should be noted that the correlations and experimental data as presented were evaluated at a standard gravitational acceleration of 980 cm/sec^2.

For the nucleate pool boiling regime, the general nucleate heat transfer correlation and the maximum nucleate heat transfer correlation of Kutateladze [1952] were selected. Empirical evidence indicates that the nucleate heat transfer flux is approximately a function of ΔT cubed at one atmosphere. Other correlations which were functions of ΔT raised to powers from 2.5 to 3.3 were those of Rohsenow [1952], McNelly [1953], Gilmour [1958], Tolubinskii [1959], Labountzov [1960], Michenko [1960], and a second correlation by Kutateladze [1952]. All of these were compared with the experimental data.

In his text on condensation and boiling, Kutateladze [1952] developed a set of basic equations from basic fluid flow considerations which described the nucleate pool boiling phenomena and by applying similarity considerations to these equations he produced a set of dimensionless groups. Groups of negligible influence were eliminated, and the remaining variables were formulated into groups which could be evaluated from available theoretical and experimental property data. This is shown below as (2.1).

$$\frac{h_{Nucl.}}{k_\ell}\left(\frac{\sigma}{g\rho_\ell}\right)^{1/2} = 3.25(10)^{-4}\left[\frac{(q/A)_{Nucl.}(C_p)_\ell\rho_\ell}{\lambda\rho_v k_\ell}\left(\frac{\sigma}{g\rho_\ell}\right)^{1/2}\right]^{0.6} \left[g\left(\frac{\rho_\ell}{\mu_\ell}\right)^2\left(\frac{\sigma}{g\rho_\ell}\right)^{3/2}\right]^{0.125}\left[\frac{P}{(\sigma g\rho_\ell)^{1/2}}\right]^{0.7} \tag{2.1}$$

Finally, these groups in (2.1) were rearranged into the conventional form of heat flux as a function of difference between the wall and the saturated liquid temperature. Since all the properties were functions of the saturation pressure, a family of pressure curves was generated for each fluid on a digital computer and compared with the elevated pressure data of Lyon, et al. [1964], Roubeau [1960], Class, et al. [1960], and Graham, et al. [1965]. These curves appear as the pressure dependent lines in the nucleate boiling regime of figures 2.5, 2.6, 2.7, and 2.8. Figure 2.9 shows a representative sample of dimensionless elevated pressure data as a function of ΔT to illustrate general agreement or deviation from (2.1).

As the heat flux is increased, a point is reached where any increase in ΔT will decrease the total heat flux. This nucleate boiling limit is known as the maximum or peak nucleate boiling heat transfer flux. It is of interest to designers since heat fluxes are markedly reduced at this point and fluxes greater than this maximum will occur only in the film boiling region at relatively high values of ΔT. It is also of interest to researchers because some of the boiling variables appear to be negligible at this point, making the data more reproducible. The exact mechanism of this transition remains controversial, but the maximum flux is associated with the inception of transition from nucleate to film boiling. However, the correlations generally in use which predict the maximum heat flux are of similar form, being functions of fluid properties only and not being dependent on ΔT.

Kutateladze [1952] proposed that the maximum heat flux occurs when the stability of the liquid films penetrating the two-phase boundary layer is destroyed. From this analysis, his maximum nucleate pool boiling correlation is

$$\frac{(q/A)_{Max.\,Nucl.}}{\lambda\rho_v^{1/2}(\sigma g\Delta\rho_v)^{1/4}} = K_1. \tag{2.2}$$

A value of $K_1 = 0.16$ was chosen as the numerical average of the values presented in his text. Also, he recommended this value when the exact evaluation of the constant was unknown. More recently, Zuber, et al. [1959] have also developed a correlation based on a hydrodynamic analysis similar to that of Kutateladze. After negligible groups were eliminated, their expression was essentially the same as (2.2).

Since the maximum is not a function of ΔT, the intersection between (2.1) and (2.2) is required to determine approximate ΔT values at which the maximum will occur. These are shown in the nucleate regime as the circles in figures 2.5, 2.6, 2.7, and 2.8 and as the horizontal lines in figures 2.1, 2.2, 2.3, and 2.4. In this respect, Lyon, et al. [1964) indicate that the data begin to deviate from the maximum correlation predictions above 0.6 of their critical pressures and that they become virtually useless above 0.8. Thus, both of the Kutateladze correlations in the nucleate regime are shown only up to 0.6 of critical pressure for their respective fluids, because the general boiling correlation uses the same parameters as the peak correlation and thus would also appear to be incorrect at the higher reduced pressures. Figure 2.10 illustrates the agreement of data from various investigators with the Kutateladze maximum nucleate boiling correlation, (2.2), where the dashed portion indicates pressures exceeding 0.6 of critical. It is of interest to note that the maxima for the predicted peak values occur at a reduced pressure of 0.3, which is in agreement with experimental evidence for the non-cryogenic liquids and for the cryogenic data of Lyon, et al. [1964, 1965] and Roubeau [1960].

2.3. Presentation of Predictive Film Correlations

For the film pool boiling regime the general film heat transfer correlation of Breen and Westwater [1962] and the minimum film heat transfer correlations of Linehard and Wong [1963] and of Berenson [1960] (which is an empirical adjustment of the Zuber, et al. [1959] analysis) were selected. These correlations were chosen on a basis of empirical agreement with the available data, theoretical exploration by the respective investigators, and inclusion of previous work. In all, eight correlations were investigated, some of the major ones being those of Bromley [1950], Hsu and Westwater [1960], Chang [1959], Berenson [1960], and Breen and Westwater [1962].

Breen and Westwater [1962] base their correlation upon the Taylor instability theory by considering the maintenance of the minimum wavelength on the bottom surface of the boiling liquid which will release vapor bubbles into the liquid from the supporting vapor film. A significant parameter in this analysis which was neglected by some previous authors is surface tension. Also, for cylinders, heater diameters up to 1.0 cm play a significant role in film boiling, as opposed to nucleate boiling where that effect appears negligible. In dimensionless form, the Breen and Westwater correlation is

$$h_{\substack{\text{Film}\\ \text{Cond.}}} \left(\frac{\sigma}{g\Delta\rho_f}\right)^{1/8} \left(\frac{\mu_f \Delta T}{k_f^3 \rho_f \Delta\rho_f g\lambda'}\right)^{1/4} = 0.37 + 0.28\left(\frac{\sigma}{gD^2\Delta\rho_f}\right)^{1/2} . \tag{2.3}$$

For this correlation, λ' is an effective heat of vaporization, given by

$$\lambda' = \frac{[\lambda + 0.340(C_p)_f(\Delta T)]^2}{\lambda} . \tag{2.4}$$

It is of interest to note that this correlation coincides with the Bromley [1950] correlation over the range of diameters from which the Bromley correlation was developed. Figures 2.5, 2.6, 2.7, and 2.8 show this correlation as a function of varying heater diameters at a constant pressure of one atmosphere, only, since the available cryogenic data indicate somewhat contradictory results at elevated pressures.

As the heat flux is decreased, a point is reached where a further decrease in ΔT will markedly increase the total heat flux. This film boiling limit is known as the minimum film boiling heat transfer flux. At this point, the transition from film boiling to nucleate boiling occurs, but not

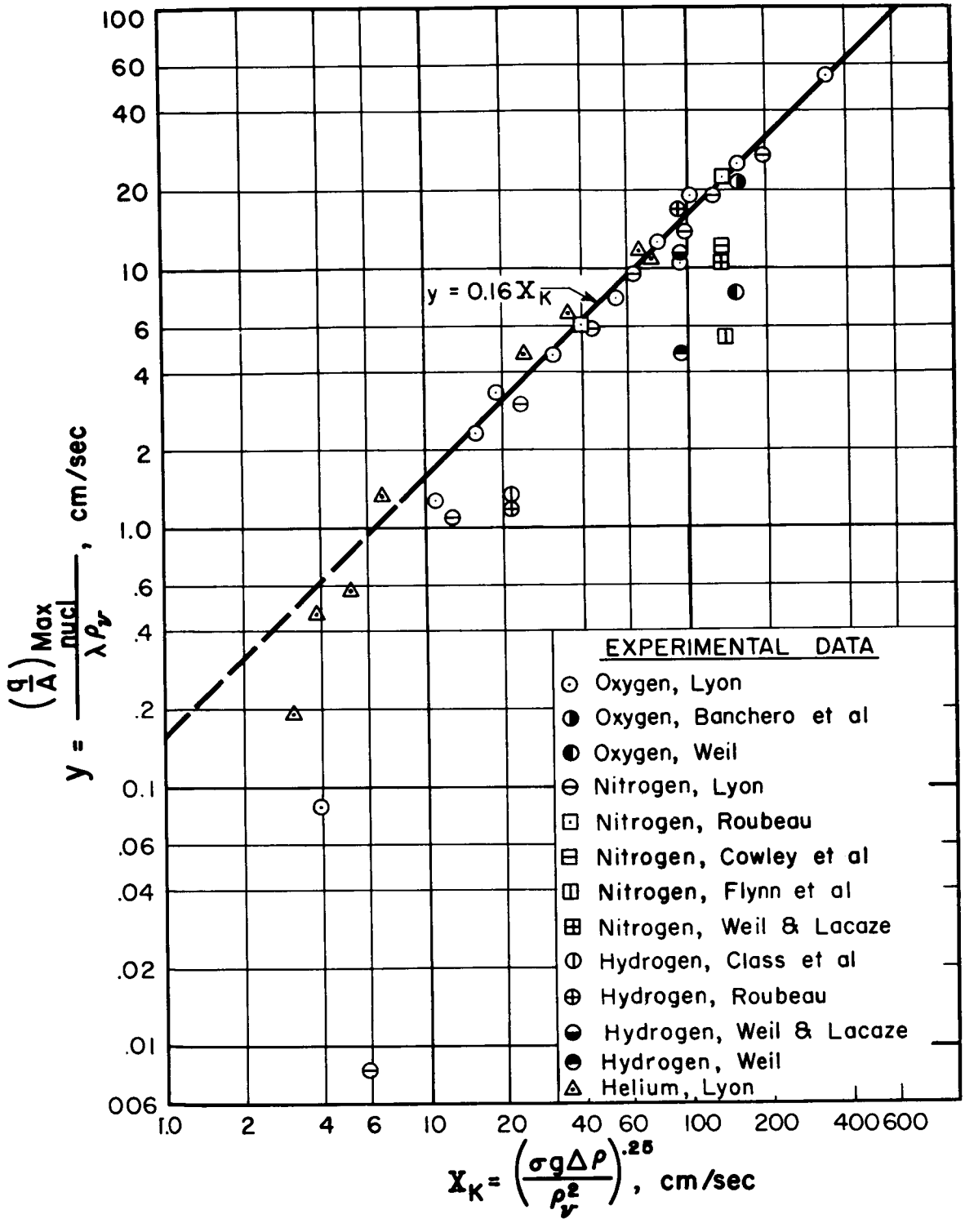

FIGURE 2.10
Comparison of the Maximum Nucleate Heat Transfer Fluxes with the Kutateladze Maximum Correlation

necessarily at the same value of ΔT as the maximum nucleate boiling flux. However, the correlations predicting this minimum are again functions of fluid properties only, being independent of ΔT.

Lienhard and Wong [1963] also utilize Taylor instability theory by considering the critical surface wavelength that creates surface waves of sufficient amplitude to break down the vapor film and carry liquid to the heater surface. Their expression, after empirical adjustment to the same units as shown in the nomenclature is

$$\left(\frac{q}{A}\right)_{\substack{\text{Min.}\\ \text{Film}\\ \text{Cond.}}} = 0.114\left(\frac{\rho_f \lambda}{D}\right)\left[\frac{2g\Delta\rho_f}{(\rho_\ell+\rho_f)} + \frac{4\sigma}{D^2(\rho_\ell+\rho_f)}\right]^{1/2}\left(\frac{g\Delta\rho_f}{\sigma} + \frac{2}{D^2}\right)^{-3/4} \tag{2.5}$$

In essence, (2.5) is an extension of the Zuber, et al. analysis by Lienhard and Wong [1963] for a flat plate, to account for small diameters. Thus, as D was increased, the Zuber prediction was used as the absolute minimum heat flux for film boiling. After adjustment by an empirical constant, this is

$$\left(\frac{q}{A}\right)_{\substack{\text{Abs.}\\ \text{Min.}\\ \text{Film}\\ \text{Cond.}}} = 0.16\lambda\rho_f\left[\frac{g\sigma\Delta\rho_f}{(\rho_\ell+\rho_f)^2}\right]^{1/4} \tag{2.6}$$

Since these minima are not functions of ΔT, the intersections between (2.3) and either (2.5) or (2.6) are required to determine the approximate ΔT values at which the minima will occur. These are shown in the film regime as the circles in figures 2.5, 2.6, 2.7, and 2.8 and as the horizontal lines in figures 2.1, 2.2, 2.3, and 2.4. As an example of the other correlations which were investigated, Figure 2.11 shows the relationships between various nucleate and film correlations with respect to the body of hydrogen data. A similar analysis was performed for each of the other three fluids. A more rigorous comparison such as the statistical methods of section 3 was not used because much of the data were shown in general curves and not reported as data points which are necessary for such a study. In general, these additional nucleate correlations were taken from Drayer [1965] while the additional film correlations were taken from Richards, et al. [1957]. Also, a recent report by Seader, et al. [1964] provides an excellent survey of oxygen, nitrogen, and hydrogen pool boiling.

It should be noted that (2.3), (2.5), and (2.6) do not include the heat transfer due to radiation. These equations predict the film boiling flux by conduction through the vapor film only. However, if ideal radiative transfer is assumed ("black body" emissivity and absorptivity) then heater surface temperatures of the order of 400 to 425°K can be tolerated for all of the four fluids without exceeding 5% error from the radiation even if it is neglected in the calculations. Figure 2.12 illustrates the heat flux due to radiation under the "black body" assumptions which would, of course, yield somewhat larger values than would actually be experienced in practice.

2.4. Conclusions - Pool Boiling

For nucleate boiling, the correlation of Kutateladze [1952] appeared to fit the available experimental data best. At higher pressures the agreement was poorer but perhaps acceptable for some design studies. For film boiling the correlation of Breen and Westwater [1962] was chosen for the best fit of experimental data. At higher pressures there were insufficient experimental data for comparison. For maximum and minimum heat fluxes in the region of transition from nucleate to film boiling the correlations of Kutateladze [1952] and Lienhard and Wong [1963] were selected for presentation.

It would appear from the rather wide range of experimental data that some variables, such as surface conditions, orientation, etc., are missing and others are perhaps not properly taken into account in the correlations. There is a further discussion of some of these variables in section 4. Finally, the predictive correlations mentioned above were evaluated in the figures at one standard "g" only.

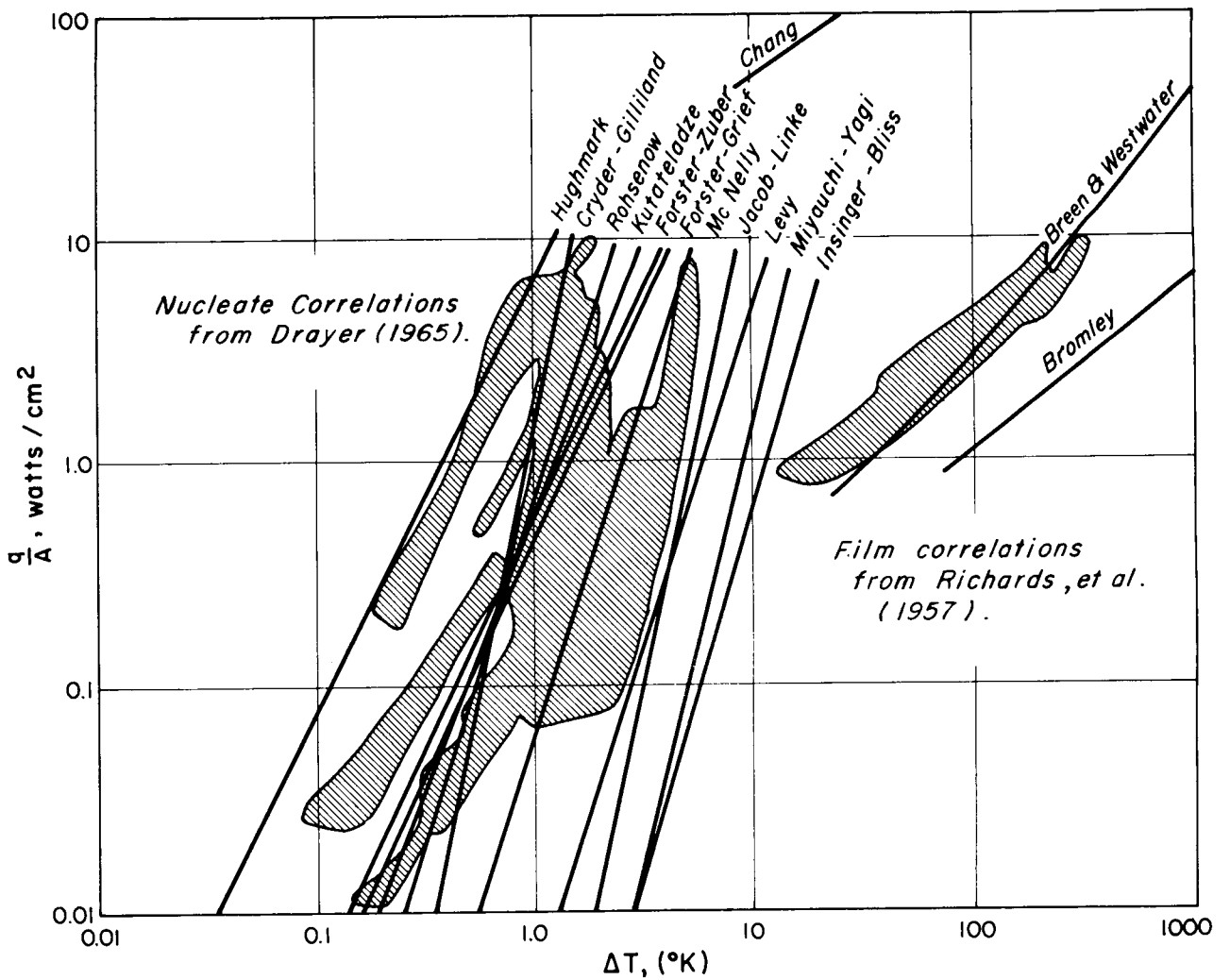

FIGURE 2.11
Comparison of Various Boiling Heat Transfer Correlations from the Literature for Hydrogen at One Atmosphere Pressure with the Reported Experimental Data Shown as Crosshatched Areas

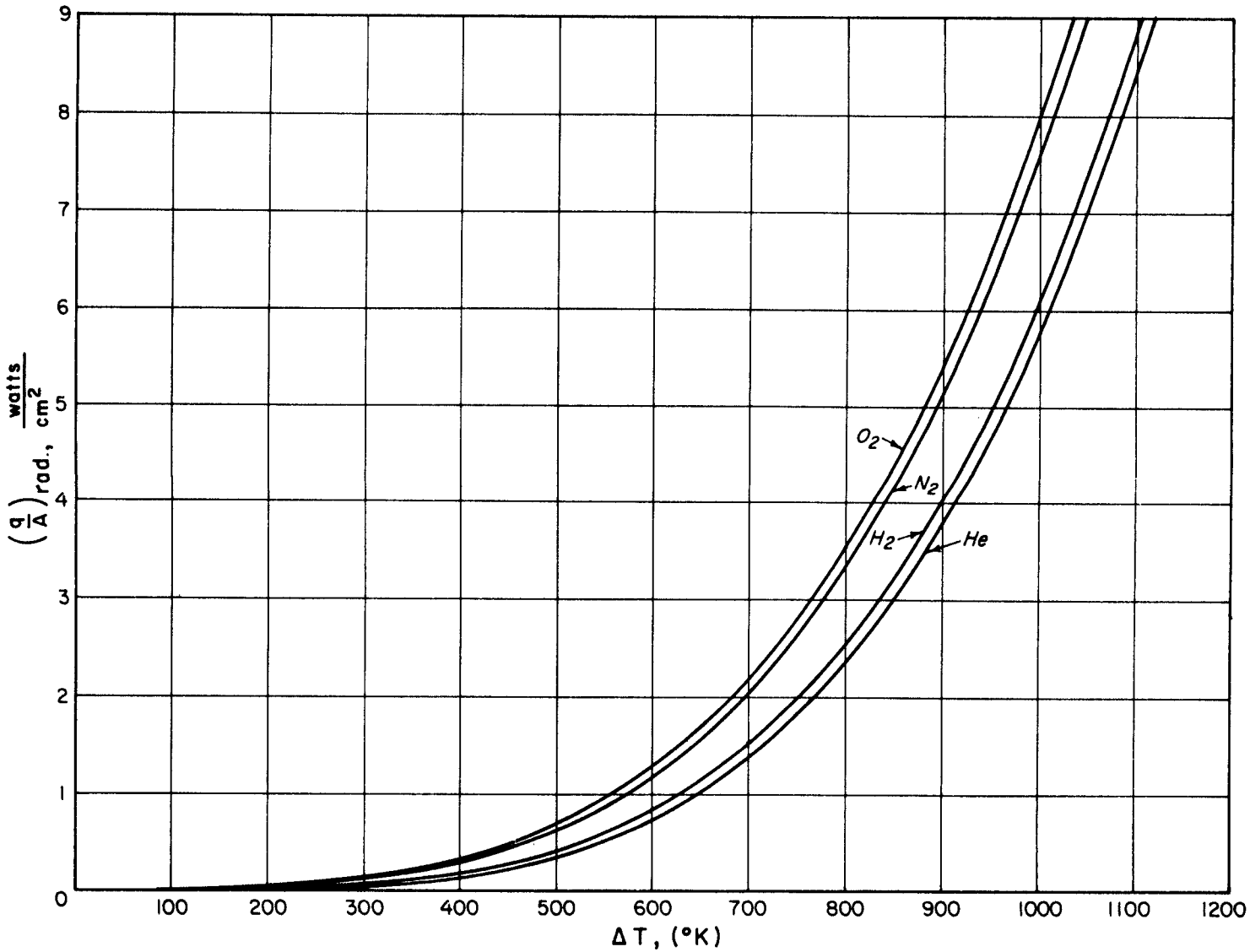

FIGURE 2.12
Heat Transfer Flux Due to "Black Body" Radiation through the Vapor Film

3. Forced Convection Boiling

3.1. Introduction

The purpose of this study was to investigate the relative merits of proposed predictive methods which may be used to determine required design information from data normally available. The required design information was assumed to be values of heat flux in the nucleate and film boiling regions and conditions for the transition between the two regions often referred to as the critical or burnout point. It has been assumed that flow rate, quality, fluid properties, and system geometry data are available or may be determined in most design studies; thus these quantities constitute the independent variables for the equations or correlations presented.

Since both the forced convection and the boiling phenomena when considered separately are poorly understood, one may expect only broad treatments of a subject involving their interaction rather than rigorous and specific studies.

3.1.1. Boiling Regimes

Some general divisions for the forced convection boiling regions have been proposed, for example, by Davis [1960] :

(1) Region I - The nucleate boiling (wet wall) region where the nucleate boiling contribution is significant, as for low velocity flows.
(2) Region II - The wet wall region where the forced convection effects are more significantly controlling for high velocity flows.
(3) Region III - The dry wall or liquid deficient region where the heat transfer is through a vapor film to a liquid or two-phase core.

Since almost all of the cryogenic data available were in Region III, most of this study was oriented toward that region. The data used are entirely hydrogen since these were the only complete and tabulated cryogenic data available.

3.1.2 Transition Points

The transition points from single-phase flow to flow with bubble inception and the transitions between the three regions previously described are often of prime design interest; studies of these transition points may produce a better understanding of the phenomena. In this study very few transition data points were found; however, the boiling inception point and the transition between Regions II and III (burnout) will be briefly discussed.

3.1.2.1. Bubble Inception

Bubble inception will be defined as the point of discontinuous slope change of a heat flux vs ΔT curve. This change of slope may be attributed to the change in heat transfer mechanism as boiling occurs. For the forced convection case this change of slope may occur for low velocity flow (Region I) where the boiling effect is not negligible. The only cryogenic fluid data are for pool boiling [Mikhail 1952, Tuck 1962, Ehricke 1963, Graham, et al. 1965] , and these are discussed in the Boiling Variables section of this report. It would appear that this inception point is quite sensitive to surface conditions.

3.1.2.2. Transition to Film Boiling

The transition from Region II to Region III may not produce an actual burnout in many cryogenic systems because, although the solid surface temperature may be markedly increased it may still be below the temperature for failure conditions for the heated solid surface. This discontinuity in the heat flux vs ΔT curve does mark the transition, however, and essentially all work has been for flow inside conduits.

Most of the analytical studies for the transition from Region II to Region III use a general superposition approach[Levy 1962, Gambill 1963a] since the cryogenic burnout data were for a change from a wetted wall to a dry wall condition. Gambill [1963b] has prepared an excellent review of the subject of forced-convection burnout in which he discusses in detail the primary variables which are:

(1) Liquid properties.
(2) Velocity past the heated surface.
(3) System pressure [closely related to (1)] .
(4) Subcooling or quality.
(5) Local acceleration forces (gravity).

For the case of flow over surfaces, Vliet and Leppert [1962] have reported studies on critical heat flux for saturated and subcooled water flowing normal to a cylinder. These results showed that the primary variables were (T_{wall}-T_{sat}), velocity, and cylinder diameter.

3.1.3. Predictive Expressions

Generally, the predictive expressions fall into two categories:

(1) Correlating a simple or modified Nusselt number ratio with the Martinelli correlating parameter or a similar term, primarily reflecting quality. The Nusselt number ratio used is the ratio of the experimental (or actual) Nusselt number to that value obtained by use of a Dittus-Boelter or Sieder-Tate type of equation with either single-phase properties or some modifications involving two-phase properties.
(2) Simple superposition, that is, adding the separately determined pool boiling and forced convection (without boiling) contributions.

Many other predictive systems have been proposed, but many of them include empirical constants (previously determined for water data), values of which for cryogenic fluids the authors assumed would not be generally available to designers. (For instance, see Tippets, 1964).

3.2. Experimental Data

The experimental data considered by this study are shown in table 3.1. Other experimental data found are shown in table 3.2 but were not included in this study because of lack of complete tabulated data which were necessary for calculations, or because of complex system geometry.

None of the experimental data used were culled for experimental accuracy.

3.3. Correlations

(See Appendix for Nomenclature)

3.3.1 Film Boiling - Nusselt No. Ratio vs X_{tt}

A X_{tt} correlation for the film boiling regime or Region III (as proposed by Hendricks, et al. 1961) used in this study was

$$\frac{Nu_{exp}}{Nu_{calc,\,f,\,t.p.}} = f(X_{tt}) \,, \tag{3.1}$$

where

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_\ell}\right)^{0.5} \left(\frac{\mu_\ell}{\mu_v}\right)^{0.1} \tag{3.2}$$

$$Nu_{calc,\,f,\,t.p.} = 0.023\, Re^{0.8}_{f,\,m,\,t.p.}\, Pr^{0.4}_{f,\,v} \tag{3.3}$$

$$Re_{f,\,m,\,t.p.} = \frac{\rho_{f,\,m,\,t.p.}\, U_{avg}\, D}{\mu_{f,\,v}} \tag{3.4}$$

TABLE 3.1 DATA USED BY THIS STUDY

Source and/or Author(s)	Test Medium	Test Section Geometry & Material	Boiling Region	Experimental Test Conditions					
				Inlet Press psia	ΔT $T_w - T_{bulk}$ °R	Sub-cooling °R	Mass Velocity lb/hr ft^2	Heat Flux B/hr ft^2	Type of Heating
Core, Harkee, Misra, and Sato [1959]	Hydrogen	Vertical, stainless steel, 0.168" I.D., 2.50" long	Film	30 to 138	50 to 1250	None	378,000 to 725,000	5200 to 2,600,000	Electrical
Hendricks, Graham, Hsu, and Friedman [1961]	Hydrogen	Vertical, inconel, 0.313" I.D., 12.00" long	Film	27 to 72	50 to 700	None	425,000 to 1,220,000	118,600 to 524,000	Electrical
Lewis, Goodykoontz, and Kline [1962]	Hydrogen	Vertical, stainless steel, 0.555" I.D., 16.125" long	Burnout	30 to 74	900° Max	0 to 9	2,800 to 17,000	4,000 to 50,000	Electrical
Wright and Walters [1959]	Hydrogen	Horizontal, copper, 0.250" I.D., 6.00" long	Nucleate and Film	20 to 40	1 to 280	None	306,000 to 865,000	3,000 to 123,000	Electrical

TABLE 3.2 DATA CONSIDERED BUT NOT USED

Source and/or Author	Test Medium	Boiling Region	Reason for not using
Dean and Thompson [1955]	Nitrogen	Nucleate, Film, & Burnout	Geometry
Richards, Robbins, Jacobs, Holten [1957]	Nitrogen Hydrogen	Nucleate	Geometry
Sydoriak and Roberts [1957]	Nitrogen Hydrogen	Nucleate	Geometry
von Glahn and Lewis [1959]	Nitrogen Hydrogen	Film and Burnout	Lack of complete tabulated data
Hendricks and Simon [1963]	Nitrogen	Film Boiling	Geometry
Aerojet [1963]	Hydrogen	Film Boiling	Geometry
Chi [1964]	Hydrogen	Nucleate Film	Lack of complete tabulated data

$$Pr_{f,v} = \left(\frac{Cp_{f,v}\,\mu_{f,v}}{k_{f,v}}\right) \tag{3.5}$$

$$\rho_{f,m,t.p.} = \frac{1}{\frac{x}{\rho_f} + \frac{1-x}{\rho_\ell}} \tag{3.6}$$

$$U_{avg} = \frac{\dot{m}}{\rho_b A_c} \tag{3.7}$$

and

$$\rho_b = \frac{1}{\frac{x}{\rho_v} + \frac{1-x}{\rho_\ell}} \tag{3.8}$$

From the definition of the Reynolds number it is apparent that $Nu_{calc,f,t.p.}$ is a two-phase type of Nusselt number which will, however, approach the value of the single gaseous phase Nusselt number as the quality approaches 1.

A variation of the above correlation was also considered. The correlation used was

$$\frac{Nu_{exp}}{Nu_{calc,v,s.p.}} = f(X_{tt}) , \tag{3.9}$$

where

$$Nu_{calc,v,s.p.} = 0.026\, Re_{v,s.p.}^{0.80}\, Pr_v^{0.33} \left(\frac{\mu_v}{\mu_w}\right)^{0.14} \tag{3.10}$$

$$Re_{v,s.p.} = \left(\frac{\rho_v U_{avg} D}{\mu_v}\right) \tag{3.11}$$

and

$$Pr_v = \left(\frac{C_{p_v}\,\mu_v}{k_v}\right) \tag{3.12}$$

Since the heat transfer from the wall is assumed to be through a gaseous film adjacent to the wall for film boiling (Region III), the Reynolds number was defined as a gaseous single-phase Reynolds number based on the average velocity of the mixture. The Sieder-Tate equation was chosen and properties of the gas were evaluated at bulk temperatures of the stream, with the exception of μ_w which is the viscosity of the gas at the temperature of the inner wall. The general form of the Sieder-Tate equation was taken from Bird, et al. [1962] . The results of plotting (3.1) and (3.9) are shown in figures 3.1 and 3.2 respectively.

Finally, as suggested by Ellerbrock, et al. [1962] , (3.1) was modified by the use of the dimensionless boiling number in the following manner:

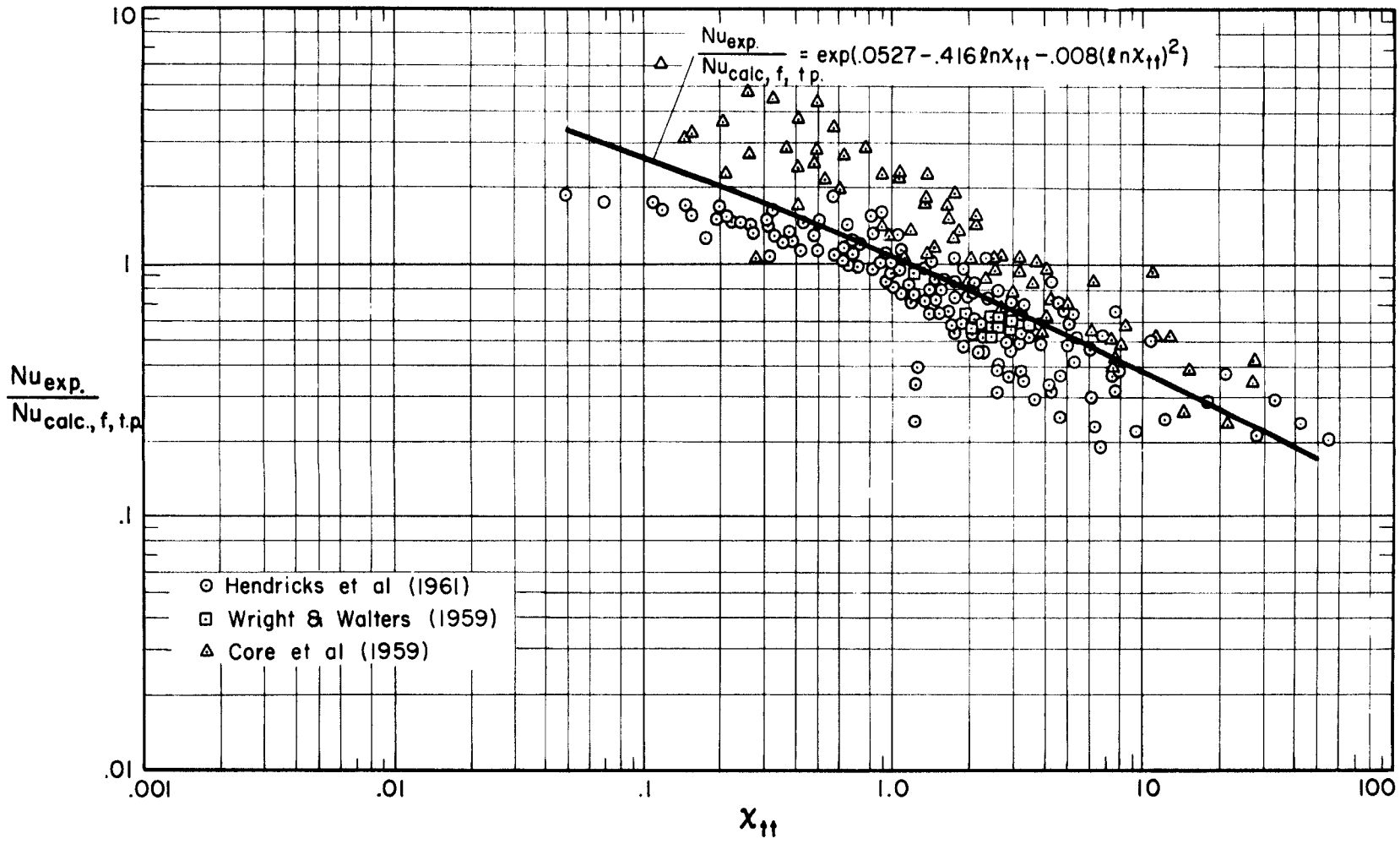

Figure 3.1 Two-phase Nusselt number ratio vs X_{tt}

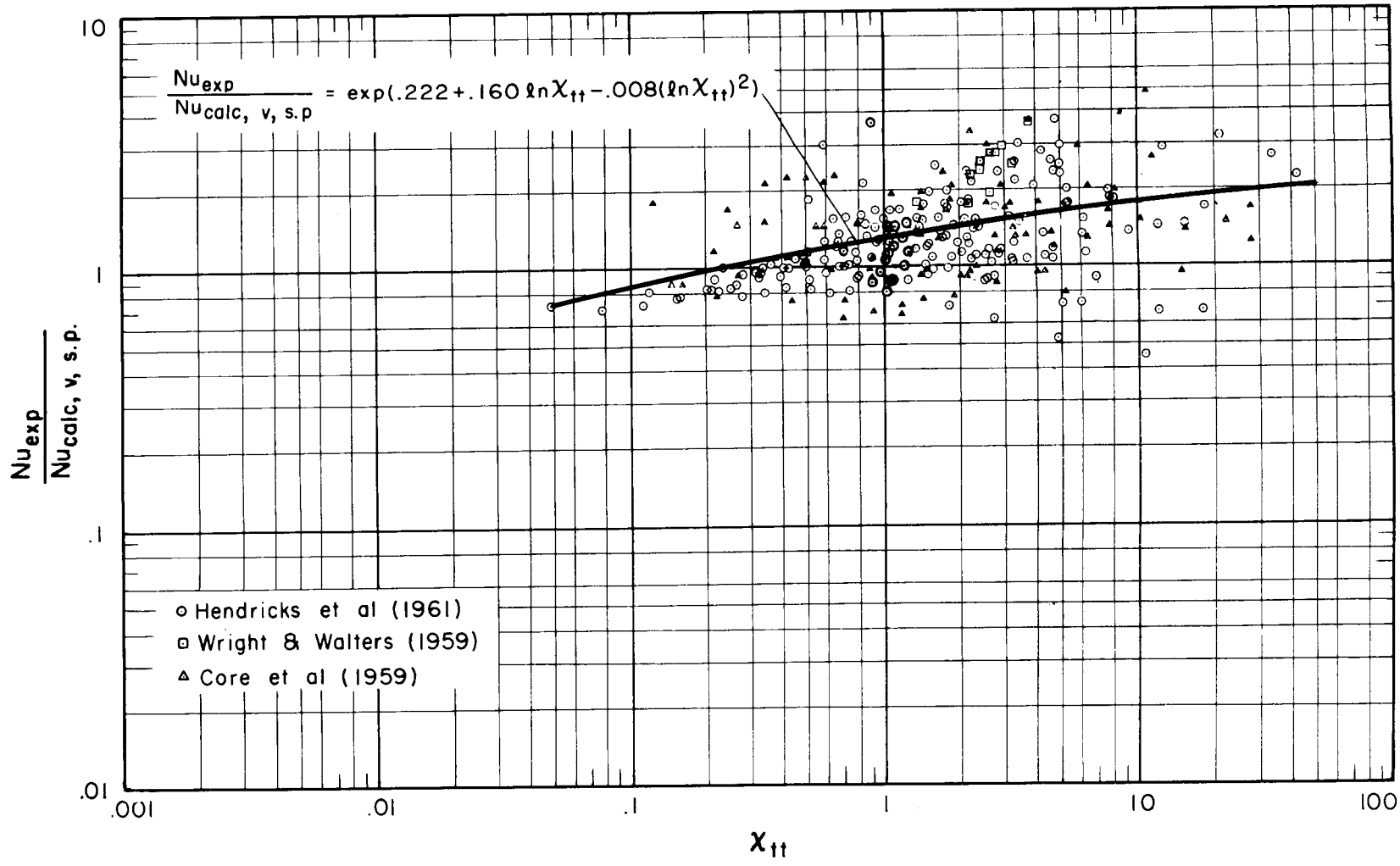

Figure 3.2 Single-phase Nusselt number ratio vs X_{tt}.

$$\left(\frac{Nu_{exp}}{Nu_{calc,f,t.p.}}\right)(Bo.No.)^{-0.40} = f(X_{tt}) , \tag{3.13}$$

where

$$Bo.No. = \frac{q/A}{\lambda G_{mix}} \tag{3.14}$$

Examination of the factors involved in the definition of the boiling number leads to the interpretation of the boiling number as being a ratio of the vapor generation to the mass flow rate in the tube or in a sense an index of the boiling-induced flow normal to the axis relative to the axial flow.

Thus, for a fixed power input to the tube, a large boiling number would indicate well developed boiling where velocity is not influential and a small boiling number would indicate forced convection effects are controlling (high velocity).

The results of this plot are shown in figure 3.3.

3.3.2. Film Boiling-Nusselt Number Ratio vs x(quality)

Since quality appeared to be the controlling parameter in X_{tt} and, perhaps, in the heat transfer mechanism, (3.1), (3.9), and (3.13) were all plotted as a function of quality (f(x)) in place of $f(X_{tt})$. Results of these plots are shown in figures 3.4, 3.5, and 3.6.

