Representative Equations for the Thermal Conductivity of Water Substance

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The paper documents the development of the available information for the thermal conductivity of fluid H_2O since the promulgation of the first international formulation for the transport properties of water substance in 1964. As a result of this development, the International Association for the Properties of Steam has adopted new recommended interpolating equations for the thermal conductivity of fluid H_2O at pressures up to 100 MPa and at temperatures up to 800 °C. These new international equations are discussed.

Key words: IAPS; Prandtl number; steam; thermal conductivity; thermal diffusivity; water; water vapor.

Contents

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1. Introduction

During the past five decades, steps have been taken to formulate and standardize values for the thermophysical properties of water and steam (water substance) through a series of international conferences on the properties of steam. Since 1968 these activities have been and continue to be directed and coordinated by the International Association for the Properties of Steam (IAPS).

The first international formulation for the transport properties of water substance was completed in 1964 by a panel elected for the purpose by the 6th International Conference on the Properties of Steam held in 1963.[K1] The 6th International Conference on the Properties of Steam also established an International Formulation Committee which completed a Formulation for the Thermodynamic Properties of Water Substance for Industrial Use in 1967 (IFC 67 Formulation)[M1,S1] and a Formulation for the Thermodynamic Properties of Water Substance for Scientific and General Use in 1968 (IFC 68 Formulation).[I1,R1]

The formulation for the transport properties adopted in 1964 was based on the information available at the time. Since then a considerable body of new experimental data for the transport properties of water substance has become available. This new information makes it possible to repair deficiencies in the first formulation, to extend the range of pressures and temperatures, and to reduce the "tolerances" that indicate the experimental uncertainties in the values of the transport properties of water substance.

In view of these considerations, the 8th International Conference on the Properties of Steam, held in 1974, resolved that the international formulation for the transport properties of water substance had become obsolete and that it should be replaced with a revised and updated formulation. A Special Committee, with J. Kestin as chairman, was created for the purpose of completing a new formulation for the viscosity and the thermal conductivity of water substance. The Special Committee consisted of representatives from the Federal Republic of Germany, France, Japan, the United Kingdom, the USA, and the USSR. The names of the committee members are listed in Appendix IF. The Special Committee met in Schliersee, Germany, April 1975, in Ottawa, Canada, September 1975, in Kyoto, Japan, September 1976, in Providence, Rhode Island, USA, May 1977, and finally in Moscow, USSR, September 1977. Based on the recommendations of the Special Committee, IAPS issued a document entitled "Release on Dynamic Viscosity of Water Substance" in 1975 and a document entitled "Release on Thermal Conductivity of Water Substance" in 1977.[M1]

The tables and equations for the transport properties contained in the releases issued in 1975 and 1977 were to be used in conjunction with the IFC 67 and IFC 68 formulations for the equation of state mentioned above. However, the 9th International Conference on the Properties of Steam, held in 1979, empowered the Executive Committee of IAPS to take steps to replace the IFC 1968 Formulation for the Thermodynamic Properties of Water Substance for Scientific and General Use with a new formulation for the thermodynamic properties. As a consequence of this decision, IAPS adopted in 1982 a new formulation, designated as the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use.[I2] For the sake of brevity, we shall refer to this new formulation for the thermodynamic properties as the IAPS 82 formulation. At the same time, IAPS issued amended releases for the transport properties of water substance so as to make the international formulations for the transport properties fully consistent with the new IAPS 82 formulation for the thermodynamic surface.

The releases on the dynamic viscosity of water substance have been discussed earlier in this journal.[N1,S2] It is the purpose of the present paper to give a complete description of the new formulation for the thermal conductivity of water substance and to give an account of the information that led IAPS to adopt this new formulation. A verbatim copy of the Release on Thermal Conductivity of Water Substance issued in 1977 and amended in 1982 is incorporated in this paper as Appendix I.

2. Survey of Experimental Information

2.1. General Comments

Three major experimental methods have been used for measuring the thermal conductivity of water and steam: the hot-wire method, the concentric-cylinder method, and the parallel-plate method. In the hot-wire method, a platinum wire, located at the axis of a cylinder containing the fluid, is

Table 1. Primary experimental data set (International Input)

First Author	Ref.	Year	Method	Region	Pressures bar	Temperatures °C	Evaluated uncertainty %
Schmidt	[S3]	1932	conc. cyl.	L	1-74	9-269	3
Timrot	[T1]	1935	hot wire	G	0.3-1	69-253	3
Vargaftik	[V2]	1935	hot wire	G	1	99-477	3
Milverton	[M2]	1935	hot wire	G	0.2-0.5	72-95	2
Timrot	[T2]	1939	hot wire	G	20-152	256-396[a]	3
Timrot	[T3]	1940	hot wire	L	1-392	28-331	3
Vargaftik	[V3]	1946	hot wire	G	1	52-783	3
Schmidt	[S4]	1955	conc. cyl.	L	1	20-84	2
Challoner	[C1]	1956	par. plates	L	1	0-80	2[b]
Vargaftik	[V4]	1956	hot wire	G	1	177-505	2
Vargaftik	[V4]	1956	conc. cyl.	G	1	231-442	2
Vargaftik	[V5]	1959	hot wire	G	5-343	350-724	3
Vargaftik	[V6]	1959	hot wire	L	1-93	21-299[a]	2
Lawson	[L3]	1959	hot wire	L	1-7845	30-130	3
Vargaftik	[V7]	1960	hot wire	G	5-490	320-568	3
Vines	[V8]	1960	conc. cyl.	G	1	270-560	3
Tarzaminov	[T4]	1962	hot wire	G	2-147	232-351	2
Vukalowich	[V9]	1963	conc. cyl.	G	98-490[a]	322-655	5
Keyes	[K2]	1964	conc. cyl.	G	1-207	139-380	3
Vargaftik	[V10]	1964	hot wire	G	1	487-896	3
Venart	[V11]	1965	conc. cyl.	G	1	134-201	3
Brain	[B3]	1967	conc. cyl.	G	1	142-159	2
Cherneeva	[C2]	1968	conc. cyl.	L	100-1000	100-350[a]	4
Le Neindre	[L4,L5]	1968	conc. cyl.	L	1-507	37-370	2
Le Neindre	[L6]	1968	conc. cyl.	G	1-125	110-330	3
Tarzimanov	[T5]	1968	hot wire	L	29-983	29-155	2
Mashirov	[M3]	1968	hot wire	G	0.2-1	106-311	2
Brain	[B4]	1969	conc. cyl.	G	1	142-604	2
Bach	[B1]	1970	interferometer	L	1	20-90	2[c]
Tarzimanov	[T6]	1970	hot wire	G	300-650	501-551	2
Le Neindre	[L7]	1973	conc. cyl.	L&G	1-507	339-515	2[d]
Tarzimanov	[T7]	1973	conc. cyl.	G	1-1000	166-500	2
Bury	[B5]	1973	conc. cyl.	G	1-500	104-515	2
Vargaftik	[V12]	1973	hot wire	G	1	157-725	2
Minamiyama	[M4]	1974	conc. cyl.	L	104-1009	38-200	2
Rastorguyev	[R2]	1974	conc. cyl.	L	1-2010	-15-210	2
Sirota	[S5]	1974	par. plates	L&G	201-276	207-399	2[d]
Castelli	[C3]	1974	conc. cyl.	L	10-1400	2-30	2
Amirkhanov	[A1]	1974	par. plates	L	1-2453	25-350	2[c]
Takizawa	[T8]	1974	hot wire	L	1-487	0-100	2
Minamiyama	[M5,Y1]	1975	conc. cyl.	L	98-1471	31-200	2
Minamiyama	[M6,Y2]	1976	conc. cyl.	L&G	98-1470	104-420	2
Tsederberg	[T9]	1976	conc. cyl.	G	99-982	434-799	2

[a] Range restricted by Special Committee

[b] Weight of 1% assigned in analysis

[c] Weight of 4% assigned in analysis

[d] Larger uncertainties in the critical region

heated; the heating can be performed either in a steady state or in a transient mode of operation. In the concentric-cylinder method, the fluid is enclosed between two coaxial cylinders with different temperatures located usually in a vertical position; during the experiments, heat flows from the inner cylinder radially toward the outer cylinder. In the parallel-plate methods, the fluid is contained between two horizontal plates heated from above. For a detailed description of these experimental methods, the reader is referred to articles by Leidenfrost[L1] and Ziebland.[Z1] More recently, Grigull and co-workers have determined the thermal conductivity of fluids, including water, by measuring the transient temperature distribution in the fluid with optical interferometry.[B1,B2]

There are a number of complications that limit the accuracy of experimental thermal conductivity data. These include convective and radiative heat transfer in the fluid, temperature jumps at the solid–fluid boundaries, parasitic heat transfer via heat leaks, contamination of the fluid or of the solid surfaces during the experiments, and deviations from the idealized temperature distribution assumed in the working equations. A discussion of some of these factors, as they pertain to the measurements of the thermal conductivity of steam, was prepared for IAPS by Leidenfrost[L2] and by Vargaftik.[V1]

As a consequence of these difficulties, discrepancies between data from different sources are often found. Hence, as a first step, the Special Committee was faced with the task of judging the quality and reliability of the available experimental information. This task led to the adoption of a primary experimental data set on the basis of which the new formulation for the thermal conductivity of water substance was developed. This primary experimental data set, referred to by the Special Committee as the "International Input," is presented in Table 1. This table contains the references of the data sources, the experimental methods by which the data were obtained, the regions (liquid region or gaseous region) as well as the ranges of pressures and temperatures of the data and the evaluated uncertainty assigned to the data. A complete listing of all experimental data of the International Input is contained in a report prepared by a group at the Technical University of Munich.[S6] In evaluating the experimental literature, the Committee has also benefited from a review prepared by Tarzimanov.[T10]

2.2. Thermal Conductivity of Water Vapor and of Steam at Low Pressures

The experimental literature concerning the thermal conductivity of steam at low and moderate pressures has been reviewed by Brain[B4] and by Vargaftik.[V1] In developing the first international formulation for the transport properties of steam, the panel, elected for the purpose by the 6th International Conference on the Properties of Steam, had been confronted with a serious discrepancy that appeared to exist between the thermal conductivity data reported by Vargaftik and co-workers in the USSR on the one hand and the results found by Keyes and Sandell in the USA and by Geier and Schäfer in Germany on the other hand.[K1] The resolution of this problem has been discussed by Brain[B4] and the Committee agreed with the conclusions reached by Brain. It accepted the extensive body of thermal conductivity data for steam reported by Vargaftik and co-workers,[T1,V2,V3,V4,V10] the data of Venart[V11] and the data of Brain.[B3,B4] The data of Keyes and Vines[K2] supersede the data of Keyes and Sandell.[K3] The Committee rejected the data of Geier and Schäfer.[G1] Additional evidence that the data of Geier and Schäfer are too low was subsequently provided by Zimina and Kunitsa.[Z2] The measurements of Vines[V8] at 270 and 560 °C were retained, but it was realized later that his data point at 560 °C has an error of about 4%.[B4,V1] Baker and Brokaw[B6] measured the thermal conductivity of atmospheric steam between 380 and 525 °C; their data are in satisfactory agreement with those of Vargaftik *et al.* The above-mentioned information for the thermal conductivity of steam at low pressures was supplemented with new experimental data subsequently obtained by Le Neindre and co-workers,[B5,L6,L7] Tarzimanov *et al.*,[M3,T7] and Vargaftik *et al.*[V12]

Reliable information concerning the thermal conductivity of water vapor below 100 °C is very limited. The major source of information is the work of Milverton published in 1935.[M2] In addition, Timrot and Vargaftik[T1,V3] have reported some data for water vapor between 69 and 100 °C while Fox *et al.*[F1] obtained some relative thermal conductivity values for water vapor at 79 and 100 °C. It is generally believed that the measurements of Milverton were influenced by temperature jump effects. However, because of the limited information for the pressure dependence of the thermal conductivity of water vapor, the data of Milverton were retained in the International Input. In practice, we assigned an uncertainty of 2% to the data of Milverton, but deleted 21 data points corresponding to pressures below 10 cm Hg, where the effect of a temperature jump is most severe.

2.3. Thermal Conductivity of Steam at Elevated Pressures

The thermal conductivity of steam at elevated pressures has been measured by Vargaftik and co-workers,[T2,V5,V7] Tarzimanov and co-workers,[T4,T6,T7] Amirkhanov and co-workers,[A2,A3,A4] Vukalowich and Cherneeva,[V9] Keyes and Vines,[K2] Venart,[V11] Le Neindre and co-workers,[B5,L6,L7] Sirota and co-workers,[S5,S7–S14] Minamiyama and co-workers,[M5,Y2] and Tsederberg and co-workers.[T9] The earliest work of Vargaftik[V13] gives thermal conductivity data at pressures up to 28 bar only. In the work of Timrot and Vargaftik,[T2] the thermal conductivity was measured at pressures up to 300 bar and at temperatures from 256 to 524 °C; however, the data at the higher temperatures were judged to be less accurate and the Committee retained only the data below 400 °C. The experimental temperature and pressure range was subsequently extended by Vargaftik to 725 °C[V5] and to 500 bar.[V7] Keyes and Vines[K2] measured the thermal conductivity of steam from 140 to 380 °C at pressures up to 200 bar. Venart[V11] measured the thermal conductivity of steam at temperatures up to about 200 °C and pressures up to 300 bar, although the Committee retained in practice only four of Venart's data points at atmospheric pressure. The panel that prepared the first formulation had relied heavily on the measurements of Amirkhanov and Adamov[A2] for the thermal conductivity of supercritical steam. Subsequent information has indicated these data to be less reliable. The Committee retained only the more recent work of Amirkhanov and co-workers covering pressures up to 2500 bar but only for water at subcritical temperatures.[A1] The more recent data of Amirkhanov and co-workers[A4] for steam up to 2500 bar arrived too late to be included in the International Input. The data of Vukalowich and Cherneeva[V9] were assigned a somewhat larger uncertainty than those of the other investigators; they cover pressures up to 1500 bar and temperatures up to 655 °C, but it was decided to omit the data at pressures beyond 490 bar. The data of Tarzimanov and co-workers[T4,T6,T7] cover pressures up to 1000 bar and temperatures up to 550 °C, while those of Le Neindre and co-workers[B5,L6,L7] cover pressures up to 500 bar and temperatures up to 515 °C. The Committee encountered difficulties in making an assessment of the thermal conductivity of steam at high pressures at temperatures above 500 °C. The data of Tarzimanov and co-workers up to 650 bar refer to temperatures below 550 °C and those up to 1000 bar to temperatures below 500 °C. The work of Minamiyama and Yata[M5,Y2] covers pressures up to 1470 bar but temperatures below 420 °C. In 1977, the Committee received a set of data from Tsederberg and co-workers[T9] which covers pressures up to 980 bar and temperatures up to 800 °C. Although the Committee at that time had almost completed its work in developing a new thermal conductivity formulation, the absence of other reliable data in this region of high pressures and temperatures made it desirable to add the data of Tsederberg *et al.* to the International Input.

In order to obtain a reliable formulation for the thermal conductivity, it was necessary to pay special attention to the behavior of the thermal conductivity in the critical region. When the first thermal conductivity formulation was considered in the sixties, it had been established that the thermal conductivity of gases like carbon dioxide exhibits a critical enhancement in a large range of temperatures and densities around the critical point.[M7,S15,S16] However, no comparable experimental information for a critical enhancement in the thermal conductivity of steam was at that time available.[K1] That the thermal conductivity of steam does exhibit a critical enhancement of a magnitude similar to that observed for other fluids was first demonstrated by Le Neindre and co-workers.[L7] The effect was investigated subsequently in great detail and with considerable accuracy by Sirota and co-workers.[S7–S14] With the aid of the new data supplied by Sirota *et al.*,[S5] the Committee was able to make an assessment of the divergent behavior of the thermal conductivity near the critical point.

2.4. Thermal Conductivity of Water

The thermal conductivity of water at atmospheric pressure or under its own vapor pressure at temperatures up to 100 °C has been studied by many investigators over many years. The experimental literature on this subject prior to 1958 has been discussed by Powell in a comprehensive review.[P1] Challoner and Powell made an accurate study of the thermal conductivity of water between 0 and 80 °C with a parallel-plate apparatus.[C1] The data of Challoner and Powell were judged to supersede most of the previous data in this temperature range. An apparent anomalous behavior of the thermal conductivity of liquid water between 35 and 40 °C reported by Frontasev[F2] was also shown to be spurious by Powell and Challoner.[P2] Among the data reported prior to the work of Challoner and Powell, the Committee retained the measurements of Schmidt and Sellschopp,[S3] of Schmidt and Leidenfrost,[S4] and of Timrot and Vargaftik.[T3] A more recent comprehensive study of the thermal conductivity of water between 20 and 90 °C was made by Bach and Grigull with the aid of optical interferometry.[B1] Of special interest are the values of the thermal conductivity of liquid water at 0 and 25 °C as possible reference values. The first international formulation assigned to the thermal conductivity λ of water at 0 °C and 0.1 MPa the value $\lambda = 0.569$ $\mathrm{W m^{-1} K^{-1}}$ and Takizawa *et al.*[T8] have also reported a value $\lambda = 0.568\ \mathrm{W m^{-1} K^{-1}}$ for water at 0 °C. However, Tarzimanov[T10] pointed out that the values assigned by the first formulation to the thermal conductivity of water at room temperatures and below are slightly too large. The work of Challoner and Powell indicates a lower value of $\lambda = 0.561$ $\mathrm{W m^{-1} K^{-1}}$ for water at 0 °C.[C1,P1] Also from recent work of Jamieson[J1] at the National Engineering Laboratory in the United Kingdom it is concluded that $\lambda = 0.561$ $\mathrm{W m^{-1} K^{-1}} \pm 0.5\%$ for water at 0 °C, in good agreement with the results of Challoner and Powell. Fritz and Poltz[F3] made an accurate experimental measurement of the thermal conductivity of water at 25 °C and found $\lambda = 0.608$ $\mathrm{W m^{-1} K^{-1}} \pm 0.5\%$ at this temperature. Nevertheless, because of the spread between data of different authors, the Committee was unable to agree on an absolute accuracy better than 1.5% for the thermal conductivity of water at these temperatures.

The thermal conductivity of saturated water at temperatures above 100 °C has been investigated by Schmidt and Sellschopp,[S3] Vargaftik and Oleshchuk,[V6] Le Neindre and co-workers,[L5] and Rastorguyev *et al.*[R2] Schmidt and Sellschopp[S3] measured the thermal conductivity of saturated water at temperatures up to 269 °C; they were the first to note that the thermal conductivity of saturated water goes through a maximum at a temperature of about 130 °C. Vargaftik and Oleshchuk[V6] measured the thermal conductivity at temperatures up to 350 °C, but the Committee retained only the data below 299 °C.

In an early study, Timrot and Vargaftik[T3] measured the thermal conductivity of water at pressures up to 392 bar and temperatures up to 331 °C. The measurements of Le Neindre and co-workers[L5] cover pressures up to 507 bar at temperatures up to 370 °C and include data for water at the saturation boundary up to 240 °C.

At the time that the first international formulation for the thermal conductivity of water substance was prepared, experimental information for the thermal conductivity of water at pressures beyond 500 bar was very limited. Bridgman[B7] had investigated the thermal conductivity of water at pressures up to 12 000 bar at 30 and 75 °C in a pioneering study which is now mainly of historic interest. Lawson *et* *al.*[L3] had investigated the thermal conductivity of water at pressures up to 7845 bar at temperatures up to 130 °C.

A significant body of new experimental data has become available since 1968. The thermal conductivity of water at elevated pressures has been investigated by a number of experimenters in the USSR.[A1,C2,T5,R2] Cherneeva[C2] measured the thermal conductivity of water and steam at pressures between 100 and 1000 bar and at temperatures up to 700 °C, but the Committee considered only the data reported for liquid water at temperatures between 100 and 350 °C. The measurements of Tarzimanov and Lozovoi[T5] cover pressures between 29 and 983 bar at temperatures up to 155 °C. Rastorguyev and co-workers[R2] have investigated the thermal conductivity of water at pressures up to 2010 bar in the temperature range from − 15 to 210 °C including saturated water in this temperature range; these measurements supersede earlier work reported by Rastorguyev and Pugach.[R3] The data of Amirkhanov and co-workers[A1,A4] cover pressures up to 2453 bar at temperatures up to 350 °C. In the USA, Castelli and Stanley[C3] have reported thermal conductivity measurements at pressures up to 1400 bar, but in the limited temperature range from 2 to 30 °C. The thermal conductivity of water at elevated pressures has also been investigated by two groups of researchers in Japan.[M4–M6,T8,Y1,Y2] The data of Takizawa *et al.*[T8] refer to pressures up to 487 bar at temperatures between 0 and 100 °C. The measurements of Minamiyama and Yata[M4–M6,Y1,Y2] extend to pressures up to 1470 bar and temperatures up to 420 °C. Very recently, after the new international formulation had been completed, Dietz *et al.* in Germany have reported experimental thermal conductivity data for water up to 3500 bar at temperatures up to 250 °C.[D1,D2]

3. Description of International Formulation

3.1. General Comments

The Release on Thermal Conductivity of Water Substance, reproduced in Appendix I, contains two recommended interpolating equations for the thermal conductivity of fluid H_2O: a Recommended Interpolating Equation for Scientific Use and a Recommended Interpolating Equation for Industrial Use. For the sake of brevity, we shall in the sequel refer to these recommended interpolating equations simply as the "scientific" and the "industrial" thermal conductivity equation. The two interpolating equations differ in the way they represent the enhancement of the thermal conductivity of steam in the critical region. In the scientific thermal conductivity equation, the thermal conductivity diverges towards an infinite value at the critical point as predicted by the modern theory of dynamic critical phenomena and supported by experimental evidence.[B8,S17] The industrial thermal conductivity equation yields a simplified approximation of this enhancement effect with a finite value of the thermal conductivity at the critical point.

In addition, the Release contains tables of the thermal conductivity of water substance at a uniform grid of pressures and temperatures and also of the thermal conductivity of the saturated vapor and the saturated liquid at integral temperatures. Specifically, three sets of thermal conductivity tables are presented: a set of tables with thermal conductivity values calculated from the scientific thermal conductivity equation (Tables I.5 and I.6 in Appendix I), a set of tables with thermal conductivity values calculated from the industrial equation (Tables I.3 and I.4 in Appendix I) and a set of tables with critically evaluated experimental data reduced to a uniform grid (Tables I.1 and I.2 in Appendix I), to be referred to as Skeleton Tables for the thermal conductivity. The Skeleton-Table values were deduced from the experimental data by Scheffler, Rosner, and Grigull of the Technical University at Munich[S18] with the aid of the same mathematical algorithm as was previously employed in the construction of a Skeleton Table for the viscosity of water substance[N1,S2,S19]; a description of this algorithm can be found elsewhere.[S20] In addition, the Skeleton Tables give values for the tolerances $\delta\lambda$, which constitute estimates of the accuracy with which the thermal conductivity is known and agreed upon by the Special Committee.

It should be emphasized that all three sets of tables in fact represent critically evaluated experimental data reduced to a uniform grid and the tabulated values agree within the assigned tolerances $\delta\lambda$. The difference is that the tables of calculated thermal conductivities contain smoothed values obtained by what one could call a global averaging procedure, while the Skeleton Table values are not smoothed, since they were obtained by a local averaging procedure. It is the opinion of the Committee that the quality of other possible interpolating equations for the thermal conductivity of water substance should be judged on the extent to which such equations reproduce the original experimental data as contained in the International Input, supplemented with any new thermal conductivity data, and not on the extent to which they would reproduce the thermal conductivity values listed in the Skeleton Tables.

The new international formulation for the thermal conductivity of water substance has been endorsed by IAPS for a range of temperatures and pressures bounded by

$$0\ ^\circ\mathrm{C} \leqslant T \leqslant 800\ ^\circ\mathrm{C}, \qquad 0\ \mathrm{MPa} \leqslant P \leqslant 100\ \mathrm{MPa}. \tag{3.1}$$

3.2. Recommended Interpolating Equation for Scientific Use

The scientific thermal conductivity equation is expressed in terms of dimensionless variables for the temperature T, the density ρ, and the pressure P. For this purpose, we introduce the reference constants

$$T^* = 647.27\ \mathrm{K}, \quad \rho^* = 317.763\ \mathrm{kg/m^3}, \quad P^* = 22.115 \times 10^6\ \mathrm{Pa}, \tag{3.2}$$

and define a dimensionless temperature $\overline{T}$, a dimensionless density $\bar{\rho}$, and a dimensionless pressure $\overline{P}$ as

$$\overline{T} = \frac{T}{T^*}, \quad \bar{\rho} = \frac{\rho}{\rho^*}, \quad \overline{P} = \frac{P}{P^*}. \tag{3.3}$$

The temperatures in this paper are expressed in terms of the international practical temperature scale of 1968 (IPTS 68)[I3] unless indicated otherwise. The reference constants T^*, ρ^*,

TABLE 2. Coefficients a_k^λ for $\lambda_0(\bar{T})$

$a_0^\lambda = +2.022\,23$
$a_1^\lambda = +14.111\,66$
$a_2^\lambda = +5.255\,97$
$a_3^\lambda = -2.018\,70$

P^* are close to, but not identical with the critical parameters of steam.[K4,L8] It should be noted that the dimensionless variables defined by Eq. (3.3) are identical to the dimensionless variables employed in the recommended representative equations for the viscosity of water substance.[S2]

The recommended interpolating equation for scientific use has the form

$$\lambda = \lambda_0(\bar{T}) \times \lambda_1(\bar{T},\bar{\rho}) + \lambda_2(\bar{T},\bar{\rho}). \tag{3.4}$$

The function $\lambda_0(\bar{T})$ represents the thermal conductivity in the dilute-gas limit and the function $\lambda_1(\bar{T},\bar{\rho})$ is an enhancement factor which accounts for the normal density and temperature dependence of the thermal conductivity at elevated pressures. The term $\lambda_2(\bar{T},\bar{\rho})$ represents an additional enhancement observed in a region around the critical point. The function $\lambda_0(\bar{T})$ was determined by Aleksandrov and Matveev at the Moscow Power Institute,[A5] the function $\lambda_1(\bar{T},\bar{\rho})$ by Watson at the National Engineering Laboratory in the U.K.,[W1] and the function $\lambda_2(\bar{T},\bar{\rho})$ by Basu and Sengers at the University of Maryland.[B8]

The function $\lambda_0(\bar{T})$ is defined by

$$\lambda_0(\bar{T}) = \frac{\lambda^* \sqrt{\bar{T}}}{\sum_{k=0}^{3} \frac{a_k^\lambda}{\bar{T}^k}}, \tag{3.5}$$

with

$$\lambda^* = 1 \text{ W m}^{-1}\text{K}^{-1}, \tag{3.6}$$

and with coefficients a_k^λ given in Table 2. The function $\lambda_1(\bar{T},\bar{\rho})$ is defined by

$$\lambda_1(\bar{T},\bar{\rho}) = \exp\left[\bar{\rho} \sum_{i=0}^{4} \sum_{j=0}^{5} b_{ij}^\lambda \left(\frac{1}{\bar{T}} - 1\right)^i (\bar{\rho} - 1)^j\right], \tag{3.7}$$

with coefficients b_{ij}^λ given in Table 3.