Another type of quality correlation proposed in a recent publication by von Glahn [1964] was also included herein:

$$\frac{Nu_{exp}}{Nu_{v,calc}} F_{tp} = f(X_f) \tag{3.15}$$

where

$$Nu_{v,calc} = 0.023\, Re_v^{0.8}\, Pr_v^{0.4} \tag{3.16}$$

$$Re_v = \frac{DG_{mix}}{\mu_v} \tag{3.17}$$

$$Pr_v = \frac{C_{p_v}\mu_v}{k_v} \tag{3.18}$$

$$X_f = \frac{x_f}{1 - x_c} \tag{3.19}$$

$$F_{tp} = 2.0 \times 10^{-10}\alpha_1(\beta)^{0.167}(\gamma)^{[1.8-(X_f)^a]}(0.005)^{[1-(X_f)^a]}(N_{bo.no.})^{-0.667} \tag{3.20}$$

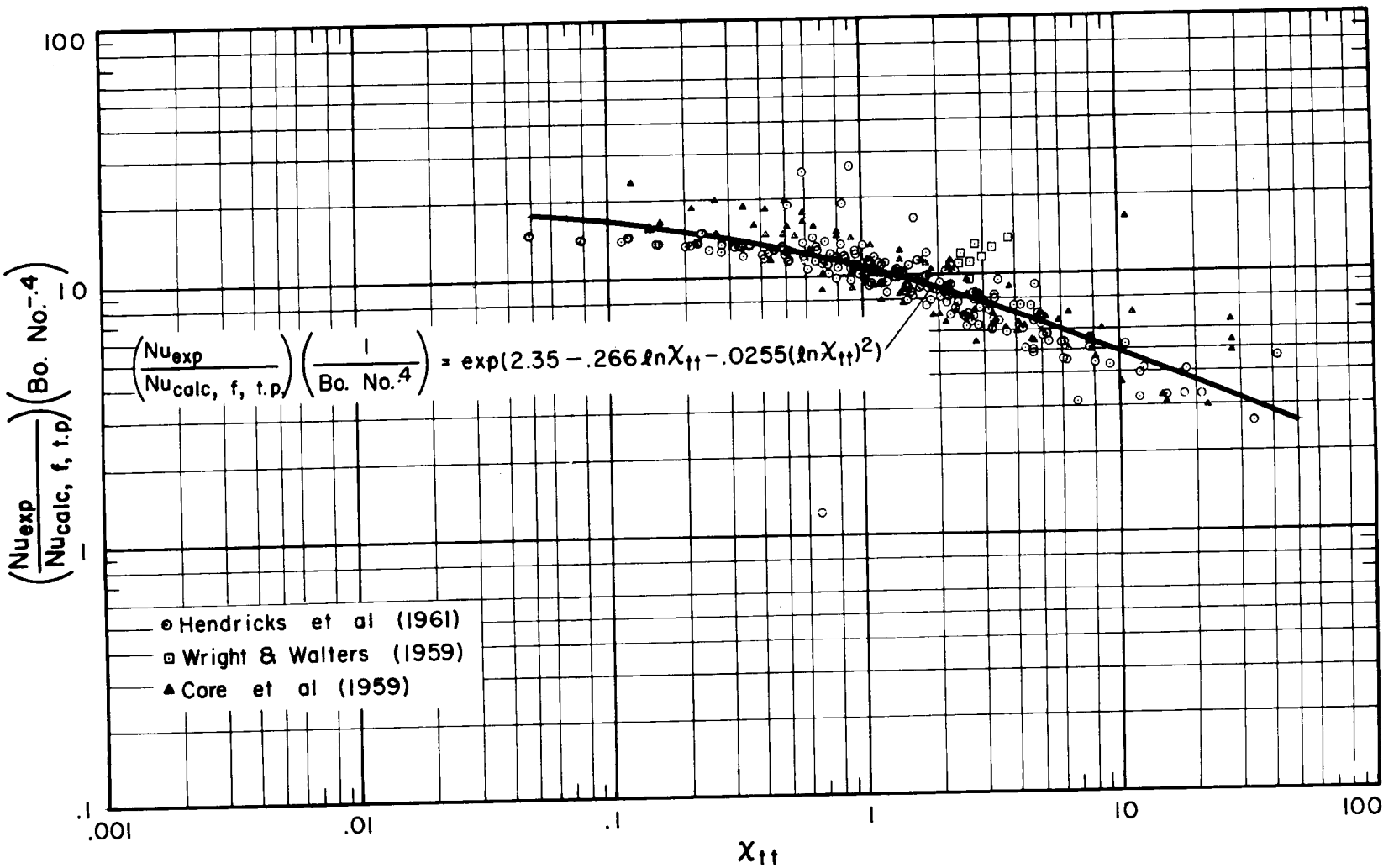

Figure 3.3 Two-phase Nusselt number ratio times boiling number factor vs X_{tt}

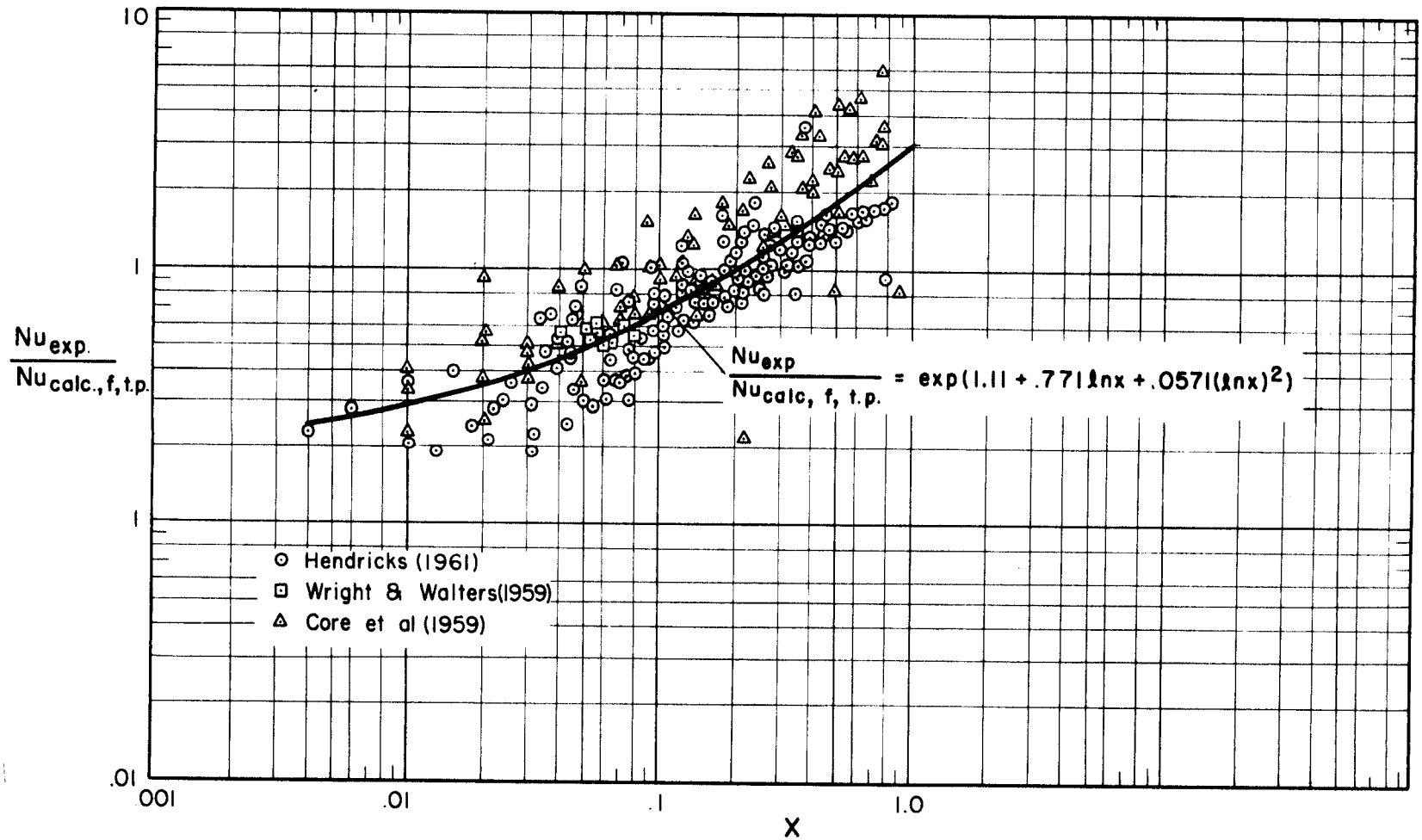

Figure 3.4 Two-phase Nusselt number ratio vs x(quality)

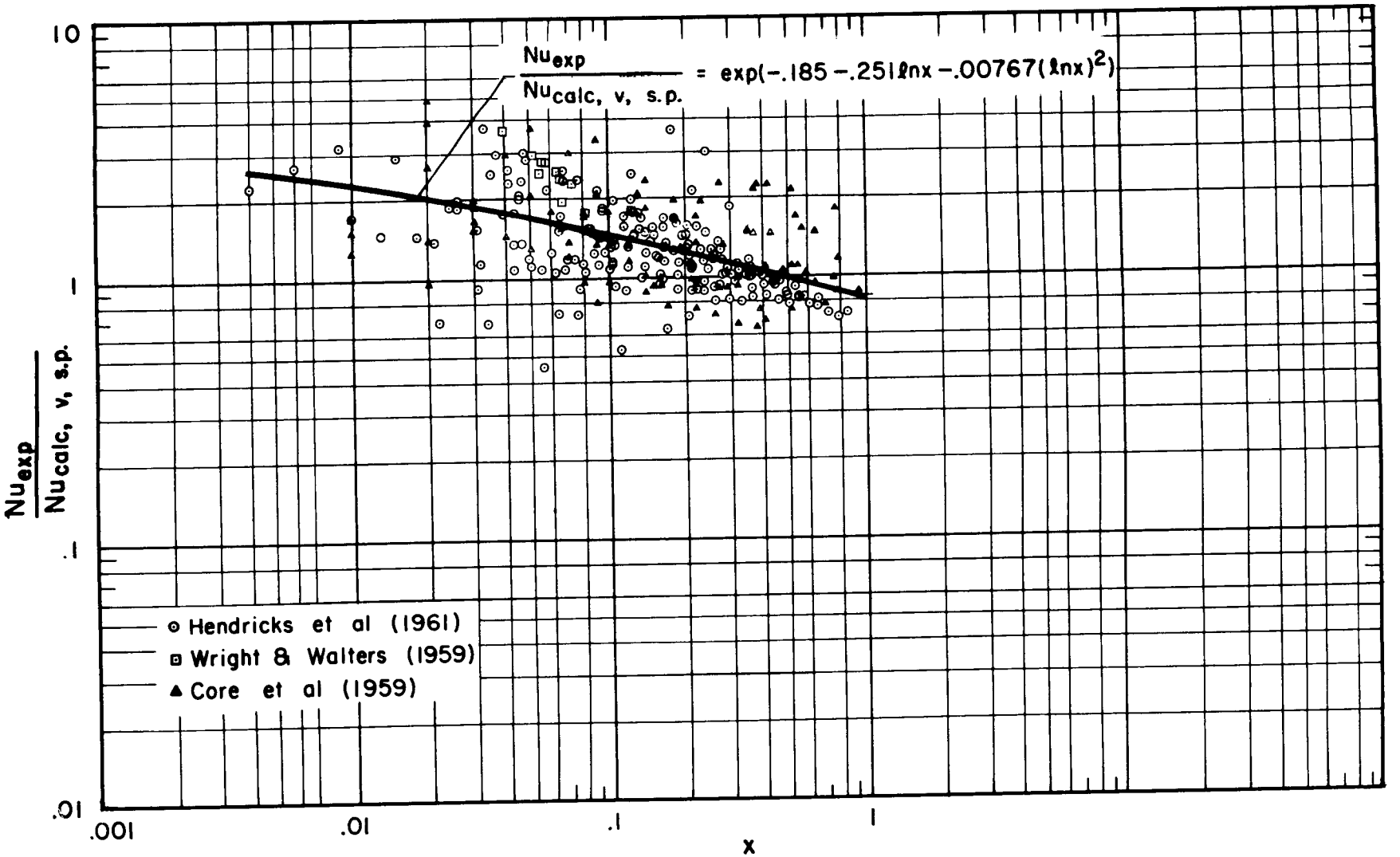

Figure 3.5 Single-phase Nusselt number ratio vs x(quality)

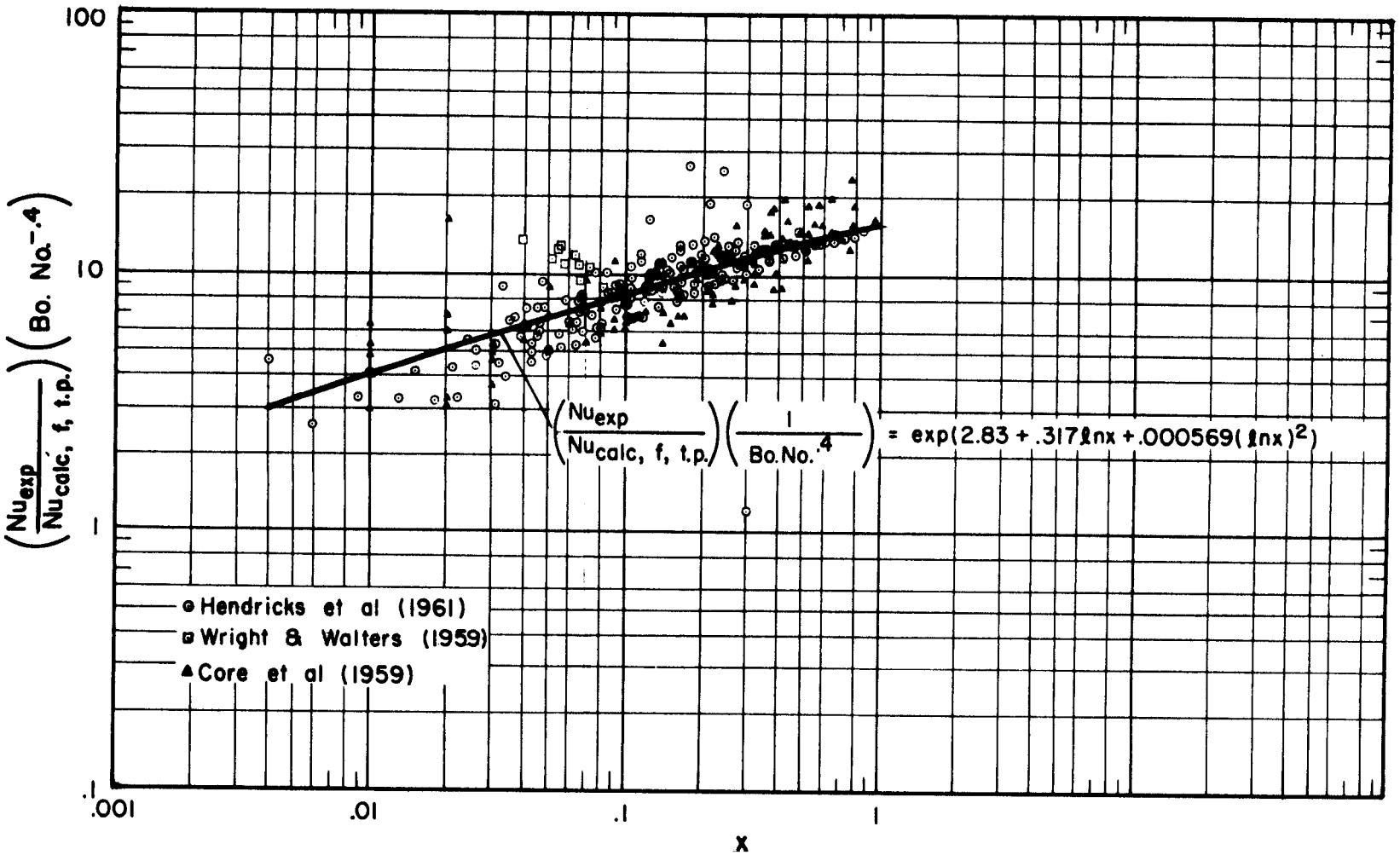

Figure 3.6 Two-phase Nusselt number ratio times boiling number factor vs x(quality)

$$\alpha_1 = \left[4.2\left(1 - \frac{Re_v^2}{Re_v^2 + 5.85 \times 10^{11}} \right) + 0.92 \right] \tag{3.21}$$

$$\beta = \left[\frac{g(\rho_\ell - \rho_v)\, D^2}{\sigma_\ell} \right] \tag{3.22}$$

$$\gamma = \left[Re_v \left(1 + \frac{2500}{\Gamma} \right) \right] \tag{3.23}$$

$$\Gamma = \left(\frac{q/A\ D}{\mu_v \lambda} \right) \tag{3.24}$$

$$N_{bo.no.} = \frac{\mu_v^2 \sqrt{g(\rho_\ell - \rho_v)}}{\rho_v (\sigma_\ell)^{1.5}} \quad \text{and} \tag{3.25}$$

$$a = \left\{ 0.5 \left[1 - \frac{(L_e/D)^2}{(L_e/D)^2 + 0.05} \right] + 0.13 \right\} = 0.13 \text{ for } L_e/D > 3.5 \tag{3.26}$$

Results for the von Glahn correlation are shown in figure 3.7 for the data of this study.

3.3.3. Film Boiling - superposition

A simple superposition correlation was tested with the available cryogenic data. This procedure has been suggested by numerous papers and textbooks. The heat transfer coefficient calculated from Breen and Westwater's [1962] film pool boiling correlation (2.3) was added directly to the heat transfer coefficient calculated from the modified Sieder-Tate single-phase forced convection correlation. That is

$$h_{pred} = h_{\substack{conv \\ s.p.v.}} + h_{\substack{film \\ pool \\ boil}} \tag{3.27}$$

where

$$h_{\substack{conv \\ s.p.v.}} = 0.026 \left(Re_{v.s.p.} \right)^{0.8} \left(Pr_v \right)^{0.33} \left(\frac{\mu_v}{\mu_w} \right)^{0.14} \left(\frac{k_v}{D} \right) \tag{3.28}$$

$$h_{\substack{film \\ pool \\ boil}} = \left\{ 4.94 \left[\frac{(\Delta\rho_f)^{0.375}}{\sigma^{0.125}} \right] + 0.115 \left[\frac{\sigma^{0.375}}{D(\Delta\rho_f)^{0.125}} \right] \right\} \left[\frac{k_f^3 \lambda' \rho_f}{\mu_f} \right]^{0.250} (\Delta T)^{-.250} \tag{3.29}$$

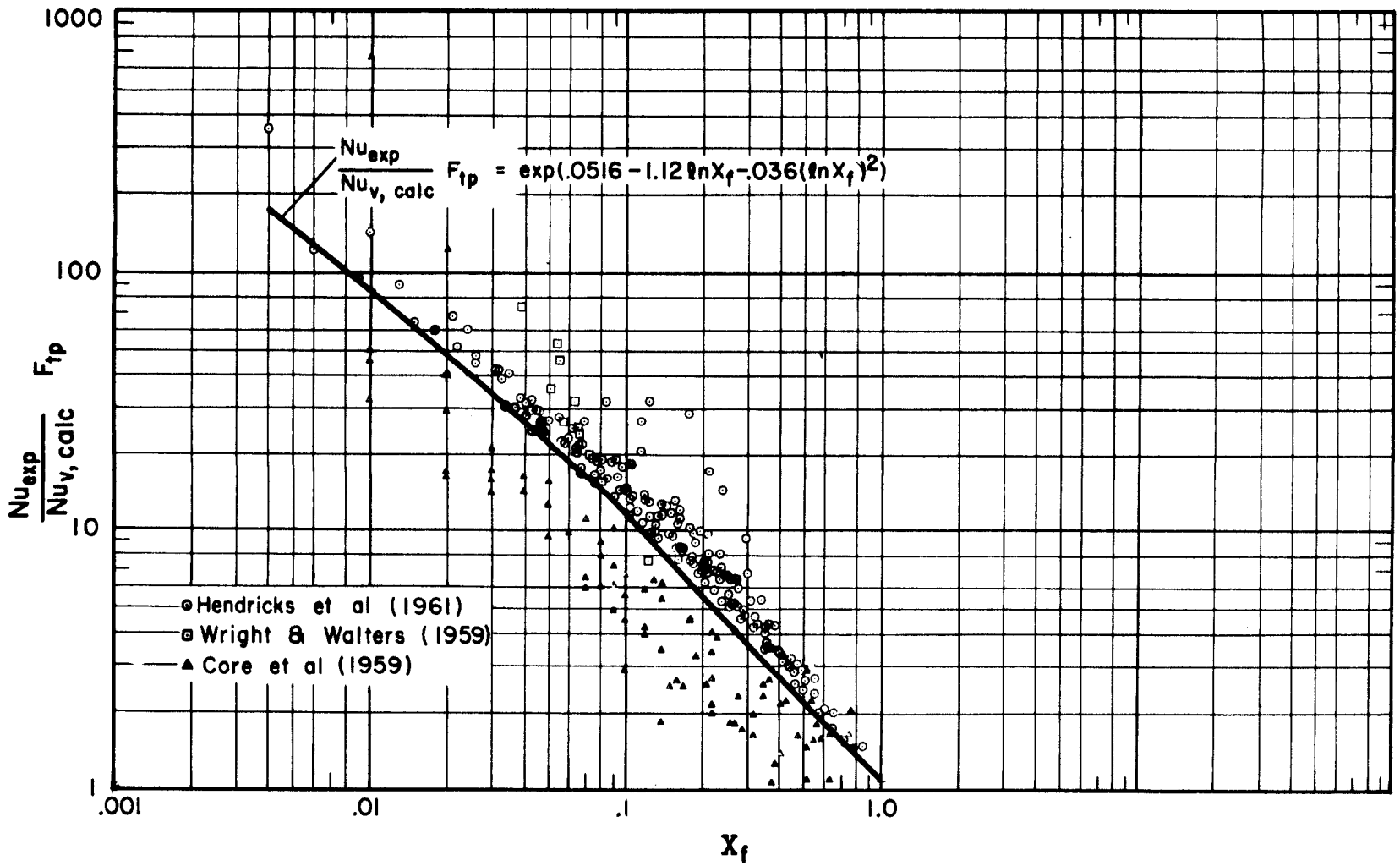

Figure 3.7 vonGlahn Nusselt number ratio times two-phase correlation factor vs film vaporization parameter, X_f

$$\lambda' = \left[\frac{\lambda + 0.340(C_p)_f(\Delta T)}{\lambda}\right]^2 . \tag{3.29a}$$

Results of plotting h_{pred} vs h_{exp} are shown in figure 3.8.

3.3.4. Nucleate Boiling - superposition

Simple superposition (h_{conv} based on the liquid phase) and the correlations of Chen [1963] and Kutateladze [1963] were tested for the nucleate boiling region.

The simple superposition correlation is

$$h_{pred} = h_{\substack{conv \\ s.p.\ell.}} + h_{\substack{nucleate \\ pool \\ boil}} \tag{3.30}$$

where

$$h_{\substack{conv \\ s.p.\ell.}} = 0.023(Re_\ell)^{.8}(Pr_\ell)^{.4}\left(\frac{k_\ell}{D}\right) \tag{3.31}$$

$$Re_\ell = DG_{mix}/\mu_\ell \tag{3.31a}$$

and

$$h_{\substack{nucleate \\ pool \\ boil}} = 0.487(10)^{-10}\left[\frac{k_\ell \rho_\ell^{1.282} P^{1.750} (C_p)_\ell^{1.500}}{(\lambda\rho_v)^{1.500}\sigma^{0.906}\mu_\ell^{0.626}}\right](\Delta T)^{1.500} . \tag{3.32}$$

Chen's correlation is

$$h_{pred} = (h_{fc})F + (h_{f-z})S , \tag{3.33}$$

where

$$h_{fc} = \left(\frac{k_\ell}{D}\right)(0.023)(Re_\ell)^{0.8}(Pr_\ell)^{0.4} \tag{3.34}$$

$$h_{f-z} = (0.00122)\frac{k_\ell^{0.79}(C_p)_\ell^{0.45}\rho_\ell^{0.49}(\Delta T)^{0.24}(\Delta P)^{0.75}}{\sigma_\ell^{0.5}\mu_\ell^{0.29}\lambda^{0.24}\rho_v^{0.24}} \tag{3.35}$$

F = correction factor which is a function of X_{tt} and accounts for increased convective turbulence due to the presence of vapor.

S = correction factor which is a function of $Re'_\ell F^{1.25}$ and accounts for suppression of bubble growth due to flow:

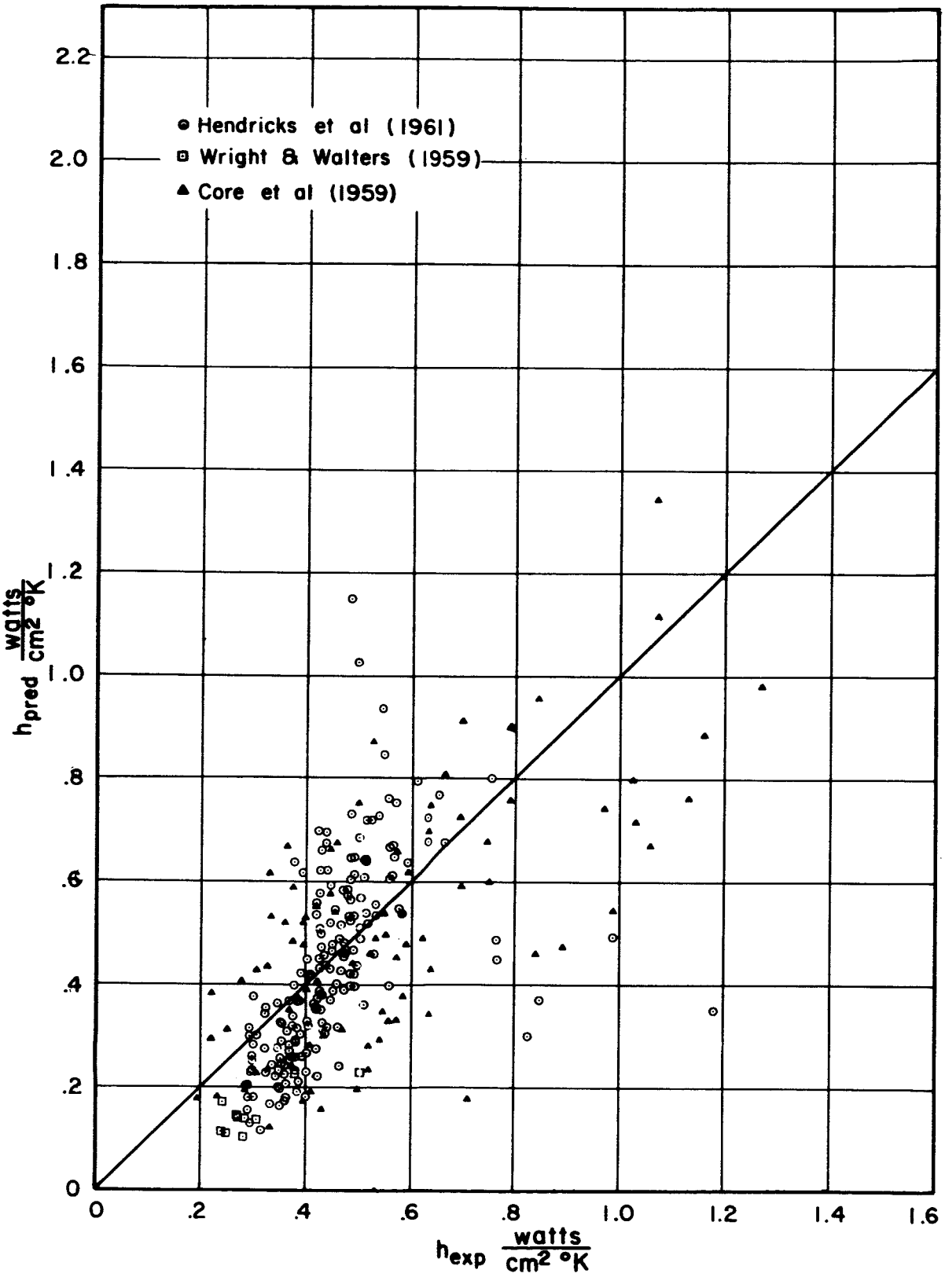

Figure 3.8 h_{pred} vs h_{exp} (film boiling superposition correlation)

$$(Re'_{\ell}) = \frac{DG_{mix}(1-x)}{\mu_{\ell}}$$

Kutateladze's correlation is

$$\frac{h_{pred}}{h_{conv\ s.p.\ell.}} = \sqrt[n]{1 + \left(\frac{h_{nucleate\ pool\ boil}}{h_{conv\ s.p.\ell.}}\right)^n} \tag{3.36}$$

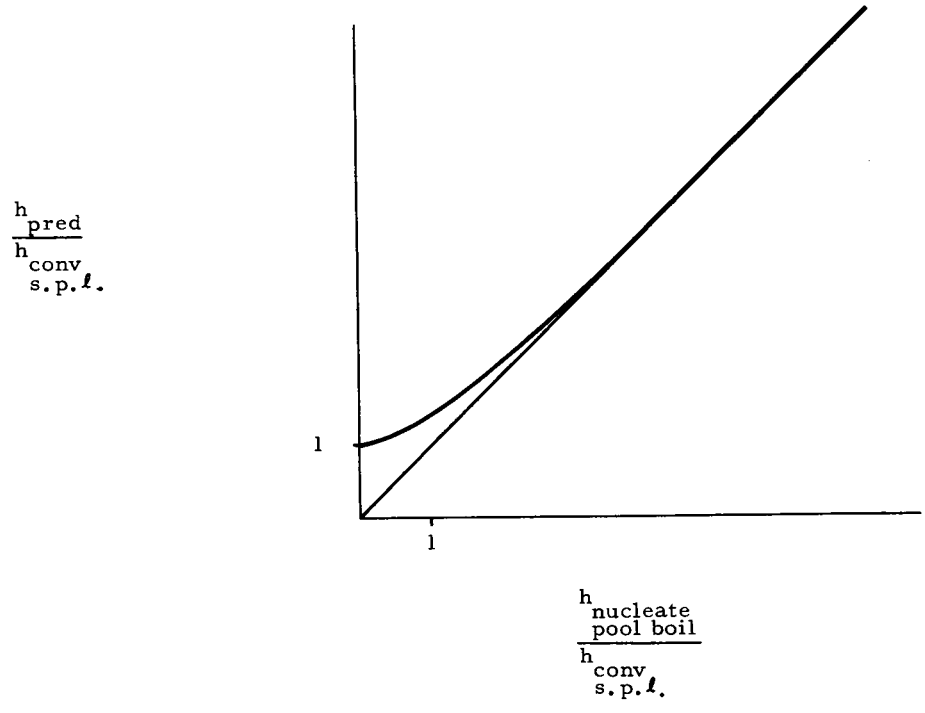

Figure 3.9 Functional dependence of h_{pred} on $\frac{h_{nucleate\ pool\ boil}}{h_{conv\ s.p.\ell.}}$ according to Kutateladze (1963).

Consider a plot of $\frac{h_{pred}}{h_{conv_{s.p.\ell.}}}$ vs $\frac{h_{nucleate\ pool\ boil}}{h_{conv_{s.p.\ell.}}}$ as shown in figure 3.9,

or $$\frac{h_{pred}}{h_{conv_{s.p.\ell.}}} = f\left(\frac{h_{nucleate\ pool\ boil}}{h_{conv_{s.p.\ell.}}}\right) .$$

As $\frac{h_{nucleate\ pool\ boil}}{h_{conv_{s.p.\ell.}}} \rightarrow 0$, i.e., for no boiling, where velocity effects are controlling,

then $\frac{h_{pred}}{h_{conv_{s.p.\ell.}}} = 1$ and $f' = 0$.

As $\frac{h_{nucleate\ pool\ boil}}{h_{conv_{s.p.\ell.}}} \rightarrow \infty$, i.e., for well developed boiling where velocity effects are not influential,

then $\frac{h_{pred}}{h_{conv_{s.p.\ell.}}} = \frac{h_{nucleate\ pool\ boil}}{h_{conv_{s.p.\ell.}}}$ and $f' = 1$.

A function which satisfies the above criteria is (3.36). Values of n from 0.7 to 2.0 were used in this study in an attempt to correlate the limited data available. Results of plots of h_{pred} vs h_{exp} for (3.30), (3.33), and (3.36) are shown in figures 3.10, 3.11, and 3.12, respectively. Figure 3.12 reflects results when n = 2 in (3.36), since that value of n produced the best results.

3.3.5. Burnout or Transition Point

Since the only burnout data for cryogenic liquids found was that of Lewis, et al. [1962], this paper has merely reproduced their curve, showing a comparison of burnout heat flux for cryogenic liquids with the water correlation of Lowdermilk, et al. [1958].

Lowdermilk's correlation is

$$\left.\begin{aligned} (q/A)_{burnout} &= \frac{270\ G^{0.85}}{D^{0.2}(L/D)^{0.85}}, \quad 1 < \frac{G}{(L/D)^2} < 150 \\ (q/A)_{burnout} &= \frac{1400\ G^{0.5}}{D^{0.2}(L/D)^{0.15}}, \quad 150 < \frac{G}{(L/D)^2} < 10000 \end{aligned}\right\} . \qquad (3.37)$$

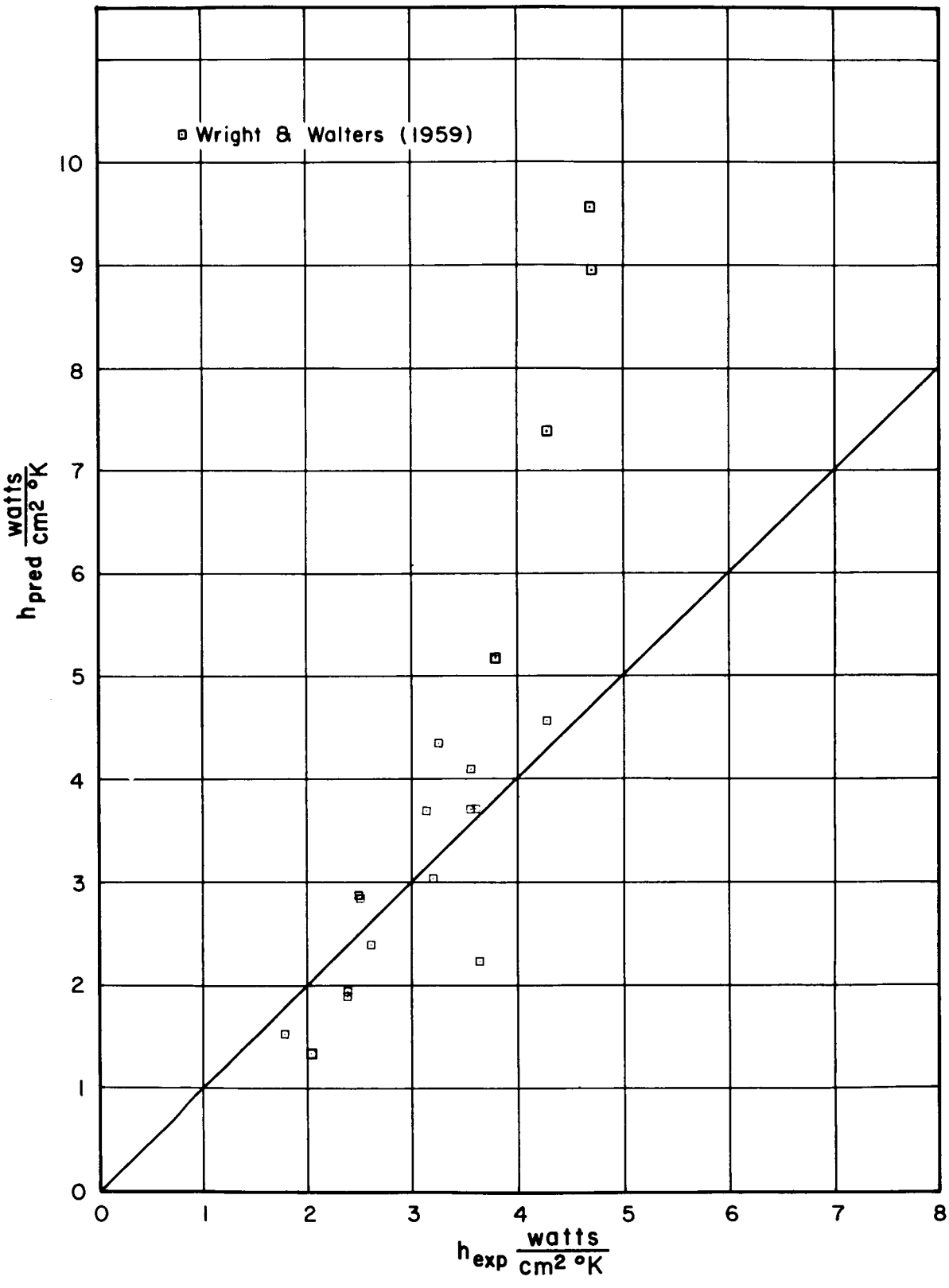

Figure 3.10 h_{pred} vs h_{exp} (nucleate boiling superposition correlation)

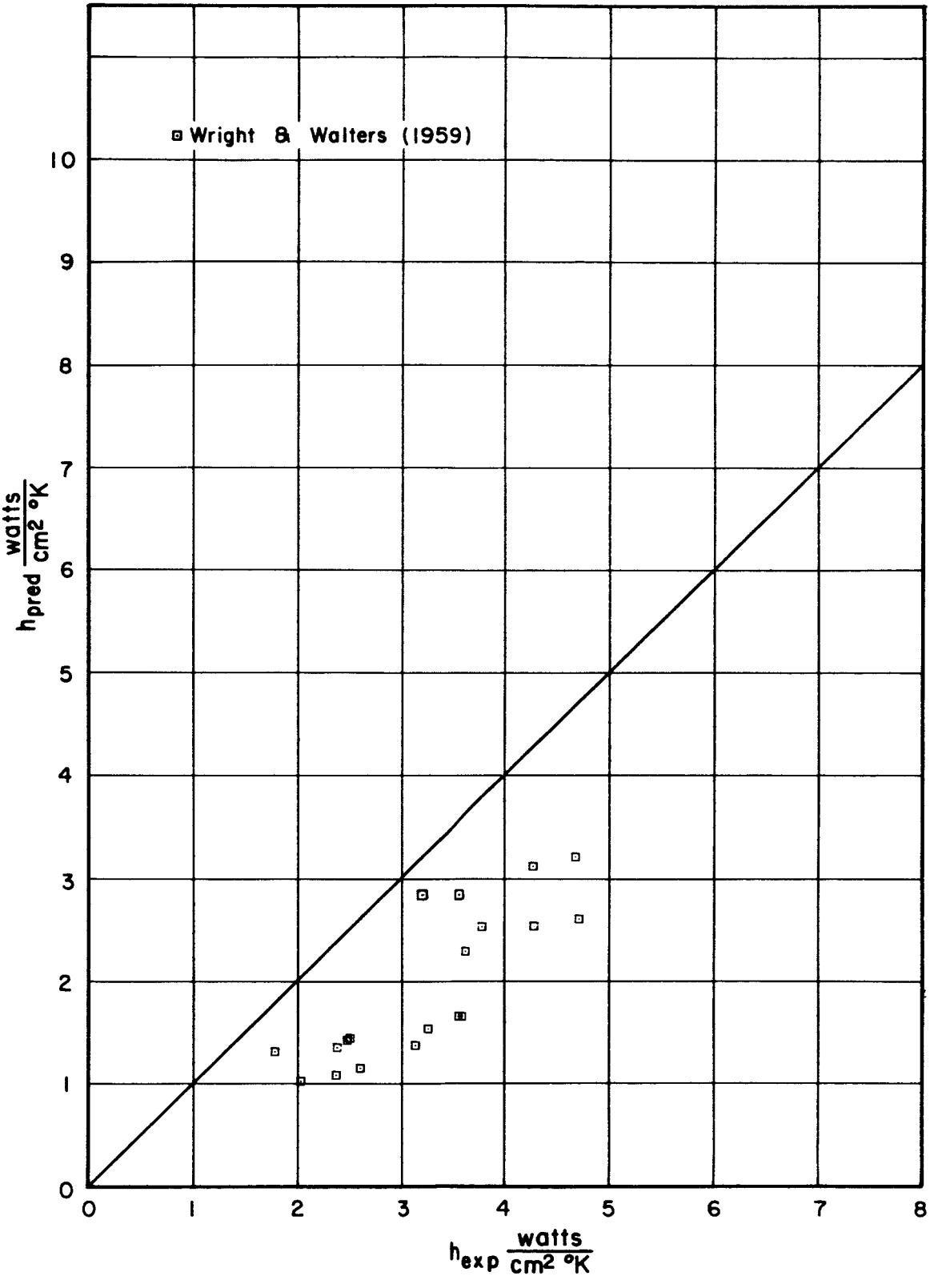

Figure 3.11 h_{pred} vs h_{exp} (Chen correlation)

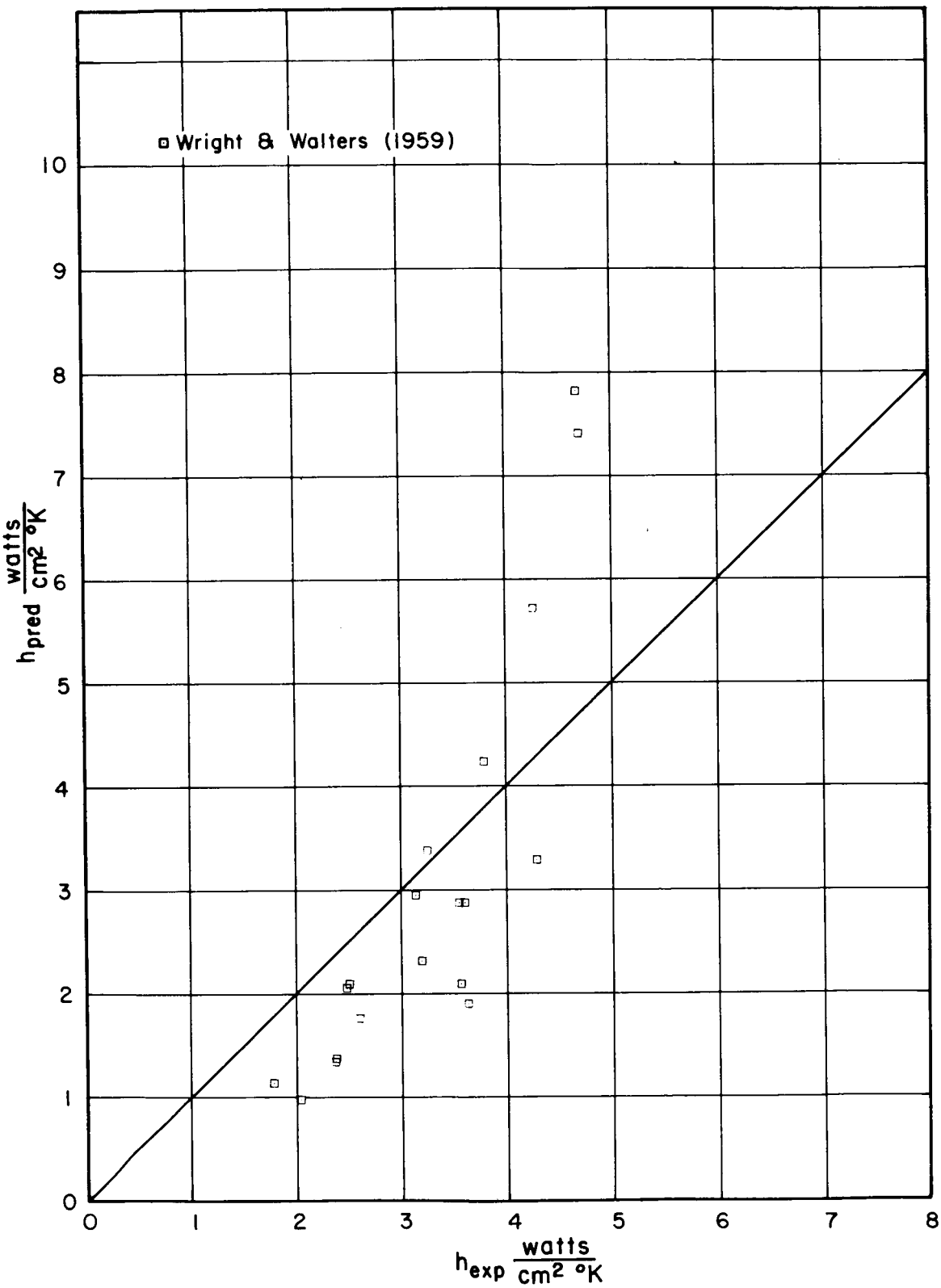

Figure 3.12 h_{pred} vs h_{exp} (Kutateladze correlation)

3.4. Discussion of Correlations and Results

The data used in this study are limited in numbers of points, ranges of fluid properties, and in experimental systems. Figures 3.1 through 3.7 illustrate significant differences in the three sets of data considered; furthermore, no attempt was made to cull the data for accuracy. Thus no conclusions regarding the absolute reliability of the correlations are implied; however it is felt that some general guides are indicated by this comparative study.

Table 3.3 gives the equations of the best fit curves of the plots given in column 2. The equations were determined using the method of least squares by means of a digital computer. By applying the resulting least squares fit curve equations and the superposition type predictive equations, an h_{pred} was then calculated for each data point. The figures given in column 5 of table 3.3 are the results of plotting h_{pred} vs h_{exp} for each correlation. As a means of comparing the relative success or failure of all the film boiling correlations and all the nucleate boiling correlations for the data considered, a root mean square fractional deviation, $\underline{d}$, of the predicted value, h_{pred}, from the measured value, h_{exp}, is given in column 7. The $\underline{d}$ is defined as

$$\underline{d} = \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{h_{pred_i} - h_{exp_i}}{h_{exp_i}} \right)^2}{n}} ,$$

where n is the number of data points. If the data population followed a normal distribution pattern, $\pm d$ would be the spread within which about 68% of the data occur and $\pm$ 2d would be the spread within which about 95% of the data are found. Even if the distribution varies considerably from a normal distribution, it is felt that $\underline{d}$ may be used as a measure of the relative reliability of all the correlations.

Although all results for $\underline{d}$ were based on the least squares equations shown in columns 4 and 6 of table 3.3, it is felt that, for the range of X_{tt} and x shown in figures 3.1 through 3.7, there would be no significant loss of accuracy if the last term in each of the least squares equations is ignored.

This study also performed the aforementioned calculations for h_{pred} and $\underline{d}$, using Hendricks, et al. [1961] data only. These results also are shown in column 7 of table 3.3. It is interesting to note that in this case the single-phase Reynolds number and superposition systems do not correlate the data as well as do the correlations of von Glahn and $\frac{Nu_{exp}}{Nu_{calc,f,t.p.}} = f(X_{tt})$ or $f(x)$. The converse is true when all the data are considered. Furthermore, for Hendricks, et al. [1961] data only, the boiling number correlations are not as effective in reducing the data spread as they are when all data are used.

However, unless specifically stated otherwise, the following remarks are made with reference to the results obtained when all data [Core, et al. 1959, Wright and Walters, 1959, and Hendricks, et al. 1961] were used in the calculations of h_{pred} and $\underline{d}$.

3.4.1. X_{tt} and x Correlations without Boiling Number

The first four correlations shown in table 3.3 may be generally considered together. The X_{tt} correlations appear to be based on the analogy between heat and momentum transport. This system has been used extensively [Guerrieri and Talty, 1956; Dengler and Addoms, 1956; Hendricks, et al. 1961] and a further use of the analogy between momentum and mass transport has been proposed and used[Wicks III, and Dukler, 1960]. It would appear, however, for hydrogen that x is the controlling factor in X_{tt} and that a correlation with x might be simpler and just as satisfactory. Also, the means

TABLE 3.3 SUMMARY OF RESULTS

FILM BOILING CORRELATIONS

Authors	Correlation	Plot of Correlation Shown in:	Least Squares Fit Curve (All Data) Y = quantity on left side of equal sign in correlation column	Plot of h_{pred} vs. h_{exp} (All Data) shown in:	Least Squares Fit Curve (Hendricks, et al. Data Only) Y = quantity on left side of equal sign in correlation column	Root Mean Square Fractional Deviation, d			No. of Data Points		
						(All Data)	(Hendricks, et al. Data Only)	(Wright & Walters Data Only)	(All Data)	(Hendricks, et al. Data Only)	(Wright & Walters Data Only)
Hendricks, Graham, Hsu, and Friedman [1961]	$\frac{Nu_{exp}}{Nu_{calc,f,t.p.}} = f(X_{tt})$	Fig. 3.1	$\ln Y = (0.0527 - 0.416 \ln X_{tt} - 0.008(\ln X_{tt})^2)$	Fig. 3.13	$\ln Y = (-0.122 - 0.393 \ln X_{tt} - 0.0142(\ln X_{tt})^2)$	.605	.259	-	281	181	-
This Study	$\frac{Nu_{exp}}{Nu_{calc,f,t.p.}} = f(x)$	Fig. 3.4	$\ln Y = (1.11 + 0.771 \ln x + 0.0571(\ln x)^2)$	Fig. 3.14	$\ln Y = (0.848 + 0.654 \ln x + 0.0371(\ln x)^2)$	.584	.236	-	281	181	-
This Study	$\frac{Nu_{exp}}{Nu_{calc,v,s.p.}} = f(X_{tt})$	Fig. 3.2	$\ln Y = (0.222 + 0.160 \ln X_{tt} - 0.008(\ln X_{tt})^2)$	Fig. 3.15	$\ln Y = (0.193 + 0.164 \ln X_{tt} - 0.0232(\ln X_{tt})^2)$	.446	.406	-	281	181	-
This Study	$\frac{Nu_{exp}}{Nu_{calc,v,s.p}} = f(x)$	Fig. 3.5	$\ln Y = (-0.185 - 0.251 \ln x - 0.00767(\ln x)^2)$	Fig. 3.16	$\ln Y = (-0.324 - 0.334 \ln x - 0.0263(\ln x)^2)$	.414	.385	-	281	181	-
Ellerbrock, Livingood, and Straight [1962]	$\left(\frac{Nu_{exp}}{Nu_{calc,f,t.p}}\right)\left(\frac{1}{Bo.No.^{0.4}}\right) = f(X_{tt})$	Fig. 3.3	$\ln Y = (2.35 - 0.266 \ln X_{tt} - 0.0255(\ln X_{tt})^2)$	Fig. 3.17	$\ln Y = (2.32 - 0.257 \ln X_{tt} - 0.040(\ln X_{tt})^2)$	.209	.158	-	272	172	-
This Study	$\left(\frac{Nu_{exp}}{Nu_{calc,f,t.p}}\right)\left(\frac{1}{Bo.No.^{0.4}}\right) = f(x)$	Fig. 3.6	$\ln Y = (2.83 + 0.317 \ln x + 0.000569(\ln x)^2)$	Fig. 3.18	$\ln Y = (2.77 + 0.256 \ln x - 0.0166(\ln x)^2)$	.240	.183	-	272	172	-
von Glahn [1964]	$\frac{Nu_{exp}}{Nu_{v,calc}} F_{tp} = f(X_f)$	Fig. 3.7	$\ln Y = (0.0516 - 1.12 \ln X_f - 0.036(\ln X_f)^2)$	Fig. 3.19	$\ln Y = (0.258 - 1.18 \ln X_f - 0.0506(\ln X_f)^2)$	.681	.175	-	281	181	-
This Study	$h_{pred} = h_{\substack{conv \\ s.p.v}} + h_{\substack{film\ pool \\ boil}}$	Not Applicable	Not Applicable	Fig. 3.8	Not Applicable	.482	.317	-	281	181	-
NUCLEATE BOILING CORRELATIONS											
Chen [1963]	$h_{pred} = h_{fc} F + h_{f-z} S$	Not Applicable	Not Applicable	Fig. 3.11	Not Applicable	-	-	0.417	-	-	19
Kutateladze [1963]	$h_{pred} = \left(h_{\substack{conv \\ s.p.\ell}}\right) \cdot \sqrt{1 + \left(\frac{h_{\substack{pool \\ boil}}}{h_{\substack{conv \\ s.p.\ell}}}\right)^2}$	Not Applicable	Not Applicable	Fig. 3.12	Not Applicable	-	-	0.338	-	-	19
This Study	$h_{pred} = h_{\substack{conv \\ s.p.\ell}} + h_{\substack{nucleate \\ pool\ boil}}$	Not Applicable	Not Applicable	Fig. 3.10	Not Applicable	-	-	0.400	-	-	19

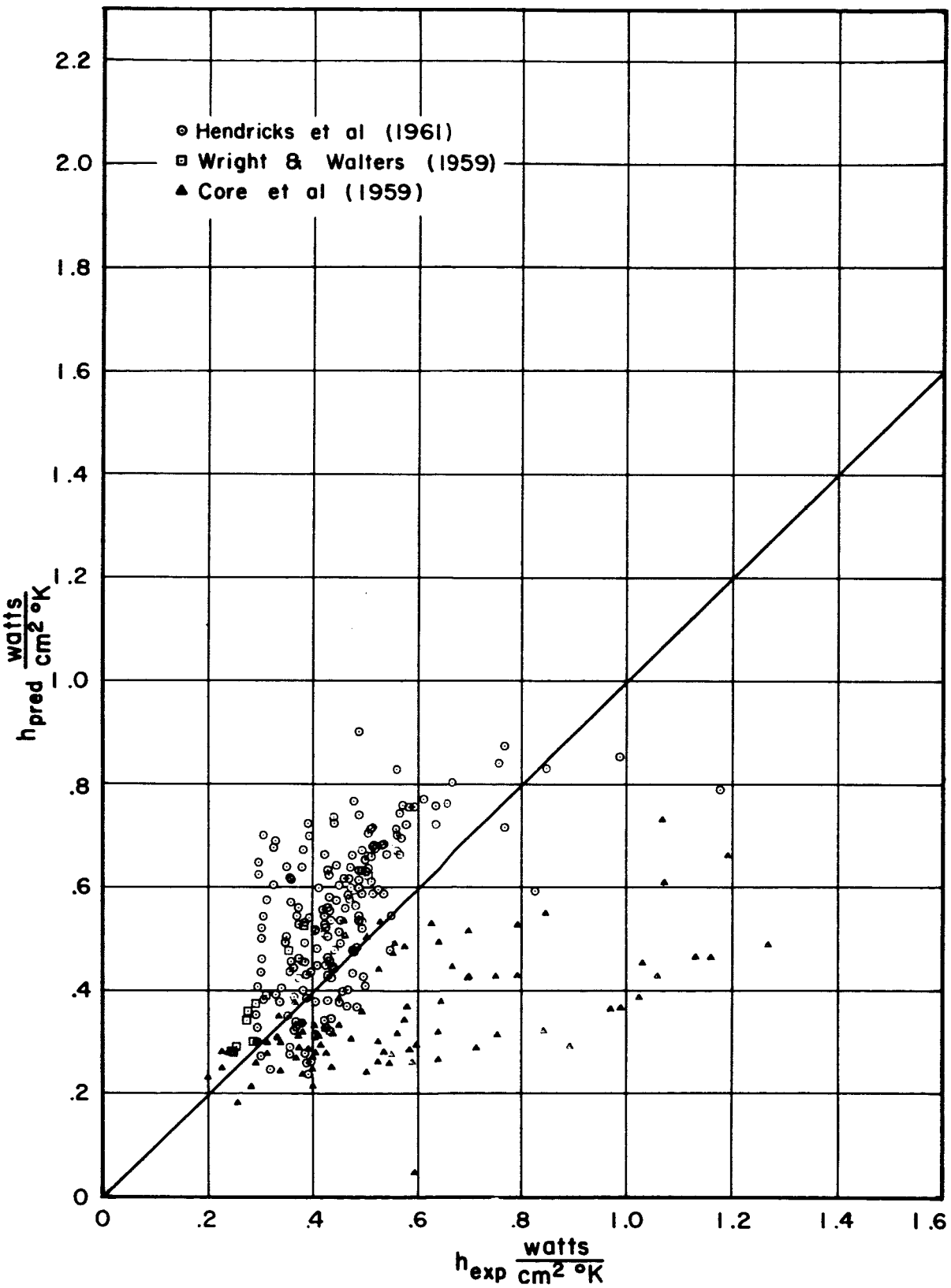

Figure 3.13 h_{pred} vs h_{exp} (two-phase Nusselt number ratio vs X_{tt} correlation)

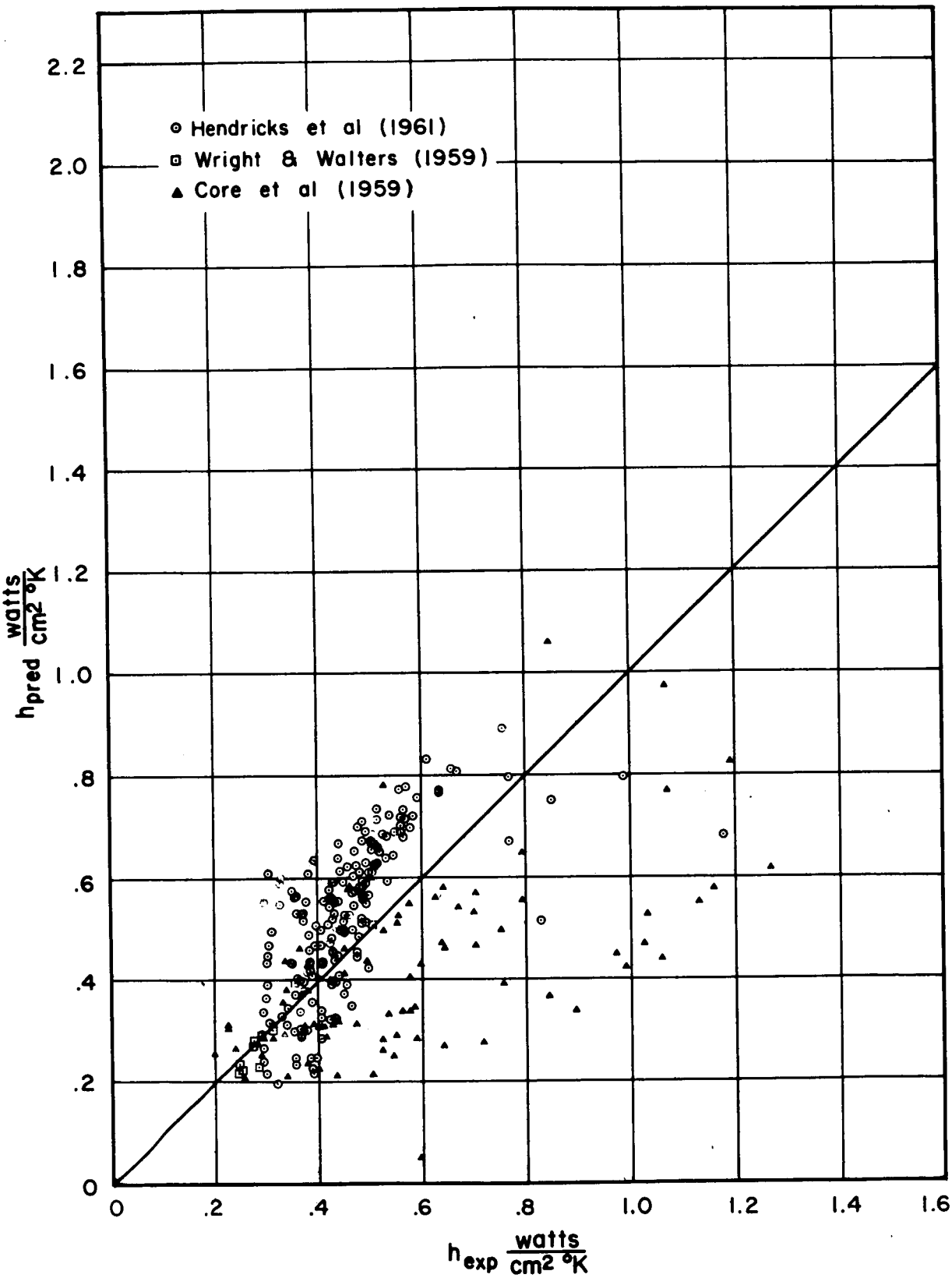

Figure 3.14 h_{pred} vs h_{exp} (two-phase Nusselt number ratio vs x correlation)

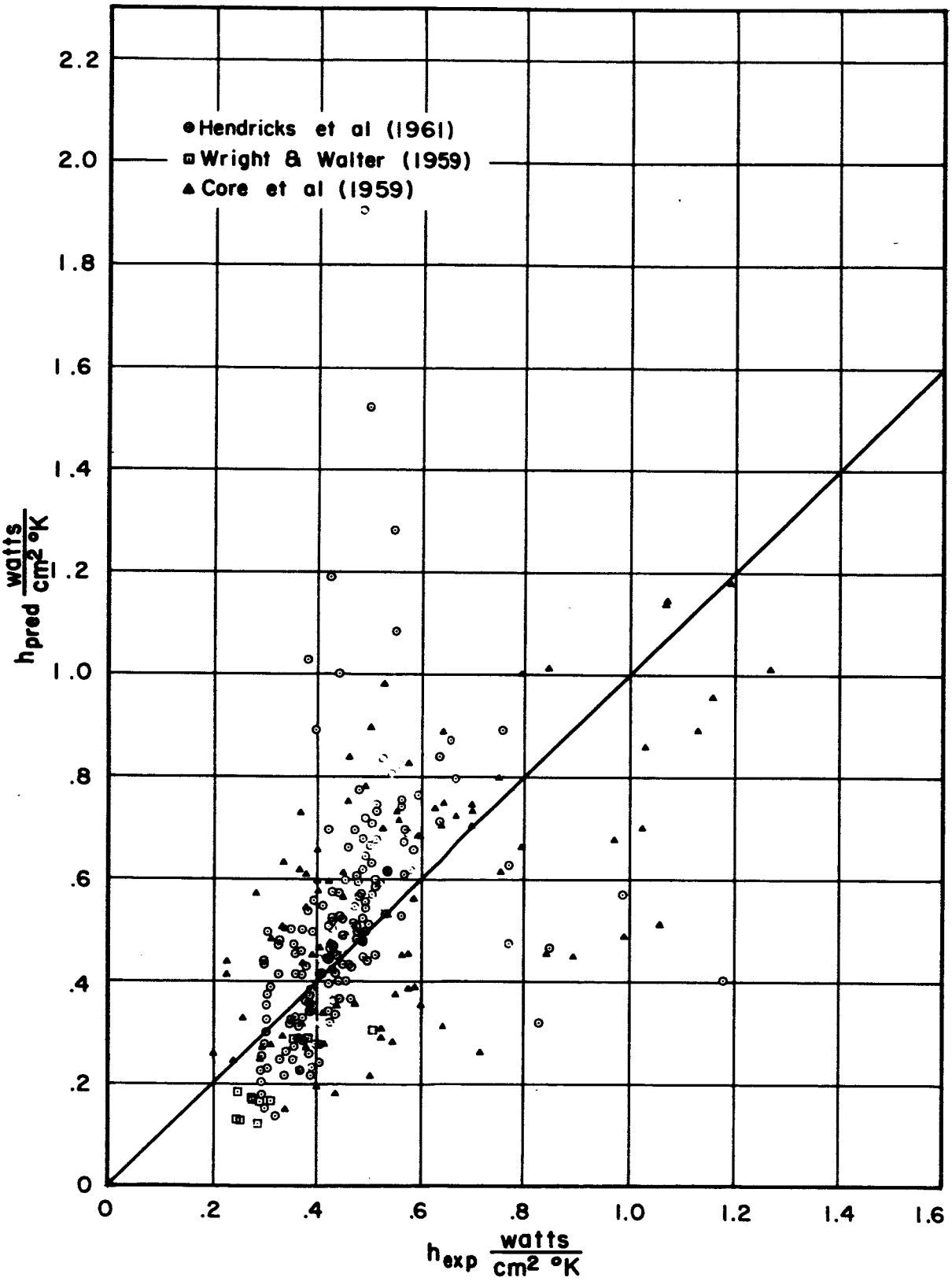

Figure 3.15 h_{pred} vs h_{exp} (single-phase Nusselt number ratio vs X_{tt} correlation)

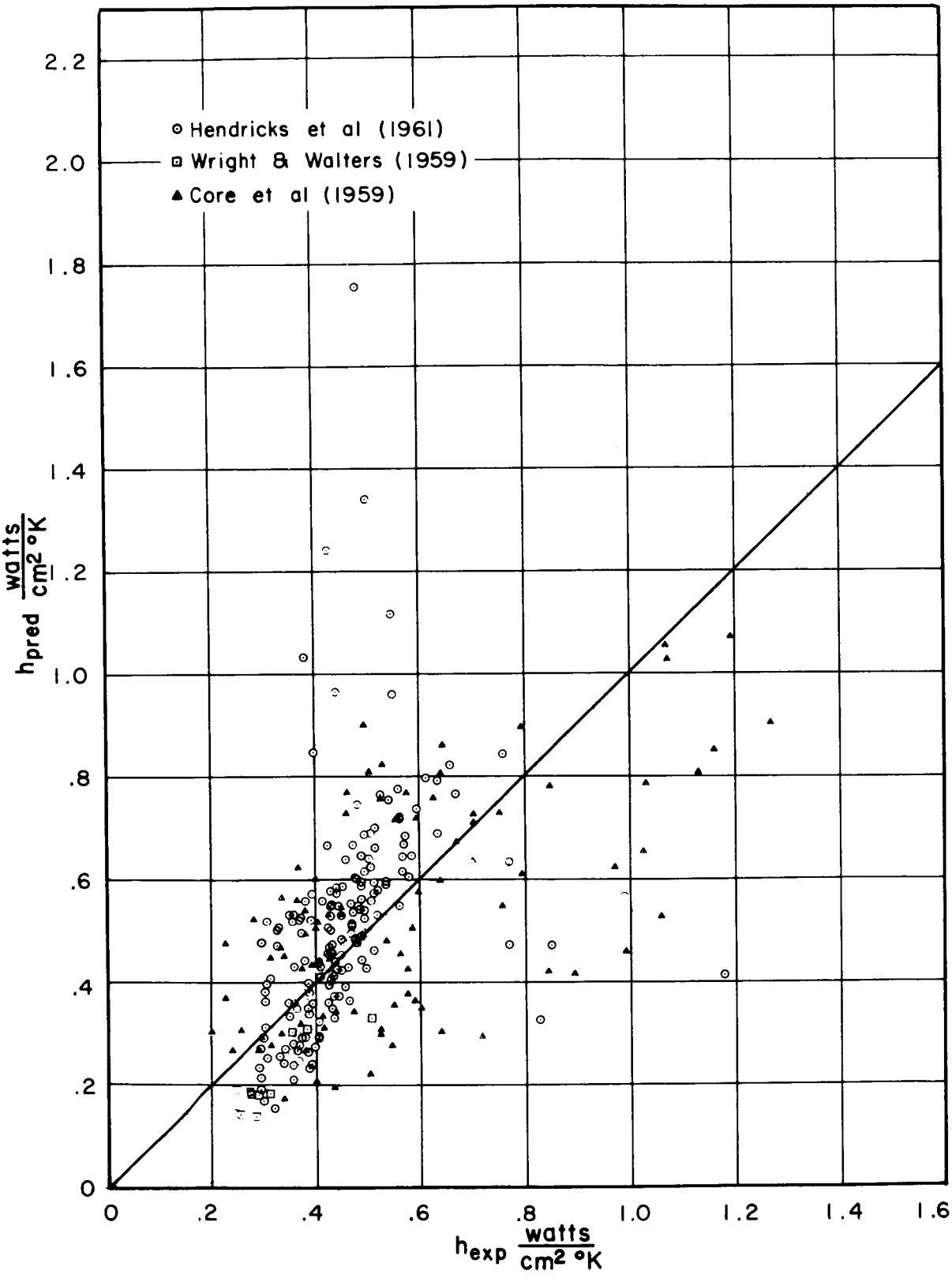

Figure 3.16 h_{pred} vs h_{exp} (single-phase Nusselt number ratio vs x correlation)

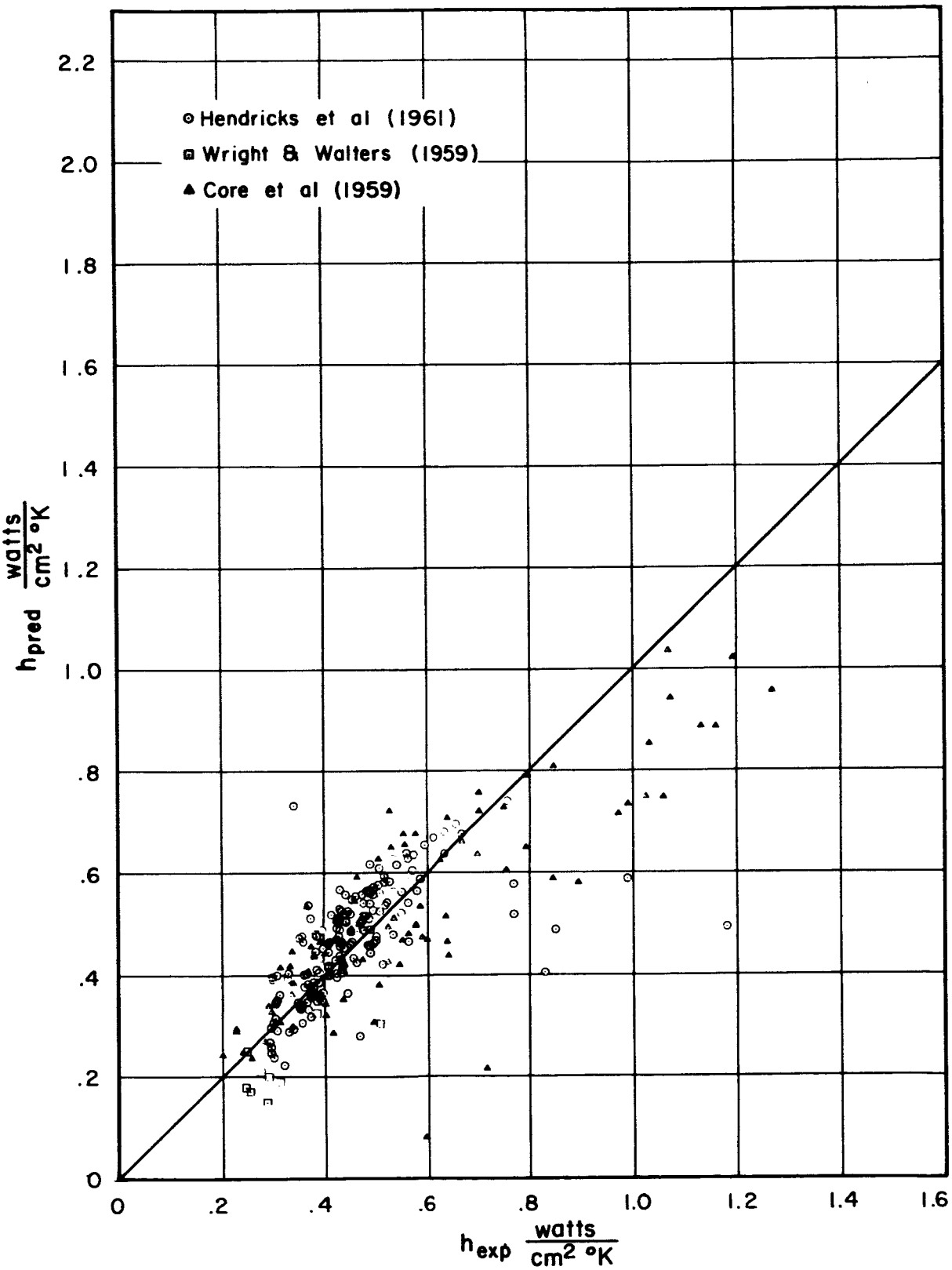

Figure 3.17 h_{pred} vs h_{exp} (two-phase Nusselt number ratio with boiling number vs X_{tt} correlation)

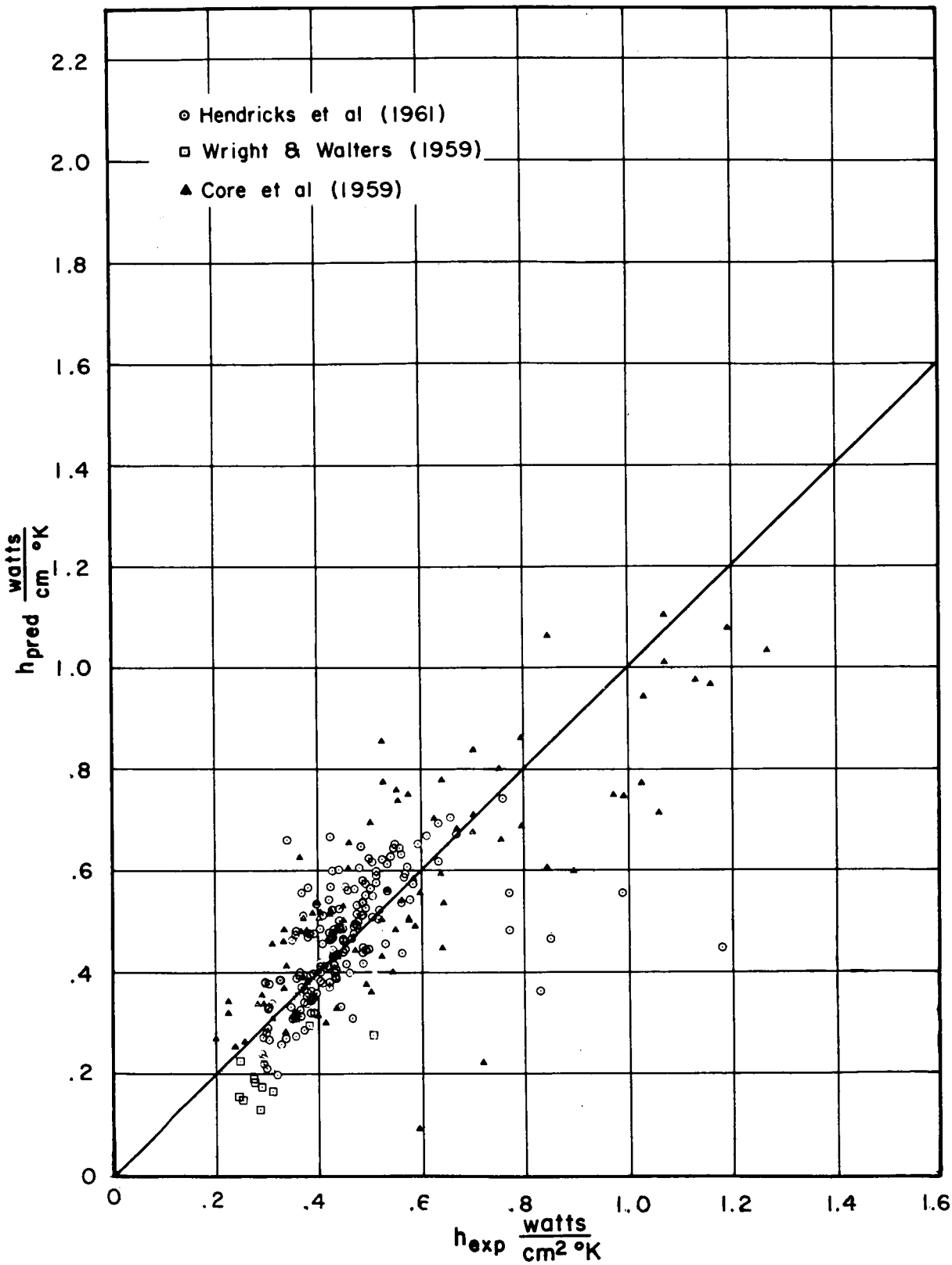

Figure 3.18 h_{pred} vs h_{exp} (two-phase Nusselt number ratio with boiling number vs x correlation)

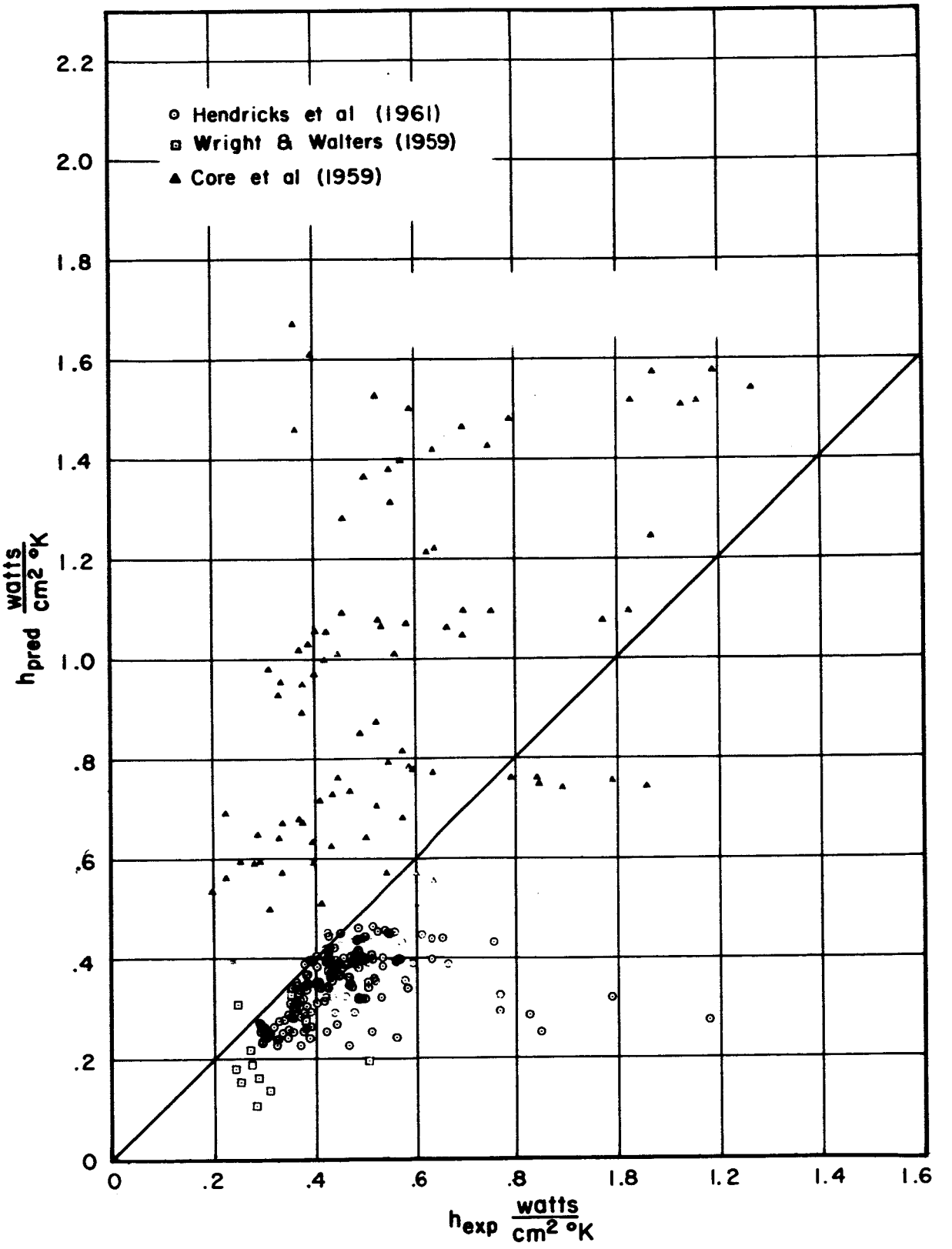

Figure 3.19 h_{pred} vs h_{exp} (vonGlahn correlation)

of computing Reynolds number varied with the investigators. Hendricks, et al. [1961] use a mean film density with the average velocity of the mixture and the viscosity of the gas evaluated at the mean film temperature $\left(\frac{\rho_{f,m,t.p.} U_{avg} D}{\mu_{f,v}}\right)$ and von Glahn [1964] evaluates the Reynolds number using the saturated vapor properties and the mass velocity of the mixture $\left(\frac{DG_{mix}}{\mu_v}\right)$. Since, for film boiling, the process is visualized as heat transfer through a vapor film to a liquid or liquid-vapor core, it was felt that perhaps a single-phase gas Reynolds number $\left(\frac{\rho_v U_{avg} D}{\mu_v}\right)$, rather than the two-phase gas Reynolds number $\left(\frac{\rho_{f,m,t.p.} U_{avg} D}{\mu_{f,v}}\right)$ used in the calculation of Nusselt number, might also produce a successful correlation. All of these considerations (except the von Glahn approach) variously combined have produced the first four correlations shown in figures 3.1, 3.2, 3.4, and 3.5. The $\bar{d}$ values for these correlations indicate that for these data the simpler system of figures 3.5 and 3.16 has provided the best correlation. This is not true when the data of Hendricks, et al. [1961] are used alone. It appears then, that for hydrogen, accuracy is not lost by the use of quality rather than X_{tt} as a correlating parameter and may not be lost by use of the single-phase gas at average velocity in the determination of the calculated Nusselt number.

3.4.2. X_{tt} and x Correlations with Boiling Number

Several investigators [Schrock and Grossman, 1959; Ellerbrock, et al., 1962] have found that by use of the boiling number the correlations have been markedly improved. Figure 3.20, which is a plot of $\frac{Nu_{exp}}{Nu_{calc,f,t.p.}}$ vs X_{tt} for some of the data of Hendricks, et al. [1961] shows, for example, how the data tend to separate according to boiling number. Thus, as shown in figures 3.3 and 3.6, when the ratio $\frac{Nu_{exp}}{Nu_{calc,f,t.p.}}$ is multiplied by (Bo. No.)-0.4, the correlation is improved. The improvement in $\bar{d}$ values is quite significant, reducing the data spread by a factor of 3 for all the data but less for the Hendricks, et al. [1961] data alone. As discussed previously, perhaps an explanation for the effectiveness of the boiling number in the correlation is that this provides a measure of the ratio of the velocity of the vapor formed to the normal stream velocity. It seems quite conceivable that this ratio would have a considerable effect on the flow pattern and subsequently on the heat transfer coefficient. No plots are shown using the boiling number with the single-phase Nusselt number ratio as it would have been necessary to make appropriate changes in the exponent on the boiling number to optimize the correlation using that Nusselt number ratio.

A disadvantage of the boiling number correlation for design purposes is that the heat flux must be known in order to use the correlation.

3.4.3 von Glahn Correlation

The value of $\bar{d}$ for the correlation proposed by von Glahn [1964] is relatively high. The best equation for this correlation given in table 3.3 was determined only from figure 3.7, which shows the data of Hendricks, et al. [1961], Wright and Walters [1959], and Core, et al. [1959]. The data of Core, et al. appear to plot at a reduced slope compared with the data of Hendricks, et al. and Wright and Walters. von Glahn points out in his report that for $0.7 < Le/D < 3.5$ such a reduced slope was obtained when the exponent $\bar{a}$ was taken to be 0.13. These authors used a = 0.13 for the data of Core, et al. The dimension L_e was not recorded, but figure 4, Appendix I of Core's report indicates an L_e/D ratio > 3.5. However, it is conceivable that L_e/D for Core's test section was in fact less than 3.5 which may account for the reduced slope plot of their data which subsequently would produce a higher $\bar{d}$ value for von Glahn's correlation. For the Hendricks, et al. [1961] data alone, the von Glahn correlation compares favorably with the boiling number correlation. Like the boiling number correlation, the von Glahn correlation requires a knowledge of the heat flux in order to determine F_{tp}.

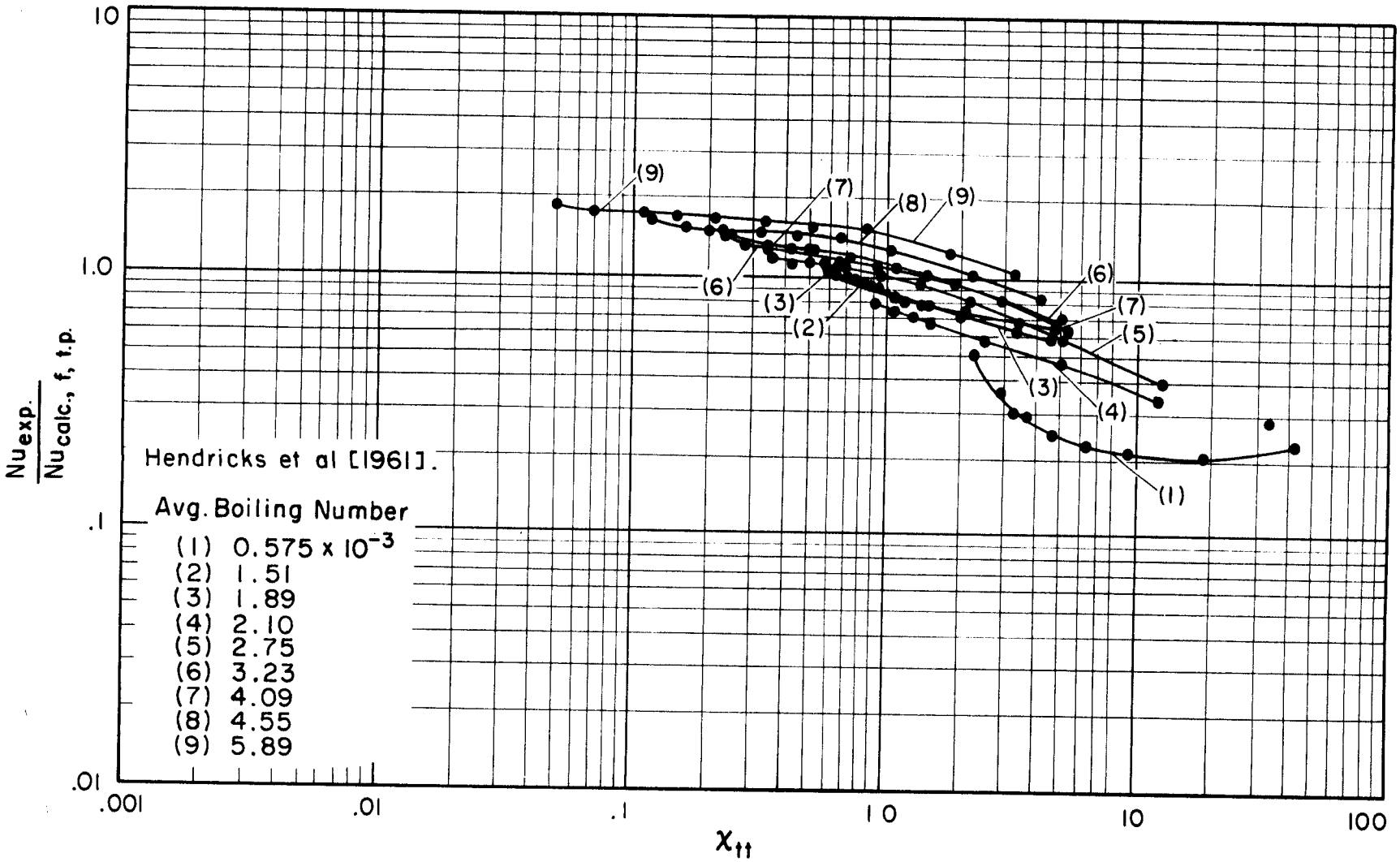

Figure 3.20 Two-phase Nusselt number ratio vs X_{tt} for only the data of Hendricks, et al illustrating separation of data according to boiling number

Another consideration present in the von Glahn correlation is that the correlating parameters were developed using both hydrogen and nitrogen data and further tested for applicability to Freon 113. Since these fluids present wider ranges of property data one might conclude that this correlation may be used over a greater range than those developed for hydrogen data only. This would be true, however, only if the properties data are accounted for properly. It may be open to question whether or not any of the correlations used in this study have reached that degree of development.

3.4.4. Film Boiling Superposition

The superposition approach is an extremely simple one, and its d value indicates that it is comparable to the other film boiling correlations. Although the results are not included herein an interesting sidelight came about when Breen and Westwater's [1962] film pool boiling equation was evaluated with saturation vapor properties rather than the film temperature properties for which the equation was developed. The result was an improved d for the superposition equation, $h_{pred} = h_{\substack{conv \\ s.p.v.}} + h_{\substack{film \\ pool \\ boil}}$. Since using the saturation properties reduced the predicted pool boiling flux, it may be that this lower value provided partial correction for the interaction between the forced convection and boiling heat transfer mechanisms.

Since the superposition approach does not consider any of the interactions of the boiling and convective heat transfer mechanisms which would appear certain to be present and significant, the comparable success of this correlation raises the question as to whether or not any of the other film boiling correlations of this study have properly accounted for such interrelationship.

3.4.5. Nucleate Boiling Correlations

It might be noted here that some researchers have proposed use of the pool boiling equations alone for the forced convection boiling case. In a review paper Zuber and Fried [1962] report the following in this category:

(1) Kutateladze [1949]
(2) Michenko [1960]
(3) Gilmour [1958]
(4) Labountzov [1960]
(5) Forster and Grief [1959]

The forced convection contributions for the data of this study, however, were significant and varied; on this basis it is assumed that the use of the boiling component alone would constitute a relatively poor predictive system.

For the limited data considered, correlations applied for nucleate boiling, Region I and Region II, appear to be as good as or better than the film boiling correlations.