It is noted that the mathematical forms of the functions $\lambda_0(\bar{T})$ and $\lambda_1(\bar{T},\bar{\rho})$ are identical with the forms of the corresponding functions $\mu_0(\bar{T})$ and $\mu_1(\bar{T},\bar{\rho})$ that define the international equation for the viscosity μ of water substance[N1,S2]

$$\mu = \mu_0(\bar{T}) \times \mu_1(\bar{T},\bar{\rho}). \tag{3.8}$$

Specifically,

$$\mu_0(\bar{T}) = \frac{\mu^* \sqrt{\bar{T}}}{\sum_{k=0}^{3} \frac{a_k^\mu}{\bar{T}^k}}, \tag{3.9}$$

$$\mu_1(\bar{T},\bar{\rho}) = \exp\left[\bar{\rho} \sum_{i=0}^{5} \sum_{j=0}^{4} b_{ij}^\mu \left(\frac{1}{\bar{T}} - 1\right)^i (\bar{\rho} - 1)^j\right], \tag{3.10}$$

with

$$\mu^* = 1 \times 10^{-6} \text{ Pa·s}, \tag{3.11}$$

and with coefficients a_k^μ and b_{ij}^μ given in Tables 4 and 5.

The critical enhancement contribution $\lambda_2(\bar{T},\bar{\rho})$ is defined by

$$\lambda_2(\bar{T},\bar{\rho}) = \frac{C}{\mu_0(\bar{T}) \times \mu_1(\bar{T},\bar{\rho})} \left(\frac{\bar{T}}{\bar{\rho}}\right)^2 \times \left(\frac{\partial \bar{P}}{\partial \bar{T}}\right)_{\bar{\rho}}^2 (\bar{\chi}_T)^{0.4678} (\bar{\rho})^{1/2} \times \exp[-18.66(\bar{T} - 1)^2 - (\bar{\rho} - 1)^4], \tag{3.12}$$

with

$$C = 3.7711 \times 10^{-8} \text{ Pa·s W m}^{-1}\text{ K}^{-1}. \tag{3.13}$$

The functions $\mu_0(\bar{T})$ and $\mu_1(\bar{T},\bar{\rho})$ in Eq. (3.12) are those defined in Eqs. (3.9) and (3.10), while $\bar{\chi}_T$ is a dimensionless symmetrized isothermal compressibility defined by

$$\bar{\chi}_T = \bar{\rho} \left(\frac{\partial \bar{\rho}}{\partial \bar{P}}\right)_{\bar{T}}. \tag{3.14}$$

An equation of state is needed, first to evaluate the derivatives $(\partial \bar{P}/\partial \bar{T})_{\bar{\rho}}$ and $\bar{\chi}_T$ in Eq. (3.12), and second to convert pressures into densities, if one wants to calculate the thermal conductivity as a function of temperature and pressure. Equation (3.4), as well as Eq. (3.8), was originally formulated so as to be used in conjunction with the IFC 68 formulation for the thermodynamic properties of water substance.[11] However, as mentioned in the introduction, the IFC 68 formulation has now been replaced with the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use.[12] This IAPS 82 formulation was developed by Haar, Gallagher, and Kell.[H1,H2] In a previous paper, we demonstrated that Eq. (3.8) for the viscosity can be used in

TABLE 3. Coefficients b_{ij}^λ for $\lambda_1(\bar{T},\bar{\rho})$

$j \diagdown i$	0	1	2	3	4
0	+ 1.329 304 6	+ 1.701 836 3	+ 5.224 615 8	+ 8.712 767 5	− 1.852 599 9
1	− 0.404 524 37	− 2.215 684 5	− 10.124 111	− 9.500 061 1	+ 0.934 046 90
2	+ 0.244 094 90	+ 1.651 105 7	+ 4.987 468 7	+ 4.378 660 6	0.0
3	+ 0.018 660 751	− 0.767 360 02	− 0.272 976 94	− 0.917 837 82	0.0
4	− 0.129 610 68	+ 0.372 833 44	− 0.430 833 93	0.0	0.0
5	+ 0.044 809 953	− 0.112 031 60	+ 0.133 338 49	0.0	0.0

TABLE 4. Coefficients a_k^μ for $\mu_0(\overline{T})$

$a_0^\mu = 0.018\ 158\ 3$
$a_1^\mu = 0.017\ 762\ 4$
$a_2^\mu = 0.010\ 528\ 7$
$a_3^\mu = -0.003\ 674\ 4$

conjunction with the IAPS 82 formulation without loss of accuracy.[S2] The same is true for the thermal conductivity equation. In Table 6 we present the difference beween the values λ_{82}, calculated from Eq. (3.4) with the aid of the IAPS 82 formulation, and the values λ_{68} calculated from Eq. (3.4) with the aid of the IFC 68 formulation. Specifically, we list the relative difference $(\lambda_{82} - \lambda_{68})/\delta\lambda$, where $\delta\lambda$ is the tolerance, at the pressures and temperatures corresponding to the Skeleton Table values. It is seen that this relative difference is much smaller than unity at all pressures and temperatures and we conclude that the two procedures lead to equivalent values for the thermal conductivity of water substance whose differences lie well within the accuracy agreed upon by IAPS. Accordingly, the Release on Thermal Conductivity, as amended in 1982, recommends that the scientific thermal conductivity equation be used in conjunction with the IAPS 82 formulation for the thermodynamic properties.

Table I.5 in Appendix I gives the values for λ calculated from the scientific thermal conductivity equation at a uniform grid of pressures and temperatures. Table I.6 in Appendix I gives the values for λ calculated from this equation for the liquid and the vapor at saturation. To obtain a uniform set of equations for the thermodynamic properties and transport properties of water substance, we found it convenient to express the IAPS 82 formulation in terms of the dimensionless variables defined by Eq. (3.3) as reported elsewhere in this journal.[K4] The densities calculated from the IAPS 82 formulation for the pressures and temperatures quoted in the thermal conductivity table are tabulated in Appendix II or Ref. S2.

It was demonstrated in an earlier paper that a better fit to the available experimental viscosity data is obtained by selecting an alternative set of coefficients in Eq. (3.10) for the function $\mu_1(\overline{T}, \bar{\rho})$.[W2] Hence, an alternative procedure for calculating the thermal conductivity is obtained, if we substitute into Eq. (3.12) the equation for $\mu_1(\overline{T}, \bar{\rho})$ proposed by Watson *et al.*[K5] This alternative procedure is presented in Appendix II.

The thermal conductivity of water substance, calculated from the recommended interpolating equation for scientific use, is shown in Fig. 1 as a function of temperature along selected isobars and in Fig. 2 as a function of pressure along selected isotherms. The thermal conductivity exhibits a pronounced enhancement in the critical region. This phenomenon is illustrated in more detail in Figs. 3 and 4 where the thermal conductivity in the critical region is shown as a function of density at selected temperatures and pressures. The enhancement in the thermal conductivity near the critical point is related to the divergent behavior of the compressibility $\overline{\chi}_T$, as given by Eq. (3.12). This relationship finds its origin in the fact that the enhancement in the thermal conductivity is a function of the correlation length which diverges at the critical point and which in turn can be related to the isothermal compressibility,[B8] as further discussed in Sec. 4.3. Relating the critical enhancement of the thermal conductivity to the compressibility has the added advantage that the thermal conductivity becomes infinite at the same critical parameter values where the compressibility, thermal expansion coefficient, and specific heat also become infinite, thus ensuring consistency between the thermal conductivity and the thermodynamic properties near the critical point. This feature is important if one wants to calculate properties such as the Prandtl number and the thermal diffusivity which involve combinations of thermodynamic and transport properties, and also if one wants to use the thermal conductivity equation with other equations of state. This advantage would be lost, if one were to represent the divergent critical enhancement function $\lambda_2(\overline{T}, \bar{\rho})$ by an explicit function of temperature and density as proposed by some other investigators.[A5,A6]

A complication arises due to the fact that the IAPS 82 formulation for the thermodynamic properties of water substance ceases to be correct at temperatures and densities in the immediate vicinity of the critical point. Specifically, the range of validity of the IAPS 82 formulation does not include a region around the critical point where[12]

$$|T - T_c| < 1\text{K and } \left|\frac{\rho - \rho_c}{\rho_c}\right| < 0.3, \tag{3.15}$$

and where T_c and ρ_c are the temperature and density of the critical point.[12,K6] There exists an international agreement that the critical point of steam is located within a region bounded by[14,K6]

$$\begin{gathered} 647.04\ \text{K} \leqslant T_c \leqslant 647.24\ \text{K}, \\ 319\ \text{kg/m}^3 \leqslant \rho_c \leqslant 325\ \text{kg/m}^3. \end{gathered} \tag{3.16}$$

TABLE 5. Coefficients b_{ij}^μ for $\mu_1(\overline{T}, \bar{\rho})$

$i=$	0	1	2	3	4	5
$j=0$	0.501 938	0.162 888	− 0.130 356	0.907 919	− 0.551 119	0.146 543
1	0.235 622	0.789 393	0.673 665	1.207 552	0.067 066 5	− 0.084 337 0
2	− 0.274 637	− 0.743 539	− 0.959 456	− 0.687 343	− 0.497 089	0.195 286
3	0.145 831	0.263 129	0.347 247	0.213 486	0.100 754	− 0.032 932
4	− 0.027 044 8	− 0.025 309 3	− 0.026 775 8	− 0.082 290 4	0.060 225 3	− 0.020 259 5

Table 6. Difference between the thermal conductivity λ_{82}, calculated from the scientific equation with the IAPS 82 formulation, and the thermal conductivity λ_{68}, calculated from the scientific equation with the IFC 68 formulation, relative to the tolerance $\delta\lambda$. Quantity listed $(\lambda_{82} - \lambda_{68})/\delta\lambda$

	TEMPERATURE, °C										
PRESSURE, MPa	0	25	50	75	100	150	200	250	300	350	375
0.1	0.00	-0.01	-0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.00	-0.01	-0.00	0.01	0.03	0.03	0.00	0.00	0.00	0.00	0.00
1.0	0.00	-0.01	-0.01	0.01	0.03	0.03	0.00	0.00	0.00	0.00	0.00
2.5	0.00	-0.01	-0.01	0.01	0.03	0.03	0.01	0.00	0.00	0.00	0.00
5.0	0.00	-0.01	-0.00	0.01	0.02	0.02	0.00	-0.01	0.00	0.00	0.00
7.5	0.00	-0.01	-0.00	0.01	0.02	0.02	-0.00	-0.01	-0.02	0.00	0.00
10.0	0.01	-0.01	-0.00	0.00	0.01	0.01	-0.00	-0.01	0.02	0.00	0.01
12.5	0.01	-0.01	-0.00	0.00	0.01	0.01	-0.01	-0.02	0.01	0.00	0.01
15.0	0.01	-0.01	-0.01	0.00	0.01	0.01	-0.01	-0.02	0.01	0.02	0.01
17.5	0.01	-0.01	-0.01	0.00	0.01	0.00	-0.01	-0.02	0.01	0.10	0.06
20.0	0.01	-0.01	0.01	0.00	0.01	0.00	-0.01	-0.02	0.00	0.03	0.26
22.5	0.01	-0.00	-0.01	-0.00	0.00	-0.00	-0.02	-0.02	0.00	0.03	0.02
25.0	0.01	-0.00	-0.01	-0.00	0.00	-0.00	-0.02	-0.02	-0.00	0.04	-0.08
27.5	0.01	-0.00	-0.01	-0.00	-0.00	-0.01	-0.02	-0.02	-0.01	0.04	-0.04
30.0	0.00	-0.00	-0.01	-0.00	-0.00	-0.01	-0.02	-0.02	-0.01	0.04	-0.01
35.0	0.00	-0.00	-0.00	-0.01	-0.00	-0.01	-0.02	-0.02	-0.01	0.04	0.03
40.0	-0.00	-0.00	-0.00	-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	0.04	0.04
45.0	-0.00	-0.00	-0.00	-0.01	-0.01	-0.02	-0.03	-0.02	-0.02	0.03	0.05
50.0	-0.01	-0.00	-0.00	-0.01	-0.01	-0.03	-0.03	-0.02	-0.02	0.01	0.02
55.0	-0.01	-0.00	-0.00	-0.01	-0.01	-0.03	-0.03	-0.02	-0.02	0.01	0.02
60.0	-0.01	-0.01	-0.00	-0.01	-0.02	-0.03	-0.03	-0.02	-0.02	0.01	0.02
65.0	-0.02	-0.01	-0.00	-0.01	-0.02	-0.04	-0.03	-0.02	-0.02	0.00	0.01
70.0	-0.02	-0.01	-0.00	-0.01	-0.02	-0.04	-0.04	-0.01	-0.01	0.00	0.01
75.0	-0.02	-0.01	-0.00	-0.01	-0.02	-0.04	-0.04	-0.01	-0.01	0.00	0.01
80.0	-0.02	-0.01	-0.00	-0.01	-0.03	-0.05	-0.04	-0.01	-0.01	-0.00	0.01
85.0	-0.02	-0.01	-0.00	-0.01	-0.03	-0.05	-0.04	-0.01	-0.00	-0.00	0.00
90.0	-0.02	-0.01	-0.00	-0.01	-0.03	-0.05	-0.04	-0.00	-0.00	-0.00	0.00
95.0	-0.02	-0.02	-0.00	-0.01	-0.03	-0.05	-0.04	-0.00	0.00	-0.01	0.00
100.0	-0.02	-0.02	-0.00	-0.02	-0.03	-0.06	-0.05	0.00	0.01	-0.01	-0.00

	TEMPERATURE, °C										
PRESSURE, MPa	400	425	450	475	500	550	600	650	700	750	800
0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00
1.0	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	0.00
2.5	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	0.00	0.00
5.0	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
7.5	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
10.0	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
12.5	0.01	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
15.0	0.01	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
17.5	0.01	0.00	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00
20.0	0.04	0.01	0.00	0.00	0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00
22.5	0.09	0.01	0.00	0.00	0.00	0.01	-0.00	-0.00	-0.00	-0.01	-0.01
25.0	0.16	0.02	-0.00	-0.00	0.00	0.01	0.00	-0.00	-0.00	-0.01	-0.01
27.5	0.42	0.02	-0.01	-0.01	0.00	0.02	0.00	-0.00	-0.00	-0.01	-0.01
30.0	-0.07	0.05	-0.02	-0.02	-0.01	0.02	0.01	0.00	-0.00	-0.01	-0.01
35.0	-0.05	0.18	0.01	-0.04	-0.03	0.03	0.02	0.01	-0.00	-0.01	-0.01
40.0	-0.02	0.05	0.10	-0.02	-0.04	0.03	0.02	0.01	0.00	-0.00	-0.01
45.0	0.01	0.03	0.06	0.03	-0.02	0.01	0.03	0.02	0.01	0.00	-0.01
50.0	0.01	0.01	0.02	0.02	0.00	-0.01	0.01	0.01	0.01	0.00	-0.00
55.0	0.02	0.01	0.02	0.01	0.00	-0.02	0.01	0.02	0.01	0.01	0.00
60.0	0.02	0.01	0.02	0.01	0.00	-0.02	0.00	0.02	0.02	0.01	0.00
65.0	0.02	0.02	0.01	0.02	0.00	-0.02	-0.00	0.01	0.02	0.01	0.01
70.0	0.02	0.02	0.01	0.02	0.00	-0.02	-0.01	0.01	0.02	0.02	0.01
75.0	0.02	0.02	0.02	0.01	0.01	-0.01	-0.01	0.01	0.02	0.02	0.02
80.0	0.02	0.02	0.02	0.01	0.01	-0.00	-0.01	0.01	0.02	0.02	0.02
85.0	0.01	0.02	0.02	0.01	0.01	0.00	-0.01	0.00	0.02	0.02	0.02
90.0	0.01	0.02	0.02	0.01	0.01	0.00	-0.01	-0.00	0.02	0.02	0.02
95.0	0.01	0.02	0.02	0.01	0.01	0.00	-0.01	-0.00	0.01	0.02	0.02
100.0	0.01	0.01	0.02	0.01	0.01	-0.00	-0.02	-0.01	0.01	0.02	0.03

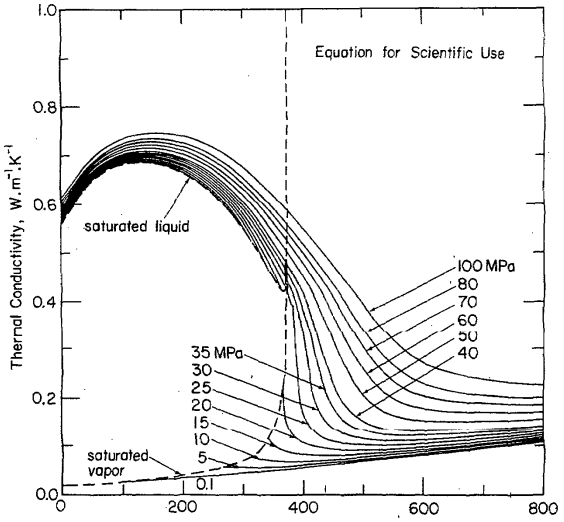

FIG. 1. Thermal conductivity, calculated from Eq. (3.4), as a function of temperature at selected pressures.

Hence, the thermal conductivity isotherm at 648 K, displayed in Fig. 3, is at the edge of the range of validity of the IAPS 82 formulation near the critical point. A procedure for calculating the thermal conductivity and related properties in the immediate vicinity of the critical point is presented in Appendix III.

3.3. Recommended Interpolating Equation for Industrial Use

For industrial applications, the thermodynamic properties of water substance are often calculated from the IFC 67 Formulation for Industrial Use.^{M1} However, the IFC 67

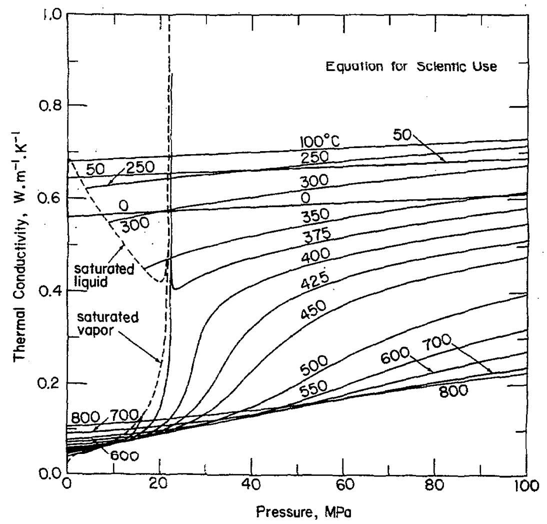

FIG. 2. Thermal conductivity, calculated from Eq. (3.4), as a function of pressure at selected temperatures.

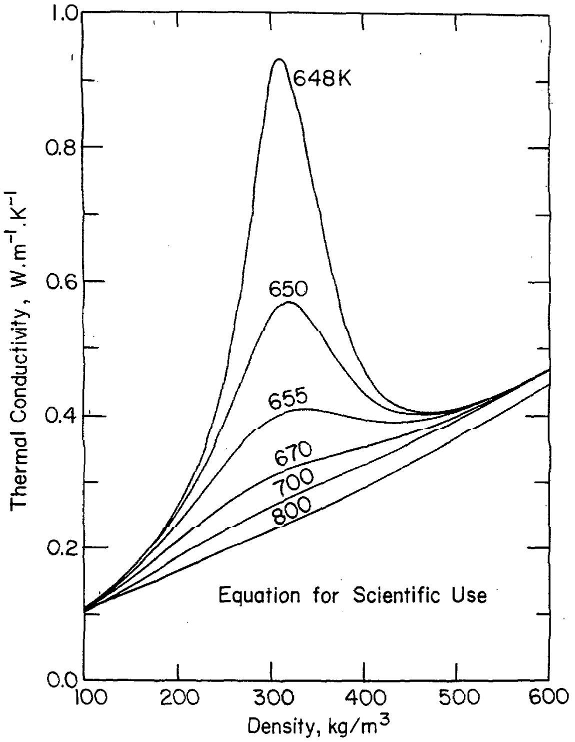

FIG. 3. Thermal conductivity, calculated from Eq. (3.4), as a function of density at selected temperatures in the critical region.

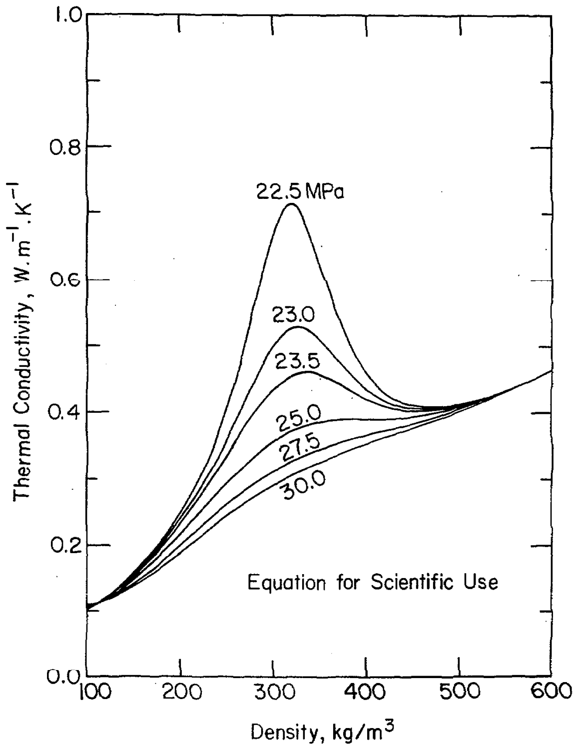

FIG. 4. Thermal conductivity, calculated from Eq. (3.4), as a function of density at selected pressures in the critical region.

TABLE 7. Coefficients a'_k for $\lambda'_0(\overline{T})$

$a'_0 =$	0.010 281 1
$a'_1 =$	0.029 962 1
$a'_2 =$	0.015 614 6
$a'_3 =$	$-$0.004 224 64

formulation does not yield a smooth representation of the derivatives of the equation of state such as $(\partial P/\partial T)_\rho$ and $\chi_T = \rho(\partial\rho/\partial P)_T$.[B9,S21] As a consequence, Eq. (3.4), and specifically Eq. (3.12) for $\lambda_2(\overline{T},\bar{\rho})$, cannot be combined with the IFC 67 formulation for industrial use. For this reason, the Special Committee also proposed a second interpolating equation to be employed specifically in conjunction with the IFC 67 formulation. In this industrial thermal conductivity equation, the thermal conductivity in the critical region is not related to the compressibility and the thermal conductivity remains finite at the critical point. The industrial thermal conductivity equation was developed by Yata and Minamiyama at the Kyoto Institute of Technology.[Y3]

The recommended interpolating equation for industrial use has the form

$$\lambda = \lambda'_0(\overline{T}') + \lambda'_1(\bar{\rho}') + \lambda'_2(\overline{T}',\bar{\rho}'). \tag{3.17}$$

The industrial equation is expressed in terms of a dimensionless temperature $\overline{T}'$ and density $\bar{\rho}'$

$$\overline{T}' = \frac{T}{T^{*\prime}}, \quad \bar{\rho}' = \frac{\rho}{\rho^{*\prime}}, \tag{3.18}$$

where the reference constants $T^{*\prime}$ and $\rho^{*\prime}$ are close to, but not identical to the reference constants T^* and ρ^* defined in Eq. (3.2). Instead

$$T^{*\prime} = 647.3\ \mathrm{K}, \quad \rho^{*\prime} = 317.7\ \mathrm{kg/m^3}. \tag{3.19}$$

The function $\lambda'_0(\overline{T}')$ in Eq. (3.17) represents the thermal conductivity in the dilute-gas limit. The difference $\lambda - \lambda'_0(\overline{T}')$, designated as the excess thermal conductivity, is in the engineering literature often approximated by a temperature-independent function of density.[S22,T11] This approximation becomes inadequate in the critical region and in the liquid region.[S23] The function $\lambda'_1(\bar{\rho}')$ in Eq. (3.17) represents the temperature-independent part of the excess thermal conductivity and $\lambda'_2(\overline{T}',\bar{\rho}')$ the residual temperature-dependent part of the excess thermal conductivity in the critical region and in the liquid region.[Y3] The function $\lambda'_0(\overline{T}')$ is defined by

$$\lambda'_0(\overline{T}') = \lambda^* \sqrt{\overline{T}'} \sum_{k=0}^{3} a'_k (\overline{T}')^k \tag{3.20}$$

with

$$\lambda^* = 1\ \mathrm{W\,m^{-1}\,K^{-1}}, \tag{3.21}$$

and with coefficients a'_k given in Table 7. The function $\lambda'_1(\bar{\rho}')$ is defined by

$$\lambda'_1(\bar{\rho}') = \lambda^*\{b_0 + b_1\bar{\rho}' + b_2\exp[B_1(\bar{\rho}' + B_2)^2]\}, \tag{3.22}$$

with coefficients b_i and B_i given in Table 8. The function $\lambda'_2(\overline{T}',\bar{\rho}')$ is defined by

$$\begin{aligned}\lambda'_2(\overline{T}',\bar{\rho}') &= \lambda^*\left\{\left(\frac{d_1}{(\overline{T}')^{10}} + d_2\right)(\bar{\rho}')^{1.8}\exp\,[C_1\,(1-(\bar{\rho}')^{2.8})]\right.\\ &\quad + d_3 S(\bar{\rho}')^Q \exp\left\{\left(\frac{Q}{1+Q}\right)[1-(\bar{\rho}')^{1+Q}]\right\}\\ &\quad \left. + d_4\exp\left[C_2(\overline{T}')^{1.5} + \frac{C_3}{(\bar{\rho}')^5}\right]\right\}.\end{aligned} \tag{3.23}$$

Here Q and S are functions of

$$\Delta\overline{T}' = |\overline{T}' - 1| + C_4, \tag{3.23a}$$

such that

$$Q = 2 + \frac{C_5}{(\Delta\overline{T}')^{0.6}}, \tag{3.23b}$$

$$S = \begin{cases} \dfrac{1}{\Delta\overline{T}'} & \text{for } \overline{T}' \geqslant 1, \\ \dfrac{C_6}{(\Delta\overline{T}')^{0.6}} & \text{for } \overline{T}' < 1. \end{cases} \tag{3.23c}$$

The coefficients d_i and C_i in Eq. (3.23) are given in Table 9.

TABLE 8. Coefficients b_i and B_i for $\lambda'_1(\bar{\rho}')$

$b_0 =$	$-$0.397 070	$B_1 =$	$-$0.171 587
$b_1 =$	0.400 302	$B_2 =$	2.392 190
$b_2 =$	1.060 000		

TABLE 9. Coefficients d_i and C_i for $\lambda'_2(\overline{T}',\bar{\rho}')$

$d_1 =$	0.070 130 9	$C_1 =$	0.642 857
$d_2 =$	0.011 852 0	$C_2 =$	$-$4.117 17
$d_3 =$	0.001 699 37	$C_3 =$	$-$6.179 37
$d_4 =$	$-$1.020 0	$C_4 =$	0.003 089 76
		$C_5 =$	0.082 299 4
		$C_6 =$	10.093 2

Table I.3 in Appendix I gives the values for λ calculated from the industrial thermal conductivity equation at a uniform grid of pressures and temperatures. Table I.4 in Appendix I gives the values for λ calculated from this equation for the liquid and the vapor at saturation. The thermal conductivity as calculated from the industrial equation is shown in Fig. 5 as a function of temperature along selected isobars and in Fig. 6 as a function of pressure along selected isotherms. These figures are to be compared with the corresponding Figs. 1 and 2 for the scientific thermal conductivity equation.