All three of these predictive equations employ a superposition approach but the correlation of Chen does attempt to account for the interaction of the boiling and convective heat transfer mechanisms by the factors F and S. However, the d values indicate that the simple superposition equation and Kutateladze's equation, neither of which attempt to account for these interactions, are just as successful in correlating the data used in this study. Unfortunately, limited data from only one source (Wright and Walters [1959]) were available for this comparison.

3.4.6. Burnout

As might be expected and as substantiated by figure 3.21, the burnout correlation of Lowdermilk, et al. [1958] cannot be applied to cryogenic fluids without modification to the constants and/or exponents in the predictive equation. Due to lack of other cryogenic fluid burnout data, no attempt was made to determine the necessary modifications.

3.5. Conclusions

The general conclusions of this study are:

(1) Within the range of fluid property variables and systems of the data of this study, the boiling number correlation appears to be more successful in predicting heat transfer

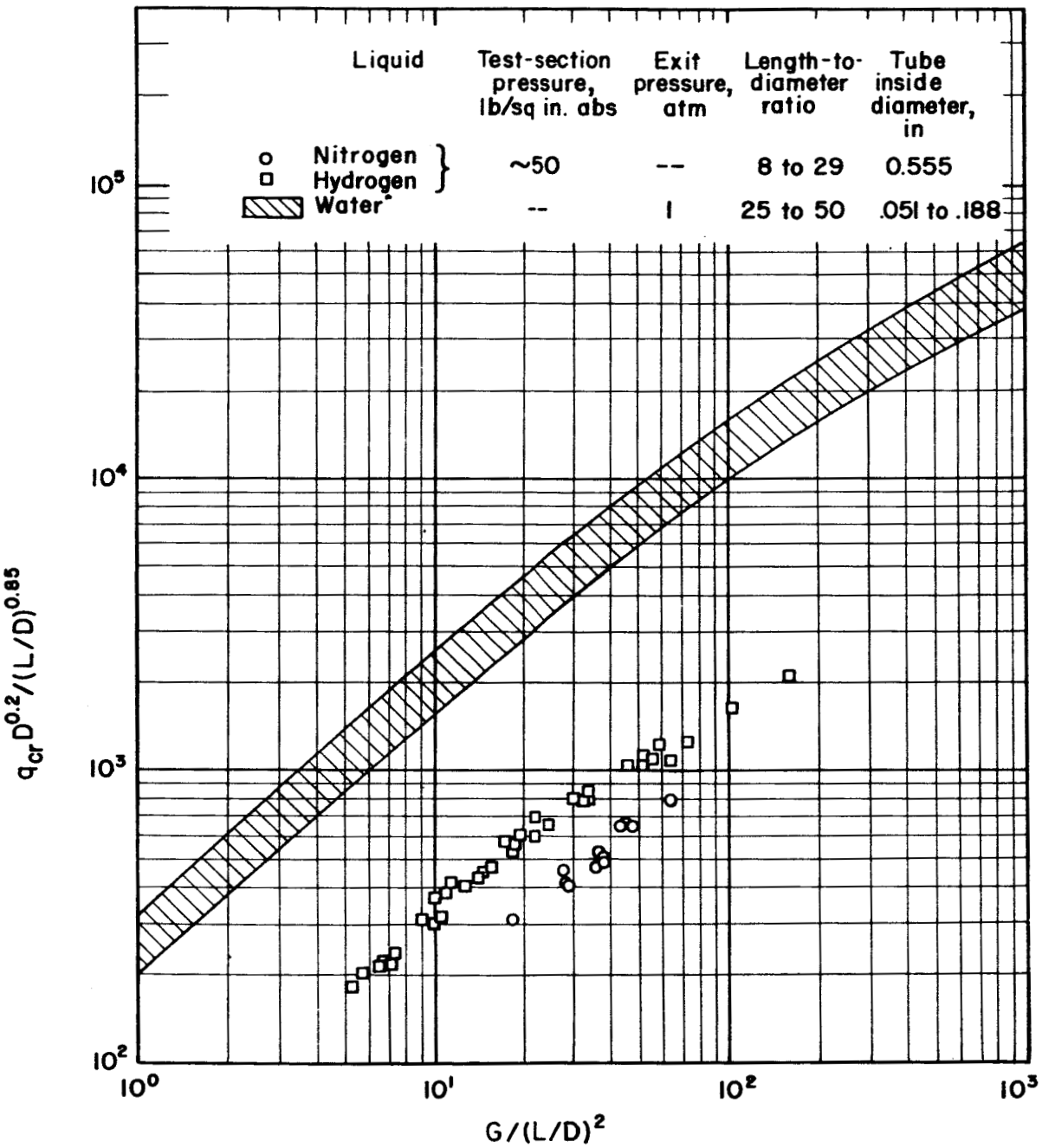

Figure 3.21 Comparison of maximum critical heat flux for cryogenic liquids with water correlation of Lowdermilk, et al. (1958)

coefficients in the film boiling region (Region III). However, for design purposes, little accuracy is lost by using the simpler systems such as the correlation using the Nusselt number ratio versus quality. It may be that further simplification, as the use of single-phase properties in determining the Nusselt number (calc) for the correlations vs x and X_{tt}, and use of the superposition method will not result in an objectionable loss of accuracy. The use of all data considered in this report indicates this to be true, but the use of the Hendricks, et al. [1961] data only does not.

Correlations for the nucleate boiling region (Region I and II) generally are better than the film boiling correlations, but on the basis of the small number of data points available for consideration, these results are not considered very significant. The Kutateladze approach appears to be the better of the nucleate boiling correlations.

(2) The conditions at which properties are to be evaluated and the interrelationship between boiling and forced convection phenomena is quite different in all of the correlations of this study. Yet their reliability as evidenced by the d values is generally the same; it would appear that all systems of approach are lacking in arrangement and treatment of the significant variables.

(3) The predictive quality of the systems of this study does not appear to fall in a respectable range for correlation, but certainly for a thorough test of the predictive systems more experimental data are needed. Further work should be in the direction of a more fundamental analytical study of the fluid mechanics and heat transfer phenomena and the acquiring of data from very carefully controlled, experimental systems.

4. Boiling Variables

4.1. Saturation Fluid Properties (Pressure)

The predictive equation of Kutateladze [1952] for nucleate pool boiling appears to account generally for the changes in boiling characteristics brought about by pressure changes which, in turn, change the saturated fluid properties. The increasing steepness of the experimental curves with pressure, however, is not reflected in the Kutateladze correlation or in other correlations proposed, as essentially all use a constant exponent for ΔT. Deviation of the peak flux from predictive expressions at pressures above 0.6 of the critical pressure as shown by Lyon, et al. [1964] would tend to indicate that the general relationships for boiling do not hold at high reduced pressures. This seems reasonable as the apparent primary factors in pool boiling heat transfer are the stirring and the vaporization effects and both of these would be greatly diminished as the critical pressure is approached. Graham, et al. [1964] show that at a pressure of 170 psig hydrogen exhibits a nucleate boiling type of curve over a very short interval and then apparently enters a film boiling regime, indicating that conventional nucleate boiling behavior does not occur as the critical pressure is approached.

It is not possible to discuss the effect of pressure on pool film boiling because there are insufficient data for comparison. In the forced-convection correlations considered, the predictions at higher pressures appeared to be as good as those at one atmosphere.

4.2. Subcooling

Apparently the temperature difference between the warm surface and the saturated liquid represents the most significant variable affecting heat flux. Therefore, this temperature difference is conventionally used in the Leidenfrost plot as shown in figures 2.1, 2.2, 2.3, and 2.4. It may be that subcooling effects are rather small, at least, when the subcooling is no larger than roughly the temperature difference between the wall and saturation necessary to produce burnout. Graham, et al. [1964] have reported hydrogen data at 175 psia which indicate subcooling temperature differences have a smaller effect on the nucleate boiling curve than temperature differences above saturation. It would seem that a major subcooling effect may occur in the normal film boiling or transition region, as a result of the increased rate of condensation. Vliet and Leppert [1964] report such changes in studies of forced convection boiling on a cylinder with water crossflow.

Most of the predictive expressions which have considered subcooling have been for pool-boiling, peak-flux studies. Among these are Griffith [1957], Zuber, et al. [1961], and three reported by

Gambill [1963a] in his peak flux survey. Results of the latter four are shown in figures 4.1, 4.2, 4.3, and 4.4. The expressions are:

Kutateladze I [1952]

$$F_{sub} = 1.0 + 0.040 \left(\frac{\rho_\ell}{\rho_v}\right)^{0.923} \left(\frac{C_p}{\lambda}\right) (\Delta T)_{sub}, \tag{4.1}$$

Kutateladze II
(from Gambill 1963a)

$$F_{sub} = 1.0 + 0.065 \left(\frac{\rho_\ell}{\rho_v}\right)^{0.800} \left(\frac{C_p}{\lambda}\right) (\Delta T)_{sub}, \tag{4.2}$$

Ivey and Morris
(from Gambill 1963a):

$$F_{sub} = 1.0 + 0.102 \left(\frac{\rho_\ell}{\rho_v}\right)^{0.750} \left(\frac{C_p}{\lambda}\right) (\Delta T)_{sub}, \tag{4.3}$$

Zuber, et al. [1961]

$$F_{sub} = 1.0 + 12.326 \left[\frac{(C_p \rho k)_\ell^{0.500} (\Delta\rho)^{0.125}}{\lambda \rho_v^{0.750} \sigma^{0.375}}\right] (\Delta T)_{sub}. \tag{4.4}$$

Considerably more work will be required before the effect of subcooling is finally determined. The general effect, however, should be indicated by these expressions.

4.3. External Force Field (Gravity)

Because buoyancy forces are significantly present in boiling and are functions, in turn, of some external force fields (viz. gravity and other accelerations, magnetic and electrostatic fields) one would expect to find the boiling phenomena changing with changes in the force field. Such changes have been reported, but the influence has been established only generally at this time.

The lack of resolution results from uncertainties in the effect of other boiling variables. As the external force field (gravity) is reduced, the normal density separation pattern is replaced by one in which the vapor tends to collect as a centrally-located sphere for wetting liquids (most cryogenic systems). Therefore, system geometry may play a major role in determining the influence of gravity forces on heat flux, since this could influence whether or not vapor will be removed from the surface.

For the pool nucleate boiling curves, the changes appear small (i.e., in the slope of a Leidenfrost plot) as evidenced by the work of Graham, et al. [1964] and Sherley [1963] except, perhaps, very near zero gravity. The inception point and the peak flux are, however, markedly influenced by the force field. Graham, et al. [1964] report that the Leidenfrost curves at one g and at seven g's separate considerably near the inception point for hydrogen and then tend to become the same curve at higher fluxes and temperature differences.

For the peak flux, (2.2) shows a one-fourth power gravitational dependence. The works of Usiskin and Siegel [1961] and Lyon, et al. [1965] using water, indicate the 1/4 power influence may be generally correct for force fields down to about 1/4 normal gravity, but then the power influence is substantially reduced.

For film boiling, one might expect larger influences on the boiling phenomena because the interface behavior may change markedly. The data of Graham, et al. [1964] for hydrogen indicate that changes in the external force field have a greater effect on the film boiling flux. The authors are not aware of any studies which consider the effects of a gravitational force field on forced convection boiling. The effect of electric fields have also been investigated by Markels and Durfee [1964] who found that the peak nucleate boiling heat flux with isopropyl alcohol and water was substantially

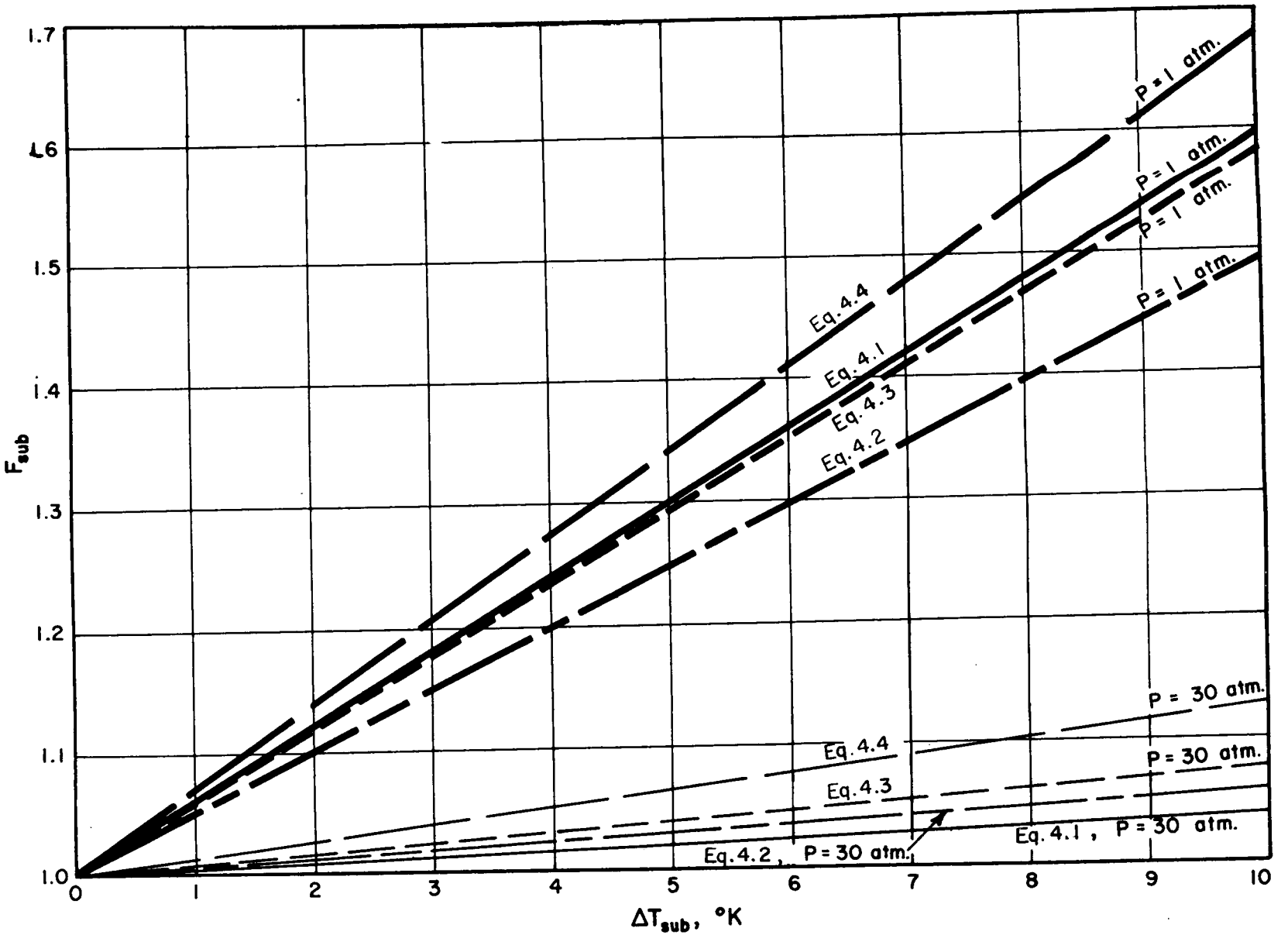

Figure 4.1 OXYGEN

Correction Factor for Peak Boiling of Subcooled Liquid

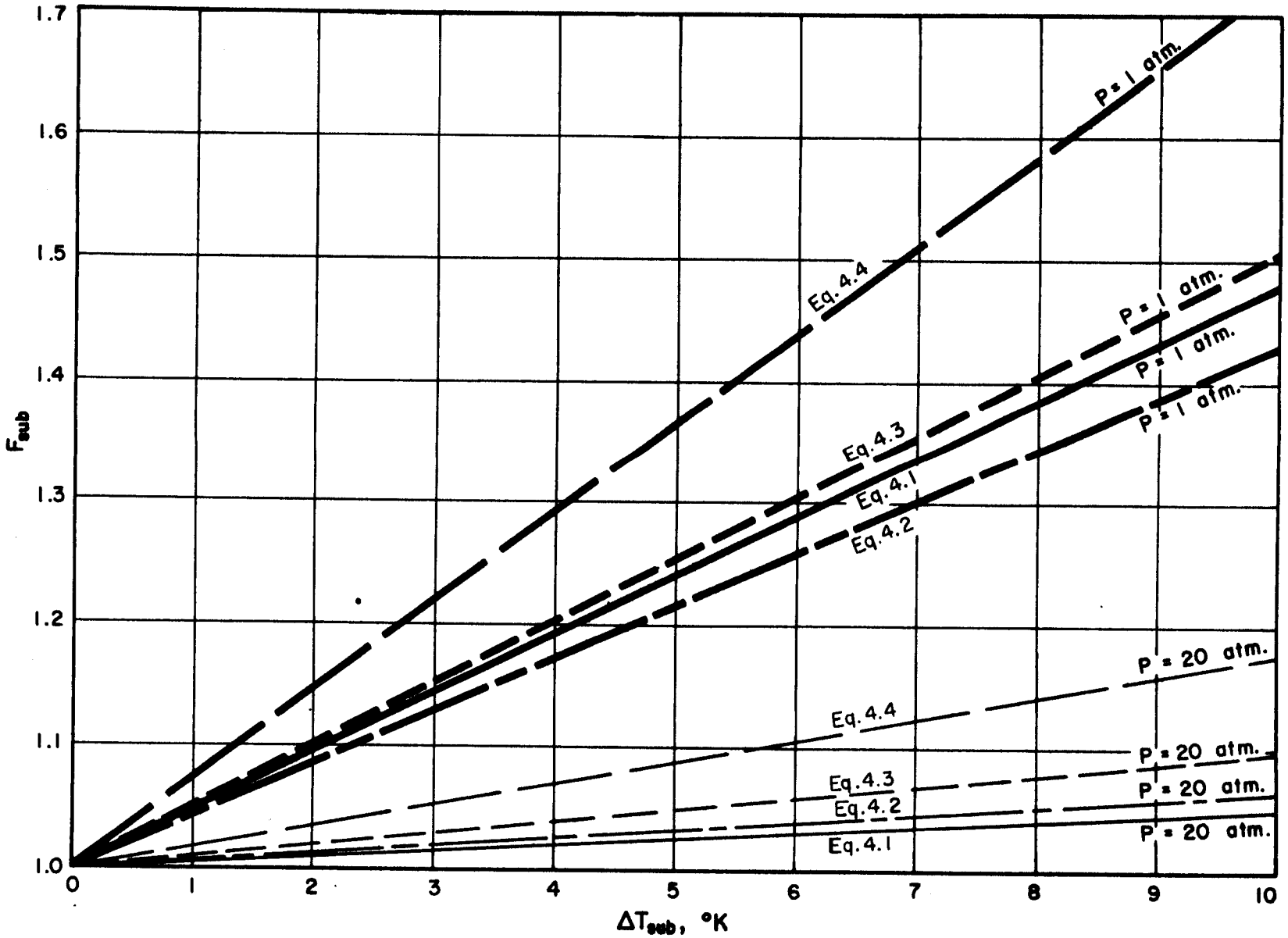

Figure 4.2

NITROGEN
Correction Factor for Peak Boiling of Subcooled Liquid

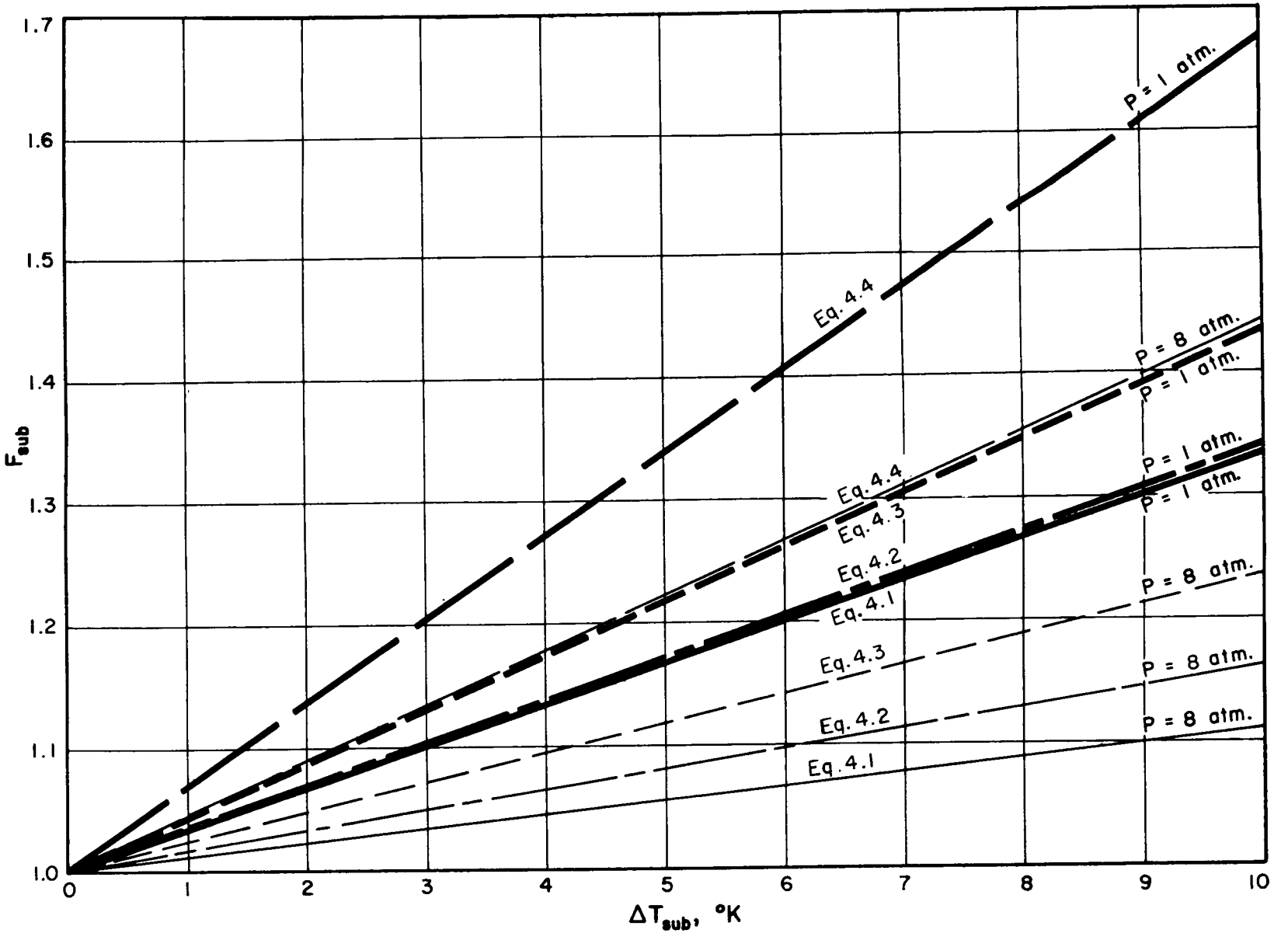

Figure 4.3 HYDROGEN
Correction Factor for Peak Boiling of Subcooled Liquid

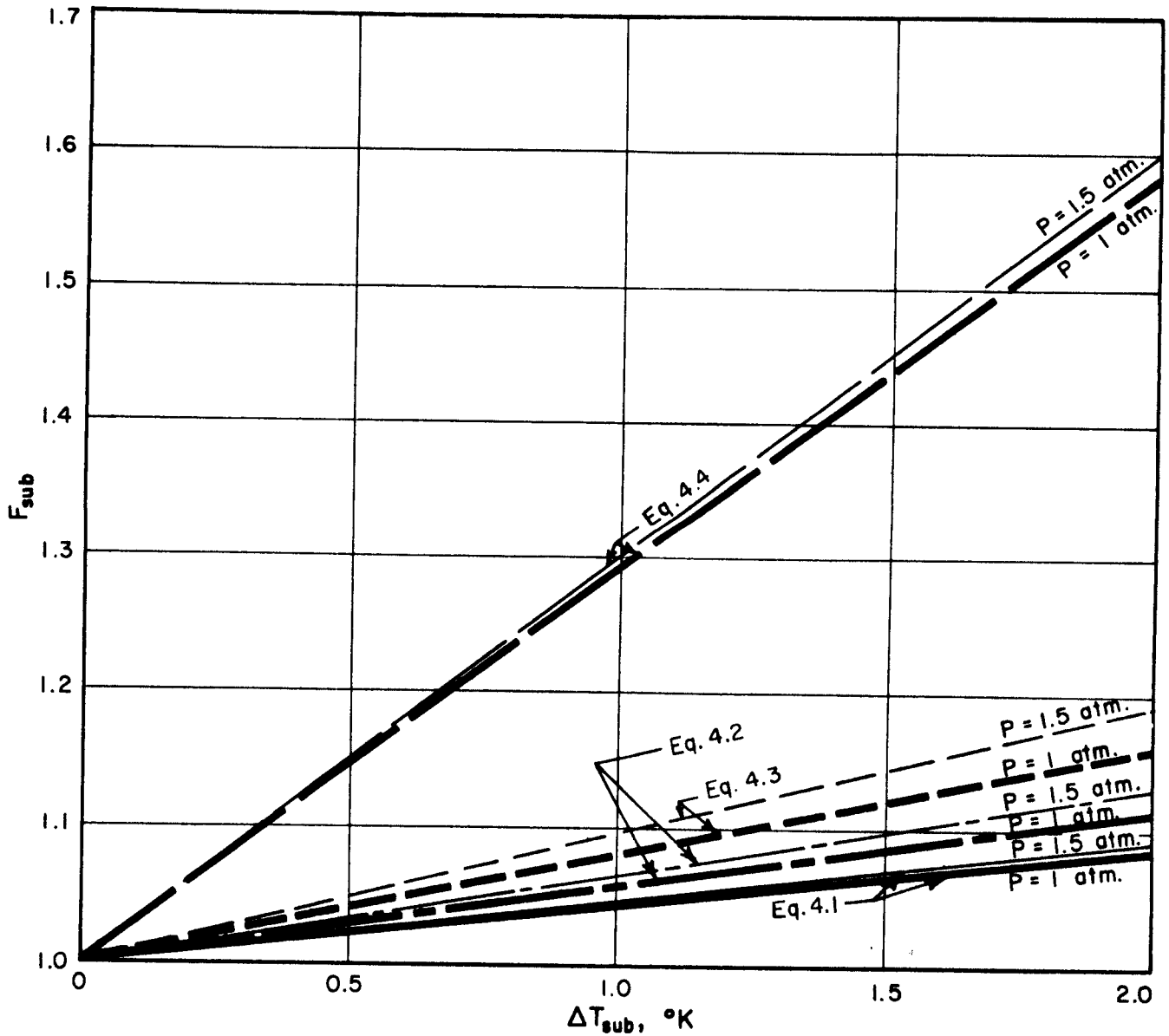

Figure 4.4

HELIUM

Correction Factor for Peak Boiling of Subcooled Liquid

increased under the influence of an electrostatic field. This was attributed to destabilization of the vapor film by the electrostatic field. Choi [1962] proposed an expression for an effective gravitational force of the electrostatic field.

4.4. Surface Orientation and Size

Pool-nucleate boiling is generally regarded as insensitive to system geometry. Several textbook authors make this observation. The work of Class, et al. [1960] and Lyon [1964] do show significant variations when changing from horizontal to vertical orientation with no other changes in the system. Unfortunately, the results of these works are somewhat contradictory regarding orientation effect, so no general conclusions can be drawn. Lyon also reports a significant orientation effect on the peak heat flux. As mentioned previously, surface orientation with respect to an external force field (gravity) may have a major effect. For example, Lyon [1965] reports marked reductions in helium boiling fluxes for horizontal surfaces facing downward, where the influence of vapor removal is significant.

Costello, et al. [1964] have reported that for pool boiling burnout heater size is quite significant. They found that one-sixteenth-inch diameter semi-cylinders burned out at fluxes 2.7 times greater than for flat plate heaters with no liquid in-flow from the sides. This suggested to the authors that such difference may be a result of different convective effects for the various heated surfaces. They show that the convective component may be approximately one-half the total flux in some cases.

4.5. Surface Condition

While it is known that surface conditions have a significant effect on the boiling phenomena, the specific influence of any given surface variable is not well understood. Enough data have been acquired, however, to permit a qualitative discussion of the effect of specific surface variations. Considered here are surface history, surface temperature variations as affected by the heated material mass and properties or by the type of heat source, surface roughness, and surface-fluid interface phenomena as influenced by the surface and fluid chemical composition.

4.5.1. Surface History

A heating surface immediately after immersion in liquid will produce a higher heat transfer coefficient than one which has been immersed for a reasonable period of time [Kutateladze 1952]. This is presumably due to additional nucleation centers provided by factors such as dissolved air and oxidation of the heating surface. Graham, et al. [1964] reported that for nucleate boiling of hydrogen, boundary layer history has a significant effect on the boiling incipient point. The apparent incipient point for nucleate boiling occurred at a much lower ΔT when a boiling run was immediately repeated rather than begun with a fresh supply of hydrogen surrounding the heating surface; the two curves then join at higher heat fluxes. The authors speculate that some residue of the thermal layer remained to change the incipient point for the succeeding test.

Vliet and Leppert [1964] studied the effect of aging or boiling for a period of time at about half peak flux. They found that with water flowing over a stainless steel tube, aging of about 90 minutes was necessary before reproducible peak fluxes could be obtained. Aging for about one-third that time produced peak fluxes only slightly greater than half the fluxes produced using the longer aging procedure.

4.5.2 Surface Temperature Variations

It is possible that surface temperature differences can occur which may be attributed to the heater surface and not to the boiling phenomena. Heaters with a small mass per unit of heater surface such as very thin materials may produce such temperature variations and, subsequently, a lower peak flux. Vliet and Leppert [1964], however, reported that there were no surface effects down to a thickness of 0.006 inch for a cylinder with water crossflow.

The source of energy for the heater may also influence surface temperature variations. Kutateladze [1952] reports that electrically heated surfaces have slightly different heat transfer characteristics than those heated by vapor condensation, probably because condensation droplets cause surface temperature differences.

Of course, the boiling phenomena also produce temperature variations at the surface, and these are reported, for example, by Kutateladze [1952], Hendricks and Sharp [1964], and Moore and Mesler [1961]. Sharp [1964] studied the microlayer film at the base of nucleate bubbles and found that the flux from this microlayer appeared to vary with $k/\sqrt{\alpha}$ for the surface material.

4.5.3. Surface Roughness

Rougher surfaces generally produce higher fluxes for the same ΔT. Mikhail [1952] reported work with oxygen using nickel surfaces with different roughness values, and his data were similar to others who investigated higher temperature fluids. Rougher surfaces cause incipient nucleate boiling to occur at a lower ΔT, and then the h vs ΔT curves rise abruptly from that point. Thus the rougher surfaces produce markedly higher coefficients for the same ΔT, in Mikhail's work as high as a factor of 4. Lyon [1964], working with cryogenic and other liquids, indicates, however, that although the nucleate boiling flux curve is changed by roughness, the peak flux does not change. Surface roughness would be expected to show a much smaller effect in the film boiling region, and work such as that of Class, et al. [1960] indicate essentially no effect of roughness for film boiling.

Tuck [1962], in experimental work with hydrogen, found that the ΔT for inception was less than 0.1°K for a rough surface but could be as great as 3°K for a surface finished to 1.25 micro-inch RMS. The Tuck experiments were at zero gravity condition; however, the results would be expected to be generally applicable under other gravitational fields, although at or near zero gravity the inception point seems to be time dependent and that time a function of the gravitational field.

4.6. Surface-Fluid Chemical Composition

The surface chemical effect is often difficult to separate from other surface effects such as roughness. Wetting characteristics would appear to be a major influence. Cryogenic fluids will wet almost all surfaces except those with a very low surface energy, illustrated, for example, in a hydrogen study by Good and Ferry [1963] and perhaps further substantiated by the reasonably effective use of a single wetting coefficient in the Rohsenhow [1952] correlation for cryogenic fluids. Lyon [1964] studied nucleate boiling with oxygen and nitrogen using clean copper and gold surfaces and surfaces with various chemical films. He found that the different surfaces produced somewhat different nucleate boiling curves and differences as much as 25% in the peak flux.

Young and Hummel [1964] have shown that higher coefficients in the lower region of the nucleate boiling regime are made possible by providing poorly wetted spots on the metal surface. Sharp [1964] has studied the microlayer at the base of bubbles and has found that non-wetting surfaces tend to destabilize the layer. Costello, et al. [1964] found that the burnout heat flux was increased by a factor of 2.3 if tap water rather than distilled water was used.

5. Summary and Conclusions

For the pool boiling case, the correlations of Kutateladze [1952] (nucleate) and Breen and Westwater [1962] (film) have been indicated as those which apparently have the greatest reliability. Although agreement with experimental data is not particularly good, the accuracy of the predictive expressions is perhaps sufficient for many design studies. Maximum nucleate flux data are reasonably well predicted by the Kutateladze [1952] expression.

For the forced convection boiling case, no correlation emerged as distinctly better; however, several simple predictive schemes are shown to be as accurate as some of the more complex systems when tested with the limited experimental data available.

For all boiling cases it is questionable as to whether or not the predictive correlations include all of the significant variables and whether the variables considered reflect their proper influence in the final expression. It would appear that new analytical approaches considering phenomena not included in the present correlations, such as a treatment of the process near the heated wall as reviewed by Zuber [1964], would be desirable. Recent experimental work indicates that to properly account for all the variables, more detailed and better controlled experiments are required. This would be particularly true for surface and geometry effects which are often averaged or neglected and in detailed studies of the boiling flow pattern or mechanism.

6. Properties Data and X_{tt} Curves

As an aid to designers, available properties data for hydrogen, nitrogen, oxygen, and helium and values of X_{tt} for hydrogen, nitrogen, and oxygen are presented in graphical form in figures 6.1 through 6.46. Values of C_p for the saturated liquid and vapor were not available for all of the cryogenic fluids included in this study. Therefore C_p at saturation was approximated by

$$C_{p_{Sat}} \approx \frac{\Delta H}{\Delta T} = \frac{H_1 - H_2}{T_1 - T_2} ,$$

where H_1 = enthalpy of liquid or vapor at saturation temperature T_1

H_2 = enthalpy of liquid or vapor at a temperature T_2 slightly higher than T_1 for the vapor and slightly lower than T_1 for the liquid (all at the same pressure).

Curves obtained in this manner are so indicated on the graph. The values for H_1, H_2 and corresponding temperatures T_1 and T_2 were obtained from NBS Technical Notes or private communications cited in the bibliography for thermodynamic properties of the various cryogenic fluids included in this study. Because of uncertainties in the data used in obtaining an equation of state for oxygen in the temperature range greater than 98°K for liquid [Stewart, Hust, and McCartyl], the C_p values for saturated liquid oxygen are not considered reliable above 90°K (or above the corresponding saturation pressure of 1 atm). Furthermore, it is pointed out that the C_p values for saturated liquid helium were obtained by extrapolation of the data of Lounasmaa [1958], and the C_p values may be inaccurate by as much as 20%.

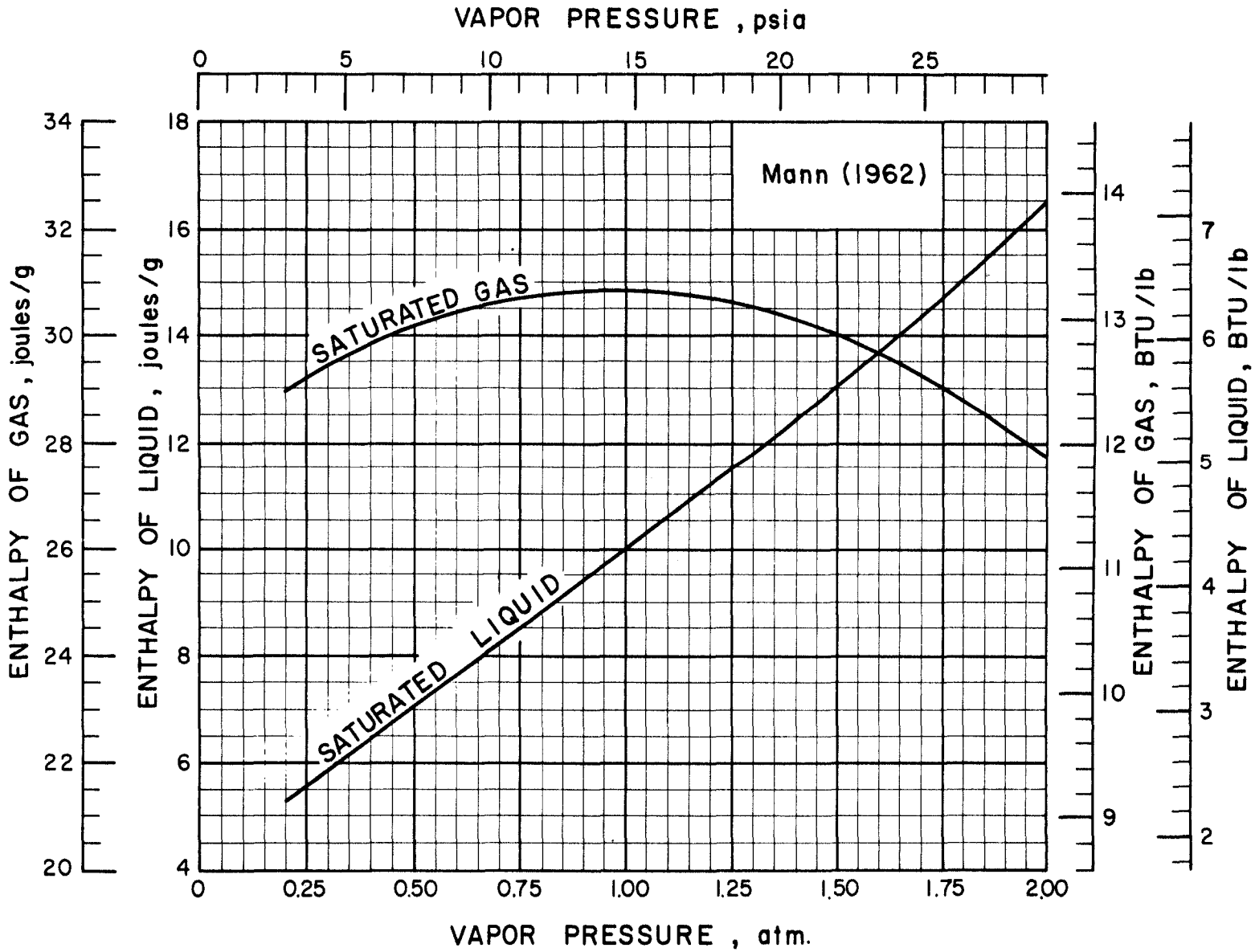

Figure 6.1 Enthalpy of saturated gaseous and saturated liquid helium

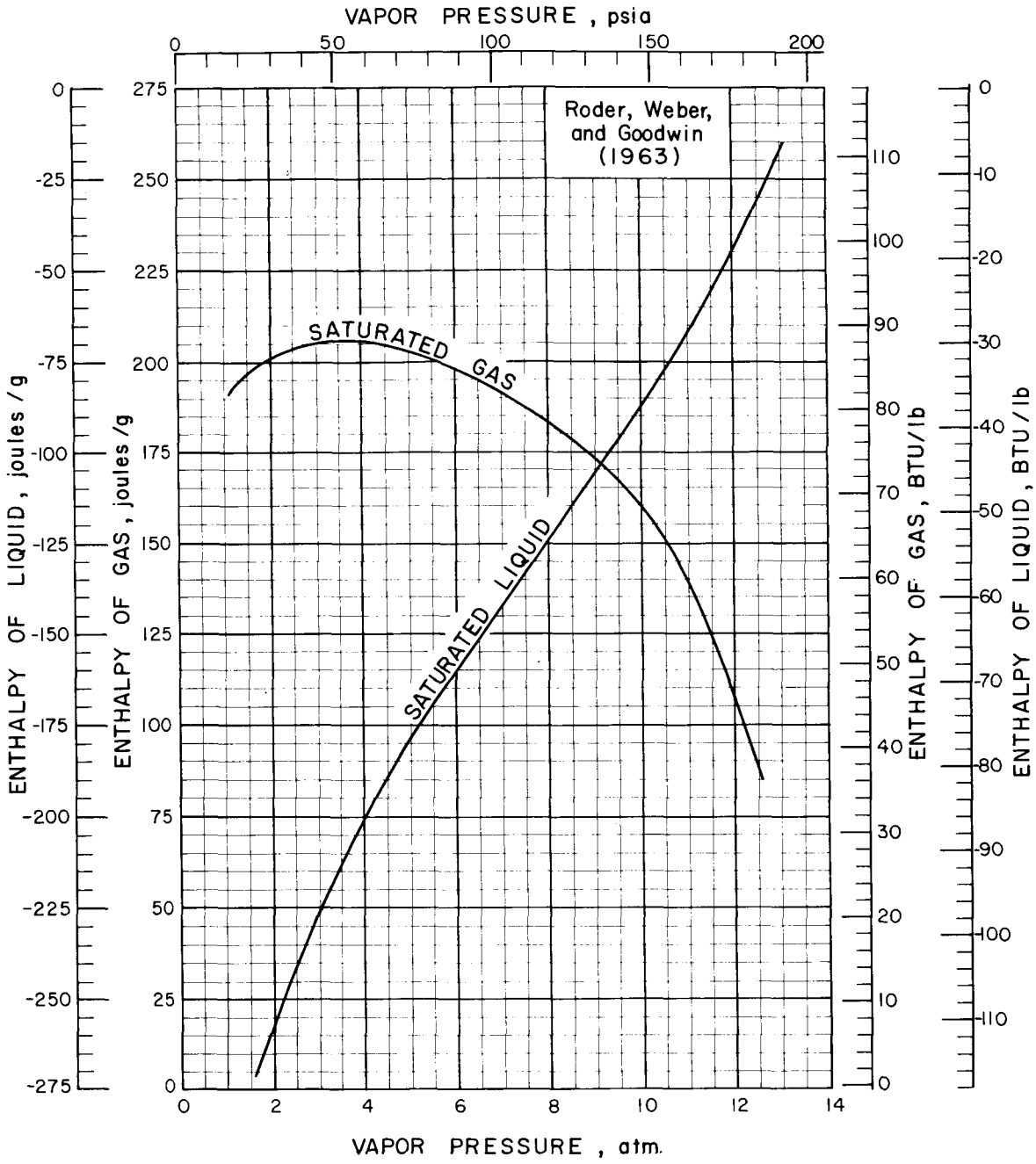

Figure 6.2 Enthalpy of saturated gaseous and saturated liquid parahydrogen

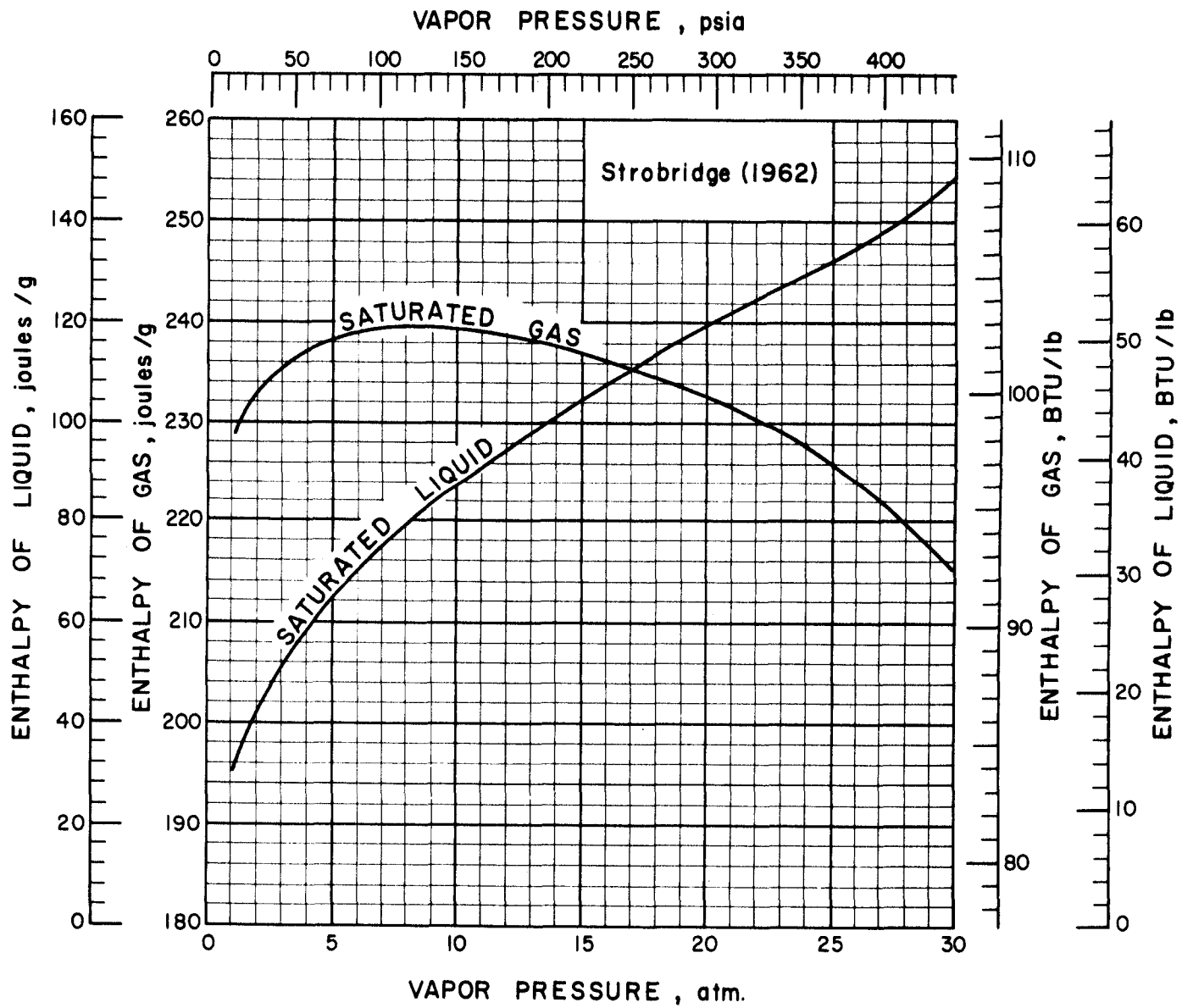

Figure 6.3 Enthalpy of saturated gaseous and saturated liquid nitrogen

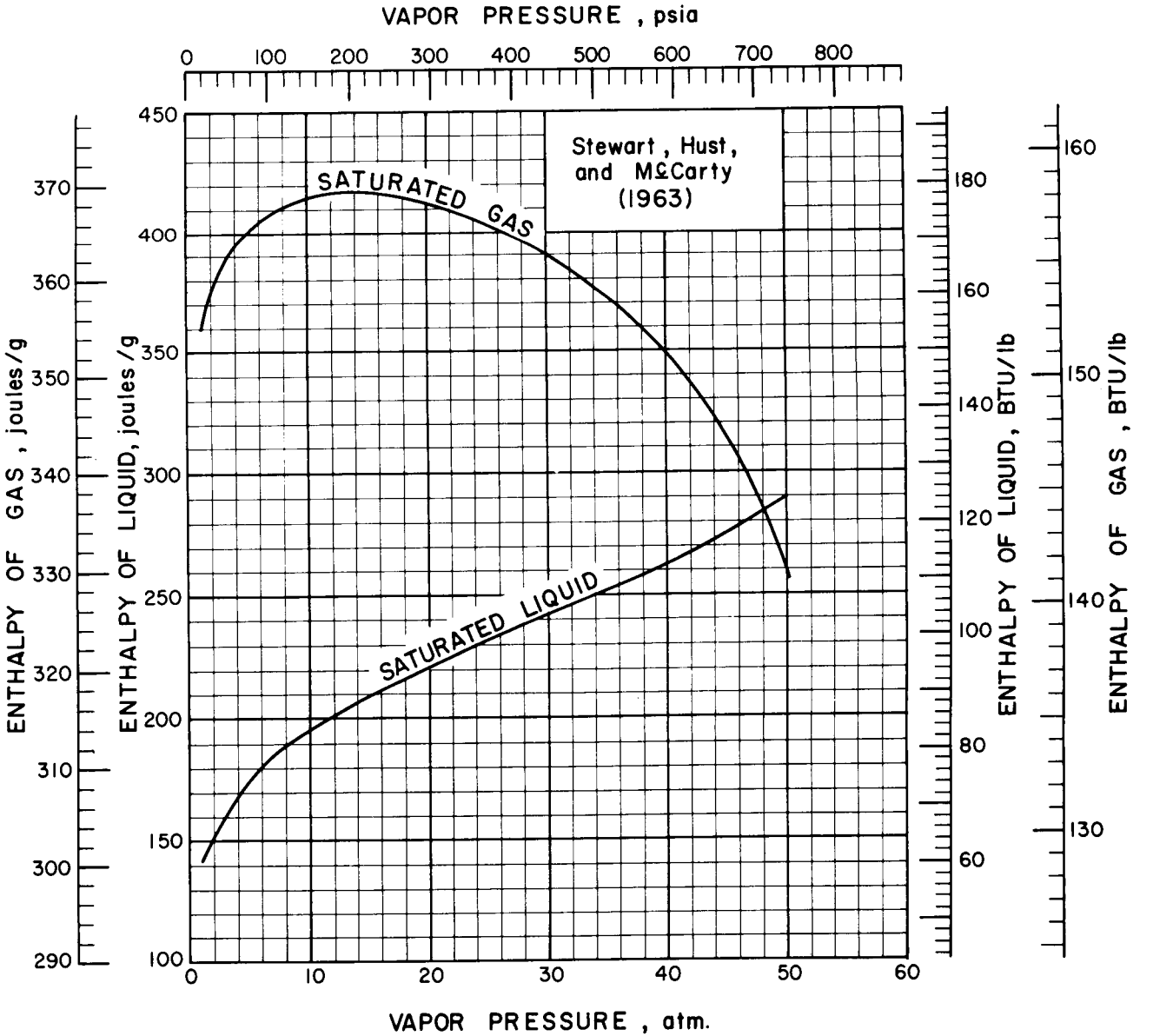

Figure 6.4 Enthalpy of saturated gaseous and liquid oxygen

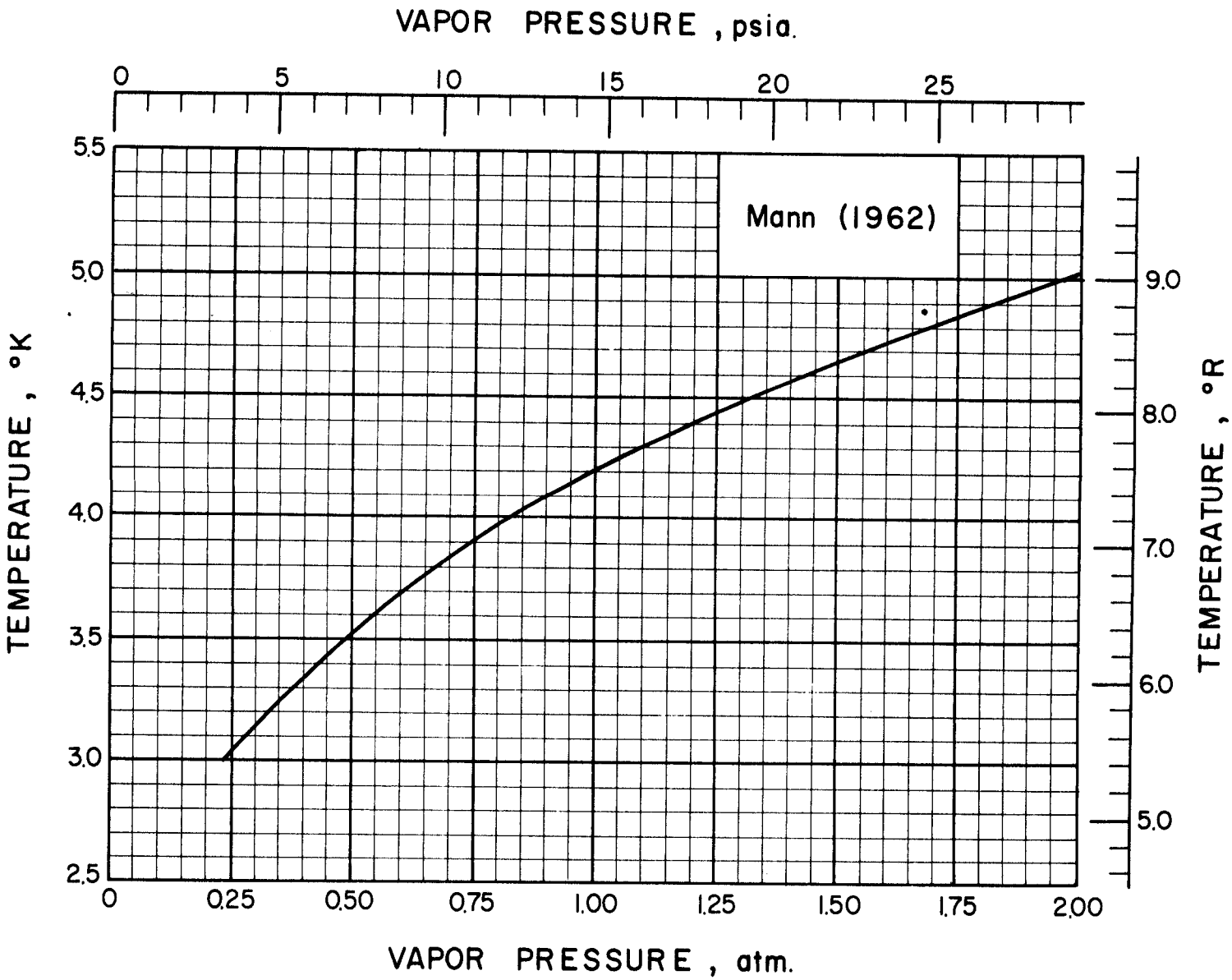

Figure 6.5 Vapor pressure of helium-4

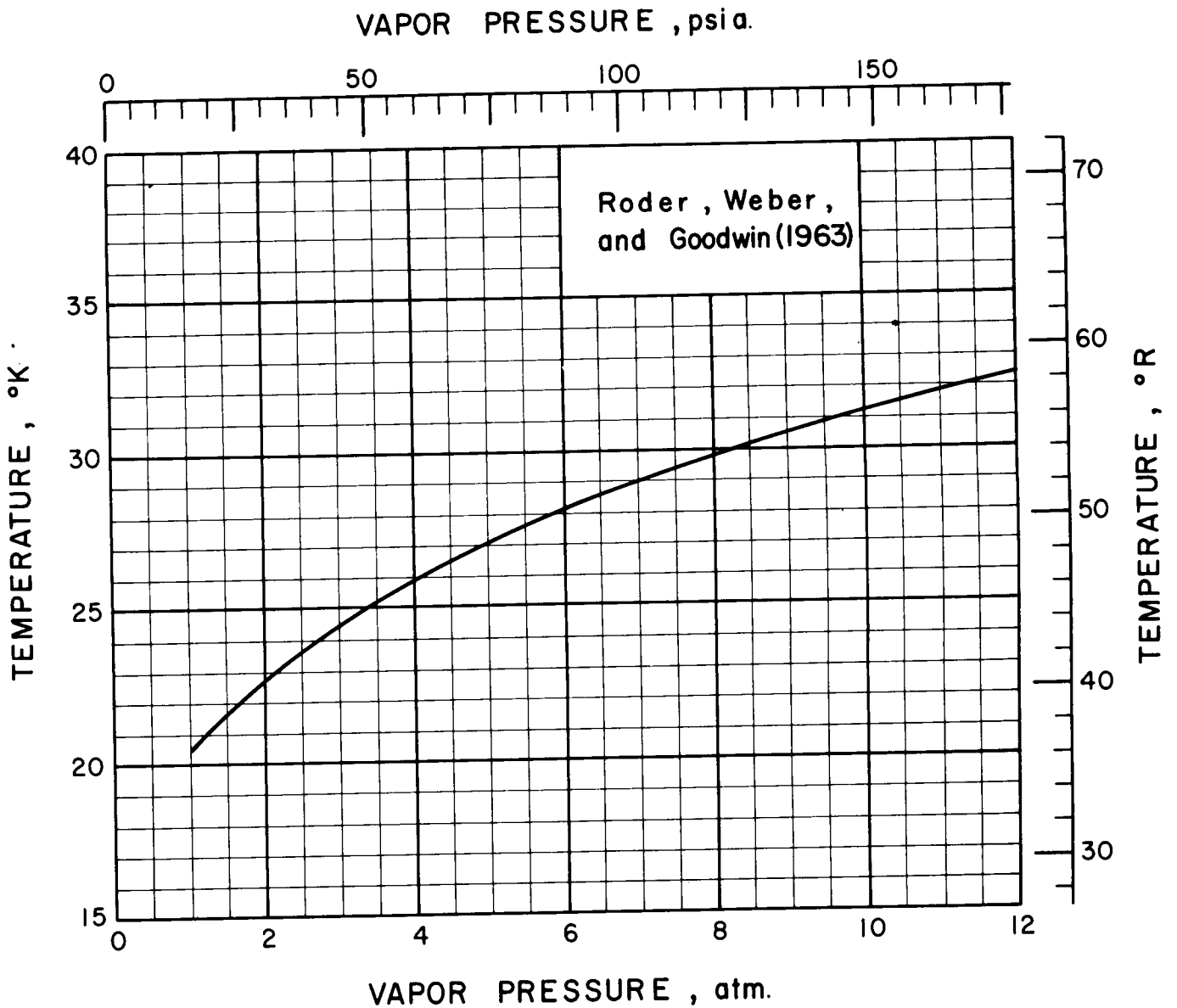

Figure 6.6 Vapor pressure of parahydrogen

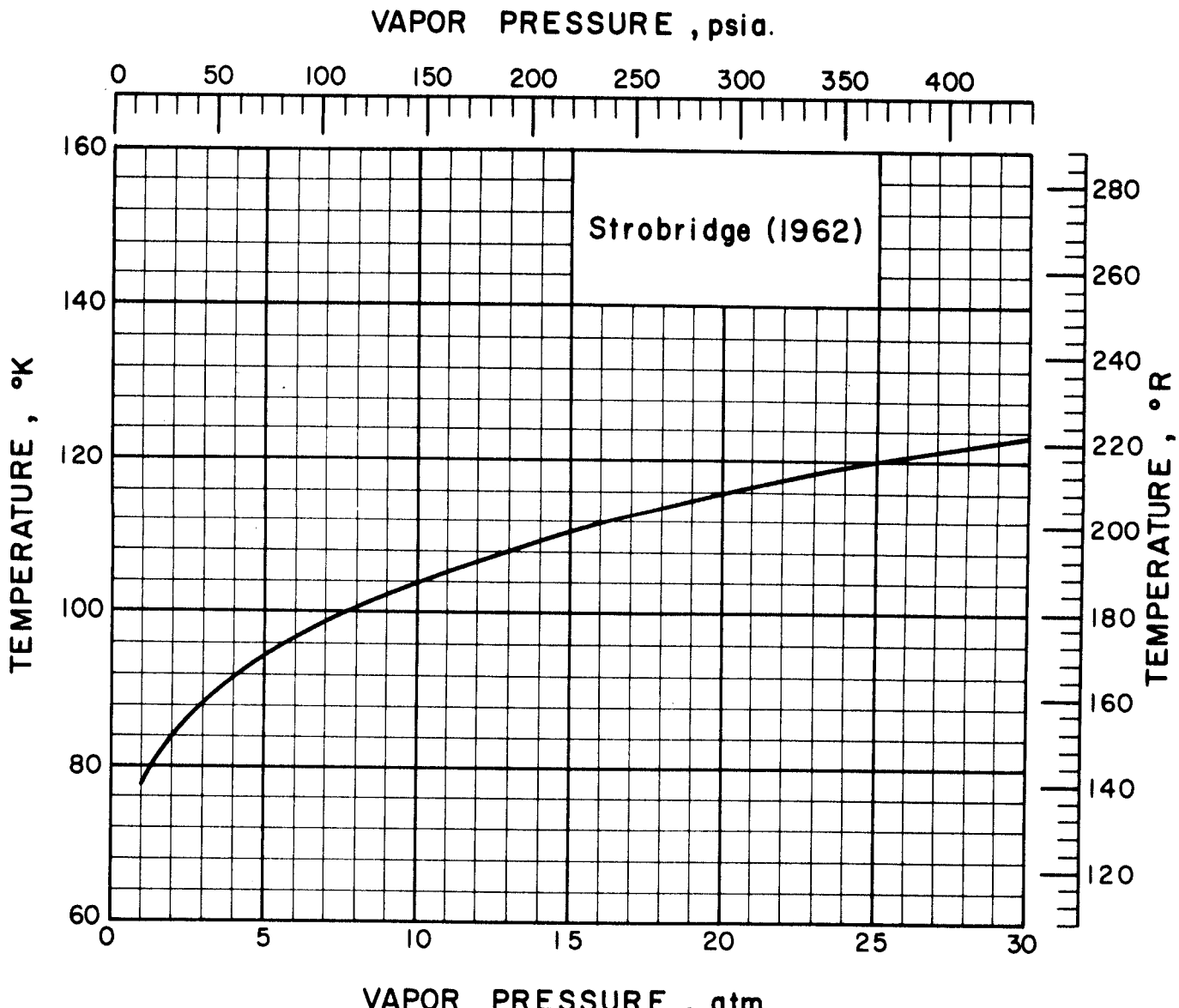

Figure 6.7 Vapor pressure of nitrogen

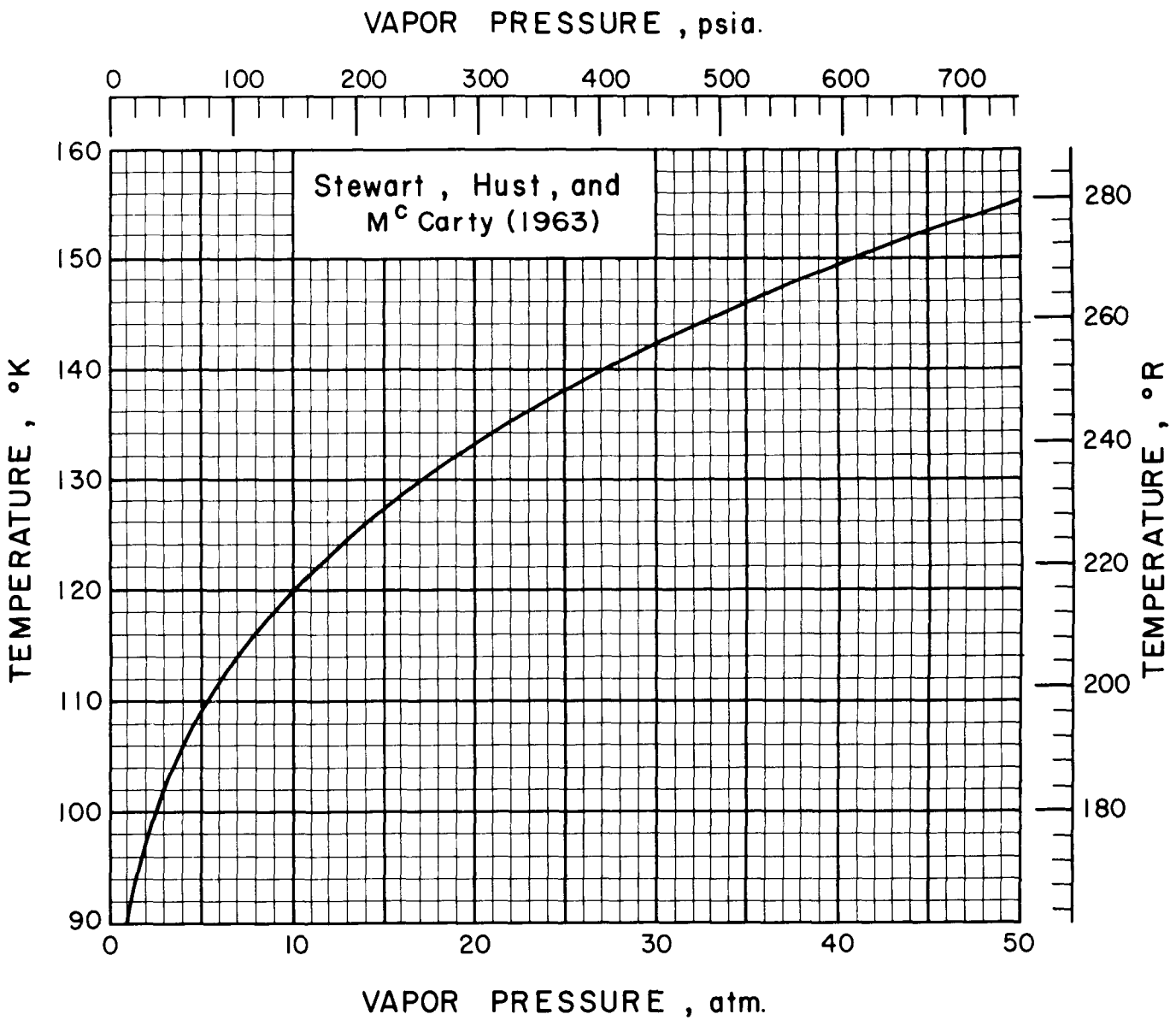

Figure 6.8 Vapor pressure of oxygen

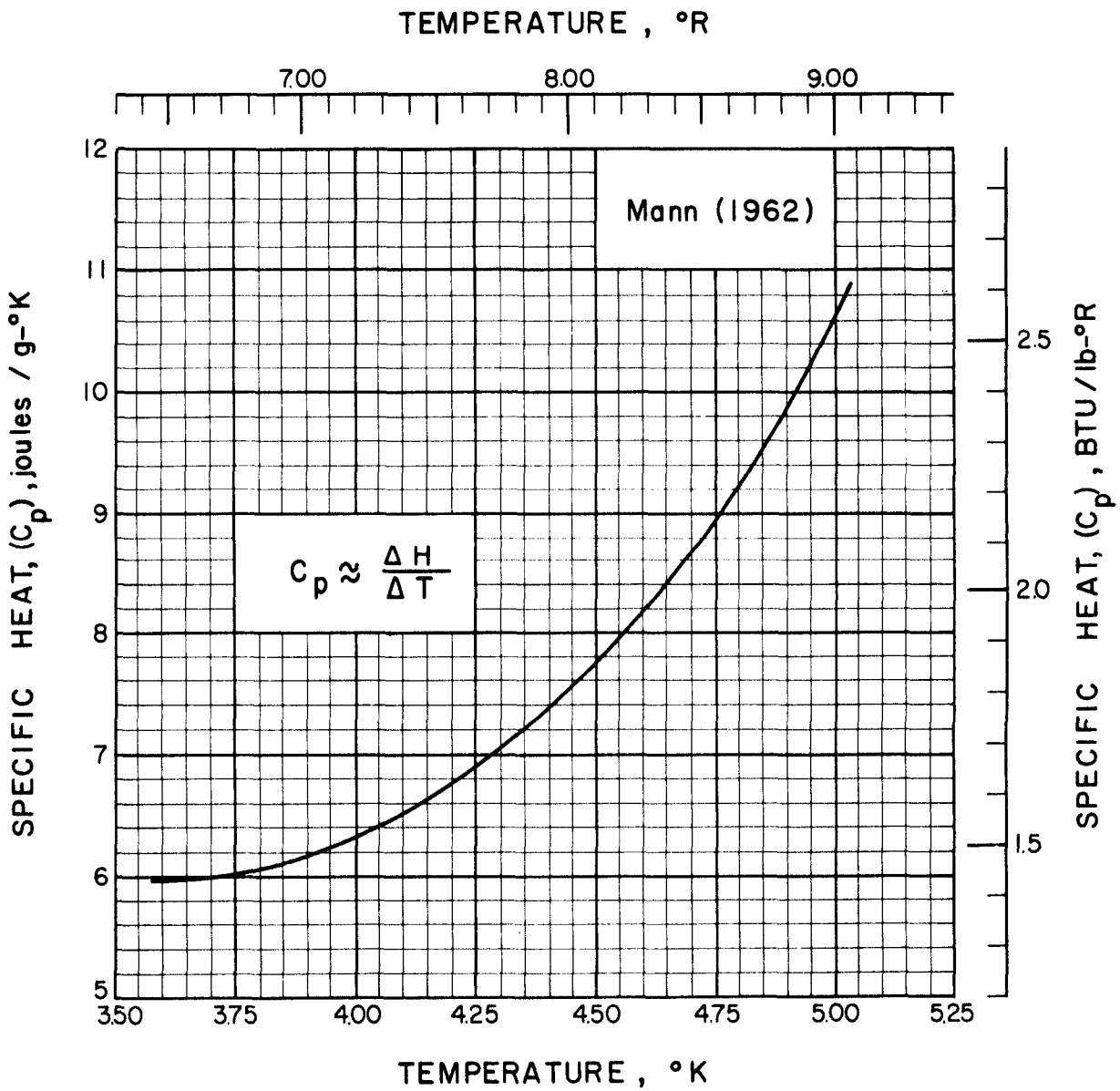

Figure 6.9 Specific heat, C_p, of saturated gaseous helium

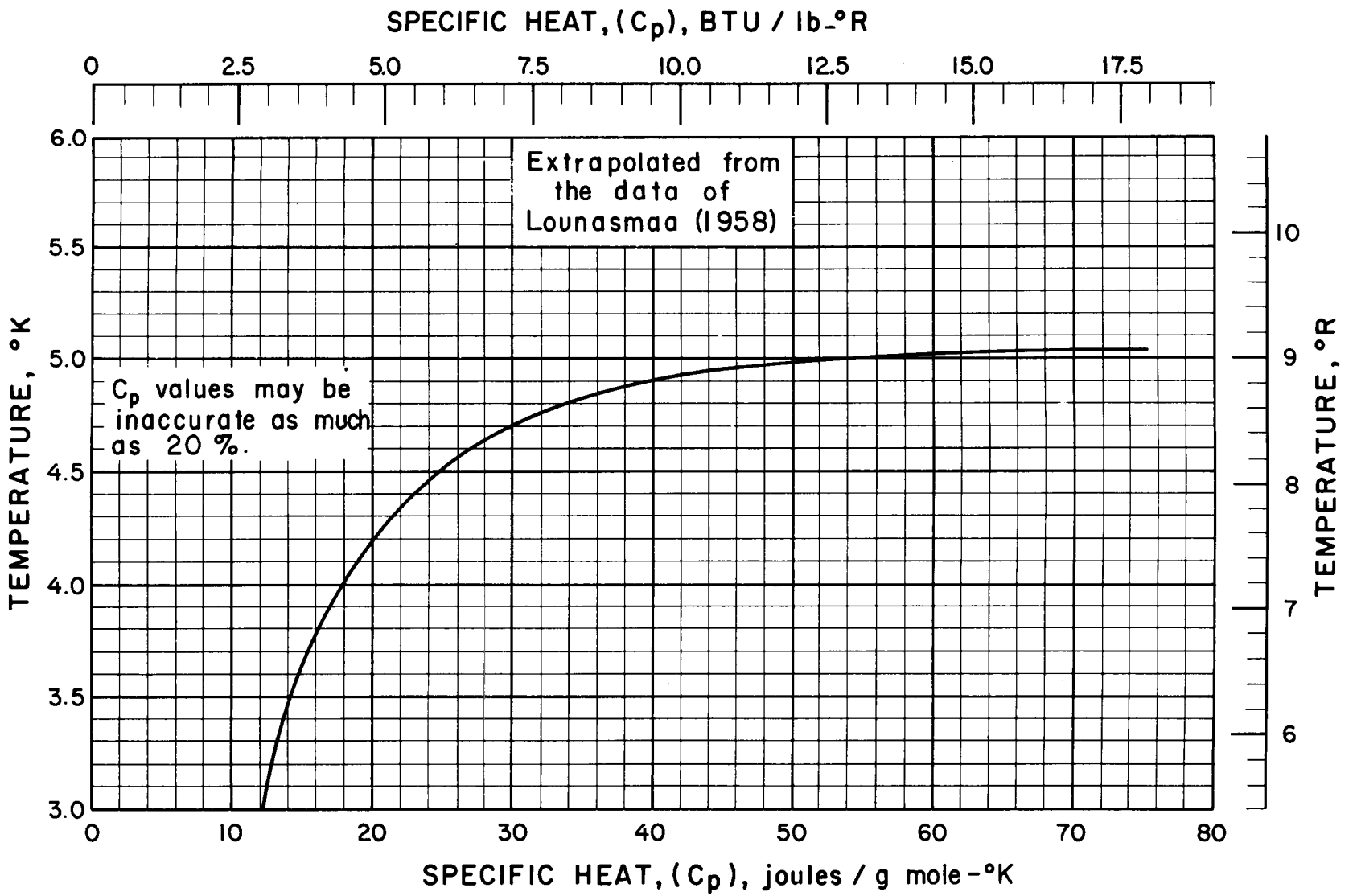

Figure 6.10 Specific heat, C_p, of saturated liquid helium

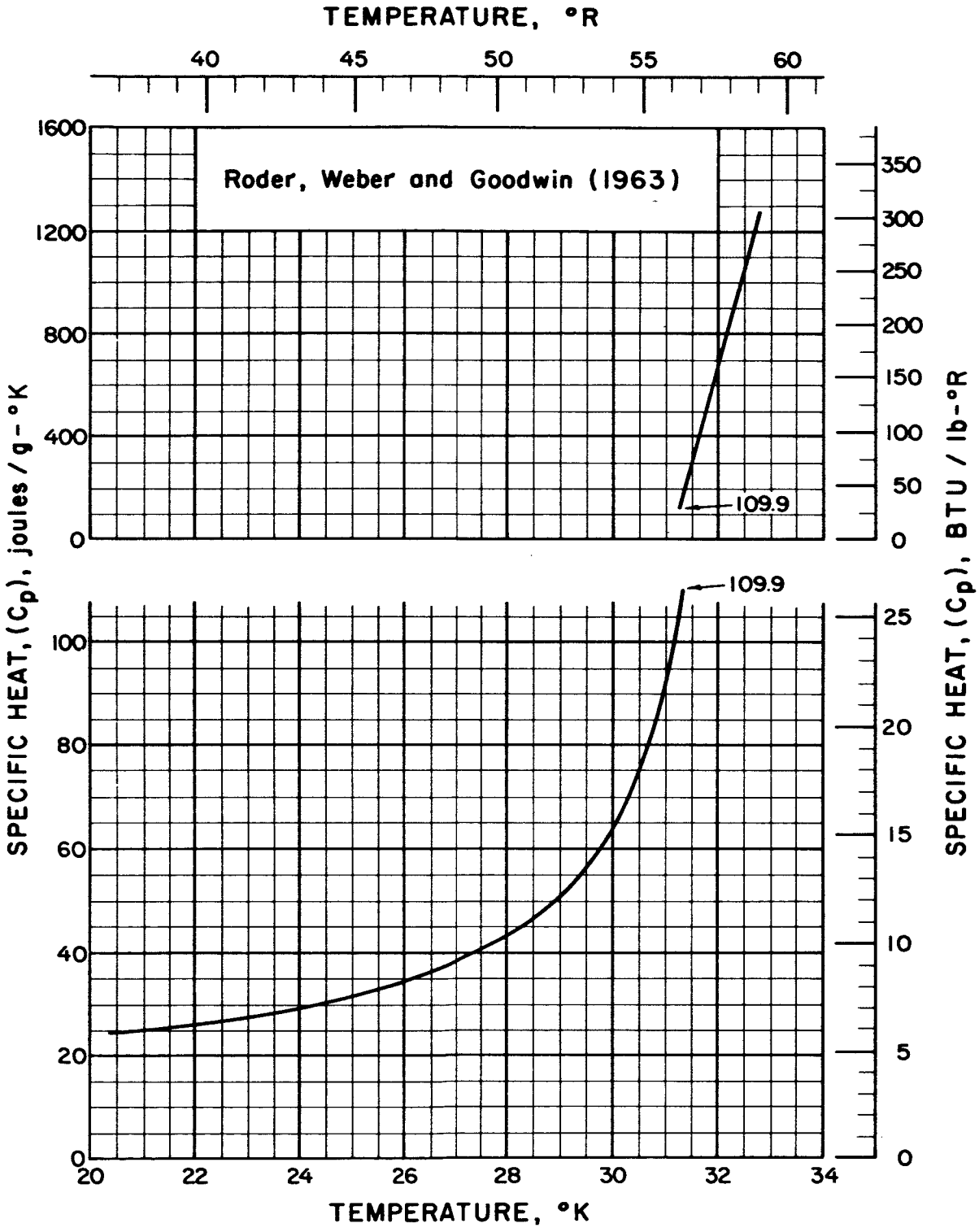

Figure 6.11 Specific heat, C_p, of saturated gaseous parahydrogen