The industrial thermal conductivity equation differs from the scientific equation in the representation of the thermal conductivity in the critical region. In Figs. 7 and 8 we show the behavior of the thermal conductivity in the critical region as calculated from the industrial equation. Comparison with Figs. 3 and 4 indicates that the industrial equation does not follow the steep rise in the thermal conductivity in the vicinity of the critical point predicted by the scientific thermal conductivity equation. In the industrial equation, the thermal conductivity does not become infinite at the

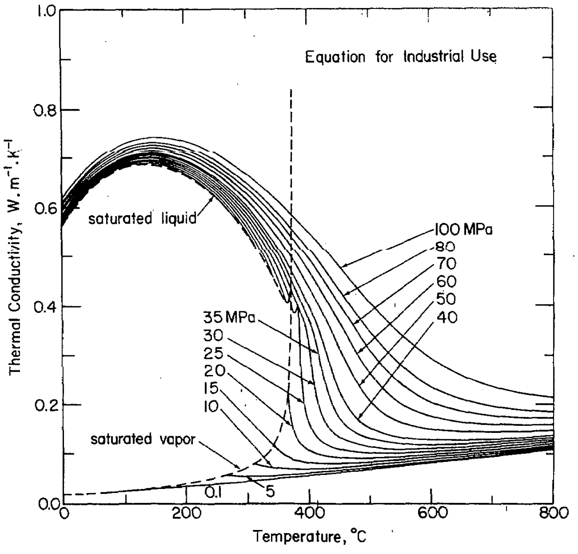

FIG. 5. Thermal conductivity, calculated from Eq. (3.17), as a function of temperature at selected pressures.

critical point but reaches a finite value of 0.836 W m^{-1} K^{-1}.

In Table 10 we show the differences between the thermal conductivity values λ_{ind}, calculated from the industrial equation, and the thermal conductivity values λ_{sci}, calculated from the scientific equation, at a uniform grid of pressures and temperatures. Specifically, we list the percentage differences in $(\lambda_{\text{ind}} - \lambda_{\text{sci}})/\lambda_{\text{sci}}$. Significant differences appear in the supercritical region at temperatures up to 425 °C and pressures between 22.5 and 27.5 MPa and also in the region of high temperatures and high pressures, i.e., at temperatures above 500 °C and pressures above 45 MPa. In the latter region, the differences increase up to 8%. The primary source of experimental information for steam at high pres-

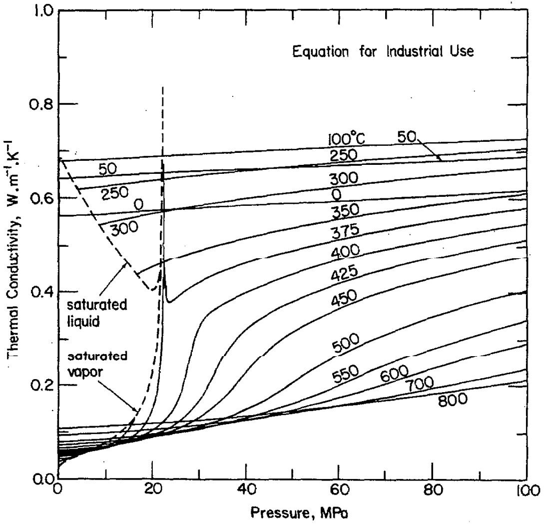

FIG. 6. Thermal conductivity, calculated from Eq. (3.17), as a function of pressure at selected temperatures.

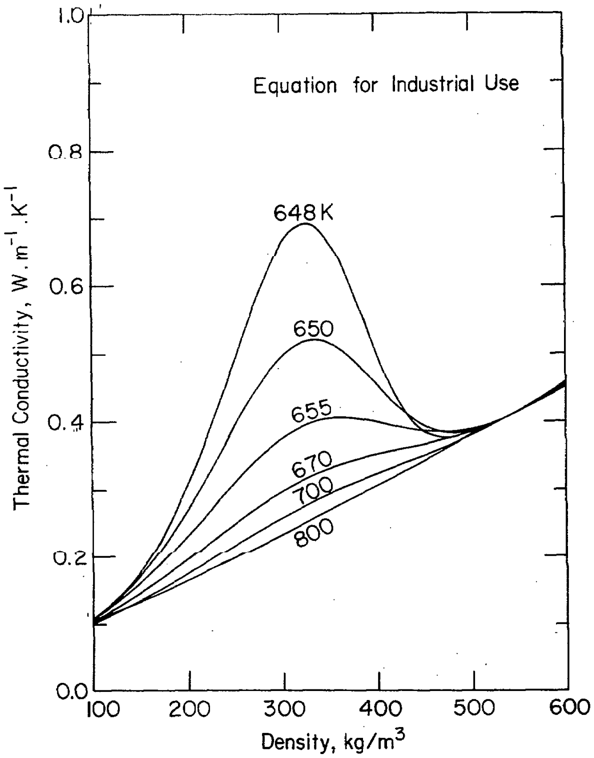

FIG. 7. Thermal conductivity, calculated from Eq. (3.17), as a function of density at selected temperatures in the critical region.

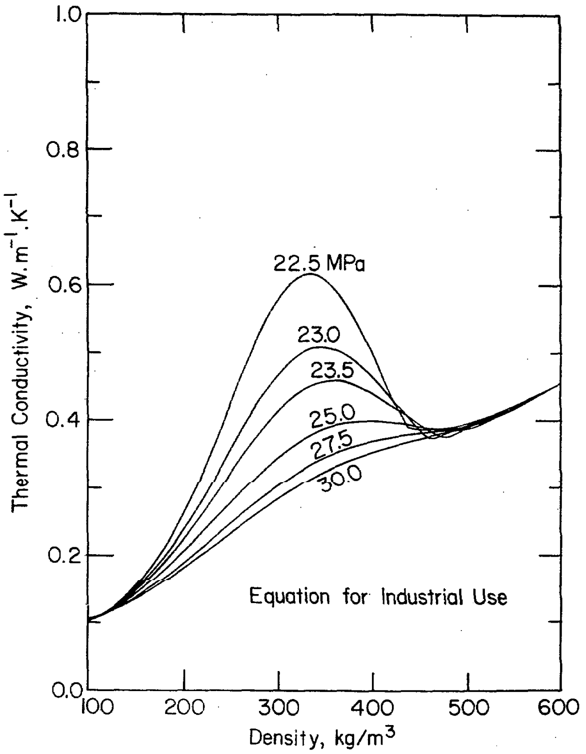

FIG. 8. Thermal conductivity, calculated from Eq. (3.17), as a function of density at selected pressures in the critical region.

Table 10. Percentage difference between the thermal conductivity λ_{ind}, calculated from the equation for industrial use, and the thermal conductivity λ_{sci} calculated from the equation for scientific use. Quantity listed: $100 \times (\lambda_{ind} - \lambda_{sci})/\lambda_{sci}$

PRESSURE, MPa	TEMPERATURE, °C										
	0	25	50	75	100	150	200	250	300	350	375
0.1	0.17	0.07	-0.48	-0.52	-1.18	-0.19	0.25	0.28	0.16	0.01	-0.04
0.5	0.17	0.08	-0.47	-0.52	-0.24	0.22	-1.97	-0.95	-0.44	-0.25	-0.22
1.0	0.17	0.08	-0.47	-0.52	-0.24	0.22	-3.10	-2.03	-1.04	-0.54	-0.41
2.5	0.18	0.10	-0.45	-0.51	-0.24	0.22	0.00	-2.76	-2.07	-1.15	-0.87
5.0	0.19	0.13	-0.43	-0.49	-0.23	0.22	0.01	-0.52	-1.51	-1.38	-1.31
7.5	0.21	0.16	-0.41	-0.48	-0.22	0.22	0.01	-0.51	1.50	-0.72	-1.46
10.0	0.22	0.19	-0.39	-0.47	-0.21	0.22	0.02	-0.50	-0.49	0.69	-1.44
12.5	0.23	0.22	-0.37	-0.46	-0.21	0.22	0.02	-0.49	-0.50	2.48	-1.34
15.0	0.24	0.24	-0.36	-0.45	-0.21	0.22	0.01	-0.49	-0.51	3.22	-1.16
17.5	0.25	0.27	-0.34	-0.44	-0.21	0.21	0.01	-0.48	-0.52	-2.40	-0.51
20.0	0.26	0.29	-0.33	-0.44	-0.20	0.20	0.00	-0.48	-0.52	-2.06	2.26
22.5	0.27	0.31	-0.31	-0.43	-0.20	0.19	-0.00	-0.48	-0.53	-1.80	12.94
25.0	0.28	0.33	-0.30	-0.43	-0.21	0.18	-0.01	-0.49	-0.54	-1.58	-6.11
27.5	0.29	0.35	-0.29	-0.42	-0.21	0.17	-0.03	-0.49	-0.55	-1.40	-4.76
30.0	0.30	0.37	-0.28	-0.42	-0.21	0.16	-0.04	-0.50	-0.56	-1.24	-3.98
35.0	0.32	0.41	-0.26	-0.41	-0.22	0.13	-0.07	-0.52	-0.59	-0.99	-2.97
40.0	0.34	0.45	-0.24	-0.41	-0.23	0.10	-0.11	-0.55	-0.61	-0.81	-2.28
45.0	0.36	0.48	-0.23	-0.41	-0.24	0.06	-0.16	-0.58	-0.65	-0.69	-1.76
50.0	0.38	0.51	-0.22	-0.42	-0.26	0.02	-0.21	-0.62	-0.68	-0.61	-1.36
55.0	0.40	0.55	-0.21	-0.42	-0.28	-0.02	-0.27	-0.67	-0.72	-0.55	-1.06
60.0	0.42	0.58	-0.20	-0.43	-0.30	-0.07	-0.33	-0.72	-0.77	-0.53	-0.83
65.0	0.45	0.60	-0.19	-0.44	-0.32	-0.12	-0.39	-0.78	-0.82	-0.52	-0.66
70.0	0.48	0.63	-0.19	-0.45	-0.35	-0.18	-0.46	-0.85	-0.87	-0.52	-0.54
75.0	0.51	0.66	-0.18	-0.46	-0.37	-0.23	-0.54	-0.91	-0.92	-0.54	-0.45
80.0	0.54	0.69	-0.18	-0.47	-0.40	-0.29	-0.62	-0.99	-0.98	-0.57	-0.39
85.0	0.57	0.72	-0.17	-0.48	-0.43	-0.35	-0.70	-1.07	-1.05	-0.60	-0.35
90.0	0.60	0.75	-0.17	-0.50	-0.46	-0.41	-0.78	-1.15	-1.11	-0.64	-0.34
95.0	0.64	0.78	-0.16	-0.51	-0.48	-0.47	-0.87	-1.24	-1.18	-0.68	-0.33
100.0	0.67	0.81	-0.16	-0.52	-0.51	-0.54	-0.96	-1.33	-1.26	-0.73	-0.34

PRESSURE, MPa	TEMPERATURE, °C										
	400	425	450	475	500	550	600	650	700	750	800
0.1	-0.09	-0.12	-0.13	-0.13	-0.12	-0.07	0.00	0.10	0.20	0.29	0.36
0.5	-0.20	-0.19	-0.17	-0.16	-0.14	-0.08	-0.00	0.09	0.19	0.28	0.36
1.0	-0.32	-0.26	-0.22	-0.18	-0.15	-0.09	-0.01	0.08	0.17	0.27	0.36
2.5	-0.62	-0.45	-0.33	-0.24	-0.18	-0.11	-0.05	0.02	0.11	0.21	0.32
5.0	-0.89	-0.64	-0.45	-0.32	-0.23	-0.16	-0.14	-0.11	-0.04	0.07	0.21
7.5	-0.97	-0.73	-0.53	-0.38	-0.28	-0.23	-0.26	-0.29	-0.24	-0.13	0.04
10.0	-0.92	-0.79	-0.60	-0.44	-0.35	-0.33	-0.43	-0.51	-0.50	-0.39	-0.19
12.5	-0.85	-0.85	-0.69	-0.53	-0.43	-0.46	-0.63	-0.77	-0.80	-0.69	-0.46
15.0	-0.90	-1.00	-0.83	-0.64	-0.54	-0.61	-0.85	-1.07	-1.13	-1.03	-0.79
17.5	-1.22	-1.31	-1.05	-0.81	-0.68	-0.77	-1.10	-1.39	-1.50	-1.42	-1.15
20.0	-1.99	-1.83	-1.37	-1.02	-0.84	-0.95	-1.36	-1.73	-1.90	-1.82	-1.54
22.5	-3.39	-2.59	-1.80	-1.27	-1.02	-1.13	-1.63	-2.09	-2.31	-2.26	-1.96
25.0	-5.64	-3.54	-2.31	-1.56	-1.21	-1.31	-1.90	-2.46	-2.74	-2.70	-2.40
27.5	-5.88	-4.53	-2.84	-1.86	-1.39	-1.48	-2.16	-2.82	-3.17	-3.16	-2.85
30.0	-1.26	-5.26	-3.27	-2.10	-1.53	-1.62	-2.41	-3.18	-3.60	-3.62	-3.31
35.0	-3.10	-1.85	-3.16	-2.18	-1.59	-1.78	-2.83	-3.85	-4.43	-4.54	-4.23
40.0	-3.69	-0.97	-0.71	-1.31	-1.11	-1.69	-3.10	-4.41	-5.19	-5.40	-5.12
45.0	-3.36	-2.43	0.61	0.62	0.03	-1.26	-3.16	-4.81	-5.83	-6.17	-5.95
50.0	-2.84	-3.00	-0.09	1.96	1.56	-0.43	-2.95	-5.03	-6.32	-6.83	-6.68
55.0	-2.31	-2.96	-1.04	2.02	2.99	0.74	-2.46	-5.02	-6.63	-7.33	-7.30
60.0	-1.82	-2.65	-1.56	1.45	3.53	2.08	-1.67	-4.77	-6.73	-7.66	-7.77
65.0	-1.40	-2.23	-1.70	0.84	3.50	3.37	-0.62	-4.27	-6.62	-7.81	-8.08
70.0	-1.05	-1.79	-1.60	0.42	3.22	4.42	0.61	-3.53	-6.30	-7.77	-8.23
75.0	-0.75	-1.36	-1.37	0.22	2.91	5.19	1.93	-2.56	-5.75	-7.53	-8.20
80.0	-0.51	-0.96	-1.06	0.18	2.67	5.79	3.22	-1.41	-5.00	-7.11	-8.00
85.0	-0.31	-0.60	-0.72	0.26	2.51	6.22	4.42	-0.12	-4.05	-6.49	-7.63
90.0	-0.15	-0.28	-0.38	0.41	2.43	6.54	5.52	1.25	-2.93	-5.70	-7.09
95.0	-0.02	0.00	-0.04	0.61	2.42	6.80	6.52	2.64	-1.65	-4.74	-6.40
100.0	0.08	0.25	0.29	0.84	2.46	6.99	7.45	4.00	-0.25	-3.63	-5.55

sures and temperatures is provided by the work of Tsederberg *et al.*[T9] As mentioned in Sec. 2.3, the Committee did not receive the data of Tsederberg *et al.* until 1977, at which time the formulation of the industrial thermal conductivity had already been completed. However, the data of Tsederberg *et al.* were taken into account in the determination of the coefficients in the scientific thermal conductivity equation. Hence, the industrial conductivity equation is less reliable than the scientific thermal conductivity equation in the region of high temperatures and high pressures.

The IFC 67 formulation, as well as the IFC 68 formulation, is based on the International Practical Temperature Scale of 1948 (IPTS 48) and not on IPTS 68. Strictly speaking, therefore, the thermal conductivity equation for industrial use yields thermal conductivity values in terms of IPTS 48. Except for the immediate vicinity of the critical point, the maximum error in λ due to conversion from IPTS 48 to IPTS 68 is approximately 0.1% and, hence, negligibly small compared to the accuracy of the experimental thermal conductivity data.

As noted in the Release, an alternative thermal conductivity equation for industrial use has been proposed by Watson.[W3] This alternative industrial equation for the thermal conductivity is presented in Appendix IV.

4. Discussion of International Thermal Conductivity Equations

4.1. Comparison with International Input

In Tables 11 and 12 we present a comparison between the thermal conductivity as calculated from the international equations and the experimental data contained in the International Input. For each source of N experimental data points, we give the average percentage deviation

$$(100/N)\sum_{i=1}^{N}(\lambda_{i,\text{exp}}-\lambda_{i,\text{calc}})/\lambda_{i,\text{calc}},$$

the mean percentage deviation

$$(100/N)\sum_{i=1}^{N}|\lambda_{i,\text{exp}}-\lambda_{i,\text{calc}}|\lambda_{i,\text{calc}},$$

and the root-mean-square percentage deviation

$$100\times\left[\frac{1}{N}\sum_{i=1}^{N}(\lambda_{i,\text{exp}}-\lambda_{i,\text{calc}})^2/\lambda_{i,\text{calc}}^2\right]^{1/2}.$$

In addition, we give the number n of data points exceeding stated multiples of their evaluated uncertainty. For these uncertainties, we used the error estimates assigned by the Committee as given in Table 1 with the following exceptions. For the data of Challoner and Powell,[C1] we reduced the

Table 11. Comparison of thermal conductivity equation for scientific use with International Input

First Author	Ref.	No. of Points	Av. % Dev.	Mean % Dev.	r.m.s % Dev.	Wt. %	$n > 1\sigma$	$n > 2\sigma$	$n > 3\sigma$
Schmidt	[S3]	24	0.10	0.36	0.45	3.0	0	0	0
Timrot	[T1]	10	-2.03	2.03	2.20	3.0	0	0	0
Vargaftik	[V2]	19	-0.85	1.62	1.96	3.0	1	0	0
Milverton	[M2]	56	1.48	1.48	1.52	2.0	0	0	0
Timrot	[T2]	11	-1.41	2.50	2.98	3.0	3	0	0
Timrot	[T3]	16	-0.29	1.57	2.31	3.0	3	1	0
Vargaftik	[V3]	7	-1.39	2.08	2.79	3.0	1	0	0
Schmidt	[S4]	8	-0.35	0.50	0.53	2.0	0	0	0
Challoner	[C1]	5	0.40	0.40	0.50	1.0	0	0	0
Vargaftik	[V4]	9	0.45	2.00	2.17	2.0	1	0	0
Vargaftik	[V5]	61	1.89	2.50	2.98	3.0	12	0	0
Vargaftik	[V6]	30	-0.90	1.01	1.32	2.0	5	0	0
Lawson	[L3]	35	-0.73	1.35	1.88	3.0	1	0	0
Vargaftik	[V7]	41	1.30	2.02	2.30	3.0	4	0	0
Vines	[V8]	2	-1.93	2.34	3.04	3.0	1	0	0
Tarzimanov	[T4]	33	1.54	3.25	3.89	2.0	15	1	0
Vukalowich	[V9]	39	-0.55	2.33	3.02	5.0	5	0	0
Keyes	[K2]	50	-1.25	2.65	3.18	3.0	7	0	0
Vargaftik	[V10]	21	-0.02	1.22	1.38	3.0	0	0	0
Venart	[V11]	4	-1.58	2.20	2.63	3.0	0	0	0
Brain	[B3]	3	-0.69	1.01	1.11	2.0	0	0	0
Cherneeva	[C2]	60	0.11	0.78	0.94	4.0	0	0	0
Le Neindre	[L5]	226	-0.20	0.69	0.86	2.0	6	0	0
Le Neindre	[L6]	65	-1.07	1.70	2.29	3.0	7	0	0
Tarzimanov	[T5]	19	-0.15	0.69	0.83	2.0	0	0	0
Mashirov	[M3]	14	-0.03	0.36	0.42	2.0	0	0	0
Brain	[B4]	36	-0.73	1.84	2.08	2.0	5	0	0
Bach	[B1]	374	0.07	0.61	0.76	4.0	0	0	0
Tarzimanov	[T6]	8	1.48	2.04	2.44	2.0	5	0	0
Le Neindre	[L7]	98	-0.83	2.69	3.07	2.0	28	0	0
Tarzimanov	[T7]	86	0.06	2.41	2.94	2.0	28	6	0
Bury	[B5]	102	-1.94	2.56	3.07	2.0	42	0	0
Vargaftik	[V12]	11	0.29	0.94	1.10	2.0	0	0	0
Minamiyama	[M4]	45	0.53	0.60	0.84	2.0	2	0	0
Rastorguyev	[R2]	442	0.11	0.56	0.70	2.0	1	0	0
Sirota	[S5]	214	-1.31	2.30	3.07	2.0	18	0	0
Castelli	[C3]	48	-0.93	0.93	1.04	2.0	0	0	0
Amirkhanov	[A1]	695	0.77	1.14	1.36	4.0	0	0	0
Takizawa	[T8]	29	1.23	1.28	1.40	2.0	3	0	0
Minamiyama	[M5]	180	0.01	0.57	0.77	2.0	4	0	0
Minamiyama	[M6]	241	-0.19	0.70	0.88	2.0	4	0	0
Tsederberg	[T9]	146	0.19	2.13	2.55	2.0	54	7	0
Overall results:		3623	0.01	1.25	1.78	—	266	15	0

Table 12. Comparison of thermal conductivity equation for industrial use with International Input

First Author	Ref.	No. of Points	Av. % Dev.	Mean % Dev.	r.m.s % Dev.	Wt. %	n > 1σ	n > 2σ	n > 3σ
Schmidt	[S3]	24	0.18	0.52	0.62	3.0	0	0	0
Timrot	[T1]	10	-1.75	1.75	1.82	3.0	0	0	0
Vargaftik	[V2]	19	-0.76	1.52	1.76	3.0	0	0	0
Milverton	[M2]	56	1.39	1.39	1.54	2.0	0	0	0
Timrot	[T2]	11	0.09	2.20	2.55	3.0	0	0	0
Timrot	[T3]	16	-0.15	1.50	2.09	3.0	2	0	0
Vargaftik	[V3]	7	-1.24	1.96	2.49	3.0	1	0	0
Schmidt	[S4]	8	-0.06	0.43	0.52	2.0	0	0	0
Challoner	[C1]	5	0.60	0.66	0.72	1.0	0	0	0
Vargaftik	[V4]	9	0.43	1.89	2.09	2.0	1	0	0
Vargaftik	[V5]	61	3.47	3.96	4.28	3.0	33	1	0
Vargaftik	[V6]	30	-0.68	0.84	1.08	2.0	2	0	0
Lawson	[L3]	35	0.40	1.29	1.66	3.0	1	0	0
Vargaftik	[V7]	41	1.83	2.16	2.51	3.0	10	0	0
Vines	[V8]	2	-2.02	2.19	2.98	3.0	1	0	0
Tarzimanov	[T4]	33	1.09	1.79	2.23	2.0	5	0	0
Vukalowich	[V9]	39	0.78	2.44	3.13	5.0	4	0	0
Keyes	[K2]	50	-0.27	1.87	2.56	3.0	6	0	0
Vargaftik	[V10]	21	-0.21	1.22	1.38	3.0	0	0	0
Venart	[V11]	4	-1.43	1.93	2.39	3.0	0	0	0
Brain	[B3]	3	-0.44	0.97	0.99	2.0	0	0	0
Cherneeva	[C2]	60	0.61	0.73	0.95	4.0	0	0	0
Le Neindre	[L5]	226	0.02	0.72	1.05	2.0	18	1	0
Le Neindre	[L6]	65	-0.24	0.62	0.89	3.0	0	0	0
Tarzimanov	[T5]	19	-0.38	0.84	0.98	2.0	1	0	0
Mashirov	[M3]	14	-0.02	0.82	0.93	2.0	0	0	0
Brain	[B4]	36	-0.81	1.95	2.20	2.0	6	0	0
Bach	[B1]	374	0.40	0.61	0.77	4.0	0	0	0
Tarzimanov	[T6]	8	0.13	2.14	2.54	2.0	3	1	0
Le Neindre	[L7]	98	1.24	3.41	4.24	2.0	45	1	0
Tarzimanov	[T7]	86	-0.47	2.34	3.32	2.0	27	7	0
Bury	[B5]	102	-1.25	1.90	2.34	2.0	26	0	0
Vargaftik	[V12]	11	0.24	0.95	1.12	2.0	0	0	0
Minamiyama	[M4]	45	0.72	0.74	0.92	2.0	1	0	0
Rastorguyev	[R2]	442	0.31	0.67	0.86	2.0	3	0	0
Sirota	[S5]	214	0.34	2.98	3.92	2.0	62	3	0
Castelli	[C3]	48	-1.61	1.61	1.70	2.0	10	0	0
Amirkhanov	[A1]	695	1.97	2.37	3.03	4.0	89	0	0
Takizawa	[T8]	29	1.26	1.30	1.39	2.0	3	0	0
Minamiyama	[M5]	180	0.42	0.60	0.68	2.0	0	0	0
Minamiyama	[M6]	241	0.53	0.69	1.00	2.0	10	1	0
Tsederberg	[T9]	146	1.71	3.18	3.72	2.0	95	29	7
Overall results:		3623	0.68	1.58	2.33	—	465	44	7

error estimate from 2% to 1% in view of our assessment of the most probable value of the thermal conductivity of saturated water as discussed in Sec. 2.4. For the data of Bach and Grigull[B1] and of Amirkhanov *et al.*,[A1] we increased the error estimates from 2% to 4% to compensate for the large number of data points of these authors. A comparison between the equations and the experimental data near the critical point is presented in Sec. 4.3.

From the information in Table 11, we conclude that the scientific thermal conductivity equation yields a satisfactory representation of the experimental data. Most deviations are within one standard deviation and almost all deviations are within two standard deviations. Exceptions are some data points of Tarzimanov and Zainullin[T7] and of Tsederberg *et al.*[T9] at high pressures and temperatures.

Table 12 gives the corresponding information for the industrial equation. Comparison of Tables 11 and 12 shows that the scientific thermal conductivity equation is in closer agreement with the experimental data than the industrial thermal conductivity equation. In particular, the industrial equation does not agree with the data of Tsederberg *et al.*[T9] at high temperatures and high pressures as explained in Sec. 3.3.

There are two regions where one can make some contact with theoretical considerations. These regions are the dilute-gas limit and the neighborhood of the critical point. We, therefore, discuss the behavior of the thermal conductivity in these regions in some further detail.

4.2. Thermal Conductivity of Gaseous H_2O at Low Pressures

In Fig. 9 we compare experimental thermal conductivity data for water vapor and steam at pressures up to 1 atm with the values calculated from the scientific thermal conductivity equation. The figure shows that there exists a considerable spread between the experimental data in the literature. Furthermore, the differences between successive measurements of the same laboratories[B5,L6,L7,T1,V2-V4,V10,V12] are of the same order of magnitude as between measurements from different laboratories. The equation represents the data as a function of temperature without any apparent systematic deviations. A corresponding deviation plot for the industrial thermal conductivity equation can be found in the article of Yata and Minamiyama.[Y3]

At sufficiently low pressures, the thermal conductivity

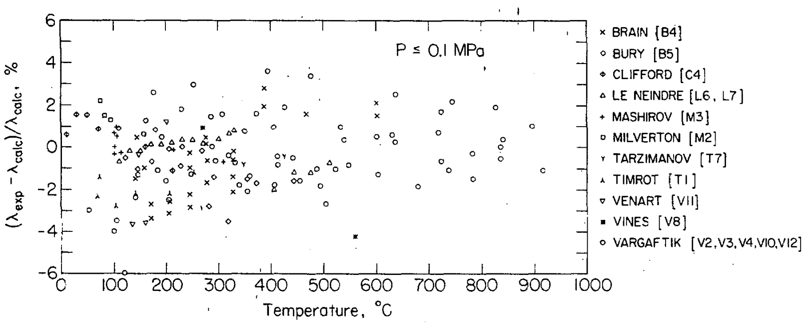

FIG. 9. Deviations of the experimental thermal conductivity data for water vapor and steam at pressures up to 1 atm from Eq. (3.4).

of gases becomes independent of density and the temperature dependence of the thermal conductivity in this dilute-gas limit is represented by the function $\lambda_0(\overline{T})$ in Eq. (3.4) or $\lambda_0'(\overline{T}')$ in Eq. (3.17). However, in extracting this dilute-gas behavior of the thermal conductivity from the experimental data, one should be aware of the fact that experimental thermal conductivity data obtained at atmospheric pressure can only be identified with the limiting low density values at temperatures above 300 °C. At temperatures below 300 °C, corrections for nonideality become important and the density dependence of the thermal conductivity at subatmospheric pressures needs to be considered. From Fig. 9, we conclude that the function $\lambda_0(\overline{T})$, as given by Eq. (3.5), represents the ideal-gas thermal conductivity up to a temperature of 1000 °C.

In Fig. 10 we compare the ideal-gas thermal conductivity $\lambda_0'(\overline{T})$ implied by the industrial equation, with the ideal-gas thermal conductivity $\lambda_0(\overline{T})$ implied by the scientific equation. At high temperatures, the agreement between the two functions is excellent: at temperatures above 300 °C, the differences are everywhere within 0.4%. At temperatures below 300 °C, the differences are slightly larger leading to + 1.5% at 100 °C and − 3.2% at 0 °C. It should be noted that there exists some uncertainty concerning the thermal conductivity of water vapor at temperatures below 80 °C. The measurements of Milverton correspond to temperatures between 72 and 95 °C.[M2] The measurements of Timrot and Vargaftik[T1] include a data point at 69 °C and 0.29 bar and a data point at 73.4 °C and 0.34 bar. Vargaftik and Oleshchuk[V3] have also reported a data point at 52.2 °C and 0.12 bar. The International Input does not contain any thermal conductivity data for water vapor at temperatures below 50 °C, nor does it contain adequate information to determine the density dependence of the thermal conductivity of water vapor at temperatures between 50 and 70 °C. More recently, Clifford and Tough[C4] made an experimental study of the thermal conductivity of water vapor at temperatures between 11 and 212 °C and at pressures between 5 and 10 mm Hg with an estimated accuracy of about ± 1.5%. The new data of Clifford and Tough are included in Fig. 9; the scientific thermal conductivity equation reproduces these data with a maximum deviation of 1.8% at 50 °C.

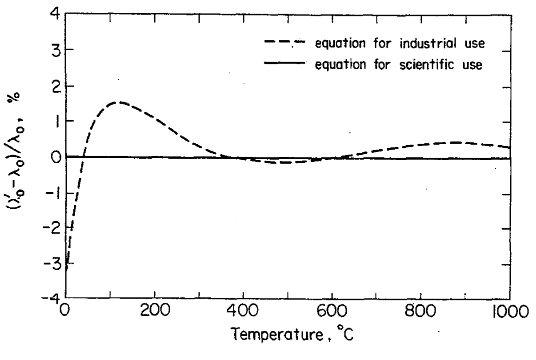

FIG. 10. Difference between the ideal-gas thermal conductivity $\lambda_0'(T)$, calculated from Eq. (3.17), and the ideal-gas thermal conductivity $\lambda_0(T)$ calculated from Eq. (3.4).

Attempts to predict the dilute-gas thermal conductivity for H_2O from the kinetic theory of gases have been made by Baker and Brokaw,[B6] O'Connell and Prausnitz,[O1] and Thoen-Hellemans and Mason.[T12] A theoretical analysis of the thermal conductivity of polar gases like H_2O is complicated by the effects of inelastic collisions and resonant exchange of rotational energy.[T11] Baker and Brokaw tried to assess the importance of the latter effect of H_2O and D_2O, but were unable to reach a definite conclusion.[B6] O'Connell and Prausnitz calculated the thermal conductivity of gaseous H_2O assuming a Kihara-Stockmayer intermolecular potential model and obtained agreement with the dilute-gas thermal conductivity values of the 1964 Skeleton Tables at higher temperatures to within the stated tolerances.[O1] The application of the kinetic theory of gases to gaseous H_2O was further considered by Thoen-Hellemans and Mason to investigate the consistency of the thermal conductivity data for steam against the more accurate viscosity data.[T12] They concluded that the dilute-gas viscosity and thermal-conductivity values of the 1964 Skeleton Tables were theoretically consistent within the stated tolerances of these table values. However, they also suspected that the thermal conductivity values of the 1964 Skeleton Tables were low by a few percent and concluded that none of the values were too high. The new international formulation for the viscosity of water substance[S2] agrees with the dilute-gas viscosity values of the 1964 Skeleton Tables to well within 1% at all temperatures above 125 °C. However, contrary to the suggestion of

Thoen-Hellemans and Mason, the new Eqs. (3.5) and (3.20) adopted for the dilute-gas thermal conductivity lead to values between 425 and 700 °C that are some 0.5% and 1% lower than the 1964 Skeleton Table values and it appears that the thermal conductivity of steam even at low pressures is not fully understood theoretically.

The initial density dependence of the thermal conductivity in the gaseous phase at low pressures can be represented by

$$\lambda = \lambda_0(T) + B_\lambda(T)\rho, \tag{4.1}$$

where

$$B_\lambda = \lim_{\rho \to 0}\left(\frac{\partial \lambda}{\partial \rho}\right)_T. \tag{4.2}$$

We refer to B_λ as the second virial coefficient of thermal conductivity. Theory predicts that the first derivative Eq. (4.2) exists but that higher-order derivatives diverge in the zero-density limit.[K7] The coefficient B_λ, as well as the corresponding second virial coefficient of viscosity B_μ, has been investigated as a function of temperature for a number of fluids.[H3,H4]

Equation (3.4) implies that the second virial coefficient of thermal conductivity B_λ can be represented by

$$B_\lambda(\overline{T}) = \frac{\lambda_0(\overline{T})}{\rho^*}\sum_{i=0}^{4} b_i^\lambda\left(\frac{1}{\overline{T}} - 1\right)^i, \tag{4.3}$$

where $\rho^* = 317.763$ kg/m^3 is the reference density introduced in Eq. (3.2) and where

$$b_i^\lambda = \sum_{j=0}^{5} (-1)^j b_{ij}^\lambda. \tag{4.4}$$

The coefficient B_λ, calculated from Eq. (4.3), is shown in Fig. 11 as a function of temperature. Below 100 °C we show the curve as a broken line; as mentioned previously at these temperatures sufficient experimental information does not exist to determine the value of B_λ with confidence. The behavior of B_λ as a function of temperature differs appreciably from the behavior of the second virial coefficient of viscosity B_μ for gaseous H_2O. The coefficient B_μ for water vapor becomes negative at low temperatures[W2]; the coefficient B_λ remains positive in the temperature range under consideration.

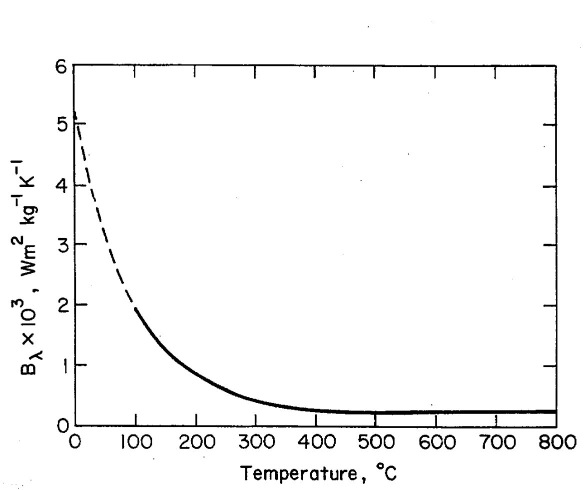

FIG. 11. Second virial coefficient of the thermal conductivity $B_\lambda(T)$ as a function of temperatures as derived from Eq. (3.4).

In Eq. (3.17), it is assumed that the excess thermal conductivity $\lambda - \lambda_0'(\overline{T}')$ is independent of the temperature in the gaseous phase at low pressures. Hence the industrial thermal conductivity equation cannot accommodate a second virial coefficient of thermal conductivity that depends on temperature and it approximates B_λ by a constant,

$$\begin{aligned}\lambda^*[b_1 + 2b_2B_1\exp(B_1B_2^2)]/\rho^{*\prime}\\ = 0.831\times10^{-3}\ \mathrm{W\,m^2\,kg^{-1}\,K^{-1}}.\end{aligned}$$

4.3. Thermal Conductivity of Steam in the Critical Region

In order to represent the behavior of the thermal conductivity of fluids in the critical region, it is customary to separate λ into the sum of a normal or ideal thermal conductivity λ_{id} which would exist in the absence of any critical-region effect, and a critical enhancement term $\Delta\lambda$[S17,S24–S26]

$$\lambda(T,\rho) = \lambda_{\mathrm{id}}(T,\rho) + \Delta\lambda(T,\rho). \tag{4.5}$$

This representation corresponds to the separation of Eq. (3.4) into the sum of $\lambda_0 \times \lambda_1$ and λ_2.

The theory of dynamic critical phenomena predicts that the critical part of the thermal diffusivity $\lambda/\rho c_p$, where c_p is the specific heat at constant pressure, close to the critical point satisfies a Stokes-Einstein diffusion law of the form[H5,K8]

$$\frac{\Delta\lambda_c}{\rho c_p} = \Lambda\frac{k_BT}{6\pi\mu\xi}. \tag{4.6}$$

Here k_B is Boltzmann's constant, ξ the correlation length associated with the critical fluctuations, and Λ is a coefficient of the order of unity. Since near the critical point

$$\begin{aligned}\rho c_p &\cong \rho(c_p - c_v)\\ &= (P^*/T^*)(\overline{T}/\overline{\rho}^2)(\partial\overline{P}/\partial\overline{T})_\rho^2\overline{\chi}_T,\end{aligned}$$

it follows from Eq. (4.6) that near the critical point the critical enhancement contribution will diverge as

$$\Delta\lambda_c = \frac{\Lambda k_B P^*}{6\pi\mu}\left(\frac{\overline{T}}{\overline{\rho}}\right)^2\left(\frac{\partial\overline{P}}{\partial\overline{T}}\right)_\rho^2\frac{\overline{\chi}_T}{\xi}. \tag{4.7}$$

At the critical density $\rho = \rho_c$, the symmetrized compressibility $\overline{\chi}_T$ diverges as $\Gamma[(T - T_c)/T_c]^{-\gamma}$ and the correlation length ξ diverges as $\xi_0[(T - T_c)/T_c]^{-\nu}$, where γ and ν are universal critical exponents and Γ and ξ_0 system-dependent amplitudes.[S27] Hence, at $\rho = \rho_c$, ξ is related to the symmetrized compressibility χ_T by

$$\xi = \xi_0(\overline{\chi}_T/\Gamma)^{\nu/\gamma}. \tag{4.8}$$

This relationship between ξ and $\overline{\chi}_T$ also holds to a good approximation at densities other than the critical density.[S27] Substitution of Eq. (4.8) into Eq. (4.7) yields

$$\Delta\lambda_c = \frac{\Lambda k_B P^*\Gamma^{\nu/\gamma}}{6\pi\mu\xi_0}\left(\frac{\overline{T}}{\overline{\rho}}\right)^2\left(\frac{\partial\overline{P}}{\partial\overline{T}}\right)_\rho^2\overline{\chi}_T^{(\gamma-\nu)/\gamma}. \tag{4.9}$$

Equation (4.9) for $\Delta\lambda_c$ refers to the asymptotic behavior of $\Delta\lambda$ near the critical point. Far away from the critical point, the critical enhancement contribution should vanish. Accordingly, we have proposed an equation for the critical enhancement contribution of the form[B8,B10,H6,S26]

$$\Delta\lambda = \Delta\lambda_c F(\Delta\bar{T},\Delta\bar{\rho}), \qquad (4.10)$$

where $F(\Delta\bar{T},\Delta\bar{\rho})$ is a crossover function such that

$$\lim_{|\Delta\bar{T}|\to 0,\ |\Delta\bar{\rho}|\to 0} F(\Delta\bar{T},\Delta\bar{\rho}) = 1,$$
$$\qquad (4.11)$$
$$\lim_{|\Delta\bar{T}|\to \infty,\ |\Delta\bar{\rho}|\to \infty} F(\Delta\bar{T},\Delta\bar{\rho}) = 0$$

in terms of the variables

$$\Delta\bar{T} = (T - T_c)/T_c \simeq \bar{T} - 1$$

and

$$\Delta\bar{\rho} = (\rho - \rho_c)/\rho_c \simeq \bar{\rho} - 1.$$

For steam, Basu and Sengers selected as the crossover function[B8]

$$F(\Delta\bar{T},\Delta\bar{\rho}) = \sqrt{\bar{\rho}}\exp[-18.66(\Delta\bar{T})^2 - (\Delta\bar{\rho})^4]. \qquad (4.12)$$

If we substitute Eqs. (4.9) and (4.12) into Eq. (4.10), adopt the critical-region parameter values $\gamma = 1.19$, $\nu = 0.633$, $\Gamma = 0.075$, $\xi_0 = 1.3$ Å as determined by Sengers *et al.*,[H7,S26,S27] and $\Lambda = 1.2$ as determined by Basu and Sengers,[B8] we obtain Eq. (3.12) for $\lambda_2(\bar{T},\bar{\rho})$.

The critical enhancement in the thermal conductivity is present in a large range of densities and temperatures around the critical point. As a consequence, it is difficult to determine the parameters in the critical enhancement term $\lambda_2 = \Delta\lambda$ and the ideal thermal conductivity $\lambda_{id} = \lambda_0\lambda_1$ independently. In practice an iterative procedure was used. First, a preliminary equation for the ideal thermal conductivity λ_{id} in Eq. (4.5) was adopted, assuming that the temperature dependence of the excess ideal thermal conductivity $\lambda_{id} - \lambda_0$ could be neglected in the critical region. Next, the amplitude Λ of the critical enhancement was determined from the values $\lambda - \lambda_{id}$, deduced from the experimental data in the critical region.[B8] Adopting the equation thus obtained for λ_2, we then determined the parameters of the function λ_1 by fitting the experimental thermal conductivity data of the International Input to the objective function[W1]

$$Y = \ln\left(\frac{\lambda - \lambda_2}{\lambda_0}\right) = \bar{\rho}\sum_{i=0}^{4}\sum_{j=0}^{5} b_{ij}^{\lambda}\left(\frac{1}{\bar{T}} - 1\right)^i(\bar{\rho} - 1)^j, \qquad (4.13)$$

with the assigned weights given in Table 11. The problem of determining optimum values for the coefficients b_{ij}^{λ} was then reduced to a linear regression problem.

We note that the viscosity μ also shows a critical enhancement in the vicinity of the critical point.[B11,S2,W2] However, unlike the thermal conductivity, the viscosity exhibits only a weakly singular behavior observable in an extremely small range around the critical point as further discussed in Appendix III. This weakly singular behavior of the viscosity near the critical point has been neglected in Eq. (3.8) for the viscosity μ.[S2] As a consequence this effect has also been neglected in determining the parameters of Eqs. (3.7) and (3.12).

The behavior of the thermal conductivity of steam in

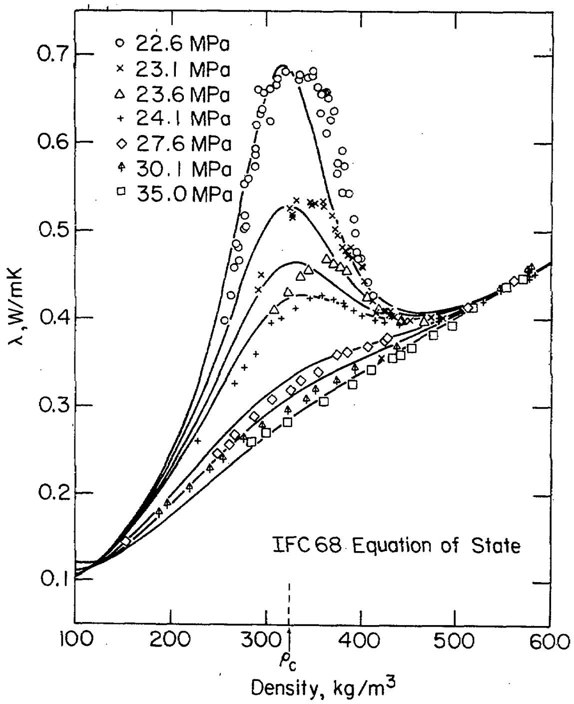

FIG. 12. The thermal conductivity of steam in the critical region as a function of density at constant pressures. The data are those of Sirota *et al.* (Ref. S5) with densities calculated from the IFC 68 formulation. The curves represent Eq. (3.4) with the thermodynamic derivatives calculated from the IFC 68 formulation.

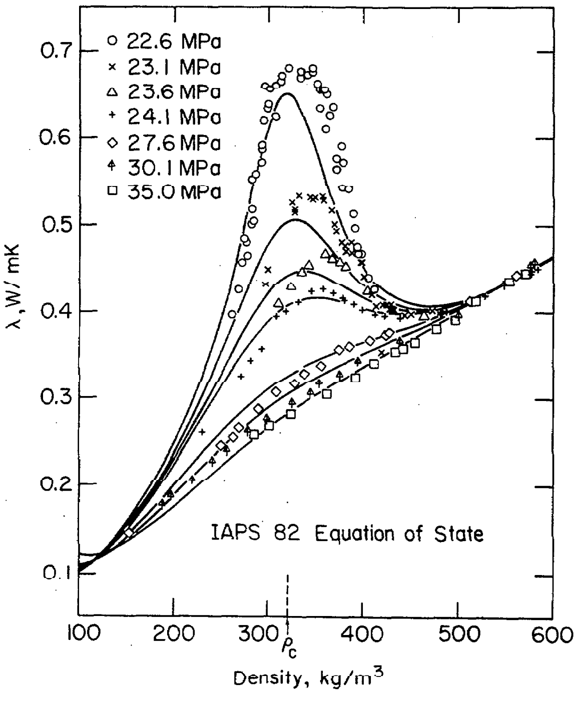

FIG. 13. The thermal conductivity of steam in the critical region as a function of density at constant pressures. The data are those of Sirota *et al.* (Ref. S5) with densities calculated from the IAPS 82 formulation. The curves represent Eq. (3.4) with the thermodynamic derivatives calculated from the IAPS 82 formulation.

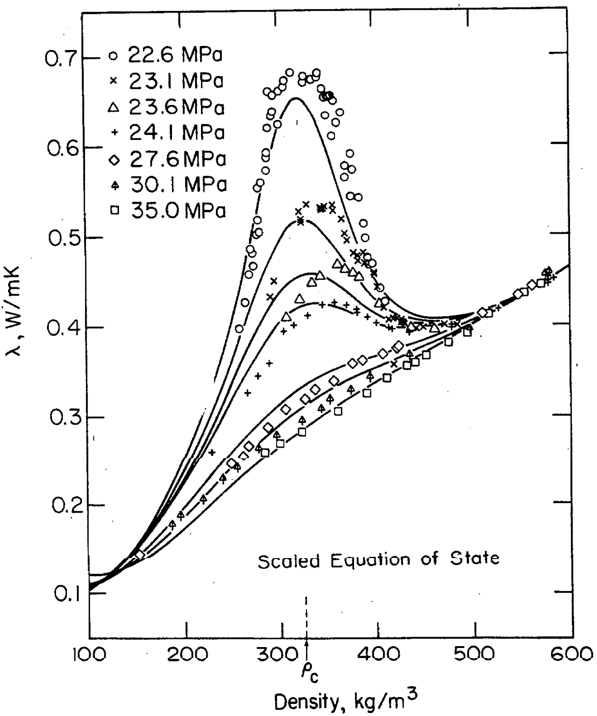

FIG. 14. The thermal conductivity of steam in the critical region as a function of density at constant pressures. The data are those of Sirota *et al.* (Ref. S5) and the curves represent Eq. (3.4), when in region defined by Eq. (III.1) the IAPS 82 formulation is replaced with the scaled equation of state of Levelt Sengers *et al.* (Ref. L8).

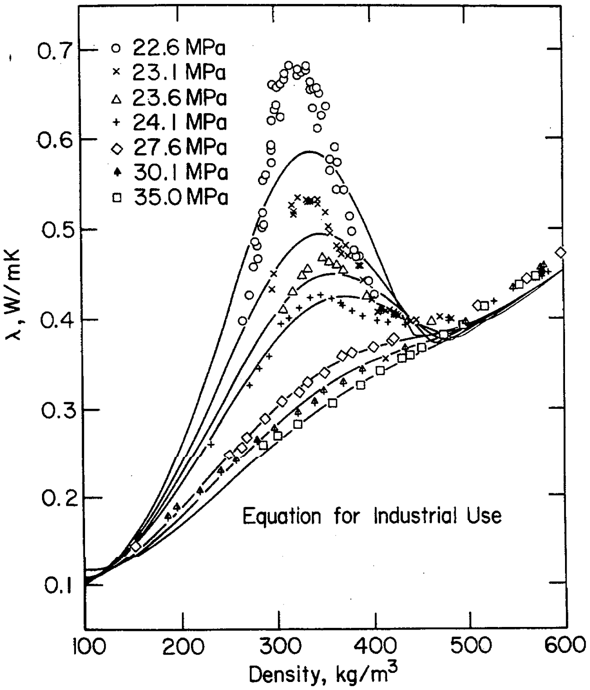

FIG. 15. The thermal conductivity of steam in the critical region as a function of density at constant pressures. The data are those of Sirota *et al.* (Ref. S5) with densities calculated from the IFC 67 formulation and the curves represent the values calculated from Eq. (3.17).

the critical region, as represented by the thermal conductivity equation for scientific use, is compared with the detailed set of experimental data of Sirota and co-workers^{S5} in Figs. 12, 13, and 14. In Fig. 12 we show the values deduced from the scientific thermal conductivity equation of state which was used in the original determination of the values of the coefficients in the scientific thermal conductivity equation. In Fig. 13 we show the values deduced from the scientific thermal conductivity equation when calculated with the aid of the newly adopted IAPS 82 formulation for the equation of state. In Fig. 14 we show the values deduced from the scientific thermal conductivity equation, when in the region bounded by (III.1) the IAPS 82 formulation is replaced with a scaled fundamental equation^{L8} as further discussed in Appendix III. It should be noted that any comparison between the calculated values of thermal conductivity and the experimental data close to the critical point is rather sensitive to any uncertainties in temperature, or more specifically the temperature differences $T - T_c$ to be attributed to the experimental data.^{B8} Hence, it is concluded that all three procedures mentioned here yield equally acceptable representations of the behavior of the thermal conductivity of steam in the critical region.

In Fig. 15 we present a comparison between the experimental data of Sirota *et al.* in the critical region and the values calculated from Eq. (3.17) for industrial use. As explained in Sec. 3, the industrial thermal conductivity equation does not yield an accurate representation of the critical enhancement in the more immediate vicinity of the critical point.

4.4. Thermal Conductivity of Saturated Vapor and Saturated Liquid

Values implied by the new international formulation for the thermal conductivity λ_{liq} ($= \lambda'$) of the saturated liquid and of the thermal conductivity λ_{vap} ($= \lambda''$) of the saturated vapor are presented in Tables I.2, I.4, and I.6. The thermal conductivity of fluid H_2O at the saturation boundary between the triple-point temperature $T_t = 273.16$ K and the critical temperature $T_c = 647.067$ K can be represented by the auxiliary equations

$$\lambda_{\text{liq}} = \lambda^* \Big[c_0' + \epsilon^{2/3} \sum_{i=1}^{5} c_i'(1-\epsilon)^{1-i} + c_6'(1-\epsilon)^4 \epsilon^{-0.57} \Big], \tag{4.14}$$

$$\lambda_{\text{vap}} = \lambda^* \Big[(1-\epsilon)^{-2} \epsilon^{-0.57} \sum_{i=1}^{8} c_i'' \epsilon^{(i-1)/3} \Big], \tag{4.15}$$

with

$$\epsilon = 1 - T/T_c \tag{4.16}$$

[and $\lambda^* = 1\ \text{Wm}^{-1}\ \text{K}^{-1}$ as earlier defined in Eq. (3.6)]. The values of the coefficients c_i' and c_i'' are presented in Tables 13 and 14.

From Eq. (4.6) it follows that near the critical temperature the thermal conductivity becomes proportional to $c_p/\mu\xi$. The theory of critical phenomena predicts that along

TABLE 13. Coefficients c_i' for λ_{liq}

$c_0' = 3.069\,495\,2\times 10^{-1}$
$c_1' = -3.285\,188\,0$
$c_2' = 1.906\,804\,4\times 10^{1}$
$c_3' = -3.733\,198\,9\times 10^{1}$
$c_4' = 3.537\,491\,7\times 10^{1}$
$c_5' = -1.286\,627\,0\times 10^{1}$
$c_6' = 5.201\,668\,7\times 10^{-3}$

TABLE 14. Coefficients c_i'' for λ_{vap}

$c_1'' = 2.710\,192\,3\times 10^{-2}$
$c_2'' = -4.400\,423\,2\times 10^{-1}$
$c_3'' = 4.560\,840\,5$
$c_4'' = -2.061\,251\,6\times 10^{1}$
$c_5'' = 4.909\,434\,5\times 10^{1}$
$c_6'' = -6.466\,597\,1\times 10^{1}$
$c_7'' = 4.441\,708\,0\times 10^{1}$
$c_8'' = -1.239\,847\,4\times 10^{1}$

either side of the phase boundary c_p will diverge as $\epsilon^{-\gamma}$, ξ as $\epsilon^{-\nu}$,[S27] while the viscosity diverges as ξ^{ϕ} with $\phi \simeq 0.06$.[B12,H5] As a consequence, the thermal conductivity will diverge as $\epsilon^{-\omega}$ with $\omega = -\gamma + \nu(1+\phi)$. Equations (4.14) and (4.15) have been constructed such that both λ_{liq} and λ_{vap} diverge as $\epsilon^{-\omega}$ with $\omega = 0.57$ in the limit $\epsilon \to 0$.

Equations (4.14) and (4.15) represent the thermal conductivity along the vapor–liquid phase boundary within the tolerances agreed upon by IAPS.

4.5. Thermal Conductivity of Fluid H_2O at High Pressures

The international thermal conductivity equations, presented in Secs. 3.2 and 3.3, have been certified by IAPS for use at pressures up to 100 MPa. The reason is that the IFC 67 Formulation for the Thermodynamic Properties of Water Substance for Industrial Use, coupled with the industrial thermal conductivity equation, and the IFC 68 Formulation for the Thermodynamic Properties of Water Substance originally employed with the scientific thermal conductivity equation, are themselves only valid at pressures up to 100 MPa. However, the new IAPS 82 Formulation, which supersedes the IFC 68 Formulation, is valid at pressures well above 100 MPa. Hence, it is of interest to investigate whether Eq. (3.4), when combined with the IAPS 82 Formulation for the thermodynamic properties, can be extrapolated to pressures beyond 100 MPa.

As can be seen from the information in Table 1, the International Input contains thermal conductivity data at pressures beyond 100 MPa reported by Lawson *et al.*,[L3] Rastorguyev *et al.*,[R2] Castelli and Stanley,[C3] Amirkhanov *et al.*,[A1] and of Minamiyama and Tata.[M5,M6,Y1,Y2] Additional experimental data for the thermal conductivity of fluid H_2O at high pressures have been reported by Amirkhanov and coworkers[A4] and by Dietz *et al.*[D1,D2] A comparison between the available experimental data at high pressures above 100 MPa and Eq. (3.4), at some representative temperatures is made in Figs. 16 and 17.