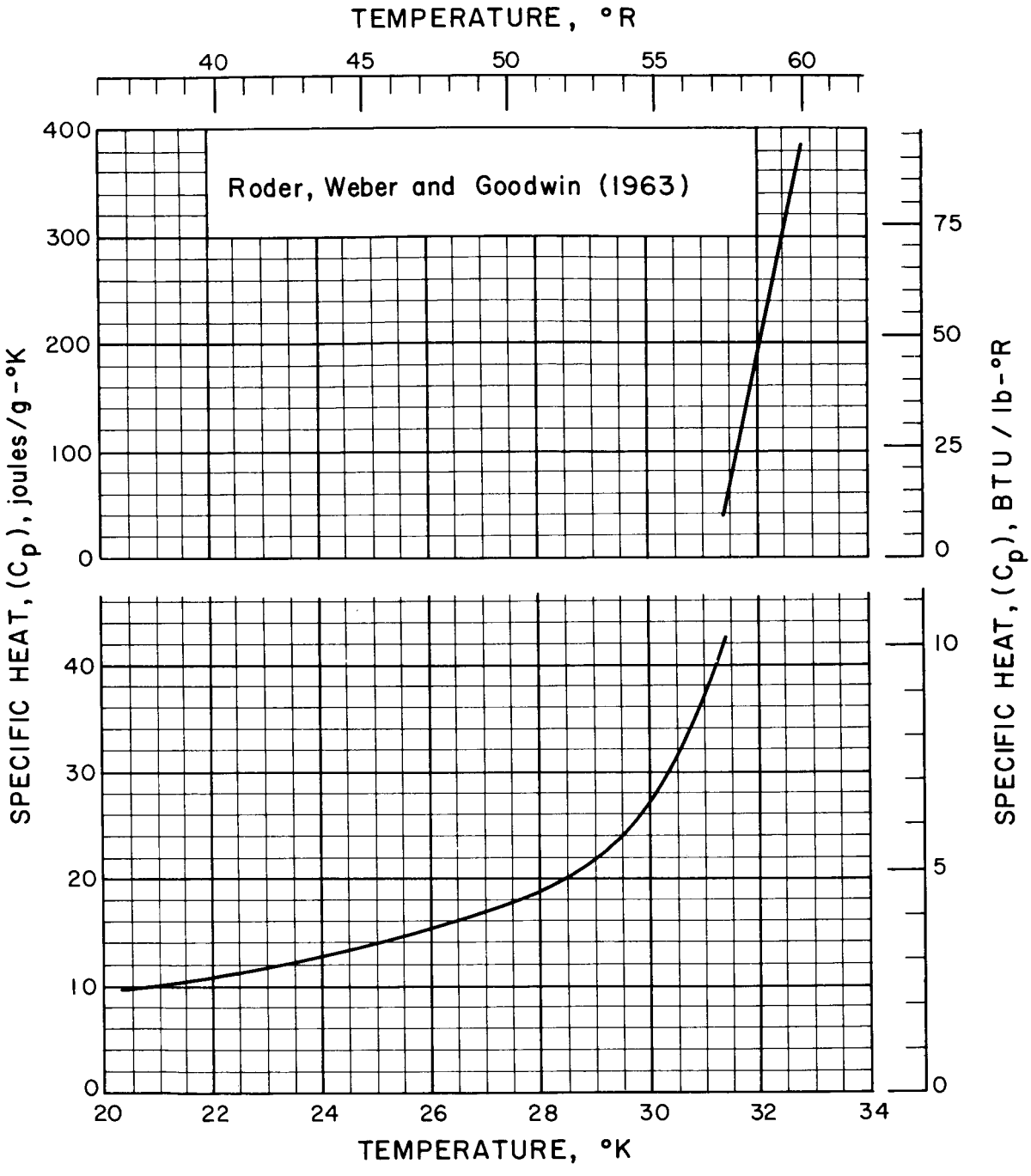

Figure 6.12 Specific heat, C_p, of saturated liquid parahydrogen

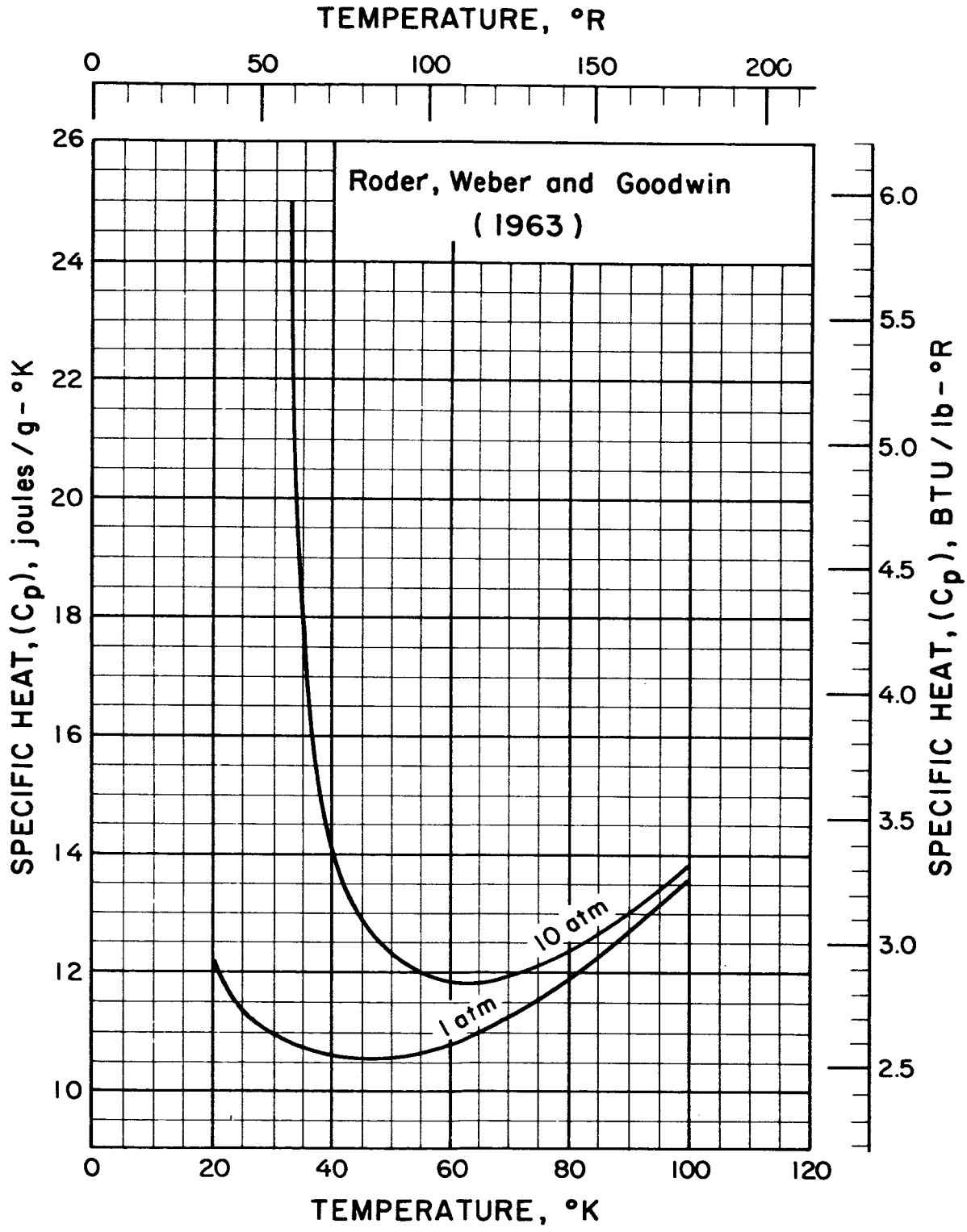

Figure 6.13 Specific heat, C_p, of gaseous parahydrogen

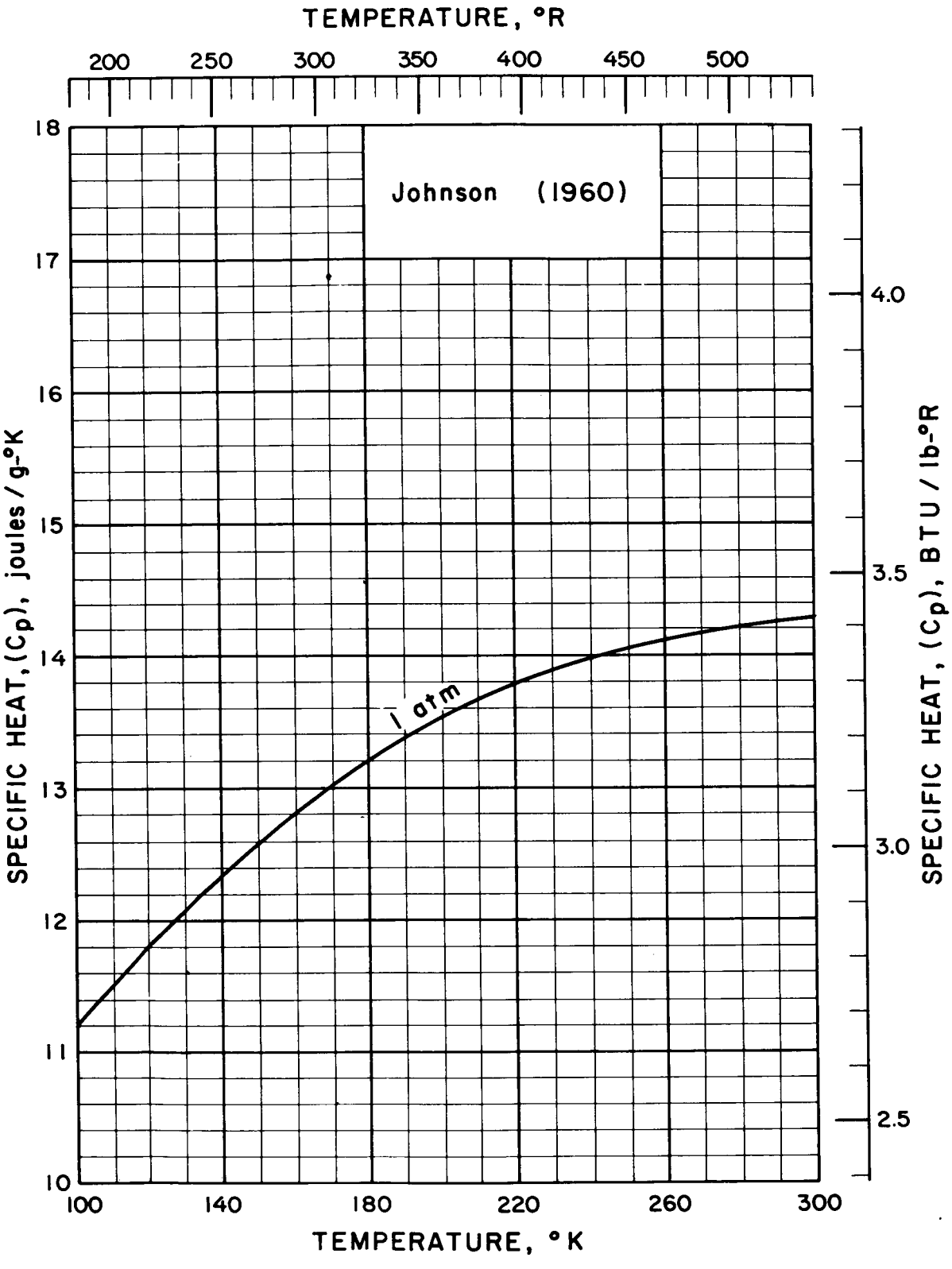

Figure 6.14 Specific heat, C_p, of normal hydrogen gas

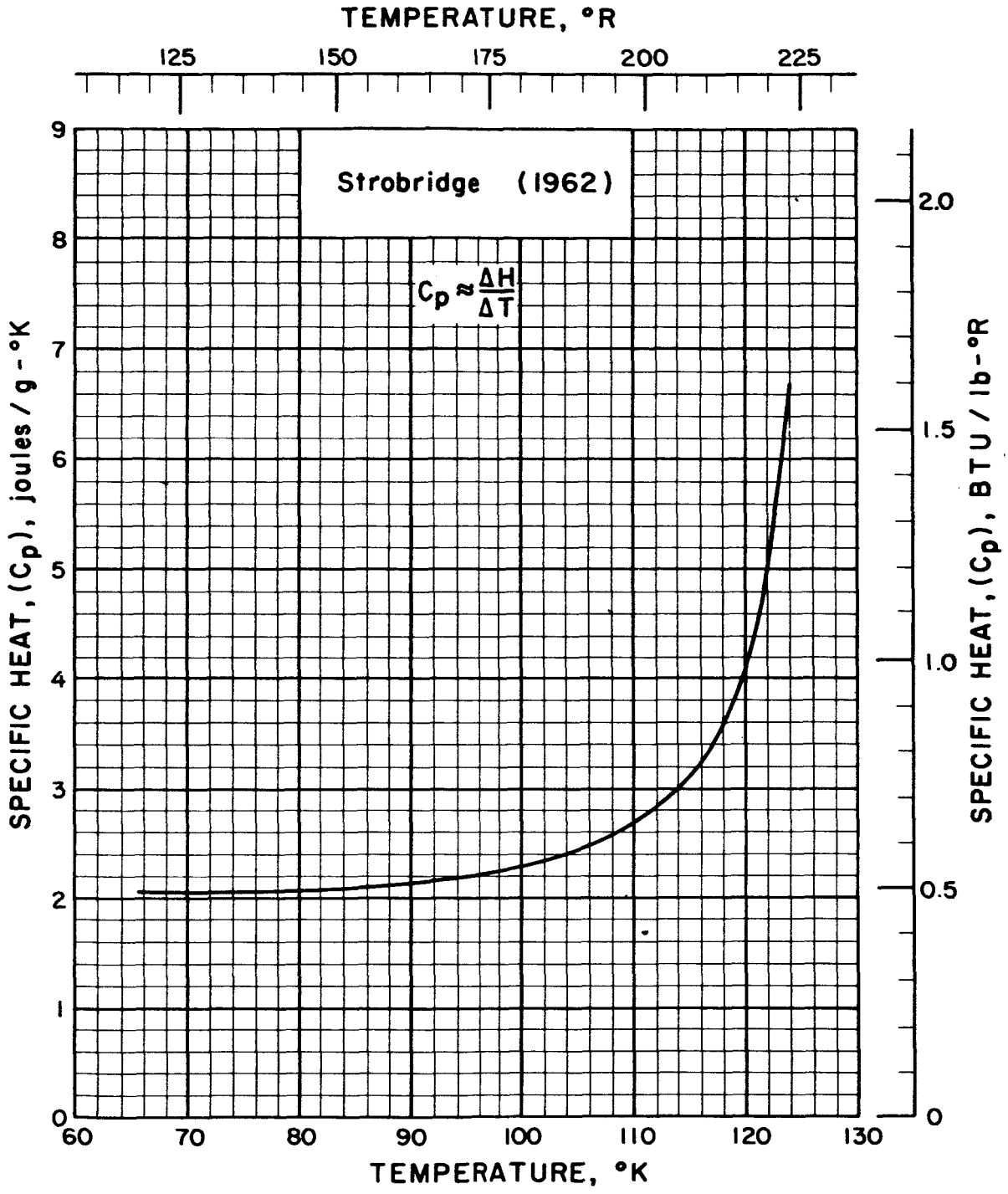

Figure 6.15 Specific heat, C_p, of saturated gaseous nitrogen

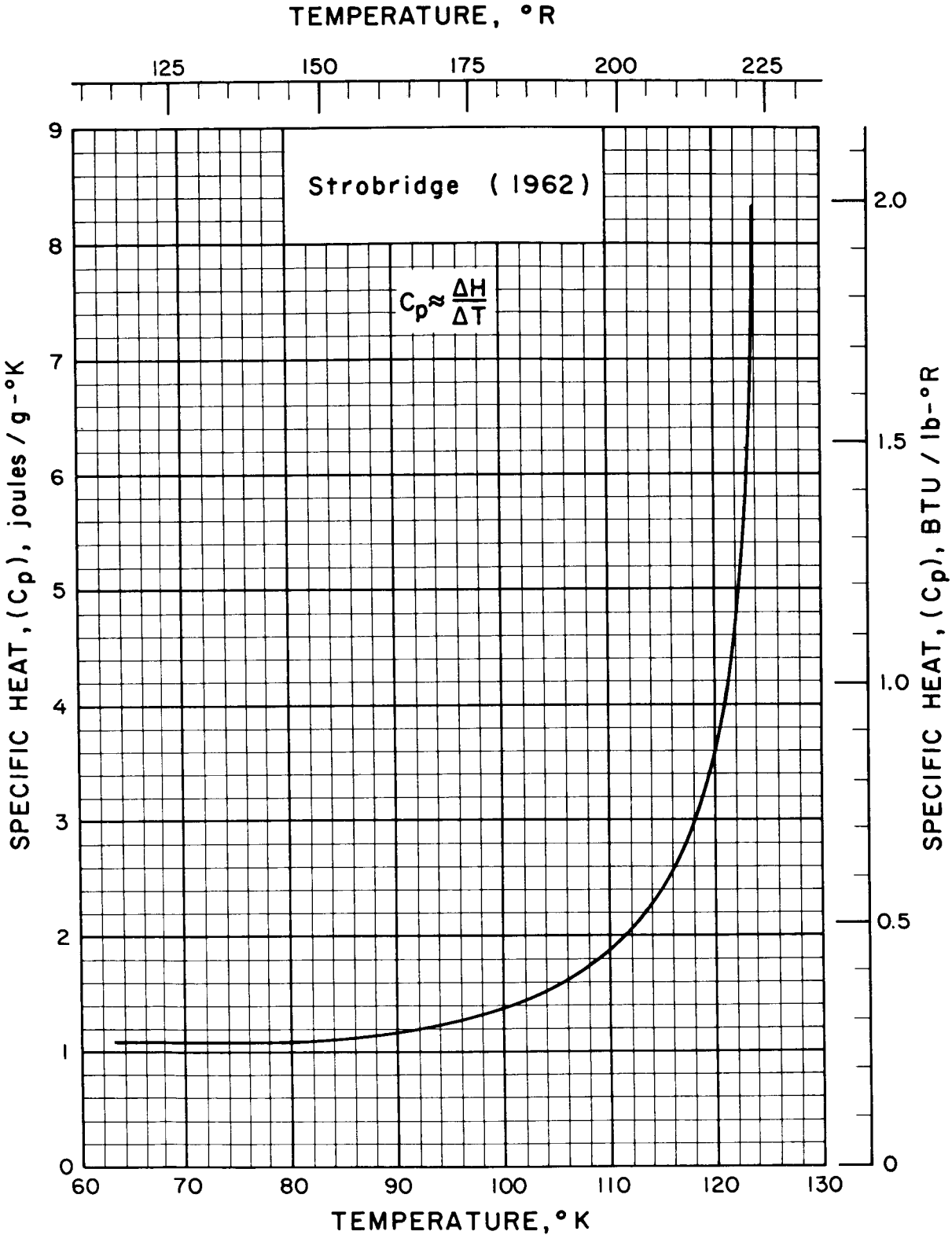

Figure 6.16 Specific heat, C_p, of saturated liquid nitrogen

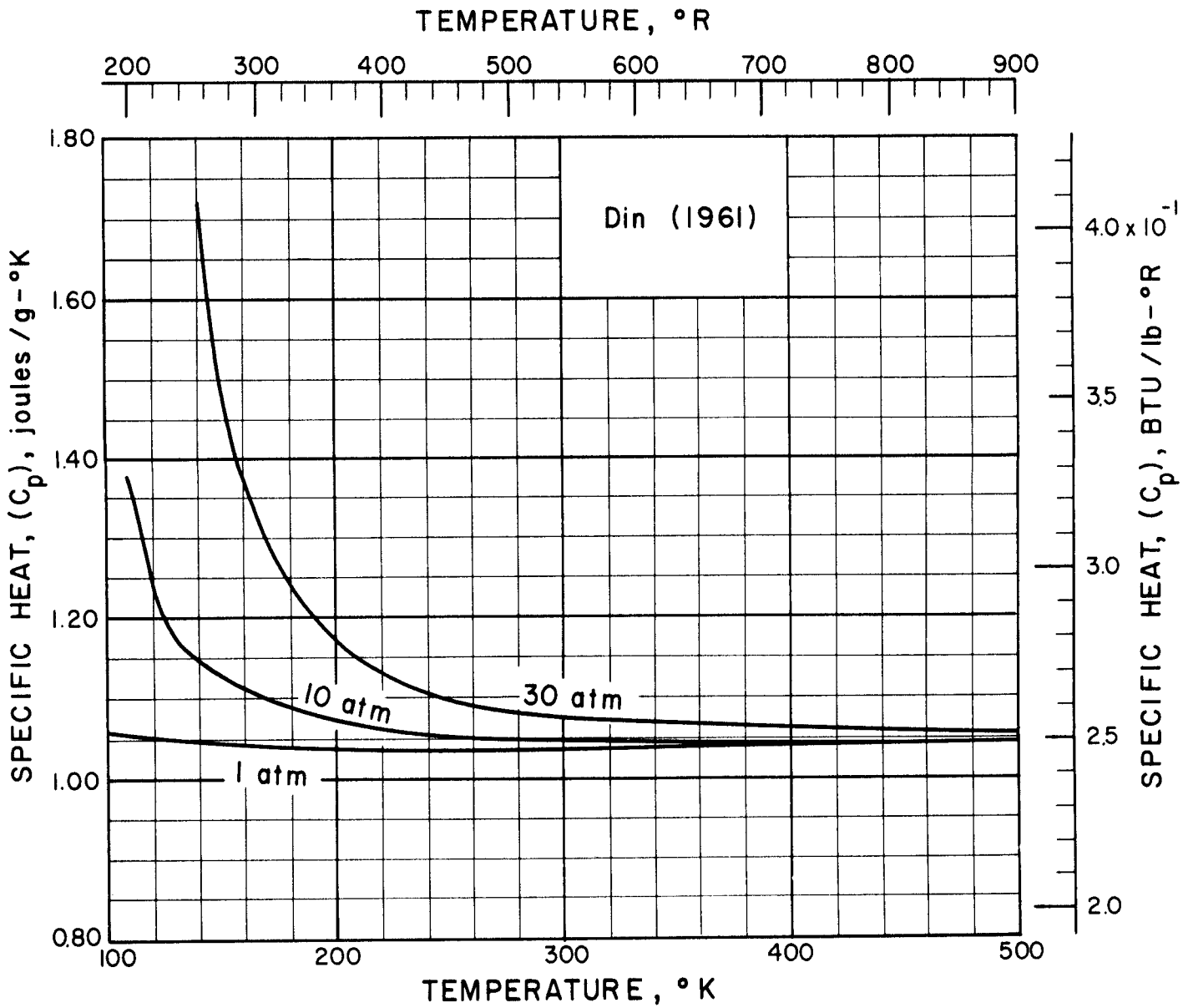

Figure 6.17 Specific heat, C_p, of gaseous nitrogen

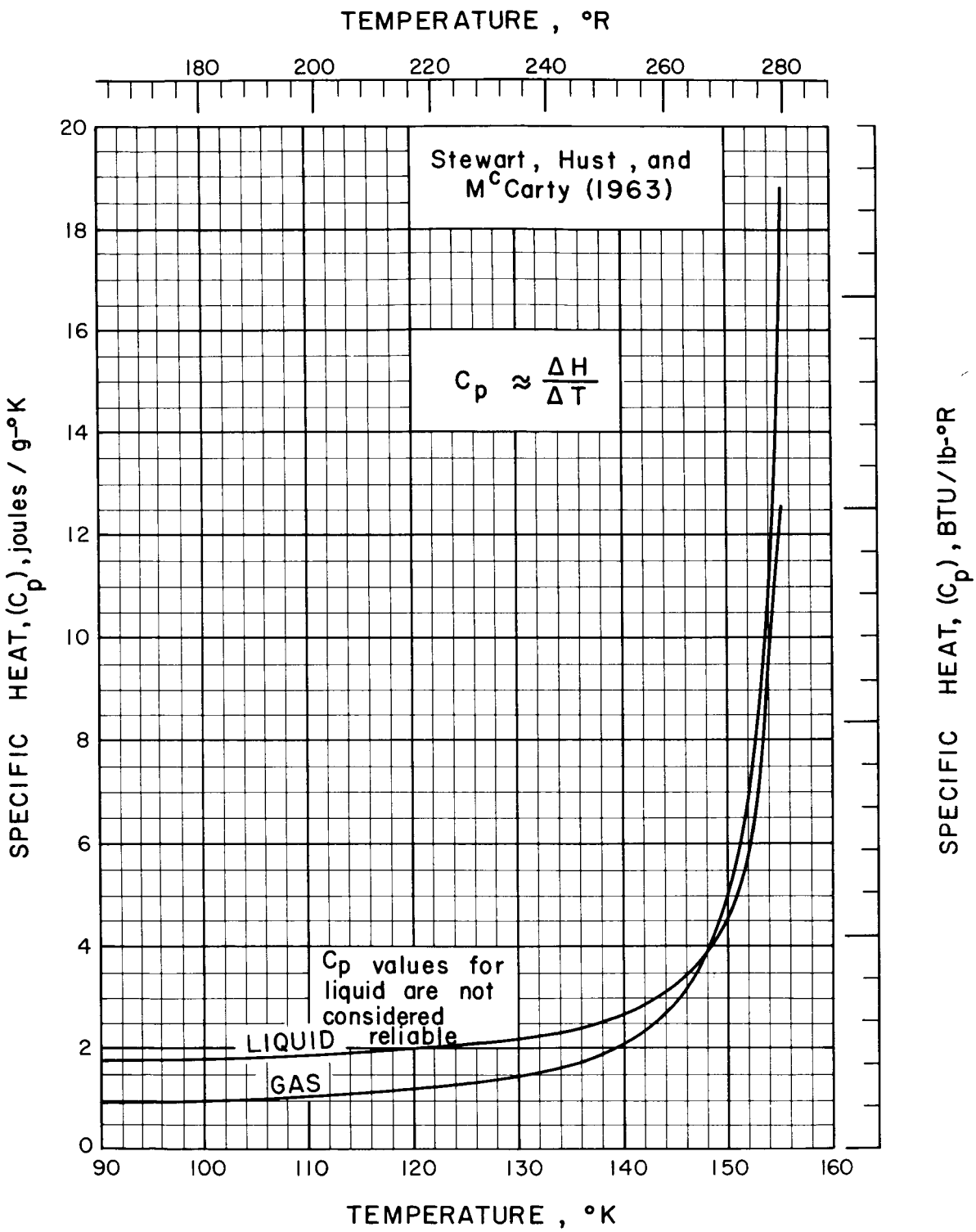

Figure 6.18 Specific heat, C_p, of saturated gaseous and liquid oxygen

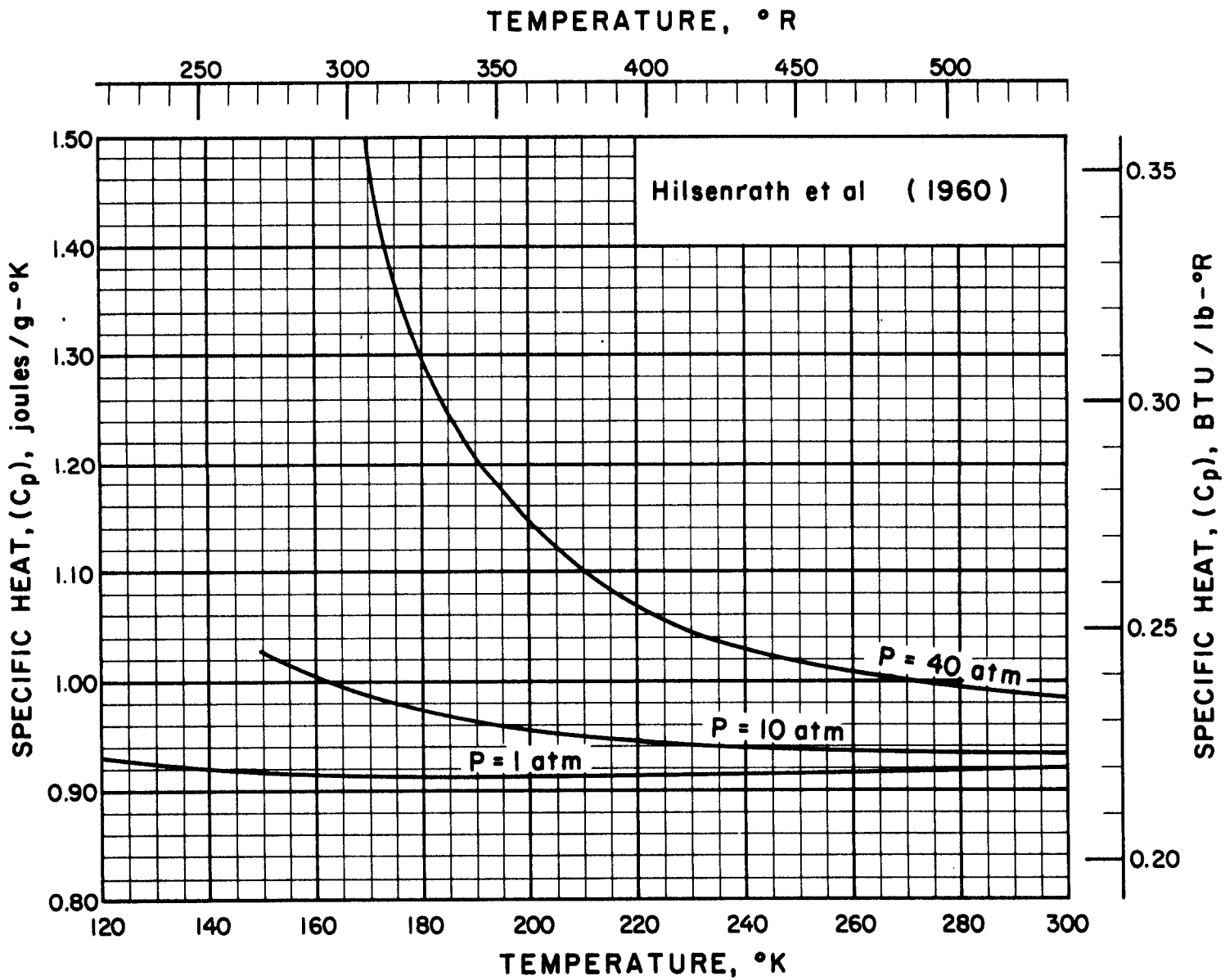

Figure 6.19 Specific heat, C_p, of gaseous oxygen

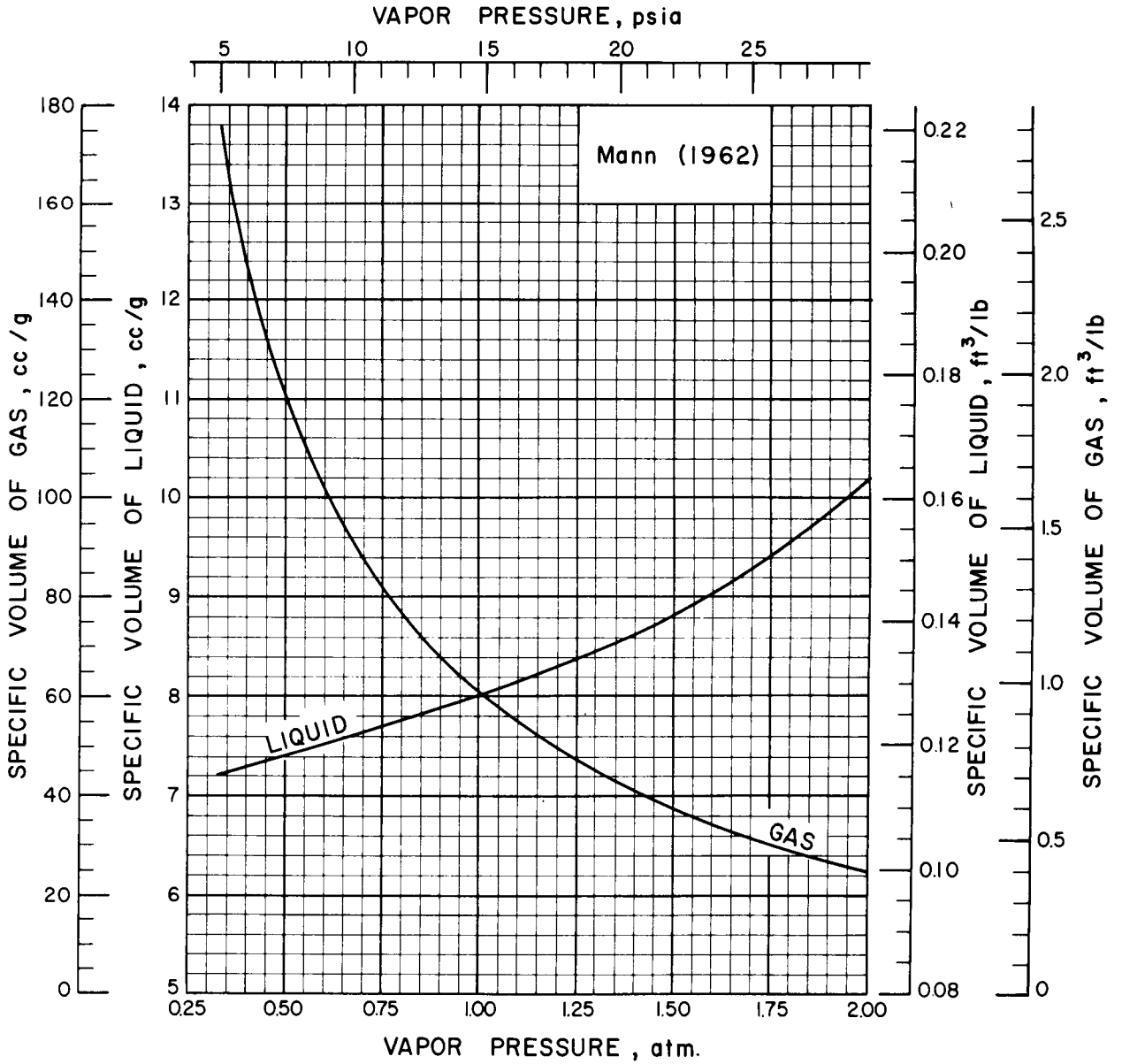

Figure 6.20 Specific volume of saturated gaseous and saturated liquid helium

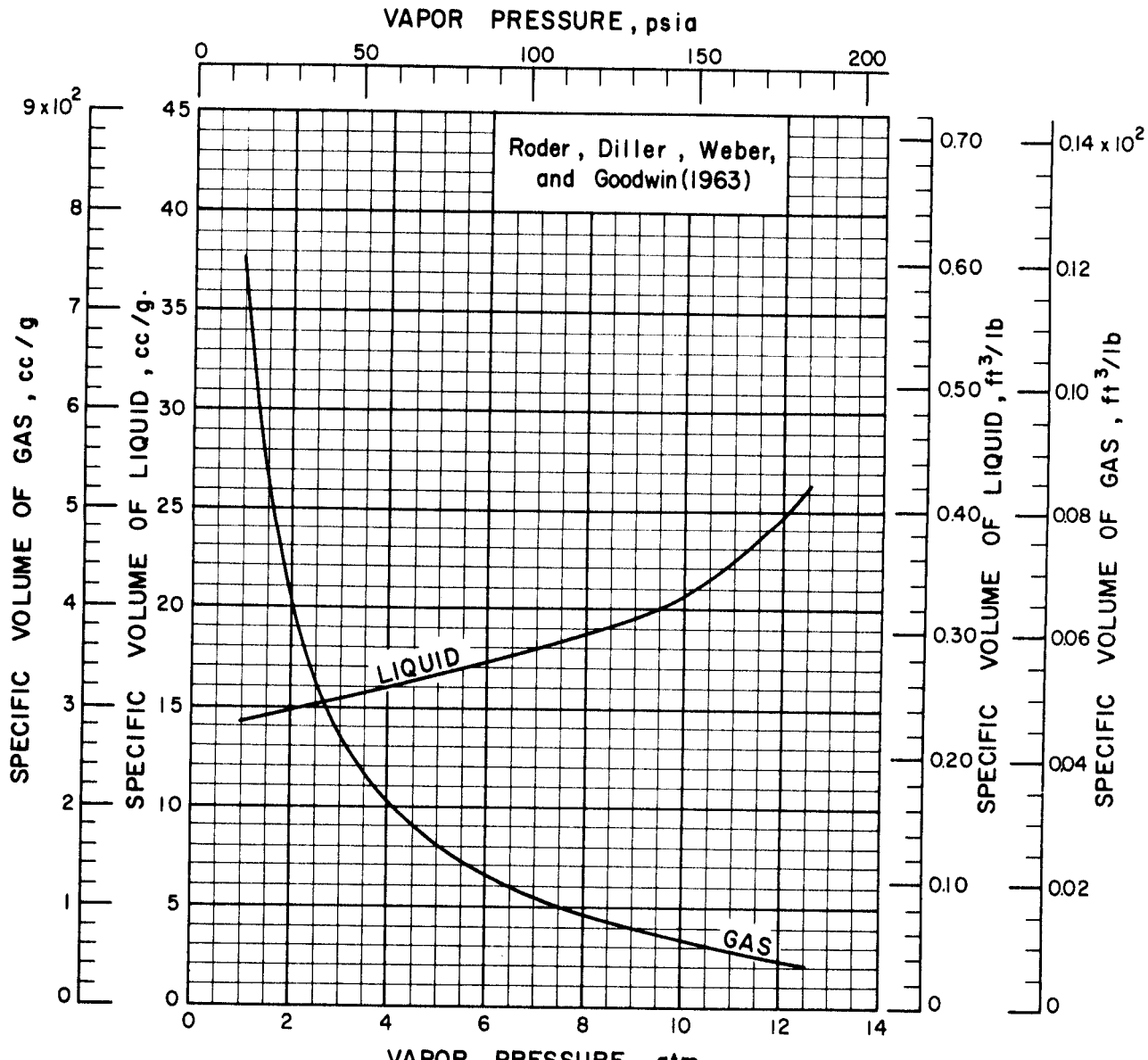

Figure 6.21 Specific volume of saturated gaseous and saturated liquid parahydrogen