In order to specify the range of validity of the thermal conductivity equation, we adopt the criterion that the equation should reproduce the experimental data at high pressures to within about 2.5%. The data of Castelli and Stanley pertain to liquid water at pressures up to 140 MPa and at temperatures between 1.8 and 30.3 °C.[C3] The data of Rastorguyev and co-workers cover pressures up to 200 MPa at temperatures between 3 and 210 °C.[R2] The data of Minamiyama and Yata pertain to fluid H_2O at pressures up to 147 MPa at temperatures from 30 to 420 °C.[M5,M6] All these data agree with the international thermal conductivity equation to within 2.5%. The data of Lawson and co-workers are for liquid water between 30 and 130 °C at pressures up to 785 MPa[L3]; these data agree with the equation at pressures up to 400 MPa at all temperatures. The earlier data of Amirkhanov *et al.*[A1] refer to water between 25 and 350 °C at pressures up to 245 MPa; the more recent data of Amirkhanov *et al.*[A4] are for steam between 376 and 576 °C at pressures up to 250 MPa. These data of Amirkhanov and co-workers are not

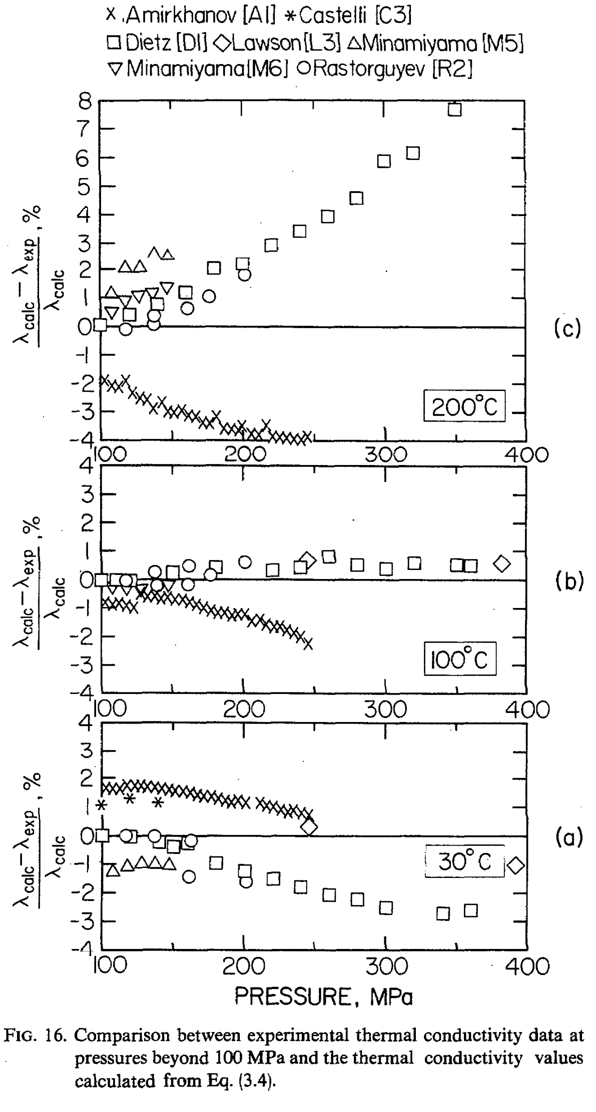

FIG. 16. Comparison between experimental thermal conductivity data at pressures beyond 100 MPa and the thermal conductivity values calculated from Eq. (3.4).

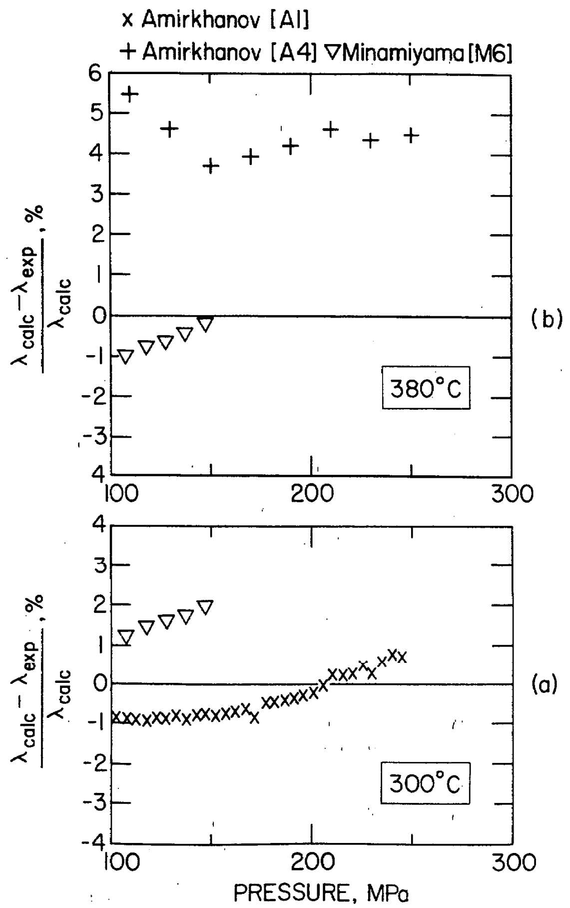

FIG. 17. Comparison between experimental thermal conductivity data at pressures beyond 100 MPa and the thermal conductivity values calculated from Eq. (3.4).

in good agreement with the equation. However, an important source of the difficulty is the existence of significant systematic deviations when the data of Amirkhanov *et al.*[A4] are compared with those of other investigators as well. This is evident when the data of Amirkhanov *et al.*[A1] for water at high pressures are compared with the data of Dietz *et al.*,[D1] of Rastorguyev *et al.*,[R2] and of Minamiyama and Yata,[M5,M6] as shown in Figs. 16c and 17a; it is also evident when the more recent data of Amirkhanov *et al.*[A4] for steam at high pressures are compared with the data of Minamiyama and Yata,[M6] as shown in (b) of Fig. 17. We conclude that the experimental data of Amirkhanov and co-workers require additional verification. A very accurate source of experimental information for water at high pressures is provided by the recent work of Dietz *et al.*[D1,D2]; the data cover pressures up to 350 MPa at temperatures between 30 and 250 °C. The equation agrees with the data of Dietz *et al.* to within about 2.5% at the temperatures between 30 and 125 °C; at 150 °C the deviations exceed 2.5% at pressures above 260 MPa; at 200 and 250 °C a similar increase of the deviations occurs at pressures above 200 MPa. At temperatures of about 200 °C and at pressures above 200 MPa, the international equation tends to yield thermal conductivity values that increase more strongly with pressure than those observed experimentally; this conclusion differs from the opposite conclusion stated in the paper of Dietz *et al.*[D1]

We conclude that the range of validity of the international thermal conductivity equation for scientific use can be extended to

$$\begin{array}{lll} P\leqslant 400\ \text{MPa} & \text{for} & 0\ ^\circ\text{C}\leqslant T\leqslant 125\ ^\circ\text{C}, \\ P\leqslant 200\ \text{MPa} & \text{for} & 125\ ^\circ\text{C}\leqslant T\leqslant 250\ ^\circ\text{C}, \\ P\leqslant 150\ \text{MPa} & \text{for} & 250\ ^\circ\text{C}\leqslant T\leqslant 400\ ^\circ\text{C}, \\ P\leqslant 100\ \text{MPa} & \text{for} & 400\ ^\circ\text{C}\leqslant T\leqslant 800\ ^\circ\text{C}. \end{array} \tag{4.17}$$

4.6. Prandtl Number and Thermal Diffusivity

In many practical applications involving heat transfer analysis, one also needs reliable information for quantities that are combinations of transport properties and thermodynamic properties. The most commonly used ratios that involve the thermal conductivity are the Prandtl number $Pr = \mu c_p/\lambda$ and the thermal diffusivity $D_T = \lambda/\rho c_p$.

In previous articles, we have discussed some problems encountered in the calculation of the Prandtl number of steam.[B9,S21] Specifically, the IFC 67 and IFC 68 formulations for the thermodynamic properties of steam do not yield a smooth representation of the specific heat c_p. However, the Prandtl number and thermal diffusivity can now be calculated by combining Eq. (3.4) for scientific use and Eq. (3.8) for viscosity with the new IAPS 82 formulation for the density ρ and the specific heat c_p. The values thus obtained for the Prandtl number and the thermal diffusivity over a uniform grid of pressures and temperatures are presented in Tables 15 and 16. The Prandtl number is shown in Fig. 18 as a function of temperature along selected isobars; since the Prandtl number becomes infinite at the critical point we have plotted the inverse Prandtl number $1/Pr$. The thermal diffusivity D_T is shown in Fig. 19. From Figs. 18 and 19 it is seen that the new international equations adopted by IAPS give a smooth representation of the Prandtl number and the thermal diffusivity.

Because the IFC 67 formulation for industrial use is not suitable for calculating the specific heat c_p, the equations for industrial use are not recommended for calculating the Prandtl number or the thermal diffusivity.[B9,S21]

Table 15. The Prandtl number $Pr = \mu c_p/\lambda$ calculated from Eq. (3.4) for λ, Eq. (3.8) for μ and the IAPS 82 formulation for c_p

	TEMPERATURE, °C										
PRESSURE, MPa	0	25	50	75	100	150	200	250	300	350	375
0.1	13.50	6.137	3.555	2.378	1.000	0.9737	0.9602	0.9499	0.9407	0.9322	0.9282
0.5	13.48	6.133	3.553	2.377	1.753	1.151	0.9835	0.9641	0.9505	0.9392	0.9342
1.0	13.46	6.128	3.551	2.377	1.752	1.150	1.028	0.9870	0.9647	0.9488	0.9422
2.5	13.39	6.113	3.546	2.374	1.751	1.150	0.9035	1.096	1.021	0.9824	0.9692
5.0	13.27	6.088	3.538	2.371	1.750	1.149	0.9019	0.8252	1.173	1.057	1.025
7.5	13.16	6.063	3.529	2.367	1.748	1.148	0.9004	0.8209	1.466	1.162	1.098
10.0	13.04	6.039	3.521	2.364	1.746	1.147	0.8989	0.8169	0.8903	1.312	1.191
12.5	12.94	6.015	3.513	2.360	1.744	1.146	0.8975	0.8132	0.8741	1.545	1.314
15.0	12.83	5.992	3.505	2.357	1.743	1.145	0.8961	0.8097	0.8601	2.006	1.484
17.5	12.73	5.970	3.497	2.354	1.741	1.145	0.8948	0.8064	0.8477	1.379	1.753
20.0	12.63	5.947	3.490	2.350	1.740	1.144	0.8936	0.8033	0.8368	1.216	2.353
22.5	12.53	5.926	3.482	2.347	1.738	1.143	0.8924	0.8004	0.8270	1.121	8.125
25.0	12.44	5.904	3.475	2.344	1.736	1.142	0.8913	0.7976	0.8181	1.057	1.937
27.5	12.34	5.883	3.467	2.341	1.735	1.142	0.8902	0.7950	0.8101	1.009	1.485
30.0	12.25	5.863	3.460	2.338	1.733	1.141	0.8891	0.7926	0.8027	0.9729	1.291
35.0	12.08	5.823	3.446	2.332	1.731	1.140	0.8871	0.7880	0.7898	0.9188	1.103
40.0	11.92	5.785	3.433	2.326	1.728	1.138	0.8852	0.7838	0.7788	0.8800	1.005
45.0	11.77	5.748	3.420	2.321	1.725	1.137	0.8835	0.7801	0.7692	0.8504	0.9430
50.0	11.62	5.713	3.407	2.315	1.723	1.136	0.8818	0.7766	0.7608	0.8269	0.8991
55.0	11.48	5.680	3.395	2.310	1.721	1.135	0.8803	0.7734	0.7534	0.8075	0.8660
60.0	11.35	5.648	3.384	2.305	1.718	1.134	0.8789	0.7705	0.7467	0.7912	0.8398
65.0	11.23	5.617	3.372	2.301	1.716	1.134	0.8775	0.7678	0.7408	0.7773	0.8183
70.0	11.12	5.588	3.362	2.296	1.714	1.133	0.8763	0.7652	0.7354	0.7653	0.8004
75.0	11.01	5.560	3.352	2.292	1.712	1.132	0.8751	0.7629	0.7306	0.7548	0.7850
80.0	10.91	5.533	3.342	2.288	1.711	1.131	0.8740	0.7606	0.7261	0.7455	0.7718
85.0	10.81	5.508	3.332	2.284	1.709	1.131	0.8729	0.7586	0.7220	0.7372	0.7602
90.0	10.72	5.483	3.324	2.280	1.707	1.130	0.8719	0.7566	0.7182	0.7297	0.7499
95.0	10.63	5.460	3.315	2.277	1.706	1.130	0.8710	0.7547	0.7147	0.7230	0.7408
100.0	10.55	5.439	3.307	2.273	1.704	1.129	0.8701	0.7530	0.7115	0.7169	0.7326

	TEMPERATURE, °C										
PRESSURE, MPa	400	425	450	475	500	550	600	650	700	750	800
0.1	0.9243	0.9207	0.9172	0.9138	0.9107	0.9047	0.8993	0.8944	0.8899	0.8856	0.8816
0.5	0.9295	0.9251	0.9209	0.9170	0.9134	0.9067	0.9007	0.8954	0.8906	0.8861	0.8820
1.0	0.9362	0.9307	0.9257	0.9211	0.9168	0.9092	0.9025	0.8966	0.8914	0.8868	0.8826
2.5	0.9582	0.9490	0.9409	0.9338	0.9275	0.9167	0.9077	0.9002	0.8940	0.8887	0.8841
5.0	1.002	0.9835	0.9688	0.9566	0.9463	0.9295	0.9163	0.9060	0.8978	0.8913	0.8862
7.5	1.055	1.024	1.000	0.9815	0.9663	0.9427	0.9249	0.9115	0.9012	0.8935	0.8877
10.0	1.118	1.070	1.035	1.008	0.9876	0.9561	0.9334	0.9166	0.9042	0.8952	0.8887
12.5	1.195	1.123	1.073	1.038	1.010	0.9699	0.9417	0.9214	0.9068	0.8965	0.8892
15.0	1.290	1.183	1.116	1.069	1.034	0.9839	0.9499	0.9259	0.9090	0.8972	0.8892
17.5	1.408	1.253	1.163	1.102	1.059	0.9982	0.9580	0.9301	0.9107	0.8976	0.8888
20.0	1.548	1.336	1.215	1.138	1.085	1.013	0.9659	0.9339	0.9121	0.8975	0.8880
22.5	1.812	1.436	1.273	1.177	1.112	1.027	0.9736	0.9374	0.9131	0.8971	0.8868
25.0	2.273	1.564	1.339	1.219	1.141	1.042	0.9811	0.9407	0.9138	0.8963	0.8853
27.5	3.363	1.737	1.416	1.264	1.171	1.057	0.9885	0.9436	0.9142	0.8952	0.8834
30.0	3.329	1.979	1.506	1.314	1.203	1.073	0.9957	0.9463	0.9142	0.8938	0.8813
35.0	1.693	2.415	1.729	1.427	1.272	1.104	1.010	0.9511	0.9137	0.8903	0.8763
40.0	1.290	1.922	1.900	1.548	1.345	1.135	1.023	0.9552	0.9125	0.8861	0.8706
45.0	1.118	1.479	1.791	1.627	1.413	1.167	1.037	0.9588	0.9108	0.8815	0.8645
50.0	1.021	1.245	1.542	1.601	1.454	1.195	1.049	0.9621	0.9089	0.8768	0.8583
55.0	0.9567	1.109	1.335	1.488	1.447	1.218	1.061	0.9653	0.9071	0.8721	0.8521
60.0	0.9110	1.022	1.190	1.354	1.396	1.231	1.071	0.9683	0.9054	0.8677	0.8462
65.0	0.8763	0.9617	1.089	1.235	1.320	1.231	1.078	0.9712	0.9041	0.8638	0.8407
70.0	0.8488	0.9169	1.016	1.140	1.238	1.219	1.083	0.9737	0.9033	0.8604	0.8357
75.0	0.8264	0.8823	0.9615	1.064	1.162	1.195	1.083	0.9757	0.9027	0.8576	0.8314
80.0	0.8076	0.8546	0.9194	1.005	1.096	1.164	1.079	0.9769	0.9026	0.8555	0.8278
85.0	0.7915	0.8318	0.8860	0.9581	1.039	1.128	1.072	0.9770	0.9027	0.8540	0.8250
90.0	0.7777	0.8128	0.8588	0.9201	0.9920	1.091	1.060	0.9760	0.9029	0.8532	0.8228
95.0	0.7655	0.7964	0.8362	0.8888	0.9523	1.055	1.046	0.9736	0.9030	0.8528	0.8214
100.0	0.7547	0.7823	0.8171	0.8627	0.9189	1.020	1.030	0.9699	0.9030	0.8529	0.8206

Table 16. The thermal diffusivity $D_T = \lambda/\rho c_p$ calculated from Eq. (3.4) for λ and the IAPS 82 formulation for ρ and c_p. (D_T in $10^{-6} m^2/s$)

PRESSURE, MPa	TEMPERATURE, °C 0	25	50	75	100	150	200	250	300	350	375
0.1	0.1327	0.1456	0.1558	0.1632	20.83	28.22	36.60	46.15	56.92	68.90	75.33
0.5	0.1328	0.1456	0.1558	0.1633	0.1681	0.1725	6.942	8.931	11.13	13.56	14.87
1.0	0.1329	0.1457	0.1559	0.1634	0.1682	0.1726	3.192	4.259	5.401	6.644	7.308
2.5	0.1333	0.1459	0.1561	0.1636	0.1684	0.1729	0.1712	1.414	1.943	2.485	2.767
5.0	0.1339	0.1463	0.1564	0.1639	0.1687	0.1734	0.1719	0.1607	0.7670	1.088	1.247
7.5	0.1344	0.1466	0.1567	0.1642	0.1691	0.1738	0.1726	0.1620	0.3599	0.6173	0.7371
10.0	0.1350	0.1470	0.1570	0.1645	0.1695	0.1743	0.1733	0.1633	0.1357	0.3790	0.4808
12.5	0.1355	0.1473	0.1573	0.1649	0.1698	0.1748	0.1740	0.1645	0.1387	0.2337	0.3266
15.0	0.1361	0.1477	0.1577	0.1652	0.1702	0.1752	0.1747	0.1657	0.1415	0.1310	0.2231
17.5	0.1366	0.1480	0.1580	0.1655	0.1705	0.1757	0.1754	0.1668	0.1440	0.0831	0.1472
20.0	0.1372	0.1483	0.1583	0.1658	0.1709	0.1762	0.1760	0.1679	0.1464	0.0948	0.0840
22.5	0.1377	0.1487	0.1586	0.1662	0.1712	0.1766	0.1767	0.1690	0.1486	0.1033	0.0143
25.0	0.1382	0.1490	0.1589	0.1665	0.1716	0.1771	0.1773	0.1700	0.1507	0.1100	0.0594
27.5	0.1387	0.1493	0.1592	0.1668	0.1719	0.1775	0.1780	0.1710	0.1527	0.1156	0.0776
30.0	0.1392	0.1497	0.1595	0.1671	0.1723	0.1779	0.1786	0.1720	0.1546	0.1203	0.0895
35.0	0.1402	0.1503	0.1601	0.1678	0.1729	0.1788	0.1798	0.1739	0.1580	0.1283	0.1054
40.0	0.1411	0.1510	0.1607	0.1684	0.1736	0.1797	0.1810	0.1757	0.1612	0.1348	0.1162
45.0	0.1420	0.1516	0.1613	0.1690	0.1743	0.1805	0.1822	0.1774	0.1641	0.1403	0.1245
50.0	0.1429	0.1522	0.1619	0.1696	0.1749	0.1814	0.1833	0.1791	0.1668	0.1451	0.1313
55.0	0.1437	0.1528	0.1625	0.1702	0.1756	0.1822	0.1844	0.1807	0.1693	0.1494	0.1370
60.0	0.1445	0.1534	0.1630	0.1708	0.1762	0.1830	0.1855	0.1822	0.1717	0.1532	0.1419
65.0	0.1453	0.1540	0.1636	0.1714	0.1769	0.1838	0.1866	0.1837	0.1739	0.1567	0.1463
70.0	0.1460	0.1545	0.1642	0.1720	0.1775	0.1846	0.1876	0.1852	0.1760	0.1600	0.1503
75.0	0.1467	0.1551	0.1647	0.1726	0.1781	0.1854	0.1887	0.1866	0.1780	0.1630	0.1539
80.0	0.1474	0.1556	0.1652	0.1731	0.1788	0.1862	0.1897	0.1879	0.1799	0.1658	0.1572
85.0	0.1481	0.1561	0.1658	0.1737	0.1794	0.1870	0.1907	0.1893	0.1817	0.1684	0.1603
90.0	0.1487	0.1567	0.1663	0.1742	0.1800	0.1877	0.1917	0.1906	0.1835	0.1708	0.1631
95.0	0.1493	0.1572	0.1668	0.1748	0.1806	0.1885	0.1927	0.1919	0.1852	0.1731	0.1658
100.0	0.1498	0.1577	0.1673	0.1753	0.1812	0.1892	0.1937	0.1931	0.1868	0.1754	0.1683

PRESSURE, MPa	TEMPERATURE, °C 400	425	450	475	500	550	600	650	700	750	800
0.1	82.07	89.09	96.40	104.0	111.9	128.4	146.1	164.7	184.4	205.1	226.8
0.5	16.23	17.65	19.12	20.66	22.24	25.58	29.13	32.88	36.83	40.98	45.32
1.0	7.999	8.718	9.464	10.24	11.04	12.72	14.51	16.40	18.38	20.46	22.64
2.5	3.057	3.357	3.667	3.987	4.317	5.008	5.739	6.508	7.314	8.155	9.033
5.0	1.407	1.569	1.734	1.904	2.077	2.438	2.817	3.214	3.627	4.056	4.500
7.5	0.8548	0.9721	1.090	1.210	1.331	1.583	1.845	2.117	2.400	2.692	2.992
10.0	0.5783	0.6737	0.7683	0.8633	0.9592	1.156	1.360	1.571	1.788	2.011	2.240
12.5	0.4126	0.4951	0.5758	0.6560	0.7366	0.9006	1.070	1.244	1.422	1.605	1.790
15.0	0.3024	0.3765	0.4481	0.5186	0.5889	0.7311	0.8771	1.027	1.179	1.334	1.492
17.5	0.2239	0.2925	0.3576	0.4211	0.4840	0.6108	0.7402	0.8724	1.007	1.142	1.279
20.0	0.1647	0.2300	0.2904	0.3486	0.4060	0.5211	0.6382	0.7573	0.8778	0.9991	1.121
22.5	0.1173	0.1816	0.2387	0.2929	0.3460	0.4519	0.5593	0.6683	0.7782	0.8883	0.9984
25.0	0.0766	0.1430	0.1978	0.2489	0.2985	0.3970	0.4968	0.5977	0.6990	0.8002	0.9009
27.5	0.0419	0.1112	0.1648	0.2134	0.2602	0.3526	0.4460	0.5403	0.6347	0.7285	0.8217
30.0	0.0368	0.0850	0.1377	0.1843	0.2287	0.3160	0.4041	0.4928	0.5815	0.6693	0.7561
35.0	0.0694	0.0558	0.0974	0.1403	0.1807	0.2597	0.3393	0.4193	0.4988	0.5771	0.6539
40.0	0.0907	0.0642	0.0758	0.1105	0.1449	0.2190	0.2918	0.3652	0.4379	0.5090	0.5784
45.0	0.1048	0.0814	0.0735	0.0933	0.1235	0.1888	0.2560	0.3240	0.3913	0.4569	0.5205
50.0	0.1151	0.0959	0.0818	0.0874	0.1090	0.1663	0.2284	0.2918	0.3547	0.4158	0.4747
55.0	0.1231	0.1072	0.0924	0.0893	0.1018	0.1497	0.2068	0.2662	0.3252	0.3826	0.4377
60.0	0.1298	0.1162	0.1025	0.0951	0.1003	0.1380	0.1898	0.2454	0.3012	0.3553	0.4071
65.0	0.1354	0.1236	0.1113	0.1023	0.1023	0.1302	0.1765	0.2284	0.2811	0.3324	0.3815
70.0	0.1402	0.1298	0.1188	0.1094	0.1063	0.1255	0.1662	0.2144	0.2643	0.3130	0.3596
75.0	0.1446	0.1351	0.1252	0.1161	0.1111	0.1233	0.1582	0.2028	0.2499	0.2963	0.3408
80.0	0.1485	0.1398	0.1308	0.1222	0.1163	0.1228	0.1523	0.1932	0.2376	0.2818	0.3242
85.0	0.1520	0.1439	0.1357	0.1276	0.1213	0.1235	0.1479	0.1852	0.2270	0.2691	0.3096
90.0	0.1553	0.1477	0.1401	0.1325	0.1260	0.1251	0.1449	0.1785	0.2177	0.2578	0.2966
95.0	0.1583	0.1511	0.1440	0.1369	0.1305	0.1272	0.1430	0.1731	0.2096	0.2477	0.2848
100.0	0.1611	0.1542	0.1475	0.1408	0.1346	0.1297	0.1419	0.1686	0.2026	0.2387	0.2742

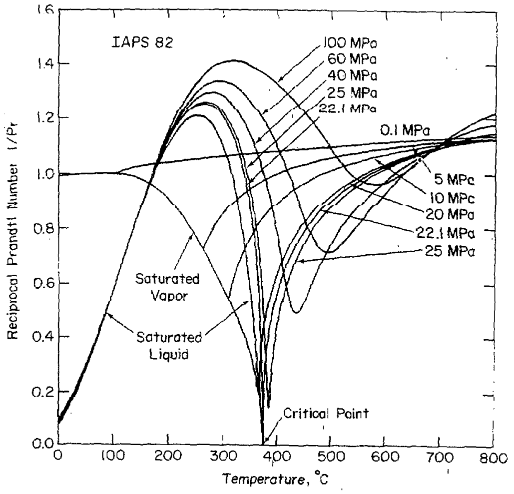

FIG. 18. The inverse Prandtl number $1/Pr = \lambda/\mu c_p$, calculated from the equations recommended by IAPS, as a function of temperature at selected pressures.

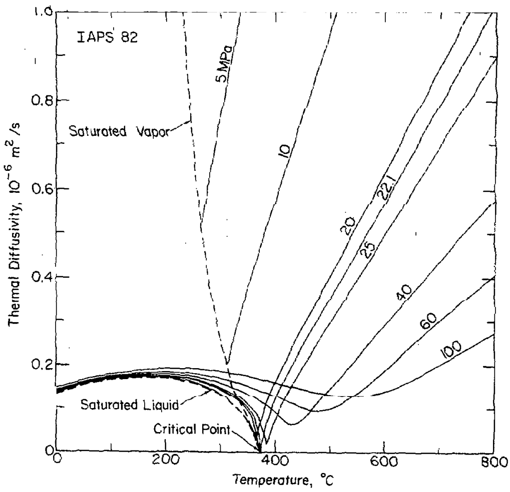

FIG. 19. The thermal diffusivity $D_T = \lambda/\rho c_p$, calculated from the equations recommended by IAPS, as a function of temperature at selected pressures.

5. Acknowledgments

We are indebted to our colleagues of the Special Committee of IAPS, listed in Appendix IF, for their many contributions to the analysis of the thermal conductivity of water substance described in this paper. We also thank Professor J. Kestin for the valuable advice we have received from him throughout this project.

The research was supported by the Office of Standard Reference Data and by NSF Grant DMR-82-05356 to the University of Maryland. Computer time for this project was provided by the Computer Science Center at the University of Maryland. The research at NEL was supported by the Mechanical and Electrical Engineering Requirements Board of the Department of Industry, and the results are published with the permission of the Director of the National Engineering Laboratory, Department of Industry (UK).

Appendix I

The Eighth International Conference on The Properties of Steam

Giens, France, September 1974

Release on Thermal Conductivity of Water Substance

December 1977

Unrestricted publication allowed in all countries.

Issued by the International Association for the Properties of Steam.

President, H. W. Bradly
Bradly Associates
3, Belleville Drive
Oadby, Leicester LE2 4HA, United Kingdom

Executive Secretary, Dr. Howard J. White, Jr.
Office of Standard Reference Data
National Bureau of Standards
Gaithersburg, MD 20899 USA

Amended in accordance with a resolution adopted by the Executive Committee of IAPS at its 1982 meeting in Ottawa, Canada.

After the Eighth International Conference on the Properties of Steam (ICPS) held in Giens, France, in September 1974, the Secretariat issued an *Announcement*. This stated that the International Association for the Properties of Steam (IAPS) has been instructed to prepare new representations of the viscosity and thermal conductivity of steam to replace those announced as a result of the Sixth ICPS in a *Supplementary Release* dated November 1964. The representations contained in that *Supplementary Release* are now considered obsolete.

The Eighth ICPS designated a *Special Committee*, consisting of representatives of France, the Federal Republic of Germany, Japan, the USA, and the USSR, with Professor J. Kestin of the USA, the then IAPS President, as its convenor, for the purpose of finalizing the new representations.

The Special Committee met in Schliersee (April 1975), Ottawa (Sept. 1975), Kyoto (Sept. 1976), Providence (May 1977) and Moscow (Sept. 1977) to complete its work with respect to the representation of the thermal conductivity of water substance.

The International Representation of the Dynamic Viscosity of Water Substance was issued by the Secretariat in April 1975.

In accordance with a resolution of the Eighth Conference, the material included in the present Release was circulated to and approved by the Heads of all National Delegations attending the Eighth Conference (Canada, Czechoslovakia, Federal Republic of Germany, France, Hong Kong, Hungary, Japan, Netherlands, Poland, Switzerland, United Kingdom, United States of America, and the Union of Soviet Socialist Republics).

This Release is issued by the Secretariat under the full authority of the Eighth Conference, and presents in the accompanying Appendices the *International Representation of the Thermal Conductivity of Water Substance, 1977.*

For further information, write to

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Attachments: Appendices IA, IB, IC, ID, IE, and IF.

Contents of this Release

The Special Committee considers that the existing data in the literature which have been collected in the document "Available Input of the Thermal Conductivity of Water Substance," by K. Scheffler, N. Rosner, and M. Reimann, Institute A fuer Thermodynamik, Technische Universitaet Muenchen, January 1974, last revision December 1977, are not sufficiently accurate and precise to allow definition of a two-dimensional representation that satisfies all of the criteria for smoothness and physical plausibility that can logically be required of it. The Special Committee draws attention to this fact and hopes that additional measurements of superior quality will become available in the future, especially in the high-pressure and temperature region of steam where the lack of data is obvious.

Each formulation considered by this Committee represents all the available data for the thermal conductivity of water substance and the Tables of Critically Evaluated Experimental Data within the latter's tolerances.

At the present time, the Special Committee issues a Representation consisting of five appendices as follows:

Appendix IA

Tabe I.1. Critically evaluated experimental data reduced to a uniform grid.

Upper value: thermal conductivity of water or steam, λ in mW/K m.

Lower value: uncertainty in the thermal conductivity, $\pm\Delta\lambda$ in mW/K m.

Pressure P in MPa; temperature T in °C.

Extrapolated values distinguished by parentheses.

The isotherms and isobars represented by this table are not smooth but reflect the trends existing in the experimental data used in its construction.

Table I.2. Critically evaluated experimental data reduced to the vapor-pressure line.

Temperature T in °C.

Pressure P in MPa.

Thermal conductivity of saturated liquid, λ' in mW/K m.

Thermal conductivity of saturated vapor, λ'' in mW/K m.

$\pm\Delta\lambda'$, $\pm\Delta\lambda''$ uncertainty in the above values in mW/K m.

Table I.1. Critically evaluated experimental data reduced to a uniform grid

T P	0.	25.	50.	75.	100.	150.	200.	250.	300.	350.	375.	400.
0.1	563	610	643	664	25.0	28.9	33.3	38.1	43.3	49.0	52.0	54.9
	11	9	9	10	0.5	0.6	0.7	0.8	0.9	1.0	1.0	1.1
0.5	563	610	643	664	680	688	34.1	38.7	43.7	49.1	52.6	55.5
	11	9	9	10	10	10	1.0	1.2	1.3	1.5	1.6	1.7
1.0	564	611	643	666	681	689	35.9	39.5	44.3	49.5	53.0	56.0
	11	9	9	10	10	10	1.4	1.2	1.3	1.5	1.6	1.7
2.5	566	611	644	666	682	690	668	43.8	46.5	50.9	54.7	56.9
	11	9	9	10	10	10	10	1.4	1.4	1.5	1.6	1.7
5.0	567	613	645	668	683	691	671	625	52.7	54.1	56.5	58.6
	11	12	12	13	13	13	13	12	1.6	1.9	1.7	1.8
7.5	570	614	647	669	685	694	673	628	63.6	59.6	60.5	62.7
	11	12	12	13	13	13	13	12	1.9	1.8	1.8	1.9
10.0	571	615	648	669	686	695	675	631	557	68.2	65.3	66.9
	11	12	13	13	13	13	13	12	11	2.0	2.1	2.0
12.5	571	616	649	672	687	697	678	634	562	81.2	73.6	72.4
	11	12	13	13	13	13	13	12	11	2.4	2.2	2.2
15.0	573	617	650	673	689	700	680	638	566	107.5	84.8	79.9
	11	12	13	13	13	14	13	12	11	6.7	2.5	2.4
17.5	573	618	651	674	691	701	682	639	571	452	104.2	90.0
	11	12	13	13	13	14	13	12	11	13	3.1	2.7
20.0	574	619	653	676	691	703	684	641	576	465	144.0	104.9
	11	12	13	13	13	14	13	12	11	14	4.7	3.1
22.5	574	620	654	678	692	705	686	646	581	476	478	124.1
	11	12	13	13	13	14	13	12	11	14	39	4.6
25.0	577	621	655	679	694	707	689	648	588	482	400	166.4
	11	12	13	13	13	14	13	13	11	14	14	6.7
27.5	578	622	656	680	696	708	690	651	589	490	413	240.8
	11	12	13	13	13	14	13	13	11	14	14	8.4
30.0	578	623	658	681	697	710	692	653	593	498	426	337
	11	12	13	13	13	14	13	13	11	15	13	12
35.0	580	625	660	684	700	714	696	660	601	511	453	384
	11	12	13	13	14	14	13	13	12	15	13	12
40.0	583	626	662	686	702	717	700	664	608	526	471	399
	11	12	13	13	14	14	14	13	12	15	14	16
45.0	584	629	664	690	705	721	704	670	615	537	486	425
	11	12	13	13	14	14	14	13	12	16	14	12
50.0	586	630	666	692	708	724	708	673	621	547	498	444
	11	12	13	13	14	14	14	13	12	44	40	36
55.0	589	633	667	694	710	726	712	678	629	558	510	461
	11	12	13	13	14	14	14	13	12	45	41	37
60.0	590	635	670	697	713	729	715	682	634	566	525	476
	11	12	13	13	14	14	14	13	12	45	42	38
65.0	592	638	673	699	715	733	718	688	639	574	535	489
	11	12	13	14	14	14	14	13	12	46	43	39
70.0	597	639	674	702	718	735	721	691	645	582	546	499
	11	12	13	14	14	14	14	13	12	47	44	40
75.0	599	641	675	705	720	738	725	696	648	589	554	511
	12	12	13	14	14	14	14	13	13	47	44	41
80.0	599	645	677	707	723	739	729	699	653	598	564	521
	12	12	13	14	14	14	14	14	13	48	45	42
85.0	601	646	680	706	726	742	732	702	659	604	571	532
	12	12	13	14	14	14	14	14	13	48	46	43
90.0	604	648	681	710	728	745	735	707	665	611	578	544
	12	13	13	14	14	14	14	14	13	49	46	44
95.0	608	650	685	713	731	748	739	711	669	615	586	553
	12	13	13	14	14	15	14	14	13	49	47	44
100.0	609	650	686	716	735	749	742	715	672	624	594	561
	12	13	13	14	14	15	14	14	13	50	47	45

Table I.1. Critically evaluated experimental data reduced to a uniform grid--Continued

P \ T	425.	450.	475.	500.	550.	600.	650.	700.	750.	800.
0.1	57.9	60.6	63.8	67.1	73.1	79.9	86.4	93.4	100.5	107.5
	1.2	1.2	1.3	1.3	1.5	2.4	2.6	2.8	3.0	3.2
0.5	58.5	61.4	64.5	67.7	74.0	80.5	87.2	93.8	100.9	108.0
	1.8	1.8	1.9	2.0	2.2	3.2	3.5	3.8	4.0	4.3
1.0	58.6	61.7	64.7	68.0	74.3	81.0	87.7	94.3	101.4	108.6
	1.8	1.9	1.9	2.0	2.2	3.2	3.5	3.8	4.1	4.3
2.5	59.6	62.6	65.6	68.7	75.1	81.5	88.8	95.3	102.4	109.5
	1.8	1.9	2.0	2.1	2.3	3.3	3.6	3.8	4.1	4.4
5.0	60.9	64.0	66.4	69.3	75.4	81.5	91.4	95.7	103.6	109.6
	1.8	1.9	2.0	2.1	2.3	3.3	3.7	3.8	4.1	4.4
7.5	64.0	66.7	69.5	73.3	80.0	87.3	96.4	101.0	108.1	112.4
	1.9	2.0	2.1	2.2	2.4	3.5	5.3	4.0	4.3	4.5
10.0	67.4	69.4	72.1	75.6	82.5	89.4	97.5	102.9	111.2	118.1
	2.0	2.1	2.2	2.3	2.5	3.6	4.6	4.1	5.1	5.2
12.5	72.0	74.1	76.1	79.4	85.0	90.7	97.9	102.9	109.9	116.3
	2.2	2.2	2.3	2.4	2.6	3.6	3.9	4.1	4.4	4.7
15.0	77.8	78.4	79.3	82.4	87.5	93.4	100.3	105.6	112.7	118.0
	2.3	2.4	2.4	2.5	2.6	3.7	4.0	4.2	4.5	4.7
17.5	84.8	84.0	84.2	85.7	90.2	96.2	102.5	106.0	114.4	119.7
	2.5	2.5	2.5	2.6	2.7	3.8	4.1	4.2	4.6	4.8
20.0	93.7	90.8	90.1	91.6	94.9	98.6	105.5	109.3	116.8	122.7
	2.8	2.7	2.7	2.7	3.0	3.9	4.2	4.4	4.7	4.9
22.5	105.9	98.6	95.9	96.0	98.1	102.6	107.6	112.1	119.2	123.7
	3.2	3.0	2.9	2.9	2.9	4.1	4.3	4.5	4.8	4.9
25.0	120.6	108.3	102.8	101.5	102.3	105.7	110.7	114.5	121.5	126.2
	3.6	3.2	3.1	3.0	3.1	4.2	4.4	4.6	4.9	5.0
27.5	139.2	120.3	111.1	107.3	106.1	108.7	113.0	118.0	123.4	127.8
	6.3	3.6	3.3	3.2	3.2	4.3	4.5	4.7	4.9	5.1
30.0	175.0	133.8	119.4	114.1	110.6	112.3	116.2	119.9	125.7	130.2
	8.1	4.0	3.6	3.4	3.3	4.5	4.6	4.8	5.0	5.2
35.0	260.5	176.3	144.3	129.7	121.1	119.8	122.7	125.1	130.0	134.6
	7.8	5.5	4.3	3.9	3.6	4.8	4.9	5.0	5.2	5.4
40.0	331	233.2	178.9	152.9	133.9	129.2	129.5	131.8	135.8	139.3
	11	7.2	5.5	4.6	4.0	5.2	5.2	5.3	5.4	5.6
45.0	365	287	219.0	180.1	148.2	138.5	136.4	137.7	141.1	144.5
	11	12	7.9	5.4	4.4	5.5	5.5	5.5	5.6	5.8
50.0	381	325	263	211	164	150	145	145	146	149
	30	26	21	17	13	12	12	12	12	12
55.0	401	354	297	244	184	162	154	152	153	155
	32	28	24	20	15	13	12	12	12	12
60.0	423	366	322	277	207	176	164	159	159	161
	34	29	26	22	16	14	13	13	13	13
65.0	438	387	332	299	228	191	175	168	166	167
	35	31	26	24	18	15	14	13	13	13
70.0	453	406	355	322	253	205	186	178	173	173
	36	32	28	26	21	16	15	14	14	14
75.0	467	421	376	327	269	218	198	186	180	178
	37	34	30	26	22	17	16	15	14	15
80.0	480	435	393	346	298	235	209	(196)	(190)	(185)
	38	35	31	28	34	19	17	16	15	15
85.0	488	448	410	366	312	246	222	(206)	(196)	(194)
	39	36	33	29	33	20	18	17	16	15
90.0	500	460	424	385	308	259	233	(215)	(205)	(201)
	40	37	34	31	25	21	19	17	16	16
95.0	510	473	434	396	322	273	243	(226)	(214)	(207)
	41	38	35	32	26	22	19	18	17	17
100.0	519	484	445	412	338	288	255	(236)	(221)	(215)
	42	39	36	33	27	23	20	19	18	17

Table I.2. Critically evaluated experimental data reduced to the vapor-pressure line

T	P	λ'	±Δλ'	λ"	±Δλ"
0.00	0.0006113	569	11	16.7	0.5
0.01	0.0006117	565	11	16.7	0.5
10	0.001228	584	12	17.4	0.5
20	0.002339	602	12	18.1	0.5
30	0.004246	617	12	19.0	0.6
40	0.007381	631	13	19.7	0.6
50	0.01234	642	13	20.4	0.6
60	0.01993	652	13	21.2	0.6
70	0.03118	660	13	22.2	0.7
80	0.04737	669	13	23.1	0.7
90	0.07012	675	14	24.0	0.7
100	0.1013	679	14	25.0	0.8
110	0.1432	681	14	25.7	0.8
120	0.1985	685	14	26.8	0.8
130	0.2700	686	14	28.7	0.9
140	0.3612	686	14	29.7	0.9
150	0.4757	686	14	31.0	0.9
160	0.6177	682	14	31.9	1.3
170	0.7915	678	14	33.6	1.3
180	1.002	674	13	35.2	1.3
190	1.254	670	13	37.2	1.2
200	1.554	664	13	38.8	1.4
210	1.906	654	13	40.5	1.7
220	2.318	643	13	43.2	1.3
230	2.795	632	13	45.3	1.4
240	3.345	626	12	47.9	1.4
250	3.974	615	12	51.0	1.5
260	4.689	602	12	54.2	1.6
270	5.500	590	12	57.7	1.7
280	6.413	577	11	61.3	1.8
290	7.438	564	11	67.3	2.8
300	8.584	547	11	73.2	3.8
310	9.861	532	11	79.8	4.3
320	11.28	512	10	88.3	4.8
330	12.85	485	10	99.1	5.9
340	14.59	455	14	116.7	7.9
350	16.52	447	14	138	11
360	18.66	425	23	174	15
370	21.03	418	36	293	55
371	21.28	429	38	331	62
372	21.54	450	42	377	83
373	21.80	520	50	464	141
374		793	--	791	--
374.15		914	--	914	--

Appendix IB
Recommended Interpolating Equation for Industrial Use

The values appearing in Tables I.1 and I.2 may be reproduced within the stated tolerances by the use of the following empirical interpolating equation which is recommended for industrial use. This equation is not based on the scaling laws and yields a finite value at the critical point instead of the theoretically justified infinity.

Here

λ denotes the thermal conductivity,

ρ denotes density,

T denotes absolute temperature on the 1968 Practical Temperature Scale,

T^* and ρ^* denote numerical constants which are close to, but do not represent the corresponding critical constants,

a_i, b_i, B_i, C_i, and d_i denote numerical constants listed later,

Q, R, and S are specified functions of T/T^* defined later.

$$\lambda = \lambda_0 + \bar{\lambda} + \Delta\lambda, \tag{I.1}$$

where

$$\lambda_0 = \left(\frac{T}{T^*}\right)^{1/2} \sum_{i=0}^{3} a_i \left(\frac{T}{T^*}\right)^i, \tag{I.2}$$

$$\bar{\lambda} = b_0 + b_1\left(\frac{\rho}{\rho^*}\right) + b_2 \exp\left[B_1\left(\frac{\rho}{\rho^*} + B_2\right)^2\right]. \tag{I.3}$$

$$\begin{aligned}\Delta\lambda = {} & \left[d_1\left(\frac{T^*}{T}\right)^{10} + d_2\right]\left(\frac{\rho}{\rho^*}\right)^{1.8} \\ & \times \exp\left\{C_1\left[1 - \left(\frac{\rho}{\rho^*}\right)^{2.8}\right]\right\} \\ & + d_3 S\left(\frac{\rho}{\rho^*}\right)^Q \exp\left\{\frac{Q}{R}\left[1 - \left(\frac{\rho}{\rho^*}\right)^R\right]\right\} \\ & + d_4 \exp\left[C_2\left(\frac{T}{T^*}\right)^{1.5} + C_3\left(\frac{\rho^*}{\rho}\right)^5\right],\end{aligned} \tag{I.4}$$

and

$$Q = 2.0 + C_5(\Delta T^*)^{-0.6}, \tag{I.5}$$

$$R = Q + 1.0, \tag{I.6}$$

$$S = \begin{cases} (\Delta T^*)^{-1.0} \text{ for } T/T^* \geqslant 1, & \text{(I.7)} \\ C_6(\Delta T^*)^{-0.6} \text{ for } T/T^* < 1, & \text{(I.8)} \end{cases}$$

with

$$\Delta T^* = \left|\frac{T}{T^*} - 1.0\right| + C_4. \tag{I.9}$$

Numerical values of the constants

$T^* = 647.3$ K
$\rho^* = 317.7$ kg/m^3
$a_0 = 1.028\ 11 \times 10^{-2}$ W/K m
$a_1 = 2.996\ 21 \times 10^{-2}$ W/K m
$a_2 = 1.561\ 46 \times 10^{-2}$ W/K m
$a_3 = -4.224\ 64 \times 10^{-3}$ W/K m
$b_0 = -3.970\ 70 \times 10^{-1}$ W/K m
$b_1 = 4.003\ 02 \times 10^{-1}$ W/K m
$b_2 = 1.060\ 00$ W/K m
$B_1 = -1.715\ 87 \times 10^{-1}$
$B_2 = 2.392\ 19$
$d_1 = 7.013\ 09 \times 10^{-2}$ W/K m
$d_2 = 1.185\ 20 \times 10^{-2}$ W/K m
$d_3 = 1.699\ 37 \times 10^{-3}$ W/K m
$d_4 = -1.020\ 00$ W/K m
$C_1 = 6.428\ 57 \times 10^{-1}$
$C_2 = -4.117\ 17$
$C_3 = -6.179\ 37$
$C_4 = 3.089\ 76 \times 10^{-3}$
$C_5 = 8.229\ 94 \times 10^{-2}$
$C_6 = 1.009\ 32 \times 10^{1}$

For preference, and to reproduce the values given in Appendix ID, the density should be computed with the aid of the 1967 IFC Formulation for Industrial Use. If another density formulation is used, a relative departure of $\Delta\rho/\rho$

induces at most a relative departure $\pm\Delta\lambda/\lambda = 2\Delta\rho/\rho$ outside the near-critical region.

Users should be aware of the fact that the above equation is subject to exponential underflows which most computers set to zero; this causes no errors in the final result.

The equation adopted in this Appendix is not the only possible, relatively simple empirical interpolation formula. An alternative form has been proposed by J. T. R. Watson of the National Engineering Laboratory at East Kilbride, Great Britain in Engineering Sciences Data Item No. 78039 (Engineering Sciences Data Unit, London, 1978), Appendix A.4.

Appendix IC
Recommended Interpolating Equation for Scientific Use

The values appearing in Tables I.1 and I.2 may also be reproduced within the stated tolerances by the following alternative equation which incorporates in it the present-day understanding of the nature of the critical anomaly in thermal conductivity. In particular, the thermal conductivity becomes infinite at the critical point.

Here

λ denotes the thermal conductivity (W/K m),

ρ denotes the density,

T denotes absolute temperature on the 1968 Practical Temperature Scale,

P denotes pressure,

μ denotes the dynamic viscosity as defined in the IAPS Release on the International Representation of Dynamic Viscosity of Water Substance, 1975, as amended in 1982 (Pa·s),

$$\chi_T = \left(\frac{\rho}{\rho^*}\right)\left(\frac{\partial(\rho/\rho^*)}{\partial(P/P^*)}\right)_T$$

is the reduced isothermal compressibility, T^*, P^*, and ρ^* denote numerical constants which are close to, but do not represent the corresponding critical constants, $C, \omega, A, B, a_k, b_{ij}$ are numerical constants listed below.

$$\lambda = \lambda_0 \exp\left\{\frac{\rho}{\rho^*}\sum_{i=0}^{4}\sum_{j=0}^{5} b_{ij} \times\left(\frac{T^*}{T}-1\right)^i\left(\frac{\rho}{\rho^*}-1\right)^j\right\} + \Delta\lambda, \qquad \text{(I.10)}$$

TABLE a. The coefficients a_k

$a_0 = +2.022\,23$ K m/W
$a_1 = +14.111\,66$ K m/W
$a_2 = +5.255\,97$ K m/W
$a_3 = -2.018\,70$ K m/W

where

$$\lambda_0 = \left(\frac{T}{T^*}\right)^{1/2}\left[\sum_{k=0}^{3} a_k\left(\frac{T^*}{T}\right)^k\right]^{-1}, \qquad \text{(I.11)}$$

$$\Delta\lambda = \frac{C}{\mu}\left(\frac{T\rho^*}{T^*\rho}\right)^2\left(\frac{\partial(P/P^*)}{\partial(T/T^*)}\right)_\rho^2 \times\chi_T^{\omega}\left(\frac{\rho}{\rho^*}\right)^{1/2} \times\exp\left\{-A\left(\frac{T}{T^*}-1\right)^2 - B\left(\frac{\rho}{\rho^*}-1\right)^4\right\}. \qquad \text{(I.12)}$$

Numerical values of the constants

$T^* = 647.27$ K

$\rho^* = 317.763$ kg/m^3

$P^* = 22.115$ MPa

$C = 3.7711\times10^{-8}$ W Pa s/K m

$\omega = 0.4678$

$A = 18.66$

$B = 1.00$

To reproduce the values given in Appendix IE, the density, the isothermal compressibility, as well as the partial derivative $(\partial P/\partial T)_\rho$ should be calculated with the aid of the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use; otherwise, a consistent formulation must be adhered to. However, the Recommended Interpolating Equation for Scientific Use should not be employed in conjunction with the 1967 IFC Formulation for Industrial Use. If another density formulation is used, a relative departure $\pm\Delta\rho/\rho$ induces at most a relative departure $\pm\Delta\lambda/\lambda = 2\Delta\rho/\rho$, except for the near-critical region.