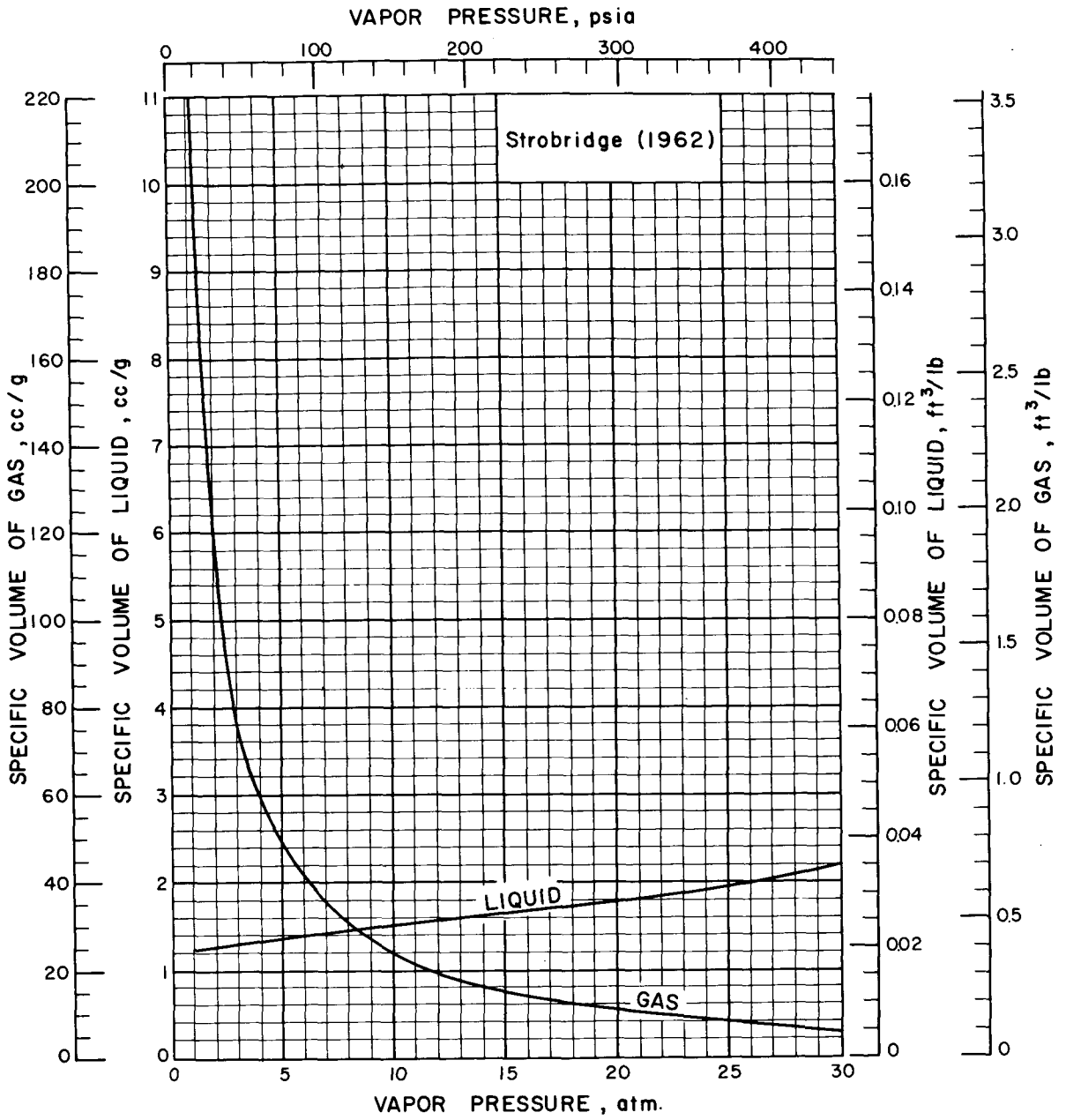

Figure 6.22 Specific volume of saturated gaseous and saturated liquid nitrogen

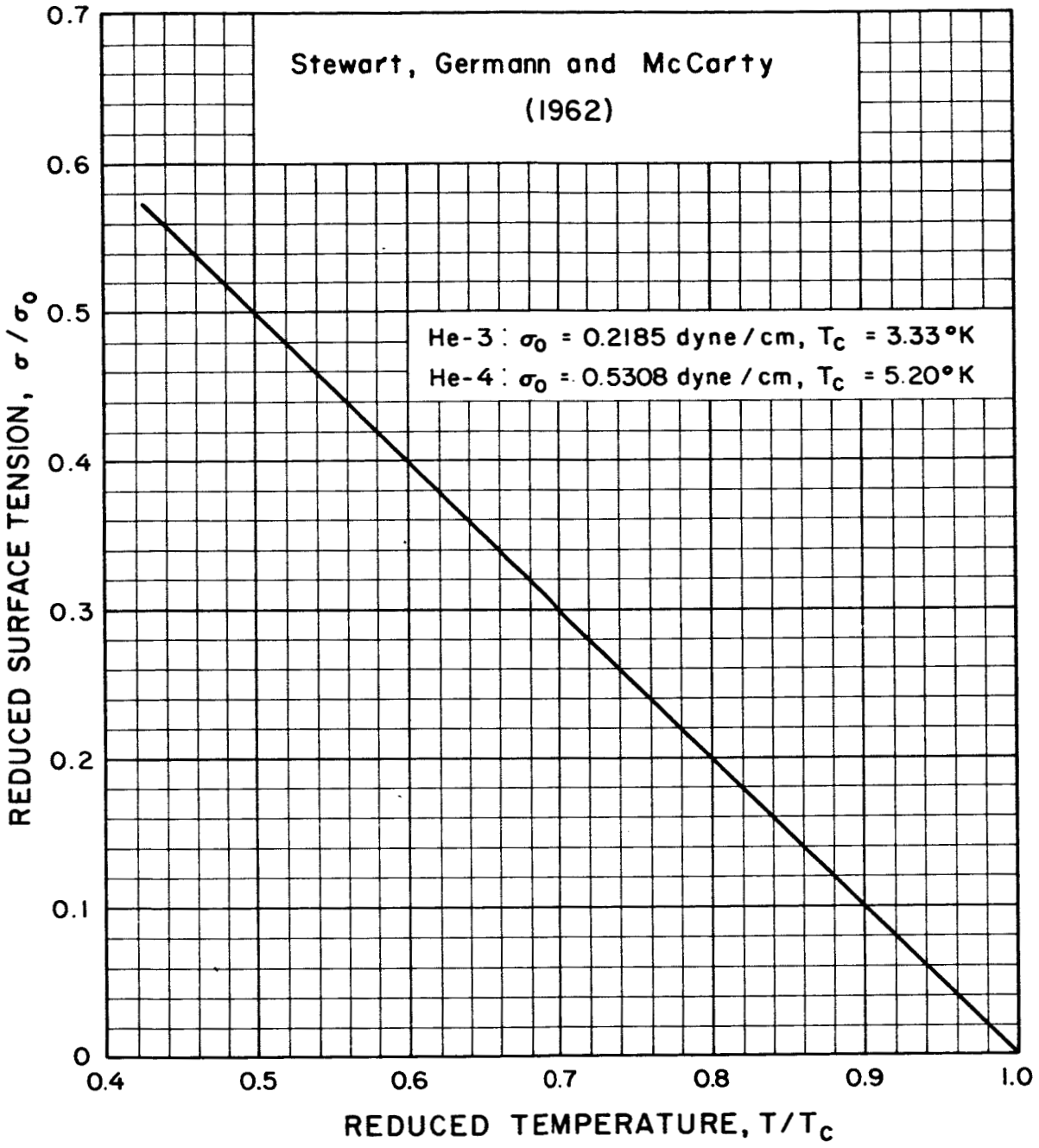

Figure 6.24 Surface tension for helium-3, and helium 4

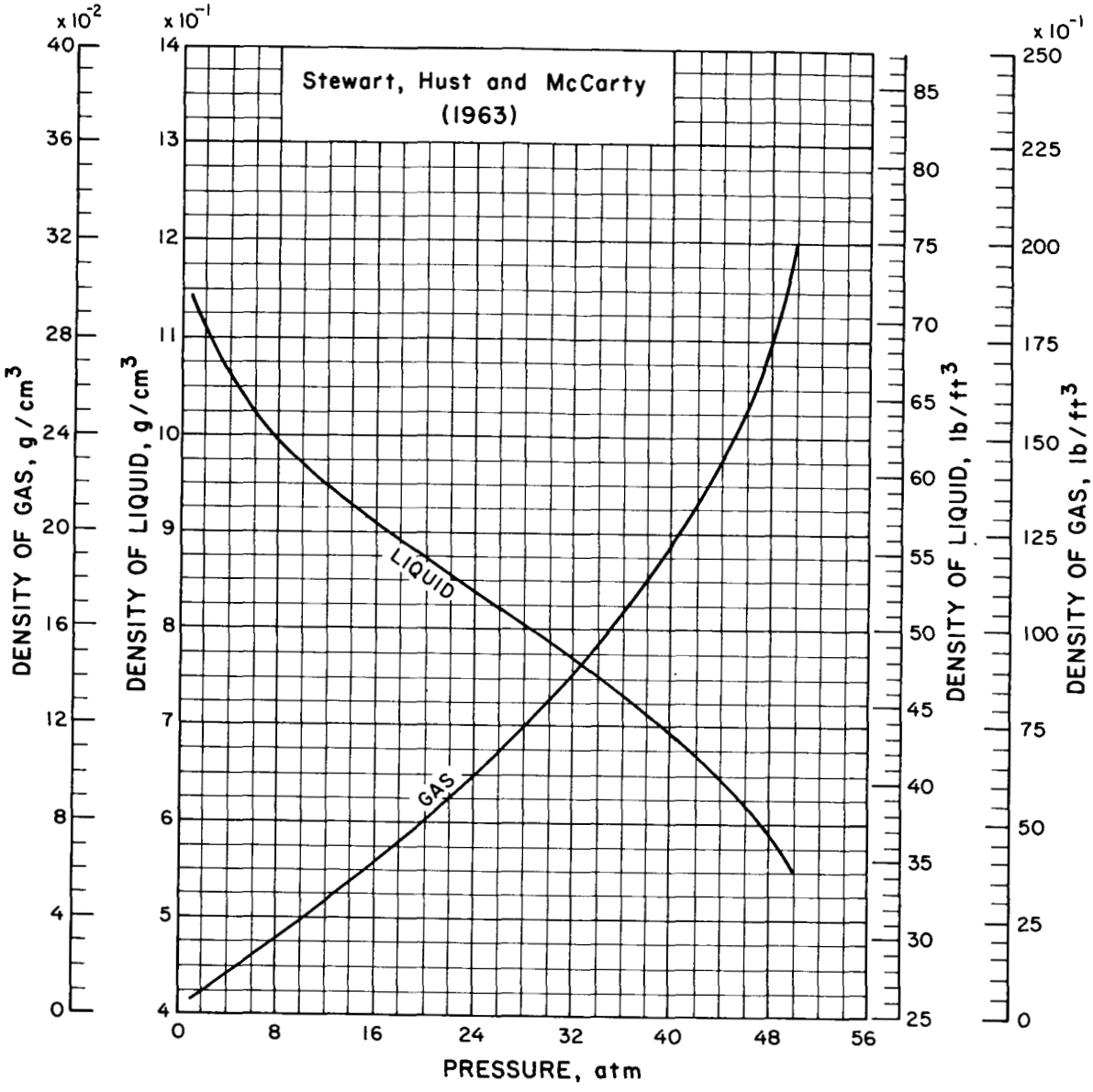

Figure 6.23 Density of saturated gaseous and saturated liquid oxygen

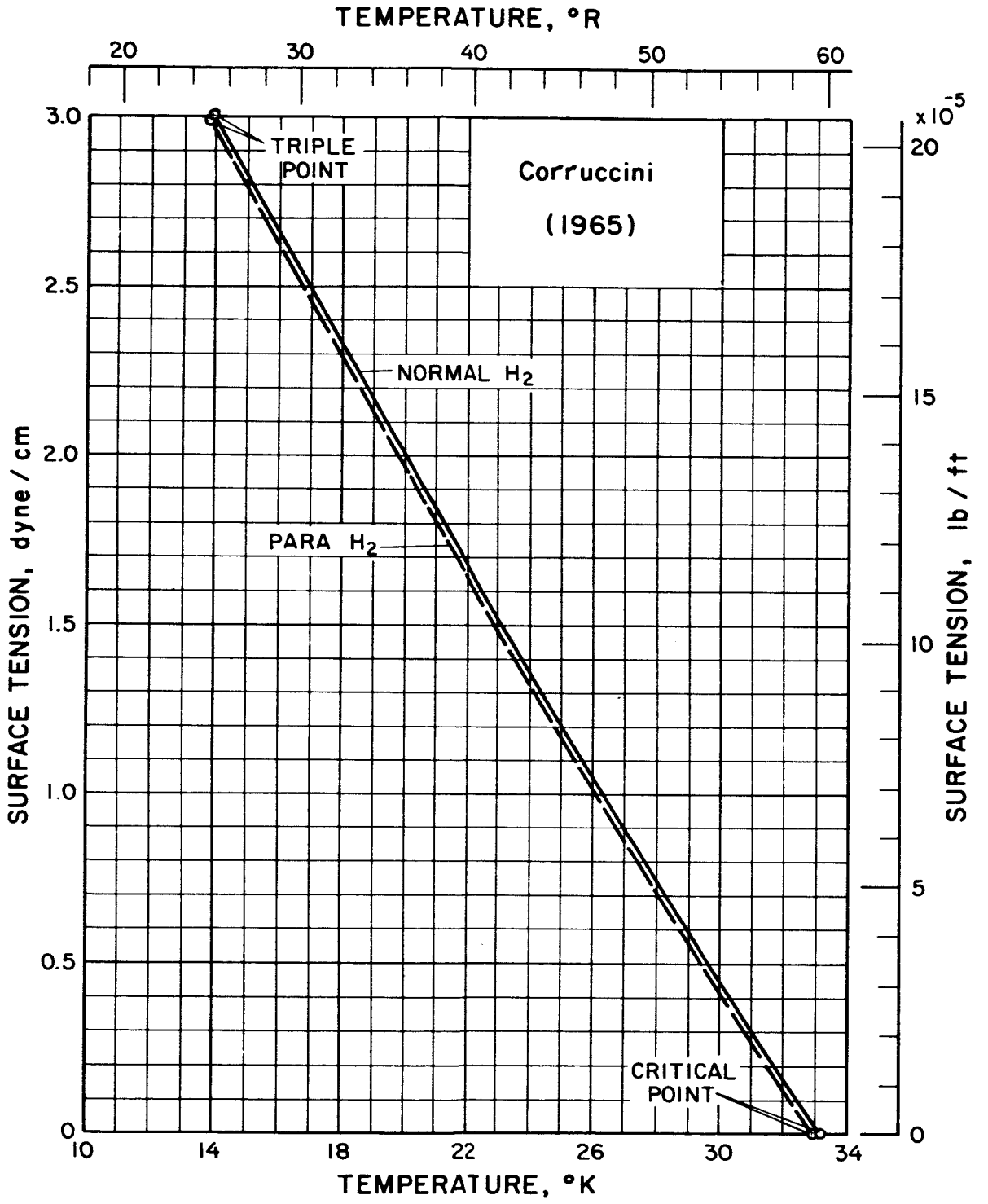

Figure 6.25 Surface tension for normal hydrogen and parahydrogen

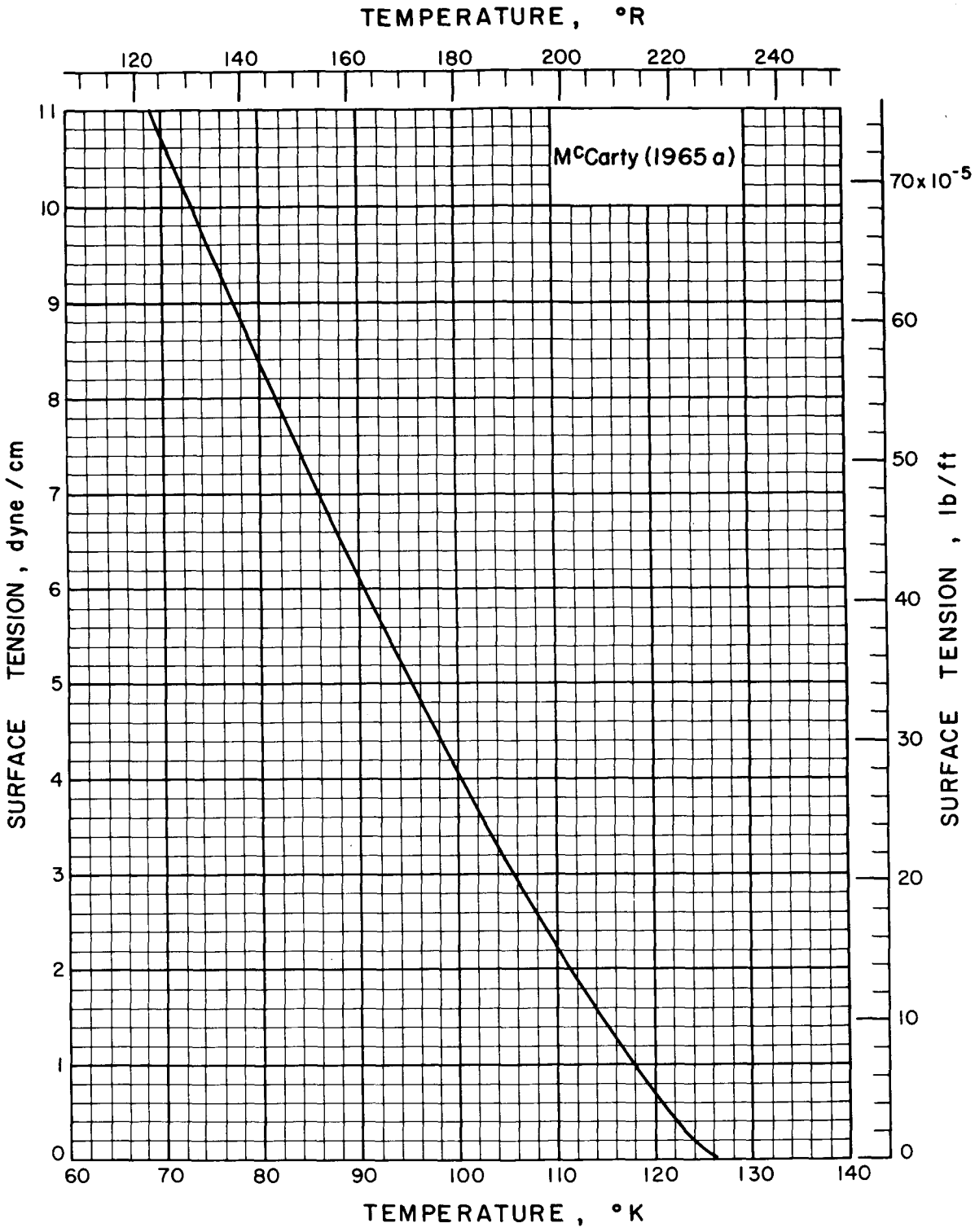

Figure 6.26 Surface tension of nitrogen

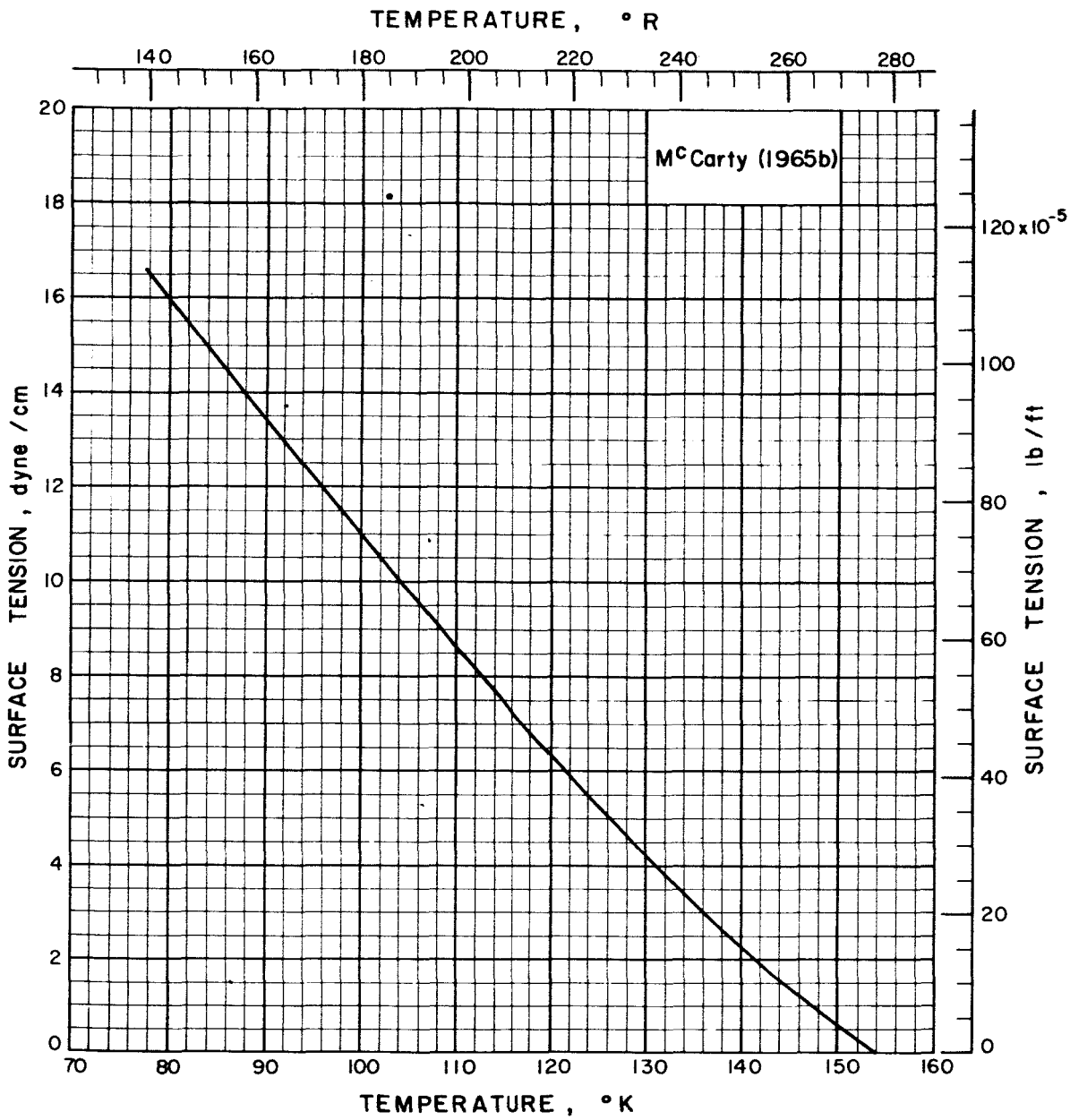

Figure 6.27 Surface tension of oxygen

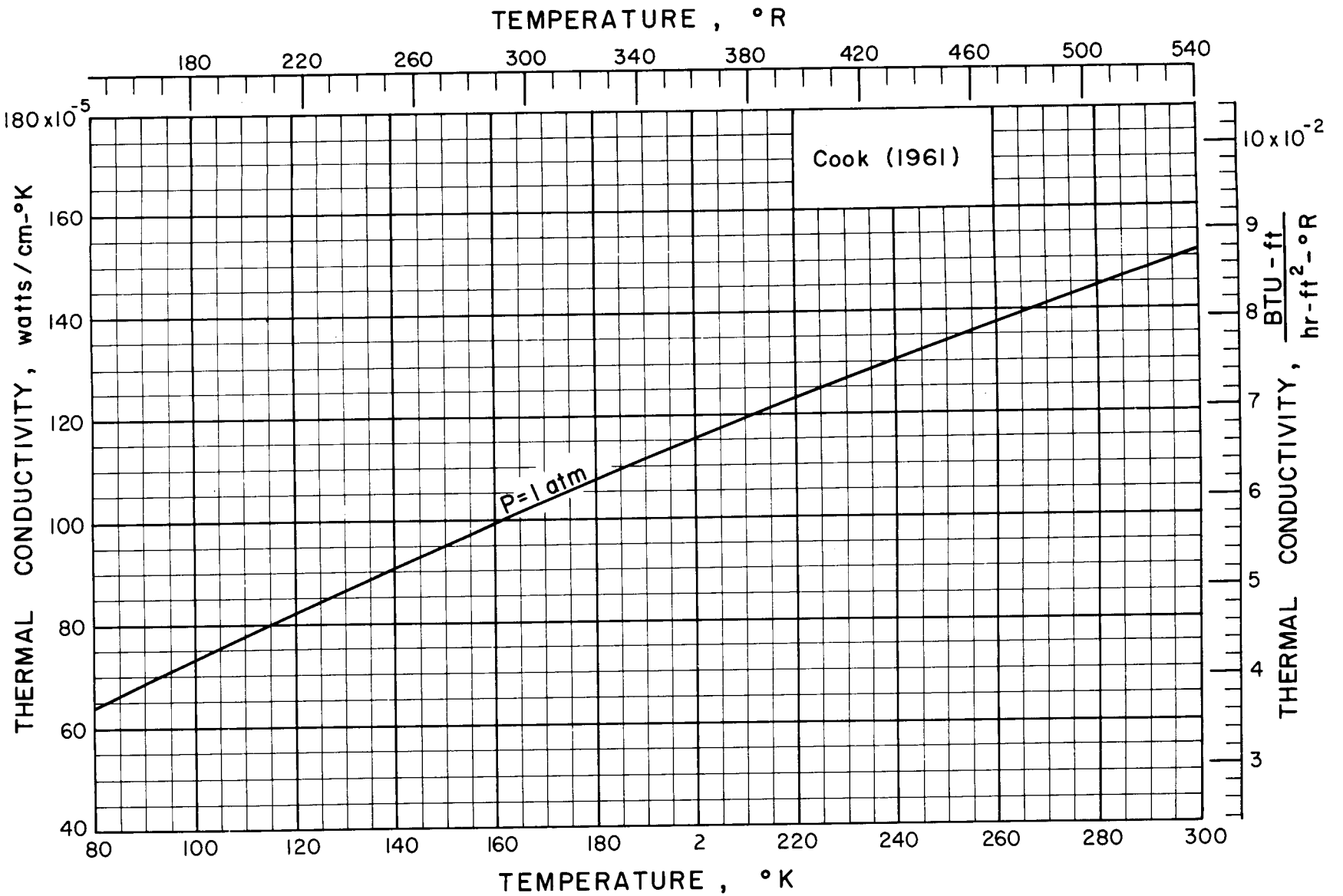

Figure 6.28 Thermal conductivity of gaseous helium from 80°K to 300°K

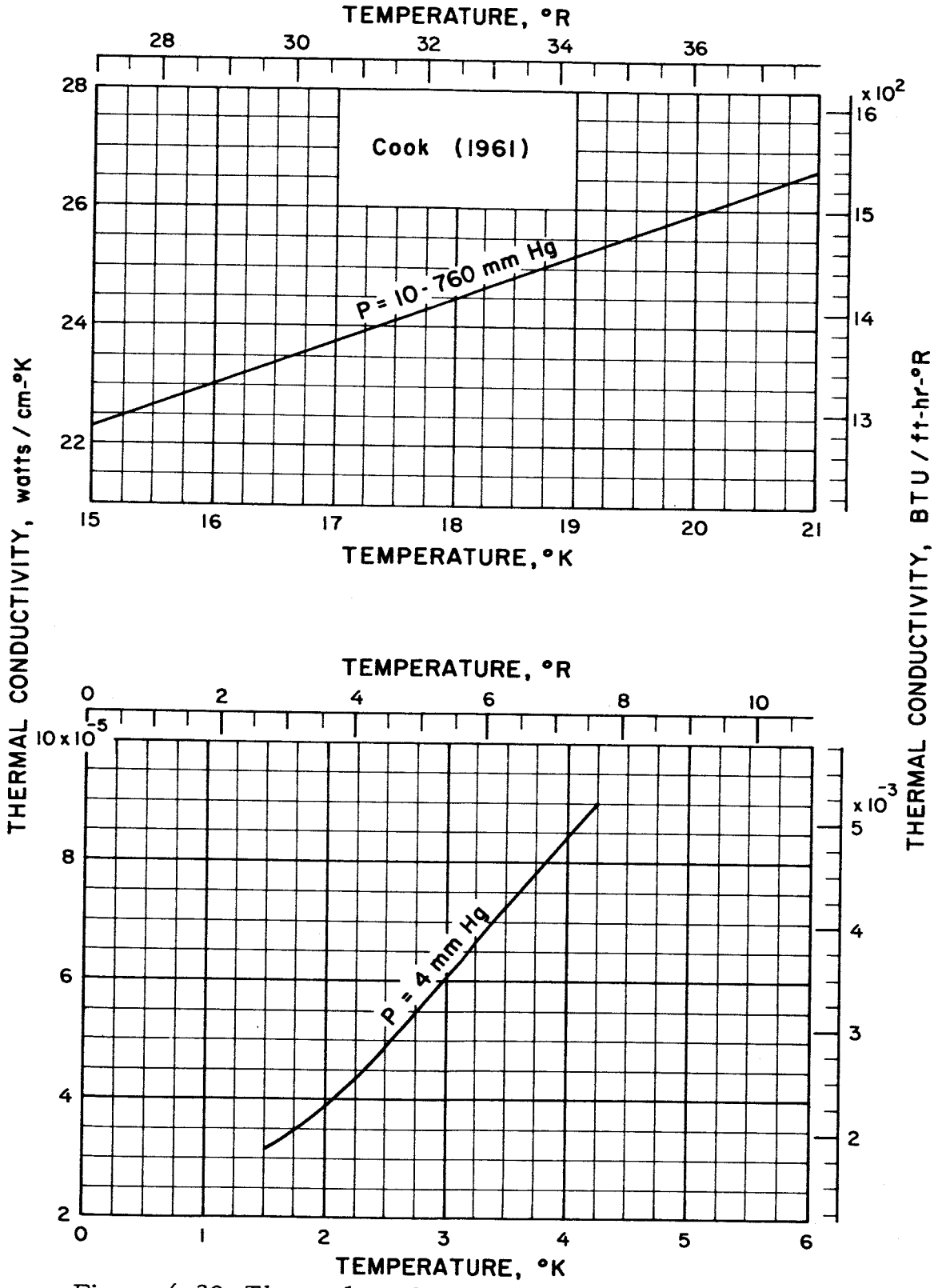

Figure 6.29 Thermal conductivity of gaseous helium from 1.5°K to 21°K

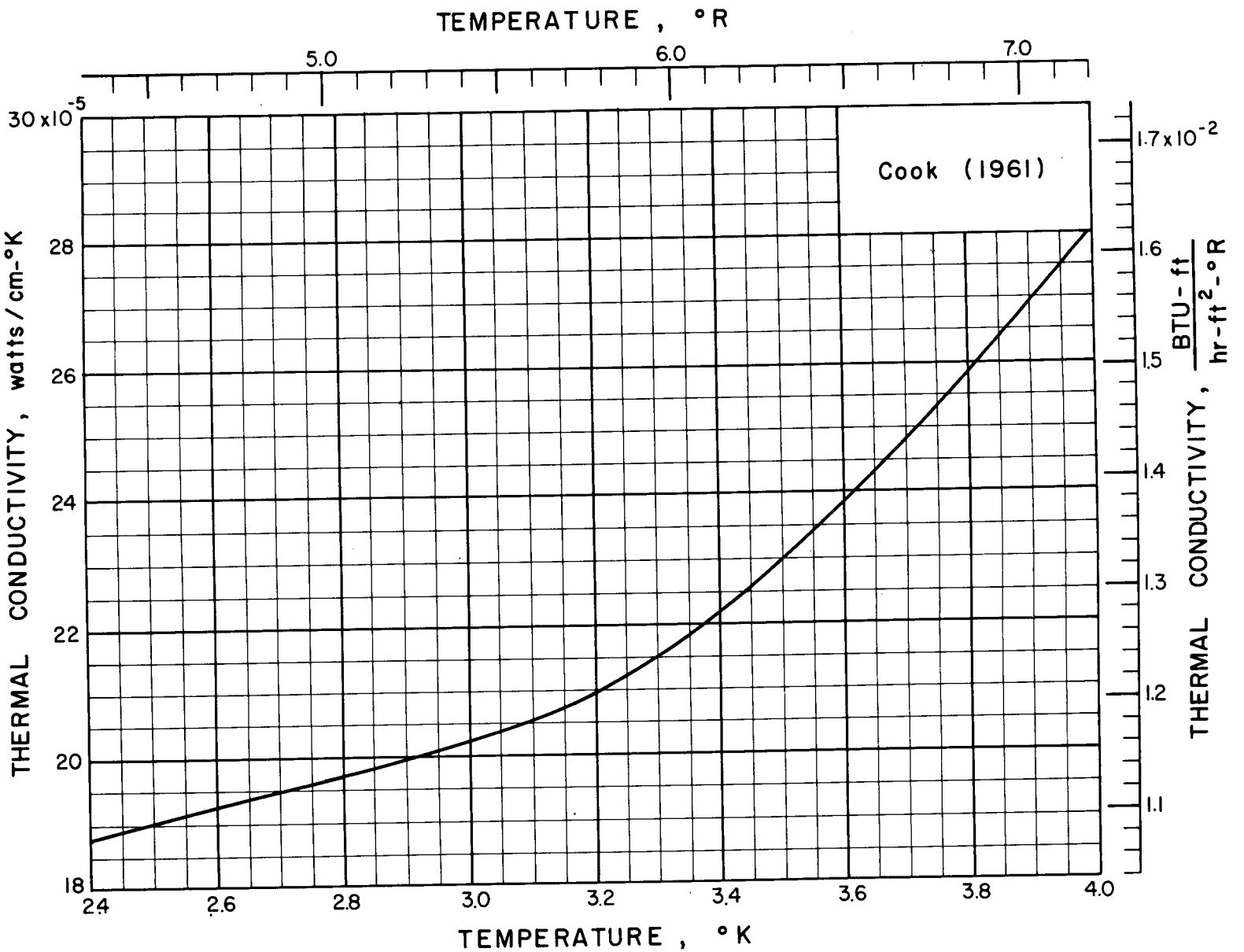

Figure 6.30 Thermal conductivity of saturated liquid helium I

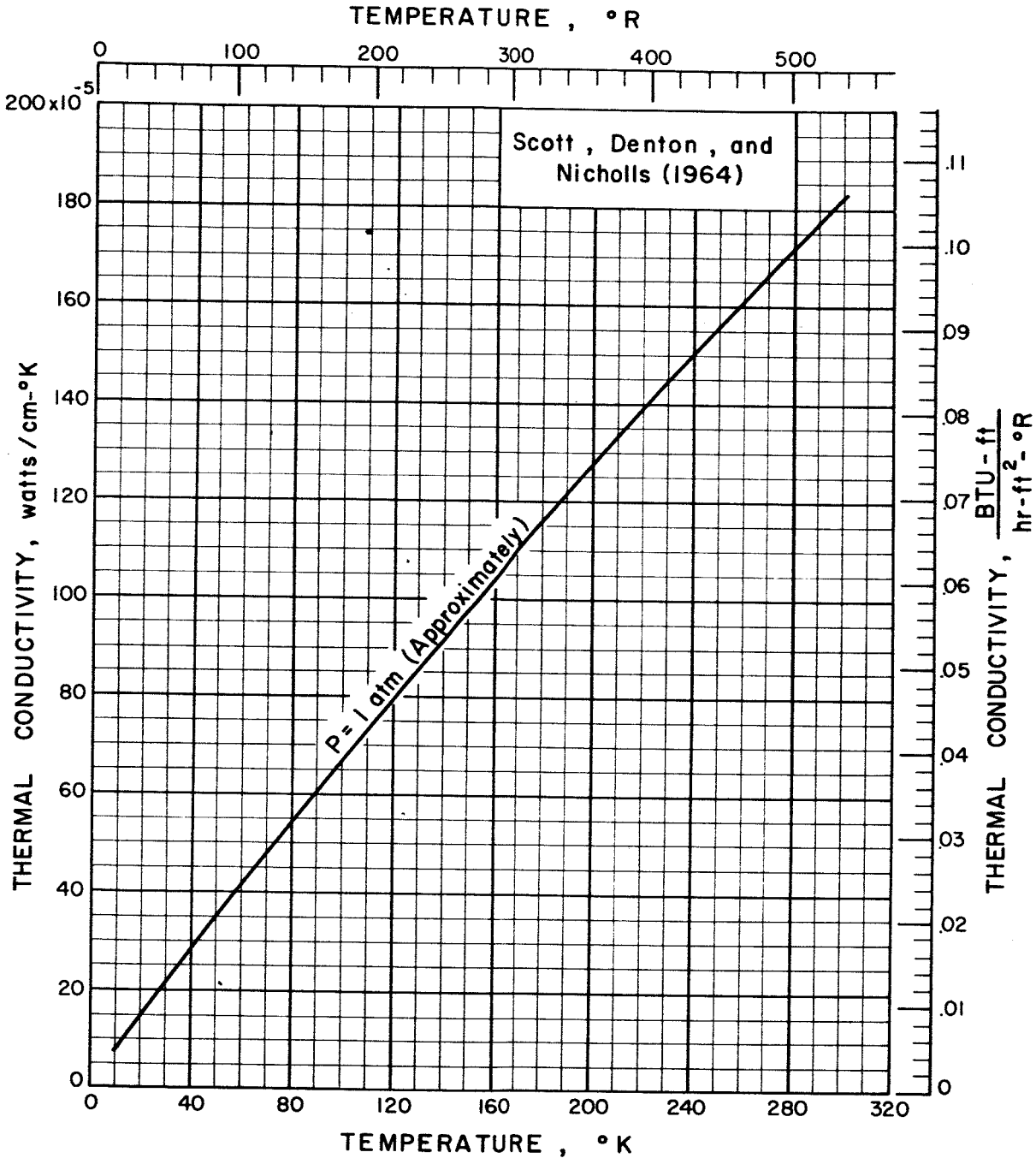

Figure 6.31 Thermal conductivity of gaseous normal hydrogen

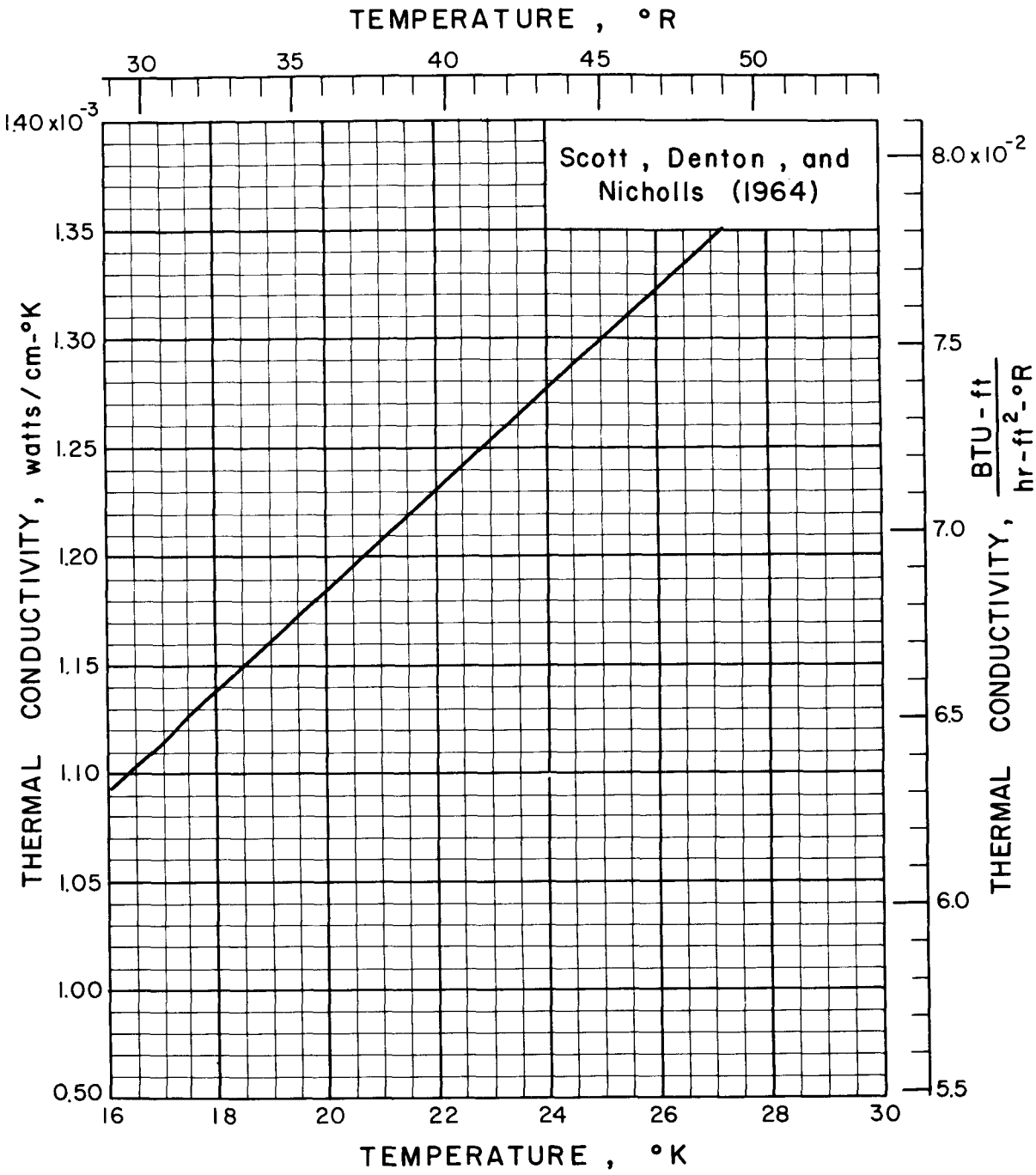

Figure 6.32 Thermal conductivity of saturated liquid normal hydrogen and saturated liquid parahydrogen