TABLE b. The coefficients b_{ij}

$j \setminus i$	0	1	2	3	4
0	+ 1.329 304 6	+ 1.701 836 3	+ 5.224 615 8	+ 8.712 767 5	− 1.852 599 9
1	− 0.404 524 37	− 2.215 684 5	− 10.124 111	− 9.500 061 1	+ 0.934 046 90
2	+ 0.244 094 90	+ 1.651 105 7	+ 4.987 468 7	+ 4.378 660 6	0.0
3	+ 0.018 660 751	− 0.767 360 02	− 0.272 976 94	− 0.917 837 82	0.0
4	− 0.129 610 68	+ 0.372 833 44	− 0.430 833 93	0.0	0.0
5	+ 0.044 809 953	− 0.112 031 60	+ 0.133 338 49	0.0	0.0

Table I.3. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Industrial Use, calculated over a uniform grid

	TEMPERATURE, °C										
PRESSURE, MPa	0	25	50	75	100	150	200	250	300	350	375
.1	562.0	607.6	640.5	663.3	24.8	28.8	33.4	38.3	43.5	49.0	51.8
.5	562.2	607.8	640.7	663.5	677.7	683.6	34.2	38.8	43.9	49.3	52.1
1.0	562.5	608.1	641.0	663.8	678.0	683.9	36.1	39.7	44.5	49.8	52.6
2.5	563.4	608.9	641.8	664.6	678.8	685.0	664.2	43.9	46.8	51.5	54.1
5.0	564.8	610.2	643.0	665.9	680.2	686.7	666.5	619.5	53.0	55.2	57.1
7.5	566.3	611.5	644.3	667.3	681.7	688.4	668.7	622.7	64.1	60.6	61.1
10.0	567.7	612.8	645.6	668.6	683.1	690.0	670.8	625.8	548.2	68.6	66.4
12.5	569.2	614.1	646.9	669.9	684.4	691.7	672.9	628.9	553.7	81.1	73.7
15.0	570.6	615.4	648.2	671.2	685.8	693.3	675.0	631.9	558.9	104.2	84.5
17.5	572.1	616.7	649.4	672.5	687.2	694.9	677.1	634.8	563.9	441.6	103.2
20.0	573.5	618.0	650.7	673.8	688.5	696.5	679.2	637.7	568.6	453.8	145.5
22.5	574.9	619.3	651.9	675.0	689.9	698.1	681.2	640.5	573.2	464.3	498.6
25.0	576.4	620.5	653.2	676.3	691.2	699.7	683.1	643.2	577.5	473.7	386.3
27.5	577.8	621.8	654.4	677.6	692.6	701.3	685.1	645.9	581.8	482.3	405.5
30.0	579.2	623.1	655.6	678.8	693.9	702.8	687.0	648.5	585.8	490.1	420.6
35.0	582.0	625.6	658.0	681.3	696.5	705.9	690.8	653.6	593.6	504.3	443.9
40.0	584.8	628.1	660.5	683.8	699.1	708.9	694.5	658.5	600.9	516.8	462.4
45.0	587.6	630.6	662.8	686.2	701.6	711.8	698.1	663.3	607.8	528.1	478.0
50.0	590.4	633.0	665.2	688.6	704.1	714.7	701.7	667.9	614.3	538.4	491.7
55.0	593.1	635.4	667.6	691.0	706.6	717.6	705.1	672.4	620.5	547.9	503.9
60.0	595.8	637.9	669.9	693.3	709.1	720.4	708.5	676.7	626.5	556.8	515.1
65.0	598.5	640.3	672.2	695.7	711.5	723.1	711.9	680.9	632.2	565.1	525.3
70.0	601.1	642.6	674.5	698.0	713.9	725.9	715.1	685.0	637.7	572.9	534.8
75.0	603.8	645.0	676.7	700.3	716.3	728.6	718.3	689.0	642.9	580.3	543.6
80.0	606.3	647.4	679.0	702.5	718.6	731.2	721.5	692.9	648.0	587.3	551.9
85.0	608.9	649.7	681.2	704.8	721.0	733.9	724.6	696.7	653.0	593.9	559.8
90.0	611.4	652.0	683.4	707.0	723.3	736.5	727.6	700.4	657.7	600.3	567.2
95.0	613.9	654.3	685.6	709.2	725.6	739.0	730.6	704.1	662.4	606.4	574.2
100.0	616.3	656.6	687.8	711.4	727.8	741.6	733.6	707.6	666.9	612.3	581.0

	TEMPERATURE, °C										
PRESSURE, MPa	400	425	450	475	500	550	600	650	700	750	800
.1	54.7	57.7	60.7	63.8	66.9	73.3	79.9	86.7	93.6	100.6	107.7
.5	55.0	58.0	61.0	64.0	67.2	73.5	80.1	86.9	93.8	100.8	107.9
1.0	55.4	58.4	61.3	64.4	67.5	73.9	80.4	87.2	94.0	101.0	108.1
2.5	56.8	59.6	62.5	65.5	68.6	74.9	81.4	88.0	94.9	101.8	108.9
5.0	59.5	62.1	64.8	67.6	70.6	76.7	83.0	89.6	96.3	103.2	110.2
7.5	62.9	65.1	67.5	70.1	72.8	78.7	84.8	91.2	97.8	104.6	111.5
10.0	67.3	68.6	70.6	72.8	75.3	80.8	86.8	93.0	99.5	106.1	112.9
12.5	72.8	73.0	74.2	76.0	78.2	83.2	88.9	94.9	101.2	107.7	114.4
15.0	80.0	78.3	78.5	79.7	81.4	85.9	91.1	96.9	103.0	109.4	116.0
17.5	89.6	85.0	83.7	83.9	85.0	88.8	93.6	99.1	105.0	111.2	117.6
20.0	103.4	93.4	89.8	88.8	89.1	91.9	96.2	101.4	107.0	113.1	119.3
22.5	124.3	104.3	97.2	94.5	93.8	95.4	99.1	103.8	109.2	115.0	121.1
25.0	159.7	118.9	106.3	101.1	99.1	99.3	102.2	106.4	111.5	117.0	123.0
27.5	234.5	138.9	117.6	108.9	105.1	103.5	105.5	109.2	113.9	119.2	124.9
30.0	326.0	167.0	131.6	118.1	111.9	108.1	109.0	112.1	116.4	121.4	126.9
35.0	372.6	254.6	170.9	141.7	128.6	118.6	116.9	118.5	121.8	126.2	131.2
40.0	398.8	320.2	226.0	173.5	149.9	131.2	125.9	125.7	127.8	131.3	135.8
45.0	420.4	354.6	278.0	212.7	176.1	146.0	136.2	133.6	134.3	136.9	140.7
50.0	438.8	379.7	315.3	251.9	205.8	163.0	147.6	142.3	141.4	142.9	145.9
55.0	454.8	400.6	342.8	285.2	236.6	181.9	160.3	151.8	149.0	149.3	151.5
60.0	469.0	418.6	365.4	312.4	264.6	202.1	174.0	162.0	157.2	156.2	157.3
65.0	481.8	434.6	384.8	335.3	289.4	222.6	188.7	172.8	165.8	163.3	163.5
70.0	493.5	448.9	401.9	355.1	311.2	242.7	203.9	184.3	174.9	170.9	169.9
75.0	504.2	461.9	417.3	372.8	330.6	261.8	219.4	196.2	184.4	178.7	176.7
80.0	514.2	473.9	431.3	388.7	348.2	279.8	234.8	208.5	194.2	186.9	183.6
85.0	523.5	484.9	444.2	403.2	364.1	296.8	249.9	221.0	204.3	195.2	190.7
90.0	532.3	495.2	456.1	416.6	378.8	312.7	264.4	233.4	214.6	203.8	198.0
95.0	540.6	504.9	467.2	429.0	392.3	327.6	278.5	245.8	225.0	212.5	205.5
100.0	548.4	514.0	477.6	440.6	404.8	341.7	292.1	257.9	235.6	221.3	213.0

Appendix ID

Table I.3. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Industrial Use, calculated over a uniform grid.

Thermal conductivity, λ, in mW/K m.

Pressure P in MPa.

Temperature T in °C.

Smoothed values obtained with the aid of Eqs. (I.1)–(I.9) of Appendix IB together with the constants listed therein, and density values based on the 1967 IFC Formulation for Industrial Use.

(Note: The tabular entries contain more significant digits than is justified by the tolerances listed in Table I.1 to assist in programming.)

Table I.4. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Industrial Use, calculated along the vapor-pressure line.

Thermal conductivity of saturated vapor, λ'', and thermal conductivity of saturated liquid, λ' in mW/K m.

Pressure P in MPa.

Temperature T in °C.

Smoothed values obtained with the aid of Eqs. (I.1)–(I.9) of Appendix IB together with the constants listed therein, and density values based on the 1967 IFC Formulation for Industrial Use.

(Note: The tabular entries contain more significant digits than is justified by the tolerances listed in Table I.2 to assist in programming.)

TABLE I.4. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Industrial Use, calculated along the vapor–pressure line

T	P	λ'	λ''
0.00	0.0006108	561.95	16.49
0.01	0.0006112	561.97	16.49
10.00	0.001227	581.94	17.21
20.00	0.002337	599.61	17.95
30.00	0.004241	615.05	18.70
40.00	0.007375	628.62	19.48
50.00	0.01233	640.47	20.28
60.00	0.01992	650.75	21.10
70.00	0.03116	659.49	21.96
80.00	0.04736	666.75	22.86
90.00	0.07011	672.80	23.80
100.00	0.1013	677.46	24.79
110.00	0.1433	680.91	25.84
120.00	0.1985	683.29	26.96
130.00	0.2701	684.47	28.15
140.00	0.3614	684.50	29.42
150.00	0.4760	683.54	30.77
160.00	0.6181	681.57	32.22
170.00	0.7920	678.46	33.77
180.00	1.003	674.47	35.42
190.00	1.255	669.41	37.20
200.00	1.555	663.37	39.10
210.00	1.908	656.35	41.14
220.00	2.320	648.29	43.35
230.00	2.798	639.31	45.74
240.00	3.348	629.22	48.34
250.00	3.978	618.11	51.18
260.00	4.694	605.93	54.33
270.00	5.506	592.56	57.84
280.00	6.420	578.00	61.82
290.00	7.446	562.22	66.40
300.00	8.593	545.01	71.78
310.00	9.870	526.40	78.26
320.00	11.29	506.27	86.34
330.00	12.86	484.49	96.93
340.00	14.60	461.10	111.79
350.00	16.53	436.27	134.59
360.00	18.67	411.84	176.79
370.00	21.05	416.36	306.42
371.00	21.31	429.03	342.42
372.00	21.56	454.72	396.08
373.00	21.82	517.54	490.23
374.00	22.08	756.50	739.61
374.15	22.12	833.52	830.49

Appendix IE

Table I.5. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Scientific Use, calculated over a uniform grid.

Thermal conductivity λ in mW/K m.

Pressure P in MPa.

Temperature T in °C.

Smoothed values obtained with the aid of Eqs. (I.10)–(I.12) of Appendix IC together with the constants listed therein, and density values as well the values of thermodynamic derivatives based on the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use. Viscosity values from IAPS International Representation of the Dynamic Viscosity of Water Substance, 1975 as amended in 1982.

(Note: The tabular entries contain more significant digits than is justified by the tolerances listed in Table I.1 to assist in programming.)

Table I.6. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Scientific Use, calculated along the vapor–pressure line.

Thermal conductivity of saturated vapor, λ'', and thermal conductivity of saturated liquid, λ' in mW/K m.

Pressure P in MPa.

Temperature T in °C.

Smoothed values obtained with the aid of Eqs. (I.10)–(I.12) of Appendix IC together with the constants listed therein, and density values as well as the values of the thermodynamic derivatives based on the Provisional IAPS Formulation 1982 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use. Viscosity values from IAPS International Representation of the Dynamic Viscosity of Water Substance, 1975, as amended in 1982.

(Note: The tabular entries contain more significant digits than is justified by the tolerances listed in Table I.2 to assist in programming.)

Table I.5. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Scientific Use, calculated over a uniform grid

	TEMPERATURE, °C										
PRESSURE, MPa	0	25	50	75	100	150	200	250	300	350	375
.1	561.0	607.2	643.6	666.8	25.08	28.85	33.28	38.17	43.42	48.96	51.83
.5	561.2	607.4	643.7	667.0	679.3	682.1	34.93	39.18	44.09	49.44	52.25
1.0	561.5	607.6	644.0	667.2	679.6	682.4	37.21	40.51	44.95	50.06	52.79
2.5	562.4	608.3	644.7	668.0	680.4	683.4	664.2	45.16	47.82	52.06	54.52
5.0	563.7	609.4	645.8	669.2	681.8	685.1	666.4	622.7	53.86	55.99	57.87
7.5	565.1	610.5	647.0	670.5	683.2	686.8	668.6	625.9	63.11	61.06	62.00
10.0	566.5	611.7	648.2	671.7	684.5	688.5	670.7	629.0	550.9	68.10	67.35
12.5	567.9	612.8	649.3	673.0	685.9	690.2	672.8	632.0	556.5	79.15	74.68
15.0	569.3	613.9	650.5	674.2	687.2	691.8	674.9	635.0	561.8	100.9	85.54
17.5	570.6	615.1	651.6	675.5	688.6	693.5	677.0	637.9	566.8	452.5	103.7
20.0	572.0	616.2	652.8	676.7	690.0	695.1	679.1	640.8	571.6	463.3	142.3
22.5	573.4	617.3	654.0	678.0	691.3	696.8	681.2	643.6	576.2	472.8	441.5
25.0	574.8	618.5	655.1	679.2	692.7	698.4	683.2	646.3	580.7	481.4	411.4
27.5	576.1	619.6	656.3	680.4	694.0	700.1	685.3	649.1	585.0	489.1	425.8
30.0	577.5	620.8	657.4	681.7	695.3	701.7	687.3	651.8	589.1	496.3	438.0
35.0	580.2	623.0	659.8	684.1	698.0	704.9	691.3	657.0	597.1	509.3	457.5
40.0	582.9	625.3	662.1	686.6	700.7	708.2	695.3	662.2	604.6	521.0	473.2
45.0	585.5	627.5	664.4	689.1	703.3	711.4	699.3	667.2	611.7	531.8	486.6
50.0	588.1	629.8	666.7	691.5	706.0	714.6	703.2	672.1	618.5	541.7	498.5
55.0	590.7	632.0	668.9	693.9	708.6	717.7	707.0	676.9	625.1	551.0	509.4
60.0	593.3	634.2	671.2	696.3	711.2	720.9	710.9	681.6	631.3	559.7	519.4
65.0	595.8	636.4	673.5	698.7	713.8	724.0	714.7	686.3	637.4	568.0	528.8
70.0	598.3	638.6	675.7	701.1	716.4	727.2	718.5	690.8	643.2	575.9	537.7
75.0	600.7	640.8	678.0	703.5	719.0	730.3	722.2	695.3	648.9	583.4	546.1
80.0	603.1	642.9	680.2	705.9	721.5	733.4	726.0	699.8	654.5	590.6	554.1
85.0	605.5	645.1	682.4	708.2	724.1	736.4	729.7	704.2	659.9	597.5	561.7
90.0	607.8	647.2	684.6	710.5	726.6	739.5	733.4	708.6	665.1	604.2	569.1
95.0	610.0	649.3	686.8	712.9	729.1	742.6	737.1	712.9	670.3	610.6	576.2
100.0	612.2	651.3	688.9	715.2	731.6	745.6	740.7	717.2	675.4	616.8	583.0

	TEMPERATURE, °C										
PRESSURE, MPa	400	425	450	475	500	550	600	650	700	750	800
.1	54.76	57.74	60.77	63.85	66.97	73.35	79.89	86.57	93.37	100.3	107.3
.5	55.13	58.08	61.08	64.14	67.25	73.61	80.13	86.80	93.59	100.5	107.5
1.0	55.61	58.51	61.48	64.51	67.60	73.93	80.44	87.09	93.87	100.8	107.8
2.5	57.15	59.89	62.75	65.69	68.71	74.94	81.39	88.01	94.75	101.6	108.5
5.0	60.06	62.49	65.10	67.86	70.74	76.79	83.13	89.67	96.34	103.1	109.9
7.5	63.56	65.54	67.82	70.33	73.03	78.84	85.04	91.49	98.08	104.8	111.5
10.0	67.89	69.19	71.00	73.17	75.61	81.11	87.14	93.47	99.97	106.5	113.2
12.5	73.40	73.63	74.73	76.43	78.54	83.62	89.43	95.63	102.0	108.5	115.0
15.0	80.69	79.13	79.19	80.20	81.85	86.39	91.92	97.96	104.2	110.6	116.9
17.5	90.76	86.10	84.54	84.58	85.61	89.45	94.63	100.5	106.6	112.8	119.0
20.0	105.5	95.12	91.04	89.70	89.89	92.82	97.57	103.2	109.1	115.2	121.2
22.5	128.6	107.1	99.01	95.70	94.75	96.51	100.7	106.0	111.8	117.7	123.5
25.0	169.3	123.2	108.8	102.7	100.3	100.6	104.1	109.1	114.6	120.3	126.0
27.5	249.1	145.5	121.0	111.0	106.6	105.0	107.8	112.4	117.6	123.1	128.6
30.0	330.1	176.3	136.0	120.6	113.7	109.8	111.7	115.8	120.7	126.0	131.3
35.0	384.5	259.4	176.5	144.9	130.7	120.8	120.3	123.3	127.5	132.2	137.0
40.0	414.0	323.3	227.6	175.8	151.6	133.5	130.0	131.5	134.8	138.8	143.1
45.0	435.0	363.4	276.3	211.3	176.0	147.9	140.6	140.3	142.6	145.9	149.6
50.0	451.6	391.5	315.6	247.0	202.7	163.7	152.1	149.8	150.9	153.4	156.4
55.0	465.5	412.8	346.5	279.6	229.7	180.6	164.3	159.8	159.6	161.2	163.4
60.0	477.7	430.0	371.2	308.0	255.6	198.0	177.0	170.1	168.5	169.1	170.6
65.0	488.6	444.5	391.4	332.5	279.6	215.4	189.9	180.6	177.6	177.2	177.9
70.0	498.7	457.1	408.5	353.6	301.5	232.4	202.7	191.0	186.7	185.3	185.2
75.0	508.0	468.3	423.1	371.9	321.3	248.9	215.3	201.4	195.6	193.3	192.4
80.0	516.8	478.5	436.0	388.0	339.1	264.5	227.5	211.5	204.4	201.1	199.6
85.0	525.2	487.9	447.5	402.2	355.2	279.4	239.3	221.2	212.9	208.8	206.5
90.0	533.1	496.6	457.9	414.9	369.8	293.5	250.6	230.6	221.1	216.1	213.1
95.0	540.7	504.9	467.4	426.4	383.0	306.8	261.4	239.5	228.8	223.1	219.5
100.0	548.0	512.7	476.3	436.9	395.1	319.3	271.8	248.0	236.2	229.7	225.5

TABLE I.6. Smoothed values of the thermal conductivity of water substance obtained with the aid of the Recommended Interpolating Equation for Scientific Use, calculated along the vapor–pressure line

T	P	λ'	λ''
0.00	0.0006113	560.97	17.07
0.01	0.0006117	560.99	17.07
10.00	0.001228	580.00	17.62
20.00	0.002339	598.41	18.23
30.00	0.004246	615.43	18.89
40.00	0.007381	630.54	19.60
50.00	0.01234	643.52	20.36
60.00	0.01993	654.32	21.19
70.00	0.03118	663.08	22.07
80.00	0.04737	669.99	23.01
90.00	0.07012	675.27	24.02
100.00	0.1013	679.12	25.09
110.00	0.1432	681.72	26.24
120.00	0.1985	683.22	27.46
130.00	0.2700	683.73	28.76
140.00	0.3612	683.34	30.14
150.00	0.4757	682.08	31.59
160.00	0.6177	680.00	33.12
170.00	0.7915	677.10	34.74
180.00	1.002	673.38	36.44
190.00	1.254	668.82	38.23
200.00	1.554	663.39	40.10
210.00	1.906	657.06	42.07
220.00	2.318	649.77	44.15
230.00	2.795	641.44	46.35
240.00	3.345	632.01	48.70
250.00	3.974	621.37	51.22
260.00	4.689	609.44	53.98
270.00	5.500	596.14	57.04
280.00	6.413	581.39	60.51
290.00	7.438	565.21	64.57
300.00	8.584	547.67	69.47
310.00	9.861	528.97	75.59
320.00	11.28	509.38	83.57
330.00	12.85	489.21	94.47
340.00	14.59	468.65	110.23
350.00	16.52	447.76	134.80
360.00	18.66	427.47	178.49
370.00	21.03	428.78	301.23
371.00	21.28	439.31	337.21
372.00	21.54	462.76	397.42
373.00	21.80	545.42	538.28

Appendix IF
Special Committee Membership

Dr. A. A. Aleksandrov	(USSR)
Dr. P. Bury	(France)
Mr. R. C. Hendricks	(USA)
Professor J. Kestin (Chairman)	(USA)
Professor T. Minamiyama	(Japan)
Professor A. Nagashima	(Japan)
Dr. M. Reimann	(FRG)
Mr. K. Scheffler	(FRG)
Dr. J. Straub	(FRG)
Professor A. A. Tarzimanov	(USSR)
Professor B. Vodar	(France)
Professor J. V. Sengers	(USA)
Mr. J. T. R. Watson	(UK)
Mr. J. Yata	(Japan)

Appendix II
Alternative Thermal Conductivity Equation for Scientific Use

The term $\lambda_2(\overline{T},\overline{\rho})$ in Eq. (3.4) is related to the viscosity μ as indicated by Eqs. (3.8) and (3.12). In calculating $\lambda_2(\overline{T},\overline{\rho})$, the viscosity is represented by the international equation for the viscosity

$$\mu = \mu_0(\overline{T}) \times \mu_1(\overline{T},\overline{\rho}), \tag{II.1}$$

with the functions $\mu_0(\overline{T})$ and $\mu_1(\overline{T},\overline{\rho})$ as defined by Eqs. (3.9) and (3.10). However, Watson and co-workers proposed an improved interpolating equation for the viscosity in which the function $\mu_0(\overline{T})$ is still identical to the one defined by Eq. (3.9), but in which the function $\mu_1(\overline{T},\overline{\rho})$ is replaced by[S2,W2]

$$\mu_1(\overline{T},\overline{\rho}) = \exp\left[\overline{\rho} \sum_{i=0}^{5} \sum_{j=0}^{6} a_{ij} \times \left(\frac{1}{\overline{T}} - 1\right)^i (\overline{\rho} - 1)^j\right], \tag{II.2}$$

with coefficients a_{ij} given in Table II.1. The alternative function $\mu_1(\overline{T},\overline{\rho})$ as defined by Eq. (II.2) has the same mathematical form as the international function $\mu_1(\overline{T},\overline{\rho})$ as defined by Eq. (3.10), but Eq. (II.2) proposed by Watson *et al.* has only 19 nonzero coefficients a_{ij} as opposed to the 30 nonzero coefficients b_{ij}^{μ} in Eq. (3.10). The viscosity Eq. (II.1) with $\mu_0(\overline{T})$ defined by Eq. (3.9) and $\mu_1(\overline{T},\overline{\rho})$ defined by Eq. (II.2) is valid in the range[W2]:

$$\begin{aligned} &P \leqslant 500\ \text{MPa for}\quad 0\,^\circ\text{C} \leqslant T \leqslant 150\,^\circ\text{C},\\ &P \leqslant 350\ \text{MPa for } 150\,^\circ\text{C} \leqslant T \leqslant 600\,^\circ\text{C},\\ &P \leqslant 300\ \text{MPa for } 600\,^\circ\text{C} \leqslant T \leqslant 900\,^\circ\text{C}. \end{aligned} \tag{II.3}$$

An alternative thermal conductivity equation for scientific use is obtained if the term $\lambda_2(\overline{T},\overline{\rho})$ in Eq. (3.4) is calculated from Eq. (3.12), but with the function $\mu_1(\overline{T},\overline{\rho})$ as defined

TABLE II.1. Coefficients a_{ij} for $\mu_1(\overline{T},\overline{\rho})$ as defined by Eq. (II.2)

i	j	a_{ij}
0	0	$a_{00} =$ 0.513 204 7
1	0	$a_{10} =$ 0.320 565 6
4	0	$a_{40} =$ − 0.778 256 7
5	0	$a_{50} =$ 0.188 544 7
0	1	$a_{01} =$ 0.215 177 8
1	1	$a_{11} =$ 0.731 788 3
2	1	$a_{21} =$ 1.241 044
3	1	$a_{31} =$ 1.476 783
0	2	$a_{02} =$ − 0.281 810 7
1	2	$a_{12} =$ − 1.070 786
2	2	$a_{22} =$ − 1.263 184
0	3	$a_{03} =$ 0.177 806 4
1	3	$a_{13} =$ 0.460 504 0
2	3	$a_{23} =$ 0.234 037 9
3	3	$a_{33} =$ − 0.492 417 9
0	4	$a_{04} =$ − 0.041 766 10
3	4	$a_{34} =$ 0.160 043 5
1	5	$a_{15} =$ − 0.015 783 86
3	6	$a_{36} =$ − 0.003 629 481

Note: Coefficients a_{ij} omitted from the table are all equal to zero identically.

Table II.2. Smoothed values of the thermal conductivity of water substance calculated from the alternative interpolating equation for scientific use with densities from the IAPS 82 formulation (λ in 10^{-3}W m^{-1}K^{-1})

PRESSURE, MPa	TEMPERATURE, °C 0	25	50	75	100	150	200	250	300	350	375
.1	561.0	607.2	643.6	666.8	25.08	28.85	33.28	38.17	43.42	48.96	51.83
.5	561.2	607.4	643.7	667.0	679.3	682.1	34.93	39.18	44.09	49.44	52.25
1.0	561.5	607.6	644.0	667.2	679.6	682.4	37.21	40.51	44.95	50.06	52.79
2.5	562.4	608.3	644.7	668.0	680.4	683.4	664.2	45.16	47.82	52.06	54.52
5.0	563.7	609.4	645.8	669.2	681.8	685.1	666.4	622.7	53.86	55.99	57.87
7.5	565.1	610.5	647.0	670.5	683.2	686.8	668.6	625.9	63.12	61.06	62.00
10.0	566.5	611.7	648.2	671.7	684.5	688.5	670.7	629.0	550.9	68.11	67.35
12.5	567.9	612.8	649.3	673.0	685.9	690.2	672.8	632.0	556.5	79.15	74.68
15.0	569.3	613.9	650.5	674.2	687.2	691.8	674.9	635.0	561.8	100.9	85.53
17.5	570.6	615.1	651.6	675.5	688.6	693.5	677.0	637.9	566.8	452.3	103.7
20.0	572.0	616.2	652.8	676.7	690.0	695.1	679.1	640.8	571.6	463.3	142.1
22.5	573.4	617.3	654.0	678.0	691.3	696.8	681.2	643.6	576.2	472.8	440.3
25.0	574.8	618.5	655.1	679.2	692.7	698.4	683.2	646.3	580.7	481.3	411.2
27.5	576.1	619.6	656.3	680.4	694.0	700.1	685.3	649.1	585.0	489.1	425.7
30.0	577.5	620.8	657.4	681.7	695.3	701.7	687.3	651.8	589.1	496.3	437.9
35.0	580.2	623.0	659.8	684.1	698.0	704.9	691.3	657.0	597.1	509.3	457.4
40.0	582.9	625.3	662.1	686.6	700.7	708.2	695.3	662.2	604.6	521.0	473.1
45.0	585.5	627.5	664.4	689.1	703.3	711.4	699.3	667.2	611.7	531.7	486.5
50.0	588.1	629.8	666.7	691.5	706.0	714.6	703.2	672.1	618.5	541.7	498.4
55.0	590.7	632.0	668.9	693.9	708.6	717.7	707.0	676.9	625.1	551.0	509.3
60.0	593.3	634.2	671.2	696.3	711.2	720.9	710.9	681.6	631.3	559.7	519.4
65.0	595.8	636.4	673.5	698.7	713.8	724.0	714.7	686.3	637.4	568.0	528.8
70.0	598.3	638.6	675.7	701.1	716.4	727.2	718.5	690.8	643.2	575.9	537.6
75.0	600.7	640.8	678.0	703.5	719.0	730.3	722.2	695.3	648.9	583.4	546.1
80.0	603.1	642.9	680.2	705.9	721.5	733.4	726.0	699.8	654.5	590.6	554.1
85.0	605.5	645.1	682.4	708.2	724.1	736.4	729.7	704.2	659.9	597.5	561.7
90.0	607.8	647.2	684.6	710.5	726.6	739.5	733.4	708.6	665.1	604.2	569.1
95.0	610.0	649.3	686.8	712.9	729.1	742.6	737.1	712.9	670.3	610.6	576.1
100.0	612.2	651.3	688.9	715.2	731.6	745.6	740.7	717.2	675.4	616.8	583.0

PRESSURE, MPa	TEMPERATURE, °C 400	425	450	475	500	550	600	650	700	750	800
.1	54.76	57.74	60.77	63.85	66.97	73.35	79.89	86.57	93.37	100.3	107.3
.5	55.13	58.08	61.08	64.14	67.25	73.61	80.13	86.80	93.59	100.5	107.5
1.0	55.61	58.51	61.48	64.51	67.60	73.93	80.44	87.09	93.87	100.8	107.8
2.5	57.15	59.89	62.75	65.69	68.71	74.94	81.39	88.01	94.75	101.6	108.5
5.0	60.06	62.49	65.10	67.86	70.74	76.79	83.13	89.67	96.34	103.1	109.9
7.5	63.56	65.54	67.82	70.33	73.03	78.84	85.04	91.49	98.08	104.8	111.5
10.0	67.89	69.19	71.00	73.16	75.61	81.11	87.14	93.47	99.97	106.5	113.2
12.5	73.40	73.63	74.73	76.43	78.53	83.62	89.43	95.63	102.0	108.5	115.0
15.0	80.68	79.13	79.18	80.20	81.85	86.39	91.92	97.96	104.2	110.6	116.9
17.5	90.74	86.10	84.54	84.58	85.61	89.45	94.63	100.5	106.6	112.8	119.0
20.0	105.4	95.11	91.03	89.70	89.89	92.81	97.57	103.2	109.1	115.2	121.2
22.5	128.5	107.0	98.99	95.69	94.75	96.51	100.7	106.0	111.8	117.7	123.5
25.0	169.0	123.1	108.8	102.7	100.3	100.6	104.1	109.1	114.6	120.3	126.0
27.5	248.4	145.4	121.0	111.0	106.6	105.0	107.8	112.4	117.6	123.1	128.6
30.0	329.7	176.1	136.0	120.6	113.7	109.8	111.7	115.8	120.7	126.0	131.3
35.0	384.5	259.3	176.4	144.8	130.7	120.8	120.3	123.3	127.5	132.2	137.0
40.0	414.0	323.5	227.7	175.8	151.6	133.5	130.0	131.5	134.8	138.8	143.1
45.0	435.0	363.6	276.6	211.5	176.1	147.9	140.6	140.3	142.6	145.9	149.6
50.0	451.5	391.5	315.8	247.3	202.8	163.7	152.1	149.8	150.9	153.4	156.4
55.0	465.4	412.8	346.6	279.8	229.9	180.6	164.3	159.8	159.6	161.2	163.4
60.0	477.6	429.9	371.2	308.2	255.9	198.1	177.0	170.1	168.5	169.1	170.6
65.0	488.5	444.3	391.4	332.6	279.9	215.5	189.9	180.6	177.6	177.2	177.9
70.0	498.6	456.9	408.3	353.6	301.7	232.5	202.7	191.0	186.7	185.3	185.2
75.0	507.9	468.1	422.9	371.9	321.4	249.0	215.3	201.4	195.6	193.3	192.4
80.0	516.7	478.3	435.7	387.8	339.1	264.6	227.5	211.5	204.4	201.1	199.6
85.0	525.1	487.7	447.2	402.0	355.1	279.5	239.3	221.2	212.9	208.8	206.5
90.0	533.0	496.4	457.6	414.6	369.6	293.5	250.6	230.6	221.1	216.1	213.1
95.0	540.6	504.7	467.1	426.1	382.7	306.8	261.5	239.5	228.8	223.1	219.5
100.0	547.9	512.6	476.0	436.5	394.8	319.2	271.8	248.0	236.2	229.7	225.5

by Eq. (II.2). This alternative thermal conductivity equation for scientific use is included in the set of interpolating equations for the thermophysical properties of fluid H_2O recommended by Kestin *et al.*[K4]

An examination of this alternative thermal conductivity equation for scientific use is documented in a technical report.[K5] It covers the same range of temperatures and pressures, Eq. (4.17), as the international thermal conductivity equation for scientific use.