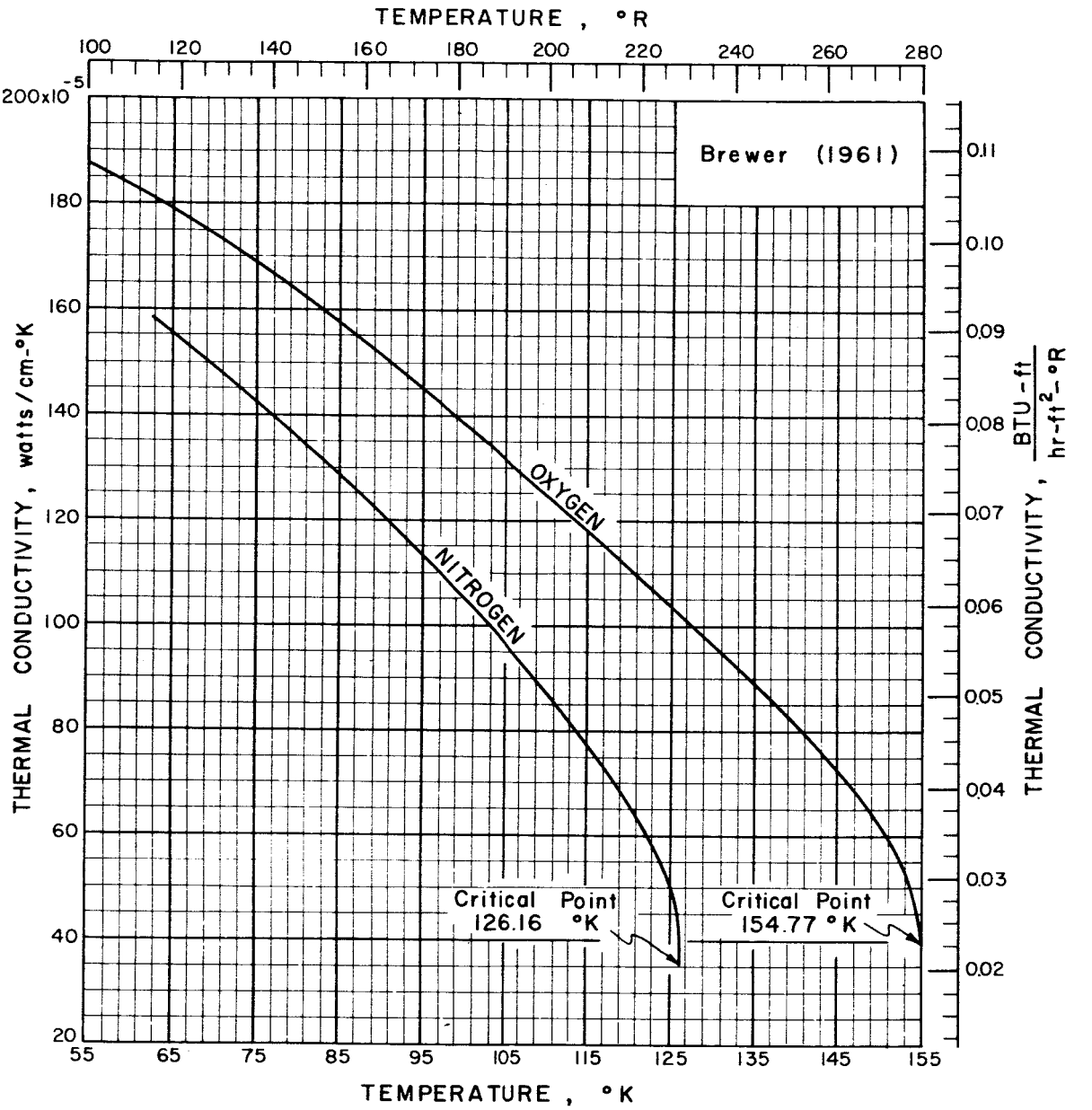

Figure 6.33 Thermal conductivity of oxygen and nitrogen saturated liquid

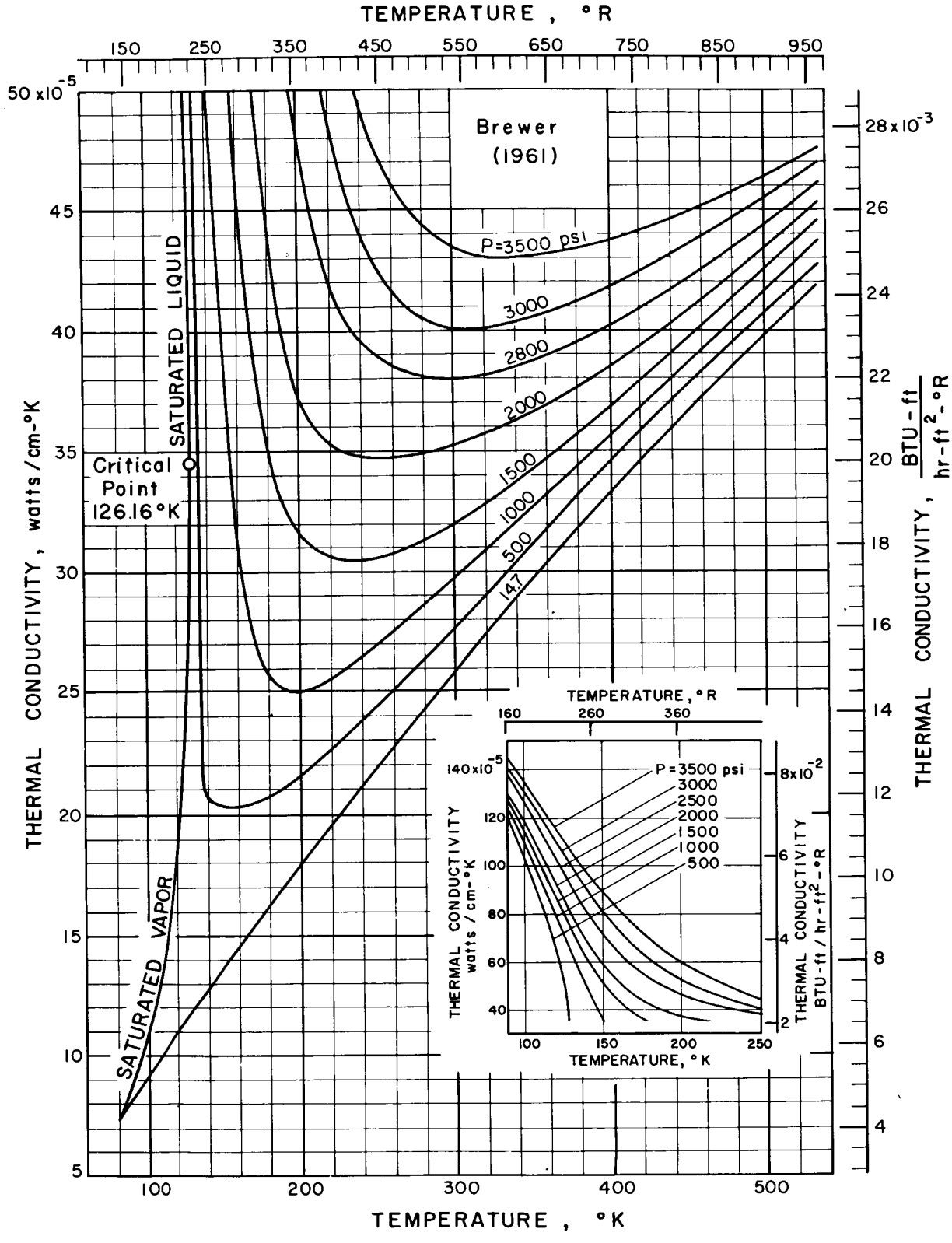

Figure 6.34 Thermal conductivity of nitrogen

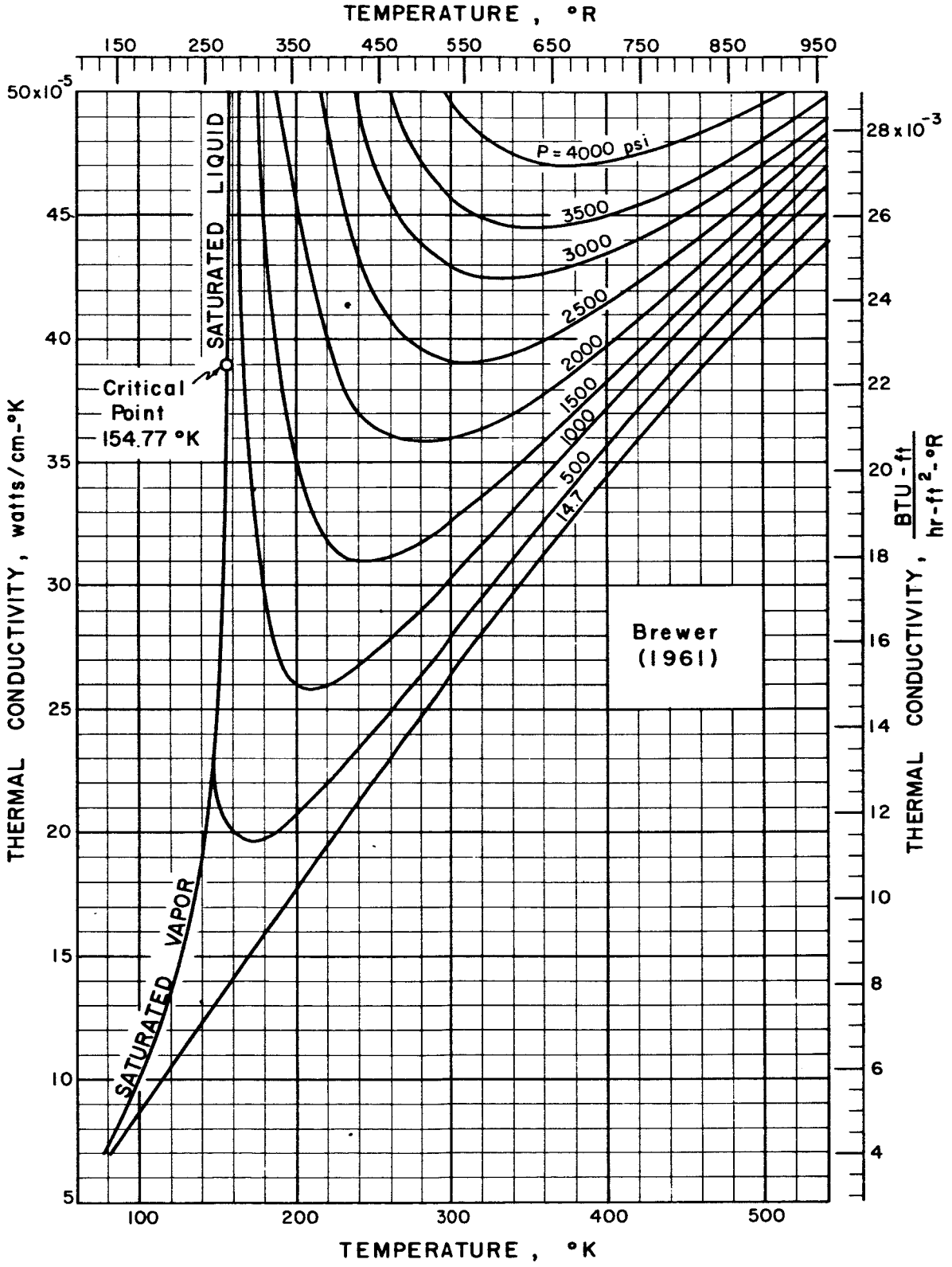

Figure 6.35 Thermal conductivity of oxygen

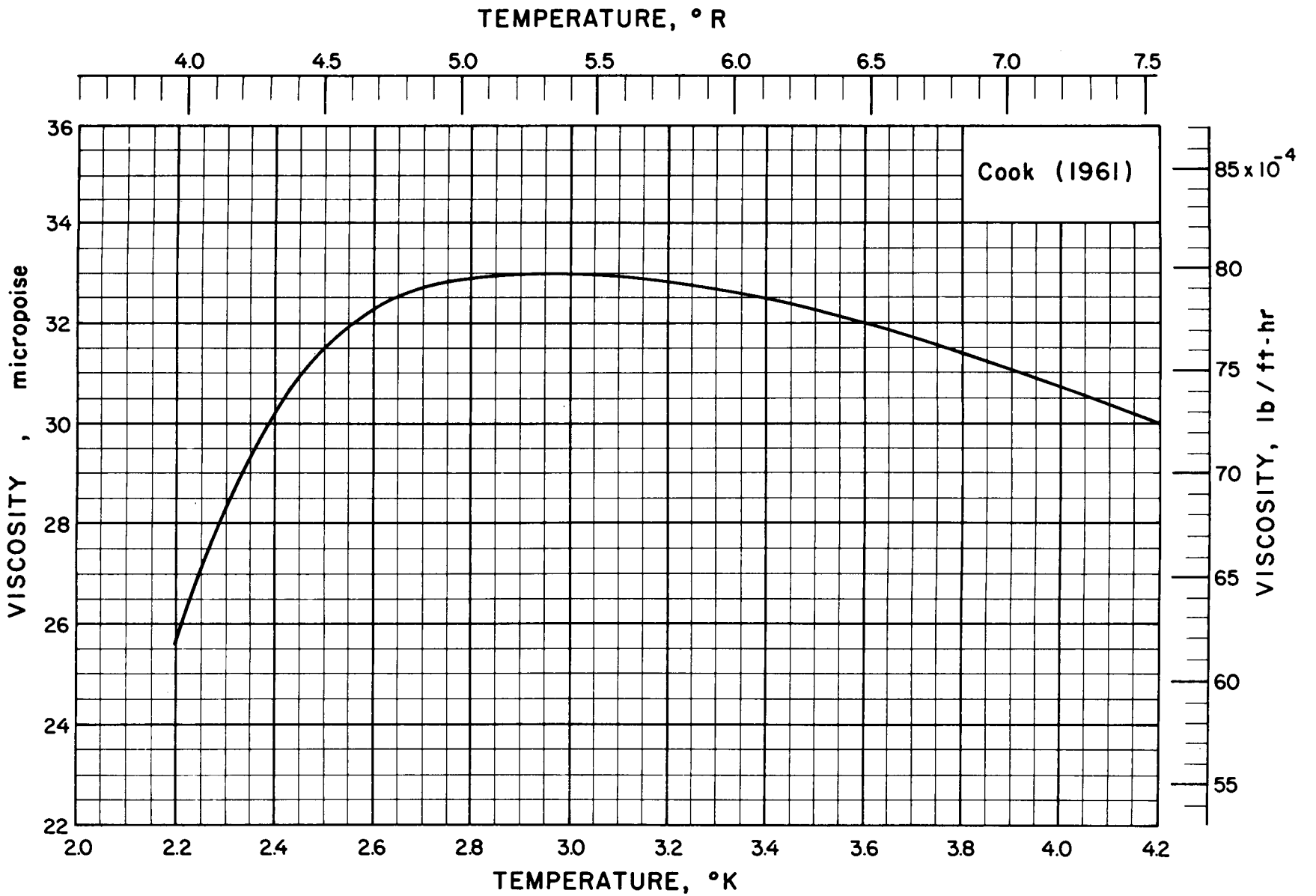

Figure 6.36 Viscosity of saturated liquid helium I

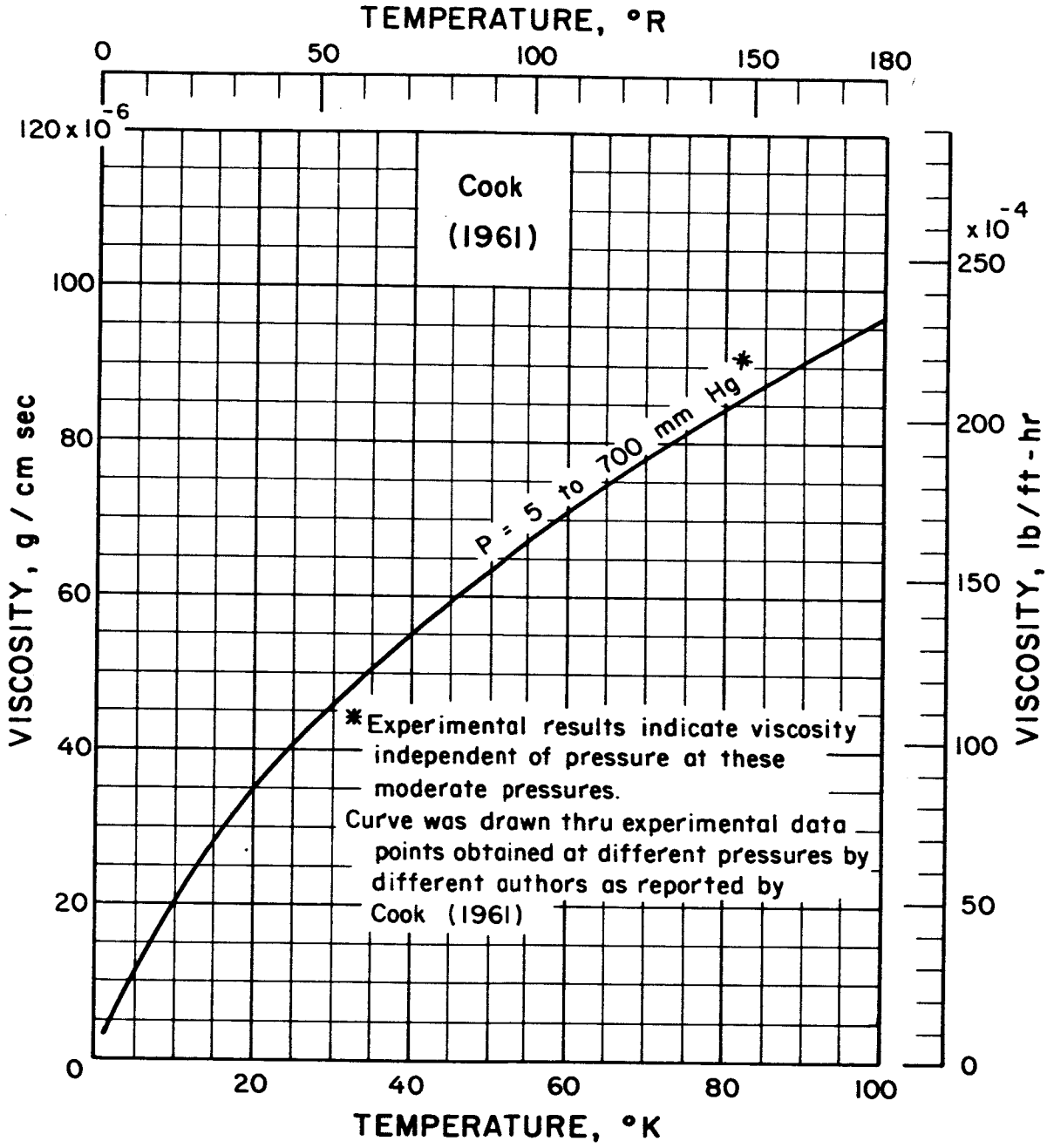

Figure 6.37 Viscosity of gaseous helium from 0° to 100°K

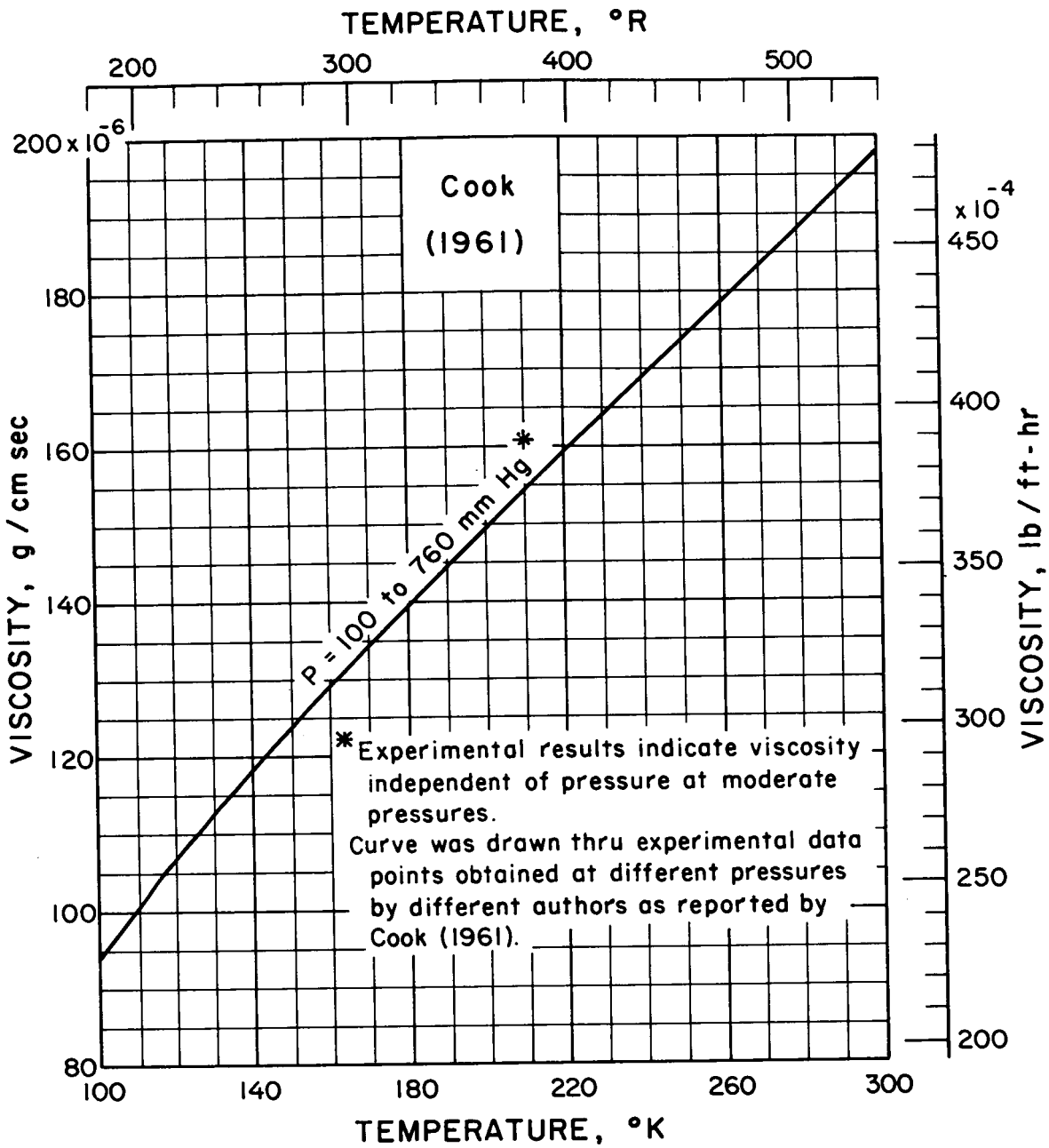

Figure 6.38 Viscosity of gaseous helium from 100° to 300°K

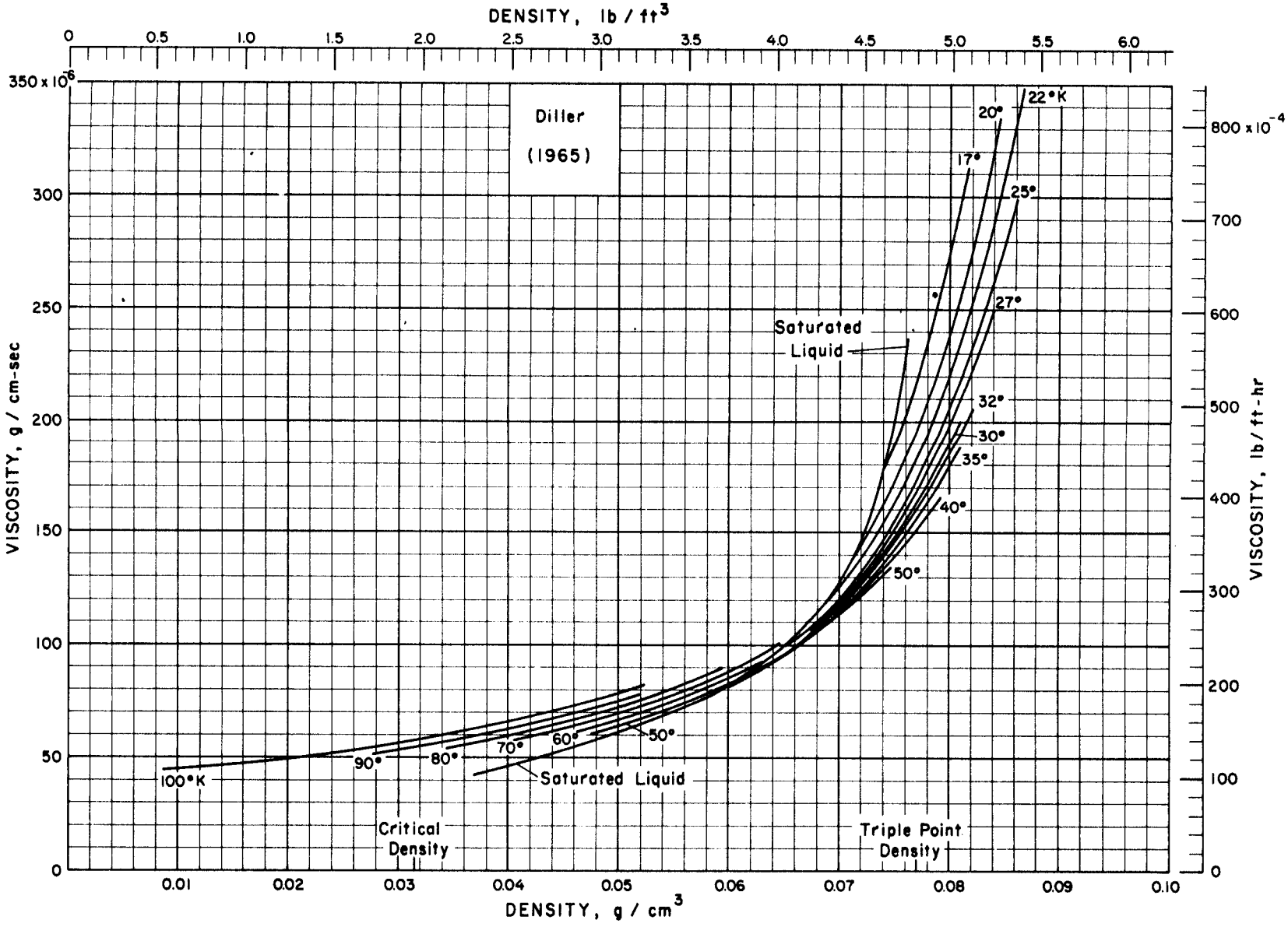

Figure 6.39 Viscosity of parahydrogen

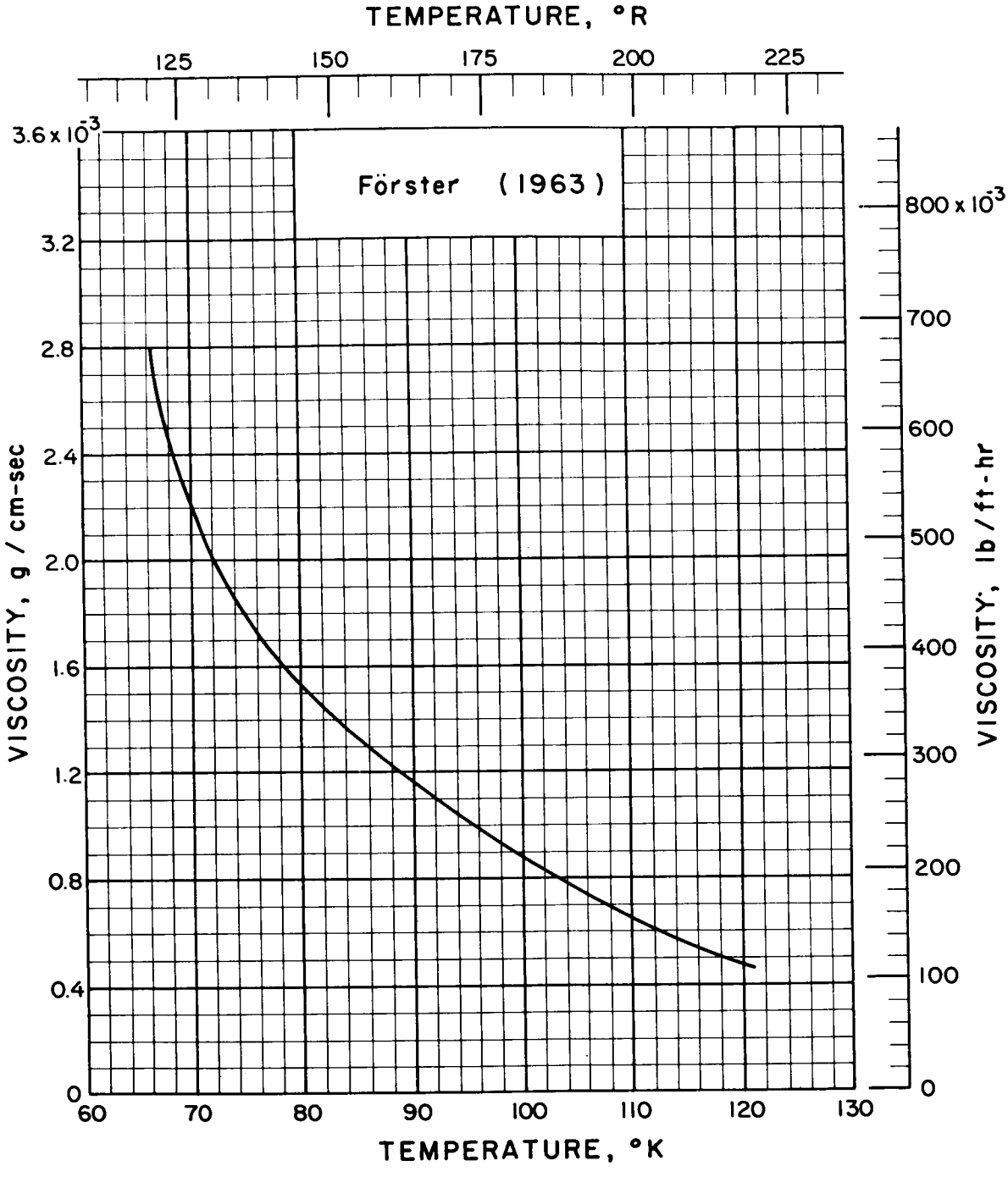

Figure 6.40 Viscosity of saturated liquid nitrogen

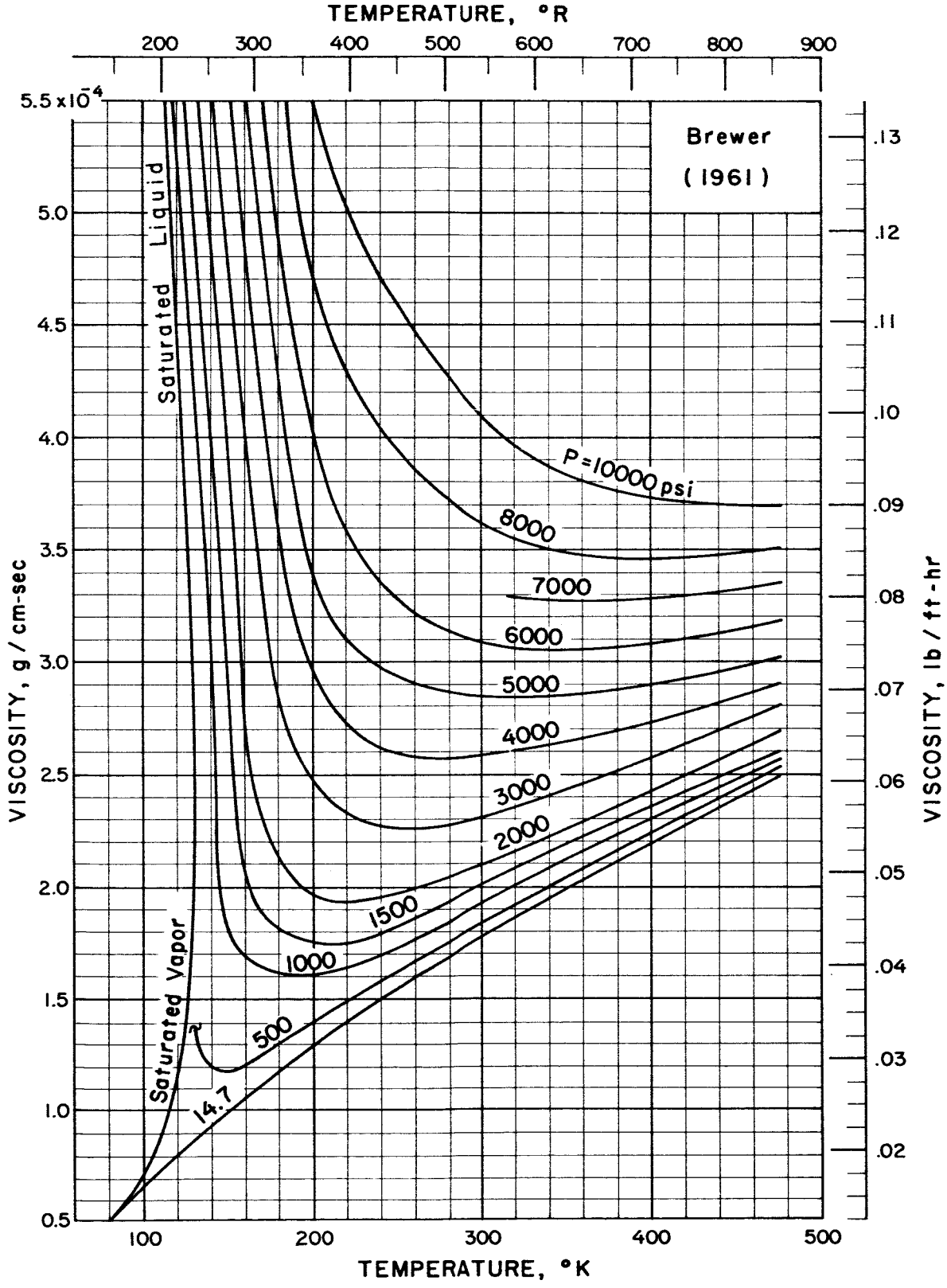

Figure 6.41 Viscosity of nitrogen

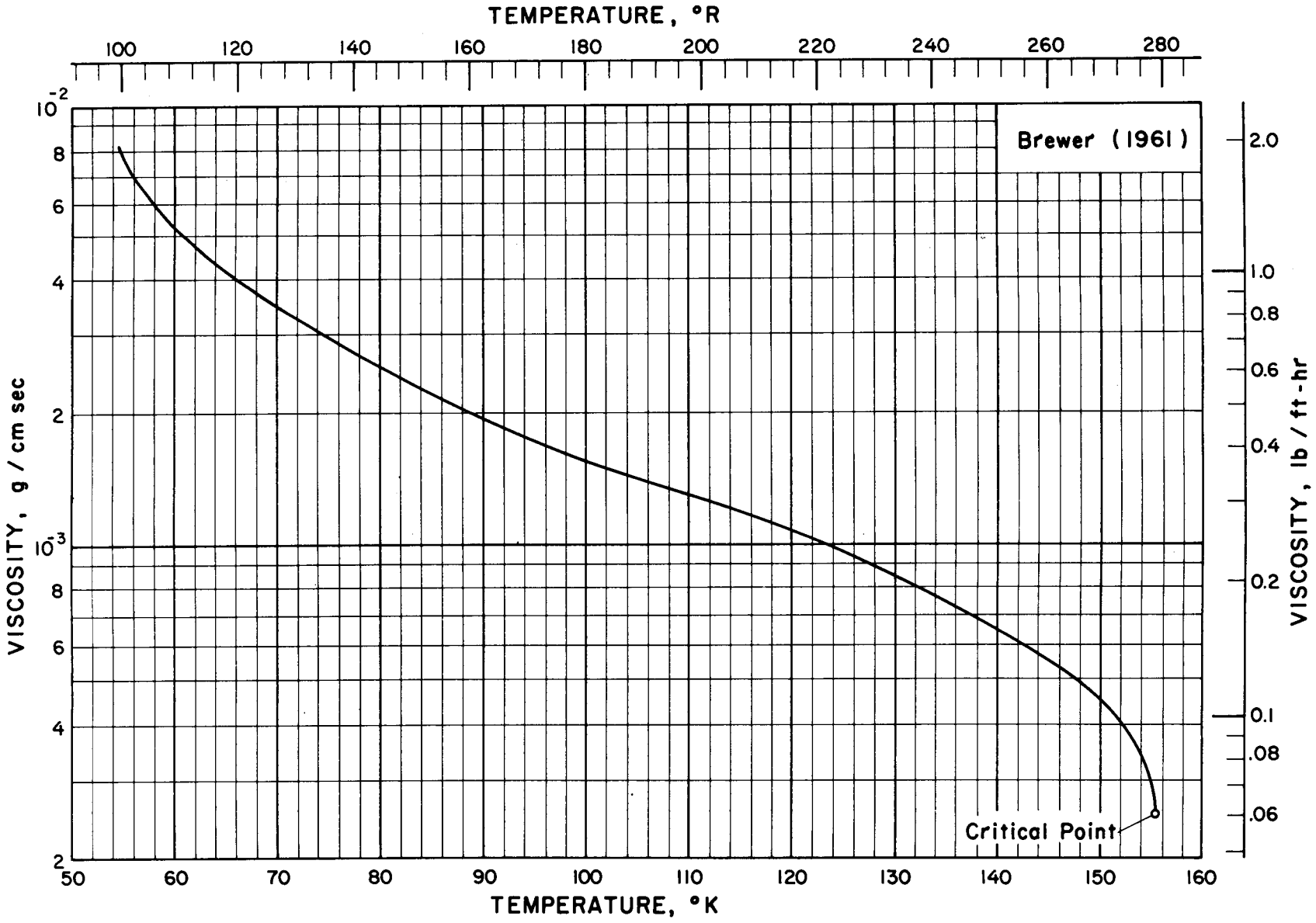

Figure 6.42 Viscosity of saturated liquid oxygen

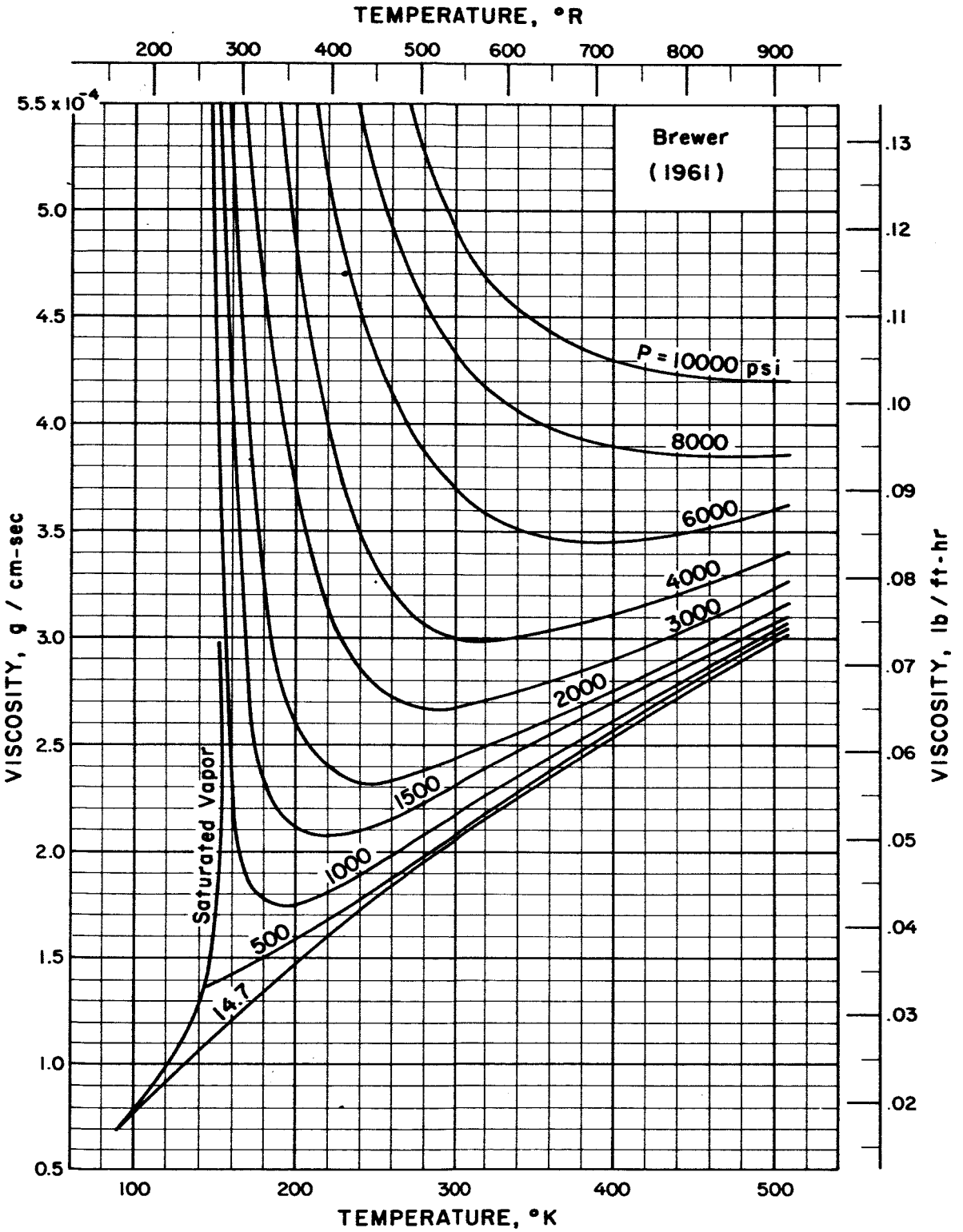

Figure 6.43 Viscosity of oxygen

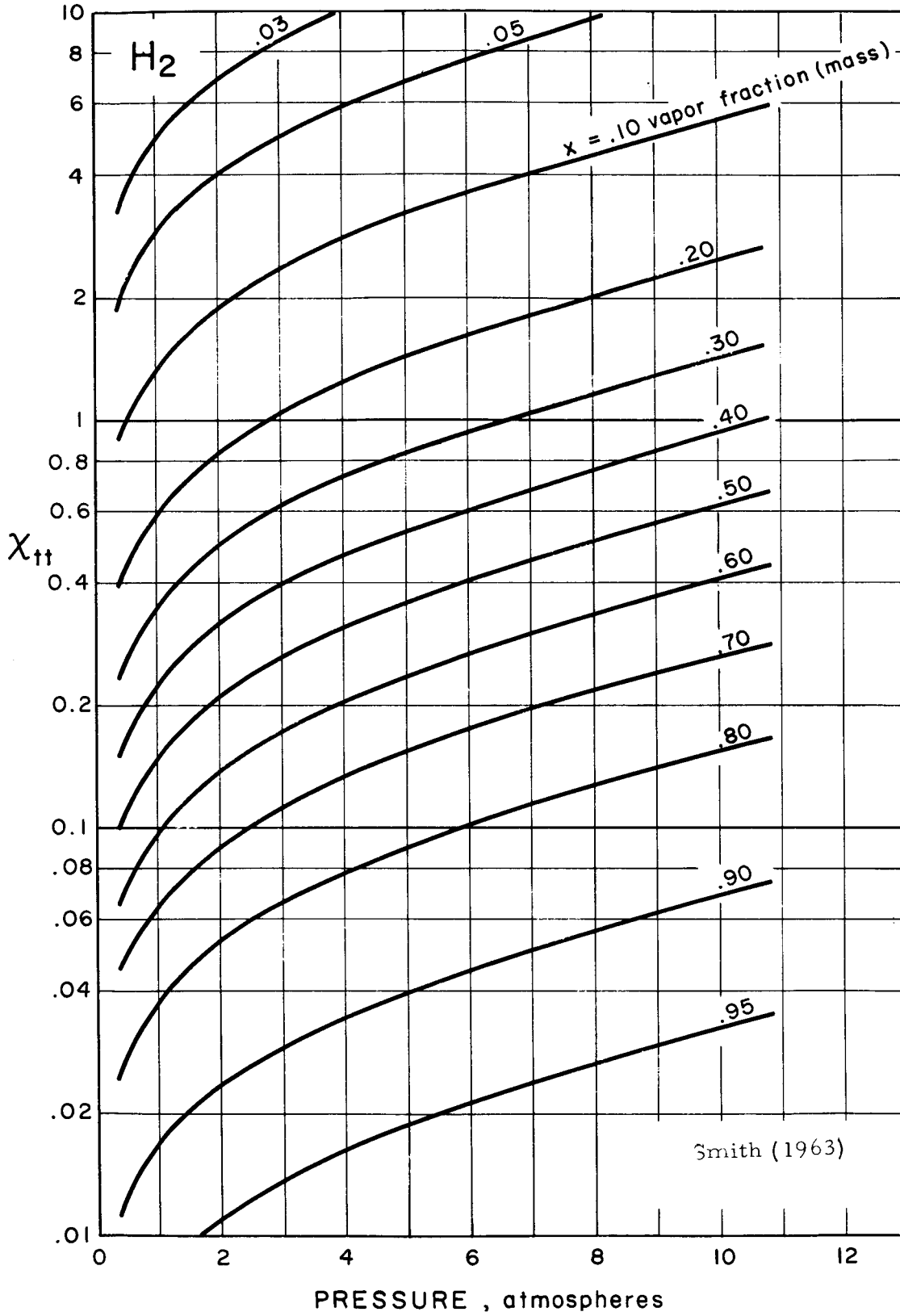

Figure 6.44 Martinelli-Nelson correlating term χ_{tt} as a function of quality and pressure for H_2

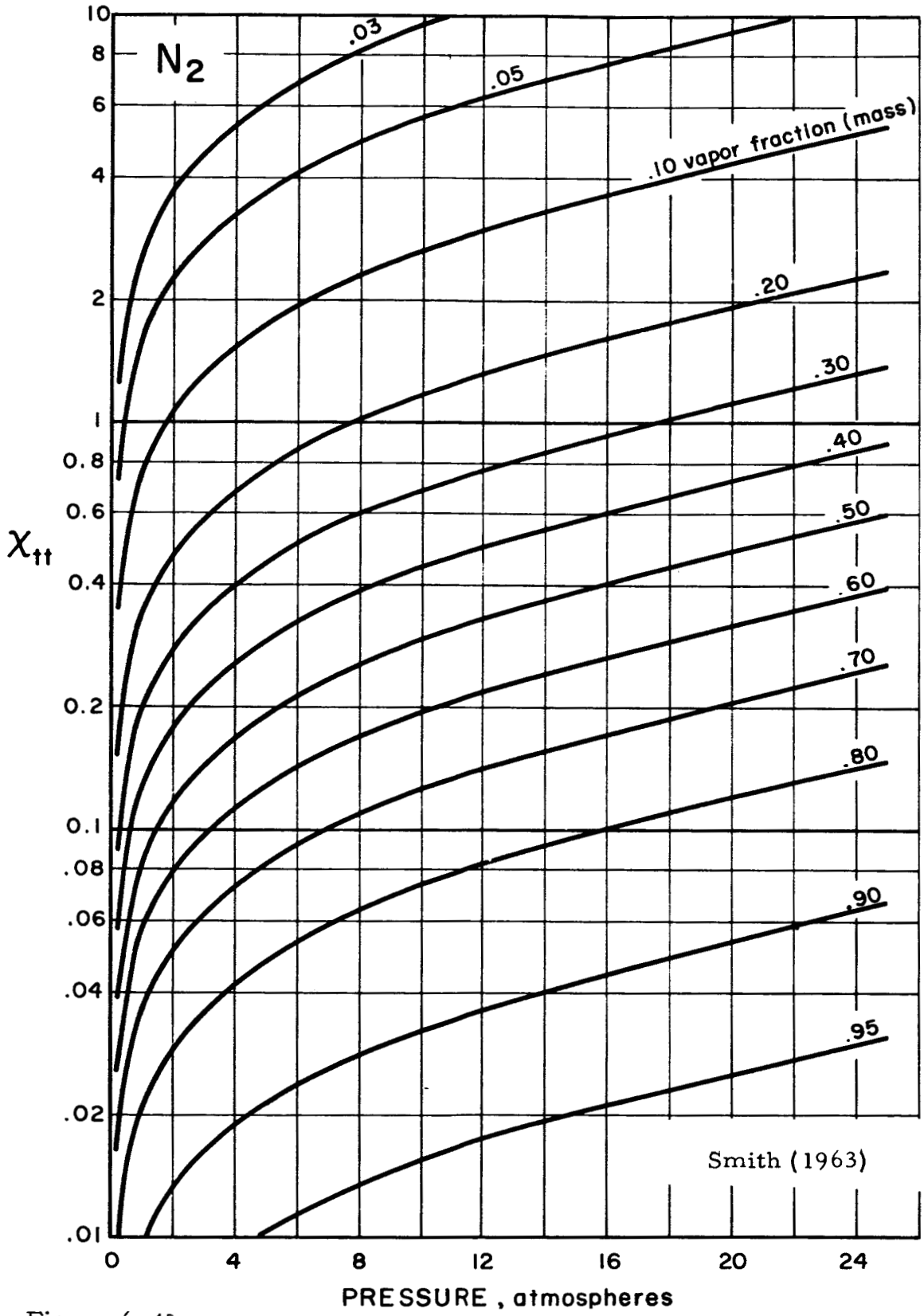

Figure 6.45 Martinelli-Nelson correlating term χ_{tt} as a function of quality and pressure for N_2

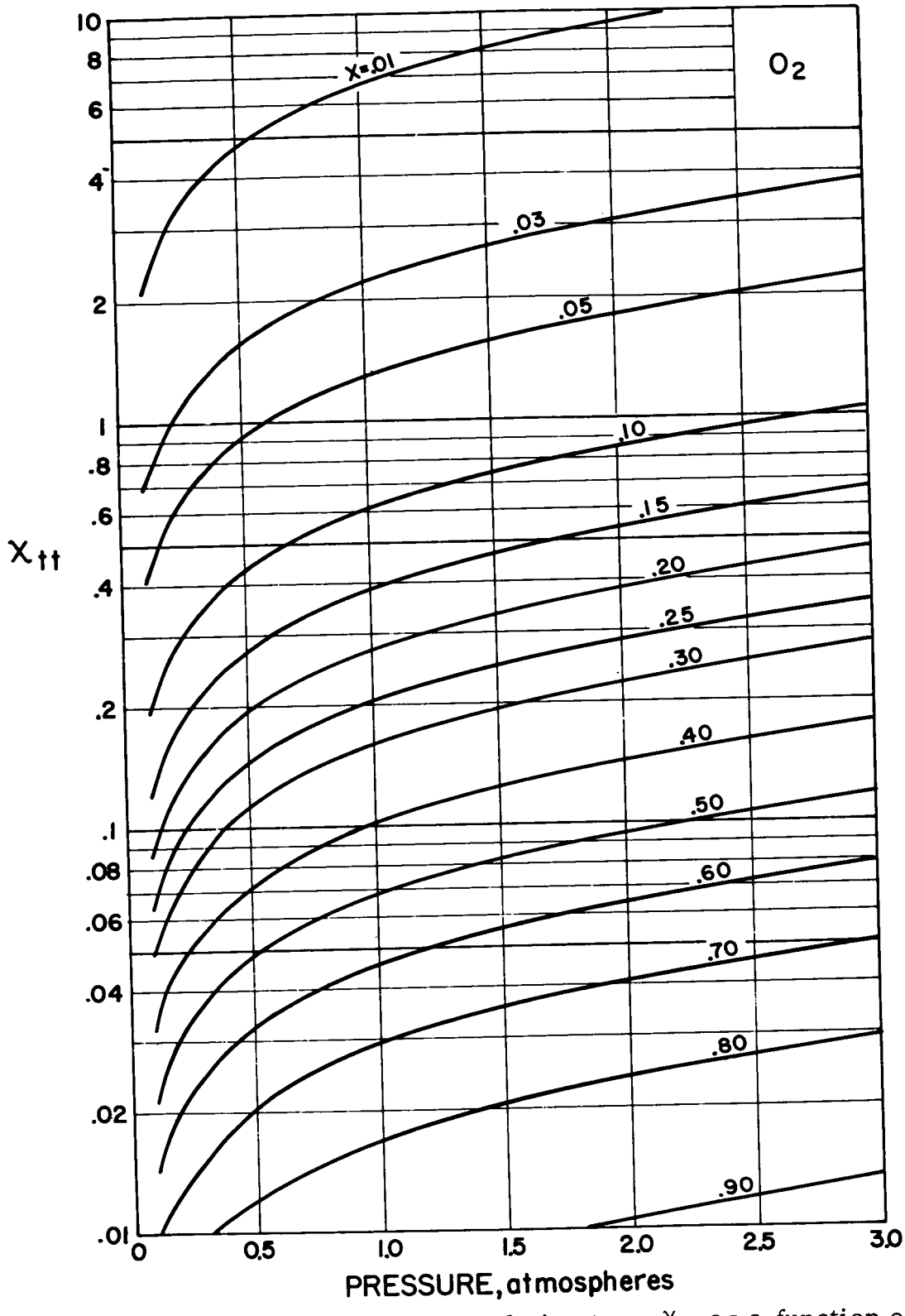

Figure 6.46 Martinelli-Nelson correlating term X_{tt} as a function of quality and pressure for O_2

7. Nomenclature

English Letters

C_p = specific heat capacity at constant pressure, $\frac{\text{joules}}{\text{g}\,°\text{K}}$

$\underline{d}$ = root mean square fractional deviation, dimensionless

D = diameter of cylindrical heater in the film boiling regime for pool boiling, and inside diameter of tube for forced convection boiling, cm

F_{sub} = multiplying factor for peak heat flux due to subcooling, $(q/A)_{sub}=(q/A)_{sat}F_{sub}$

F_{tp} = von Glahn two-phase modification factor, dimensionless

g = acceleration of gravity, $\frac{\text{cm}}{\text{sec}^2}$

G = mass velocity, $\frac{\text{g}}{\text{sec cm}^2}$

h = coefficient of heat transfer, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

$h_{\substack{conv \\ s.p.\ell.}}$ = single-phase liquid convective heat transfer coefficient, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

$h_{\substack{conv \\ s.p.v.}}$ = single-phase vapor convective heat transfer coefficient, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

h_{fc} = forced convection heat transfer coefficient from Chen's correlation, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

h_{f-z} = pool boiling heat transfer coefficient from Chen's correlation, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

$h_{\substack{film \\ pool \\ boil}}$ = film pool boiling heat transfer coefficient, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

$h_{\substack{nucleate \\ pool \\ boil}}$ = nucleate pool boiling heat transfer coefficient, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

h_{pred} = predicted heat transfer coefficient, $\frac{\text{watts}}{\text{cm}^2\ °\text{K}}$

k = thermal conductivity, $\frac{\text{watts}}{\text{cm}\,°\text{K}}$

L_e = sum of distance l and unheated upstream hydrodynamic portion of tube, where l is the critical length measured from beginning of heated portion of tube to burnout location, (cm)

(L/D) = critical-length to diameter ratio in Lowdermilk's burnout correlation, dimensionless

$\dot{m}$ = mass flow rate, $\frac{\text{g}}{\text{sec}}$

$N_{bo.no.}$ = von Glahn correlation boiling number, dimensionless

Nu = Nusselt Number, dimensionless

$Nu_{calc,f,t.p.}$ = two-phase calculated Nusselt Number with vapor properties evaluated at the film temperature $\frac{T_w+T_\ell}{2}$, dimensionless

$Nu_{calc, v, s.p.}$ = single-phase calculated Nusselt Number with vapor properties evaluated at saturation conditions, dimensionless

$\bar{Nu}_{v, calc}$ = calculated Nusselt Number with vapor properties evaluated at saturation conditions, dimensionless

P = pressure of the boiling system, $\frac{dynes}{cm^2}$

Pr = Prandtl number, dimensionless

$\frac{q}{A}$ = rate of heat transfer per unit area, $\frac{watts}{cm^2}$

$Re_{f, m, t.p.}$ = two-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at mean film conditions, dimensionless

Re_{ℓ} = two-phase Reynolds number based on the average velocity of the mixture and with liquid viscosity evaluated at bulk saturation conditions, dimensionless

Re'_{ℓ} = single-phase Reynolds number based on the average velocity of the mixture and with liquid viscosity evaluated at bulk saturation conditions, dimensionless

Re_{v} = two-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at bulk saturation conditions, dimensionless

$Re_{v, s.p.}$ = single-phase Reynolds number based on the average velocity of the mixture and with vapor viscosity evaluated at bulk saturation conditions, dimensionless

ΔT = $T_w - T_{\ell}$, °K

U_{avg} = average fluid velocity, $\frac{cm}{sec}$

x = quality, $\frac{g_{vapor}}{g_{mixture}}$, dimensionless

x_c = thermodynamic fluid quality at burnout location, dimensionless

x_f = quality in film boiling regime, dimensionless

X_f = film boiling vaporization parameter, dimensionless

Greek Letters

α	=	thermal diffusivity, $\frac{C_p \rho}{k}$, dimensionless
α_1, β, γ, Γ	=	von Glahn film boiling correlation parameters, dimensionless
λ	=	latent heat of vaporization at saturation, $\frac{\text{joules}}{\text{g}}$
λ'	=	"effective" latent heat of vaporization, defined by equation 2.4, $\frac{\text{joules}}{\text{g}}$
μ	=	Newtonian coefficient of viscosity, $\frac{\text{g}}{\text{cm sec}}$
ρ	=	density, $\frac{\text{g}}{\text{cm}^3}$
$\Delta\rho_f$	=	$\rho_\ell - \rho_f$, $\frac{\text{g}}{\text{cm}^3}$
$\rho_{f,m,t.p.}$	=	two-phase mean film density, $\frac{\text{g}}{\text{cm}^3}$
$\Delta\rho_v$	=	$\rho_\ell - \rho_v$, $\frac{\text{g}}{\text{cm}^3}$
σ	=	surface tension between the liquid and its own vapor, evaluated at T_ℓ, $\frac{\text{dynes}}{\text{cm}}$
X_{tt}	=	Martinelli parameter, dimensionless

Subscripts

Abs. Min. Film Cond.	=	indicates heat transfer conditions at the absolute minimum value theoretically possible for film pool boiling. (Some authors call this the second critical.)
avg	=	average
b	=	indicates bulk property
exp	=	indicates the subscripted h or Nu is the experimental value
f or f, v	=	indicates that the subscripted vapor property is to be evaluated at the vapor film temperature; $(1/2)(T_w + T_\ell)$
Film Cond.	=	indicates heat transfer conditions, by conduction only through the vapor film, for film pool boiling
ℓ	=	indicates that the subscripted liquid property is to be evaluated at the saturation temperature of the boiling fluid
Max Nucl.	=	indicates heat transfer conditions at the maximum value possible for nucleate pool boiling. (Some authors call this the first critical, or burnout.)
Min. Film Cond.	=	indicates heat transfer conditions at the minimum value correlated for film pool boiling. (Some authors call this the second critical.)
mix	=	mixture
Nucl.	=	indicates heat transfer conditions for nucleate pool boiling
sat	=	saturation conditions
sub	=	subcooling
t.p.	=	indicates two phase
v	=	indicates that the subscripted vapor property is to be evaluated at the saturation temperature of the boiling fluid

w = indicates that the subscripted property is to be evaluated at the temperature of the heater surface

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