Values for the thermal conductivity λ calculated from this alternative thermal conductivity equation for scientific use over a uniform grid of pressures and temperatures are presented in Table II.2. The values are very close to the values calculated from the international thermal conductivity equation for scientific use given in Table 5 of Appendix I. We present Table II.2 for those users who want to check their computer program when using this alternative form of the thermal conductivity equation for scientific use.

Appendix III

Thermal Conductivity in the Immediate Vicinity of the Critical Point

A calculation of the thermal conductivity and related properties, such as the Prandtl number and thermal diffusivity in the immediate vicinity of the critical point is complicated by the fact that λ, μ, χ_T, c_p, and c_v all diverge at the critical point. Since the actual temperature at which these properties become infinite will depend on the specific critical temperature implied by the representative equation used for the thermodynamic surface, we prefer to consider these properties near the critical point as functions of the temperature difference $\Delta T = T - T_c$, where T_c is the critical temperature of the equation of state used in the calculation of the thermal conductivity λ from Eq. (3.4).

The calculation of the viscosity μ in the immediate vicinity of the critical point was discussed in preceding papers.[S2,W2] Therefore, we restrict the discussion here to the behavior of the thermal conductivity λ in the vicinity of the critical point. In Fig. 20 we show the thermal conductivity in the critical region as a function of density at selected values of $\Delta T = T - T_c$ as calculated from Eq. (3.4) in conjunction with the IAPS 82 formulation. As can be seen from Fig. 20, the thermal conductivity thus calculated displays improbable features at the isotherm closest to the critical temperature; at $\Delta T = 0.01$ K the maximum critical enhancement in λ has shifted to a density well below the critical density ρ_c. The IAPS 82 formulation for the thermodynamic properties of water substance is analytic at the critical point. The modern theory of critical phenomena asserts that analytic equations cannot accomodate the divergent critical behavior of the thermodynamic surface correctly.[S27] To alleviate this difficulty Haar and co-workers incorporated in their analytic equation Gaussian-shaped deviation functions which led to improved agreement with the experimental data in the critical region[H1]; however, these terms cause nonphysical behavior of some thermodynamic properties in the range specified by Eq. (3.15).

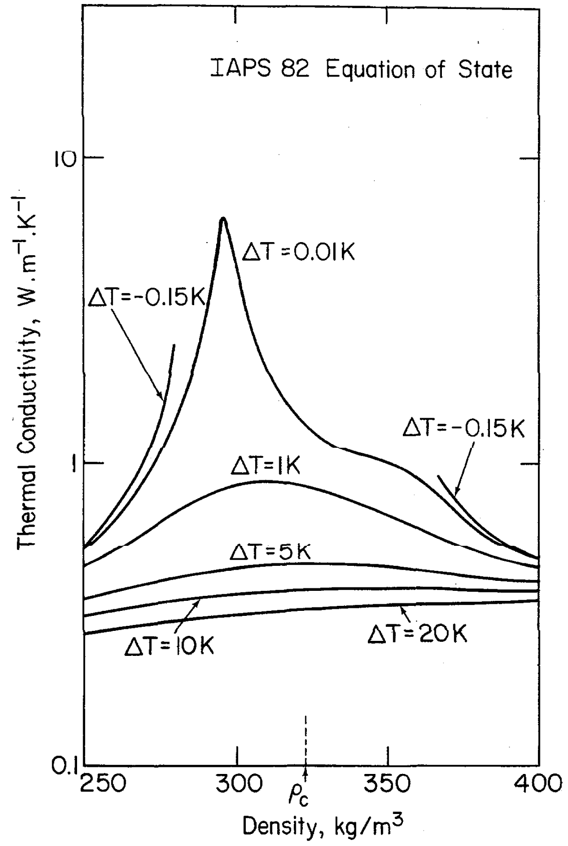

FIG. 20. The thermal conductivity in the critical region as a function of density at selected values of $\Delta T = T - T_c$, when calculated from Eq. (3.4) in conjunction with the IAPS 82 formulation.

A fundamental equation for the critical region of steam which incorporates the mathematical form of the singular behavior of the thermodynamic surface near the critical point predicted by theory has been formulated by Levelt Sengers *et al.*[L8] This scaled nonanalytic equation for the thermodynamic properties is valid in the range

$$0.995 \leqslant \bar{T} \leqslant 1.07, \quad 0.63 \leqslant \bar{\rho} \leqslant 1.32. \qquad \text{(III.1)}$$

Near the critical point, the thermal conductivity can be calculated from the scientific thermal conductivity equation in conjunction with the scaled fundamental equation of Levelt Sengers *et al.*[L8] In practice, we prefer to use the alternative thermal conductivity equation for scientific use, described in Appendix II, since it is related to a version of the equation for the viscosity μ which is better suited for the viscosity in the critical region as well. The values thus calculated for the thermal conductivity in the critical region are shown in Fig. 21.

On comparing the range, Eq. (III.1), with the range, Eq. (3.15), excluded from the IAPS 82 formulation, we note that there is a region of overlap where one can use either the IAPS 82 formulation or the scaled nonanalytic fundamental equation in calculating λ from the thermal conductivity equations for scientific use. The scaled fundamental equation is recommended in cases where it is important that the derivatives of the thermodynamic surface display the behavior expected from the modern theory of critical phenomena.[K4]

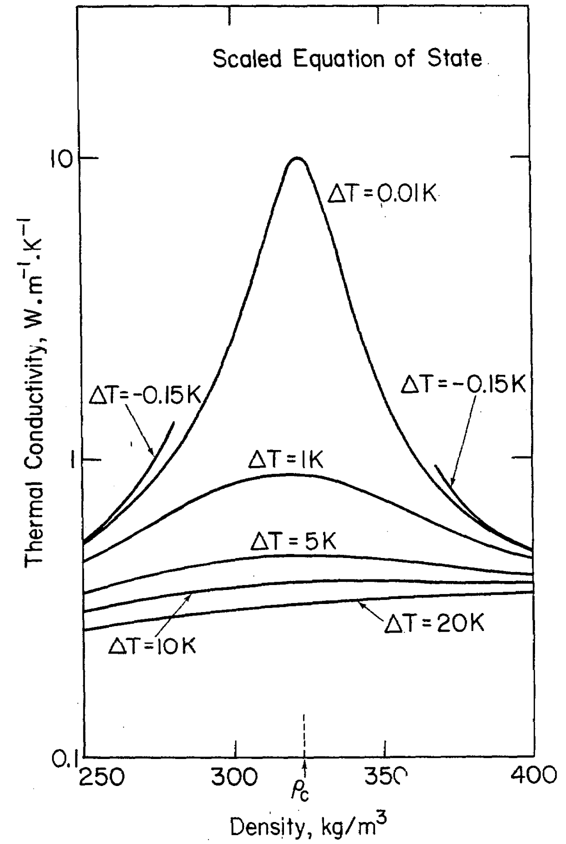

FIG. 21. The thermal conductivity in the critical region as a function of densities at selected values of $\Delta T = T - T_c$, when calculated from the alternative thermal conductivity equation for scientific use in conjunction with the scaled equation of Levelt Sengers *et al.* (Ref. L8).

Appendix IV
Alternative Thermal Conductivity Equation for Industrial Use

As mentioned in Appendix B of the IAPS Release on Thermal Conductivity, an alternative thermal conductivity equation for industrial use was proposed by Watson.[W3] This equation has the form

$$\lambda = \lambda_0(\overline{T}) \times \lambda_1''(\overline{T}, \overline{\rho}), \tag{IV.1}$$

in terms of the dimensionless variables $\overline{T}$ and $\overline{\rho}$ defined by Eq. (3.3). The function $\lambda_0(\overline{T})$ in Eq. (IV.1) is identical to the function $\lambda_0(\overline{T})$ defined by Eq. (3.5), while the function $\lambda_1''(\overline{T}, \overline{\rho})$ is

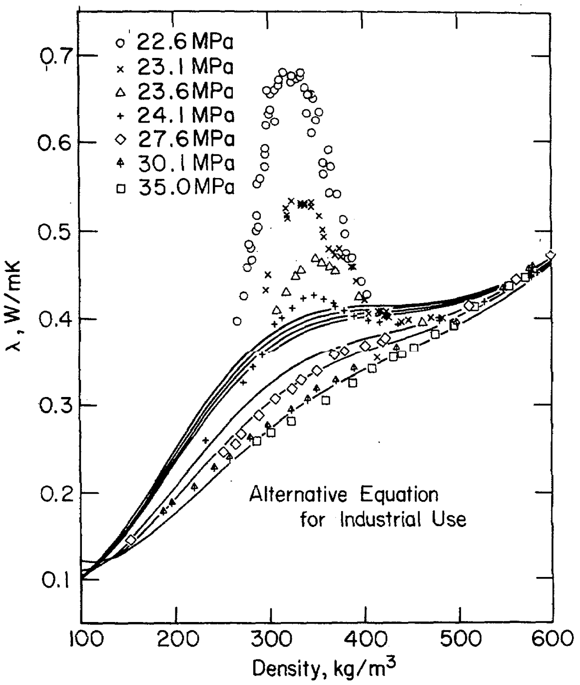

FIG. 22. The thermal conductivity of steam in the critical region as a function of density at constant pressures. The data are those of Sirota *et al.* (Ref. S5). The curves represent Eq. (IV.1) with densities from the IFC 67 formulation.

$$\lambda_1''(\overline{T}, \overline{\rho}) = \exp\left[\overline{\rho} \sum_{i=0}^{4} \sum_{j=0}^{5} c_{ij}^{\lambda} \times \left(\frac{1}{\overline{T}} - 1\right)^i (\overline{\rho} - 1)^j\right], \tag{IV.2}$$

with the coefficients c_{ij}^{λ} given in Table IV.1.

The alternative thermal conductivity equation for industrial use has the same form as Eq. (3.4), except that the term $\lambda_2(\overline{T}, \overline{\rho})$ in Eq. (3.4) has been omitted and the coefficients b_{ij}^{λ} in Eq. (3.7) have been replaced by a new set of coefficients c_{ij}^{λ}. In this alternative equation for industrial use, no attempt was made to reproduce the strong enhancement of the thermal conductivity in the critical region. This feature is illustrated in Fig. 22 where the values calculated from

TABLE IV.1. Coefficients c_{ij}^{λ} for $\lambda_1''(\overline{T}, \overline{\rho})$

$j \setminus i$	0	1	2	3	4
0	+ 2.047 600 4	+ 7.879 129 0	+ 23.260 573 6	+ 19.561 233 6	− 22.639 593 1
1	− 1.596 237 0	− 10.781 380 7	− 24.028 294 4	− 1.781 286 7	+ 19.462 098 6
2	+ 0.099 394 9	− 1.244 996 2	− 7.097 435 6	− 7.164 164 5	− 4.577 011 7
3	+ 1.377 417 9	+ 8.147 715 4	+ 12.034 091 2	+ 1.721 290 5	+ 0.204 277 1
4	− 1.024 246 4	− 3.752 168 0	− 3.330 343 4	0.0	0.0
5	+ 0.220 315 1	+ 0.441 868 6	+ 0.283 689 2	0.0	0.0

Table IV.2. Comparison of alternative thermal conductivity equation for industrial use with international input

First Author	Ref.	No. of Points	Av. % Dev.	Mean % Dev.	r.m.s. % Dev.	Wt. %	η > 1σ	η > 2σ	η > 3σ
Schmidt	[S3]	24	0.04	0.45	0.54	3.0	0	0	0
Timrot	[T1]	10	-0.72	0.83	1.01	3.0	0	0	0
Vargaftik	[V2]	19	-0.33	1.13	1.44	3.0	0	0	0
Milverton	[M2]	56	2.74	2.74	2.84	2.0	21	0	0
Timrot	[T2]	11	0.03	2.52	3.13	3.0	2	0	0
Timrot	[T3]	16	-0.34	1.73	2.73	3.0	3	1	0
Vargaftik	[V3]	7	-0.86	1.56	1.96	3.0	1	0	0
Schmidt	[S4]	8	0.54	0.59	0.63	2.0	0	0	0
Challoner	[C1]	5	0.24	0.24	0.41	1.0	0	0	0
Vargaftik	[V4]	9	0.58	2.08	2.27	2.0	2	0	0
Vargaftik	[V5]	61	1.75	2.31	2.88	3.0	13	0	0
Vargaftik	[V6]	30	-0.88	0.94	1.21	2.0	4	0	0
Lawson	[L3]	35	-0.16	2.19	3.14	3.0	6	1	1
Vargaftik	[V7]	41	1.06	1.61	1.91	3.0	2	0	0
Vines	[V8]	2	-1.86	2.40	3.04	3.0	1	0	0
Tarzimanov	[T4]	33	0.17	1.14	1.41	2.0	0	0	0
Vukalowich	[V9]	39	-0.39	2.82	3.70	5.0	7	0	0
Keyes	[K2]	50	-0.14	1.85	3.00	3.0	6	1	0
Vargaftik	[V10]	21	-0.02	1.22	1.38	3.0	0	0	0
Venart	[V11]	4	-0.75	1.81	2.00	3.0	0	0	0
Brain	[B3]	3	0.25	0.75	0.92	2.0	0	0	0
Cherneeva	[C2]	60	0.04	0.88	1.11	4.0	0	0	0
Le Neindre	[L5]	226	-0.11	0.64	0.84	2.0	6	0	0
Le Neindre	[L6]	65	-0.34	0.95	1.20	3.0	0	0	0
Tarzimanov	[T5]	19	0.18	0.60	0.76	2.0	0	0	0
Mashirov	[M3]	14	1.12	1.34	1.64	2.0	1	0	0
Brain	[B4]	36	-0.48	1.68	1.91	2.0	1	0	0
Bach	[B1]	374	-0.15	0.70	0.85	4.0	0	0	0
Tarzimanov	[T6]	8	1.30	2.10	2.60	2.0	5	0	0
Le Neindre	[L7]	98	-0.18	3.32	4.21	2.0	33	0	0
Tarzimanov	[T7]	86	-0.30	2.06	2.60	2.0	20	3	0
Bury	[B5]	102	-1.23	1.83	2.22	2.0	17	0	0
Vargaftik	[V12]	11	0.50	1.07	1.25	2.0	0	0	0
Minamiyama	[M4]	45	0.65	0.73	0.93	2.0	3	0	0
Rastorguyev	[R2]	442	0.12	0.63	0.78	2.0	2	0	0
Sirota	[S5]	214	-0.88	3.59	4.90	2.0	62	6	2
Castelli	[C3]	48	-0.88	0.89	1.10	2.0	5	0	0
Amirkhanov	[A1]	695	0.88	1.28	1.64	4.0	1	0	0
Takizawa	[T8]	29	1.32	1.40	1.55	2.0	5	0	0
Minamiyama	[M5]	180	0.03	0.66	0.91	2.0	8	0	0
Minamiyama	[M6]	241	-0.25	0.84	1.13	2.0	19	0	0
Tsederberg	[T9]	146	0.01	1.61	2.18	2.0	36	4	0
Overall results:		3623	0.12	1.33	2.05	-	292	16	3

the alternative thermal conductivity equation are compared with the data of Sirota *et al.* in the critical region. The corresponding information for the international thermal conductivity equation for industrial use was given in Fig. 15.

Just as the international thermal conductivity equation for industrial use, the alternative thermal conductivity equation for industrial use can be used with densities calculated from the IFC 67 formulation. It covers the same range, Eq. (3.1), as the international thermal conductivity equations except for the exclusion of a region around the critical point bounded by

$$0.98 \leqslant \overline{T} \leqslant 1.06, \quad 0.4 \leqslant \overline{\rho} \leqslant 1.65. \tag{IV.3}$$

Outside this range the alternative thermal conductivity equation for industrial use represents the experimental thermal conductivity data with an accuracy comparable to that of the international equation for scientific use.

In Table IV.2 we present a comparison between the thermal conductivity values calculated from the alternative equation for industrial use and the experimental data contained in the International Input. The corresponding information for the international thermal conductivity equations was given in Tables 11 and 12. Except for the large deviations encountered in the range defined by Eq. (IV.3), the alternative equation for industrial use yields a satisfactory representation of the experimental data. Also, since the data of Tsederberg *et al.* were included in its development, the alternative equation for industrial use provides a better representation of the thermal conductivity in the region of high temperatures and high pressures than the recommended interpolating equation for industrial use.

Values for the thermal conductivity λ from the alternative thermal conductivity equation with densities from the IFC 67 formulation calculated over a uniform grid of pressures and temperatures are presented in Table IV.3. The thermal conductivity as calculated from the alternative industrial thermal conductivity equation with densities from the IFC 67 formulation is shown in Fig. 23 as a function of temperature along selected isobars and in Fig. 24 as a function of pressure along selected isotherms. These figures may be compared with the corresponding Figs. 5 and 6 for the international industrial equation.

Table IV.3. Smoothed values of the thermal conductivity of water substance calculated from the alternative interpolating equation for industrial use with densities from the IFC 67 formulation for industrial use (λ in 10^{-3} W m^{-1} K^{-1})

PRESSURE, MPa	TEMPERATURE, °C										
	0	25	50	75	100	150	200	250	300	350	375
.1	561.0	607.4	645.0	669.1	24.3	28.6	33.2	38.1	43.4	48.9	51.8
.5	561.2	607.5	645.1	669.2	681.5	681.9	34.5	38.9	43.9	49.2	52.0
1.0	561.4	607.6	645.2	669.3	681.7	682.2	36.3	40.0	44.5	49.6	52.4
2.5	562.0	608.0	645.6	669.8	682.3	683.2	660.7	44.4	47.0	51.1	53.6
5.0	563.1	608.6	646.3	670.7	683.4	684.8	662.9	618.8	53.2	54.6	56.4
7.5	564.2	609.3	647.0	671.6	684.5	686.4	665.2	621.8	64.7	59.8	60.3
10.0	565.4	610.0	647.8	672.5	685.6	688.0	667.4	624.8	554.9	67.8	65.9
12.5	566.6	610.8	648.6	673.4	686.7	689.7	669.7	627.8	559.1	81.1	74.0
15.0	567.8	611.6	649.4	674.4	687.8	691.3	671.9	630.7	563.4	107.4	86.4
17.5	569.1	612.4	650.3	675.3	689.0	693.0	674.2	633.7	567.6	463.8	107.2
20.0	570.4	613.3	651.2	676.4	690.2	694.6	676.4	636.7	571.8	470.1	149.6
22.5	571.7	614.2	652.1	677.4	691.4	696.3	678.7	639.6	576.0	476.7	414.8
25.0	573.1	615.1	653.0	678.4	692.6	698.0	680.9	642.6	580.1	483.3	416.3
27.5	574.4	616.1	654.0	679.5	693.8	699.7	683.2	645.5	584.2	489.9	424.7
30.0	575.8	617.0	655.0	680.5	695.0	701.4	685.4	648.4	588.2	496.4	433.5
35.0	578.7	619.1	657.0	682.7	697.5	704.7	689.9	654.2	596.1	508.8	450.6
40.0	581.6	621.2	659.1	685.0	700.0	708.1	694.3	659.8	603.8	520.5	466.3
45.0	584.5	623.5	661.3	687.3	702.6	711.5	698.7	665.4	611.1	531.6	480.8
50.0	587.5	625.8	663.5	689.6	705.2	714.9	703.1	670.9	618.3	542.0	494.1
55.0	590.5	628.2	665.8	692.0	707.8	718.3	707.5	676.3	625.2	551.8	506.5
60.0	593.5	630.6	668.2	694.4	710.4	721.7	711.8	681.6	631.8	561.1	517.9
65.0	596.5	633.1	670.5	696.9	713.0	725.0	716.0	686.8	638.3	569.8	528.5
70.0	599.4	635.6	673.0	699.3	715.6	728.3	720.2	691.8	644.5	578.1	538.4
75.0	602.3	638.2	675.4	701.8	718.2	731.6	724.4	696.8	650.5	585.9	547.6
80.0	605.2	640.8	677.9	704.2	720.8	734.9	728.5	701.7	656.3	593.3	556.3
85.0	608.0	643.4	680.4	706.7	723.5	738.2	732.6	706.5	661.9	600.3	564.3
90.0	610.7	646.0	682.9	709.2	726.1	741.4	736.6	711.3	667.4	607.0	571.9
95.0	613.3	648.7	685.4	711.7	728.6	744.6	740.6	715.9	672.6	613.2	579.0
100.0	615.9	651.3	688.0	714.2	731.2	747.7	744.5	720.4	677.7	619.2	585.7

PRESSURE, MPa	TEMPERATURE, °C										
	400	425	450	475	500	550	600	650	700	750	800
.1	54.7	57.7	60.7	63.8	67.0	73.3	79.9	86.6	93.4	100.3	107.3
.5	54.9	57.9	60.9	64.0	67.2	73.6	80.2	86.9	93.7	100.6	107.6
1.0	55.2	58.2	61.2	64.3	67.4	73.9	80.5	87.2	94.1	101.0	108.0
2.5	56.3	59.1	62.1	65.2	68.3	74.8	81.5	88.3	95.2	102.1	109.1
5.0	58.6	61.1	63.9	66.9	70.0	76.6	83.4	90.3	97.2	104.1	110.9
7.5	61.7	63.8	66.2	69.0	72.1	78.6	85.4	92.3	99.3	106.1	112.8
10.0	66.0	67.2	69.1	71.6	74.5	80.8	87.6	94.5	101.5	108.2	114.8
12.5	71.6	71.5	72.7	74.7	77.2	83.3	90.0	96.9	103.7	110.4	116.9
15.0	79.4	77.1	77.1	78.4	80.5	86.0	92.5	99.4	106.2	112.7	119.0
17.5	90.3	84.4	82.5	82.7	84.2	89.1	95.3	102.0	108.7	115.1	121.2
20.0	106.4	93.8	89.2	87.9	88.5	92.5	98.3	104.8	111.3	117.5	123.4
22.5	131.6	106.4	97.3	94.0	93.4	96.2	101.5	107.7	114.0	120.1	125.7
25.0	174.8	123.5	107.5	101.2	99.0	100.3	105.0	110.8	116.9	122.7	128.0
27.5	259.7	147.1	120.1	109.6	105.4	104.8	108.6	114.0	119.8	125.4	130.4
30.0	340.4	179.3	135.8	119.5	112.6	109.7	112.6	117.5	122.9	128.1	132.9
35.0	377.4	266.6	177.8	144.4	130.0	120.8	121.1	124.7	129.3	133.9	138.0
40.0	400.6	319.2	230.2	176.1	151.4	133.6	130.7	132.6	136.2	139.9	143.2
45.0	420.7	349.8	273.8	212.0	176.3	148.2	141.2	141.1	143.4	146.2	148.7
50.0	438.5	374.3	305.9	245.6	203.0	164.3	152.6	150.2	151.0	152.7	154.2
55.0	454.6	395.6	332.5	274.3	229.6	181.7	164.8	159.7	159.0	159.4	159.9
60.0	469.2	414.4	355.7	299.7	254.1	199.7	177.7	169.7	167.1	166.3	165.6
65.0	482.5	431.3	376.4	322.6	276.8	217.8	191.0	180.0	175.5	173.3	171.4
70.0	494.7	446.5	394.9	343.6	298.0	235.6	204.8	190.6	184.1	180.3	177.2
75.0	505.9	460.3	411.5	362.6	317.8	252.9	218.5	201.4	192.7	187.4	183.0
80.0	516.3	472.9	426.6	379.9	336.3	269.7	232.2	212.2	201.3	194.4	188.7
85.0	525.9	484.4	440.2	395.5	353.3	285.9	245.6	223.0	210.0	201.3	194.3
90.0	534.8	495.0	452.7	409.7	368.9	301.5	258.6	233.7	218.5	208.1	199.7
95.0	543.0	504.6	464.0	422.6	383.0	316.3	271.2	244.1	226.9	214.7	204.9
100.0	550.6	513.5	474.3	434.3	395.8	330.1	283.4	254.1	235.1	221.2	209.9

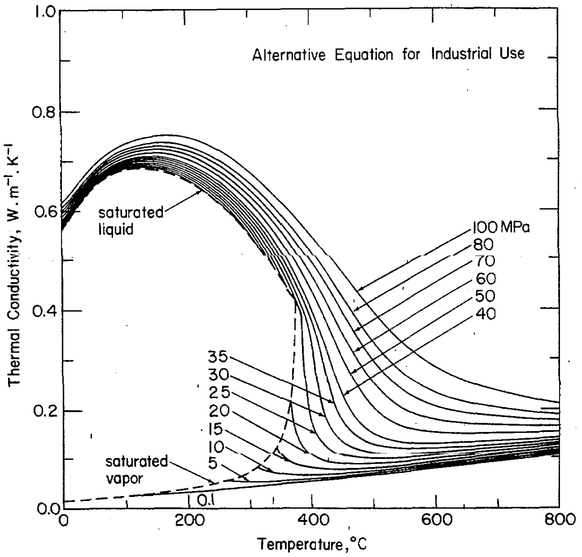

FIG. 23. Thermal conductivity, calculated from Eq. (IV.1), as a function of temperature at selected pressures.

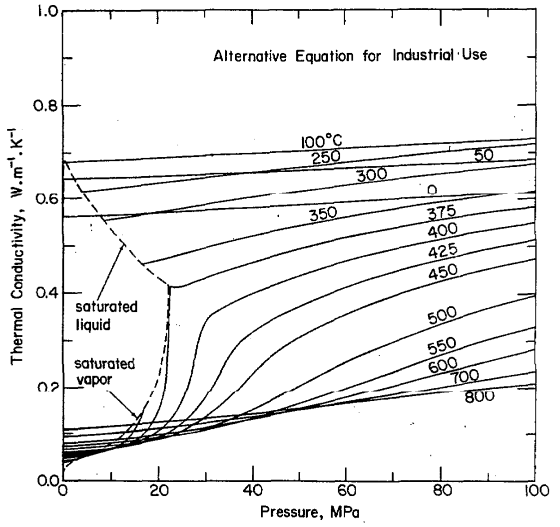

FIG. 24. Thermal conductivity, calculated from Eq. (IV.1), as a function of pressure at selected temperatures.

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